Improving Turbine Meter Measurement by Alternate Fluid Calibration

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1. INTRODUCTION

It is a well established fact that the calibration factor of a gas turbine meter shifts with pressure changes in a flowing medium. Recent studies have also shown that the calibration shift in most cases is significant. The latest revision of the AGA No.7 report recommends that a turbine meter should be calibrated close to its operating conditions in order to minimize measurement errors caused by pressure variation. This paper describes a new cost effective method of calibrating turbine gas meters by matching the Reynolds number or gas density of the test flow to the field conditions using an alternate fluid as a test medium.

2. THE EFFECT OF PRESSURE CHANGE ON METER CALIBRATION

A turbine meter is essentially a machine that converts the kinetic energy in a flowing medium into rotational motion. The rotational speed of an ideal turbine meter should be exactly proportional to the volumetric flow rate of the flowing medium.

In reality, the performance of a turbine gas meter is affected by additional factors which complicate the process. The rotational speed of the rotor in the turbine meter is roughly proportional to the volumetric flow rate of the flowing medium. However, depending on the design and the physical condition of the meter, a deviation of various degrees from the rotational speed of an ideal meter can generally be observed. This slippage is caused by a retarding torque on the rotor. The two components which constitute this retarding torque are:

a. Non-fluid forces (mechanical friction)
b. Fluid forces (fluid friction)

The non-fluid retarding forces are introduced by the friction of rotor bearings and the mechanical loading of drive train in the flow indicating registers. The fluid retarding forces are made up of fluid drag, which is a function of Reynolds number of the flow, and turbulence, which is a function of the flow velocity. The Reynolds number of a medium flowing in a piece of pipe is an expression of the ratio between the inertia force versus the viscous force of the flowing medium and can be shown mathematically as follow:

$$Re = \frac{\rho V D}{\mu} \qquad (1)$$

where ρ is the density of the gas medium, μ is the dynamic viscosity, V is the velocity of the flow, and D is the diameter of the pipe.

A relative small Reynolds number (Re < 2000) indicates that viscous forces dominate and therefore the flow is laminar in nature. Relatively large Reynolds number (Re > 4000) results in turbulent flow. The fluid flow is in a transition state when the Reynolds number is between 2000 and 4000.

Assuming that the diameter of the pipe remains constant, then equation (1) stipulates that the Reynolds number of the flow is influenced by the density, dynamic viscosity, and velocity of the flowing medium. For most gases, classical kinetic theory and experimental results show that their viscosity change very little up to a pressure of 1,500 psia. Viscosity changes are not considered significant in most natural gas flow measurements because the operating pressures typically do not reach this value. Based on the understanding of the ideal gas law, it can be said that the density of a gas is directly proportional to its pressure assuming there is no change in temperature. It is therefore possible to examine the effects of pressure, and hence Reynolds number, on the performance of a turbine gas meter.

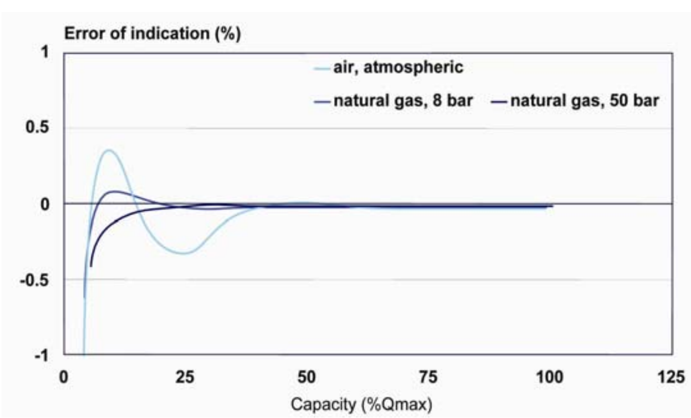

Figure 1: Typical Turbine Meter Performance vs Flow Capacity

Figure 1 shows the typical response of a turbine meter to flow rates at different operating pressures, and with different flow media. It can be seen that the flow rate and operating pressure has significant effects on the accuracy of a turbine meter. At low flow rates and low operating pressures, i.e. low Reynolds number, the non-fluid force has a dominant influence on the error performance of the meter. At high flow rates and high pressures, i.e. high Reynolds number, the non-fluid drag component of the retarding torque diminishes, and the meter responds strictly to the Reynolds number of the flow. The error curve of the meter hence becomes much more linear and predictable.

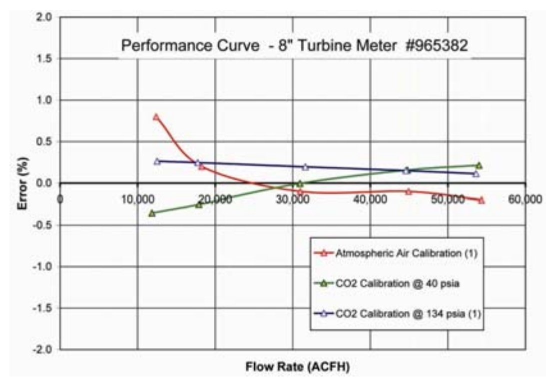

Figure 2: Metering Errors vs Flow Rates

Traditionally, a turbine meter's performance curve is expressed in terms of its metering errors versus the corresponding volumetric flow rates. In order to characterize the error performance of a turbine meter at different pressures or in different fluids, a family of curves would be necessary. An example is given in Figure 2. In this example, an 8-inch turbine meter was first calibrated in air at atmospheric pressure. The meter was then calibrated again in carbon dioxide gas at both 40 psia and 134 psia. A set of three error curves was produced. Each one of these three curves has very distinct and different attributes. Given this set of curves, one would not be able to quickly visualize the physical relationship between these curves. Furthermore, it is quite evident from Figure 2 that any one of the three calibration curves does not represent the behavior of the meter operating under the other two sets of conditions. In this example, most of the error differences did not exceed 1% when the operating environment was changed. However, research work published recently by AGA and also by the Gas Research Institute [*2,3, and 4*] reported that metering errors of this magnitude or higher are not uncommon, and accurate turbine meter calibrations can only be obtained when a calibration program is tailored to a specific flow regime. The latest revision of the AGA Report No. 7 [*1*] suggests that "a meter calibration carried out in a test facility over a particular range of Reynolds numbers characterize the meter's performance when used to measure gas over the same range of Reynolds number when the meter is in service". It also further recommends that "the expected operating Reynolds number range and/or density for a meter needs to be taken into account when designing a calibration program".

Figure 3 shows the same set of data used previously in Figure 2 consolidated into a single performance curve. This performance curve is expressed in terms of the metering errors versus Reynolds numbers of the test meter. Aside from its comparative simplicity, one can immediately recognize the resemblance of this curve to the theoretical performance curves shown in Figure 1 under various operating conditions. It also becomes apparent by observing the overlapping data points that the meter does exhibit the same error characteristics when operated at the same Reynolds numbers, thus confirming the validity of the AGA recommendations.

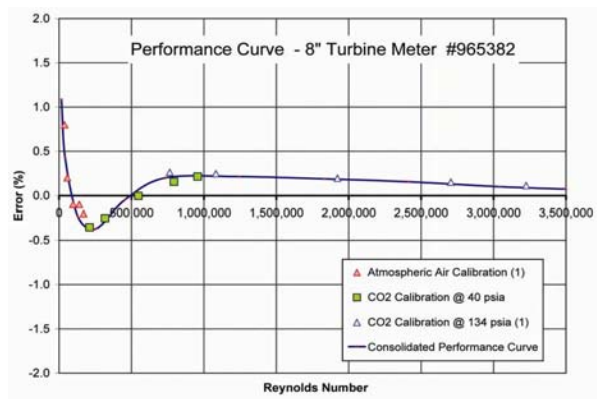

Figure 3: Metering Errors vs Reynolds

3. THE COST OF MEASUREMENT ERRORS

The pursuit of better flow measurement accuracy in the gas industry is driven by the high cost of natural gas. Although it is intuitive that the same measurement errors cost more at higher pressure, it would be instructive to examine the cost impacts of such errors more closely as demonstrated in Table 1.

In Table 1, the monetary costs for 0.5 percent flow measurement error made in a typical 6 year calibration were shown. Turbine meters ranging from 4 inches to 12 inches diameter were used in this example. An average loading factor of 30 percent of maximum capacity Q_{max} for each meter was

Turbine Meter Operating at 50 psig			
Meter Size	Energy Delivered in a 6 year Calibration Cycle *	Cost of Energy Delivered *	Cost of 0.5% Measurement Error
Inches	MMBtu	US$	US$
4	1,271,208	8,898,458	**44,492**
6	2,478,052	17,346,361	**86,732**
8	4,264,180	29,849,258	**149,246**
8 HC	6,388,224	44,717,567	**223,588**
12	9,944,389	69,610,722	**348,054**
12 HC	16,332,613	114,328,289	**571,641**

Turbine Meter Operating at 500 psig			
Meter Size	Energy Delivered in a 6 year Calibration Cycle *	Cost of Energy Delivered *	Cost of 0.5% Measurement Error
Inches	MMBtu	US$	US$
4	10,990,320	76,932,238	**384,661**
6	21,369,172	149,584,204	**747,921**
8	36,623,671	256,365,699	**1,281,828**
8 HC	54,951,598	384,661,188	**1,923,306**
12	85,476,688	598,336,817	**2,991,684**
12 HC	140,428,286	982,998,005	**4,914,990**

Note 1: Turbine meters operating at 30% of Qmax average
2. Energy content of natural gas based on 1.0205 MBtu/cu.ft.
3. Cost of energy calculated based on $7.00 USD per MMBtu (including delivery)

Table 1: The Cost of Measurement Errors

assumed. The numbers shown on the left hand side of the table represent the cost of errors operating the meters at 50 psig, while the right hand side numbers show the cost of errors for the same set of meters operating at 500 psig. All of the other operating parameters in each case were exactly the same. The measurement error costs at 50 psig were by no means trivial, but the same at 500 psig were significant. For a high capacity 12-inch turbine meter operating at 500 psig, the cost of making 0.5 percent measurement error was in excess of $4.9 million over a period of six years. This example clearly shows the importance of ensuring the accuracy of turbine meters. The GRI research work cited in references [*2*] and [*3*] demonstrated that turbine metering errors of more than 0.5 percent are not uncommon when the line pressure effect is overlooked. When the costs of such errors are understood, it is apparent that the need to calibrate turbine meters for their full operating Reynolds number range should not be ignored.

4. TURBINE METER CALIBRATION IN ALTERNATE FLUIDS

Traditionally, calibrations of turbine meters intended for natural gas measurement are carried out in natural gas test facilities. However, calibrating natural gas turbine meters using a different fluid is also a common and long accepted practice. For example, atmospheric pressure calibration of turbine meters in air is recognized by most regulatory bodies in the world as a valid procedure. Alternate fluid calibration is often done in order to minimize calibration cost, or to achieve calibration conditions which are difficult to realize in a conventional natural gas test facility.

Since November 2002, Terasen Gas in British Columbia, Canada has engaged in research work in gas turbine meter proving technologies using alternate fluids (Figure 4). The objective of this work was to design and build an efficient turbine meter calibration facility for commercial meter testing purposes. The test media examined include natural gas, air, argon, carbon dioxide, and several other gases which have densities substantially higher than that of natural gas. Carbon dioxide gas was chosen as the best test medium for the Terasen turbine meter proving facility.

Since it was established in Section 2 that Reynolds number and/or density matching to field operating conditions is a key consideration for obtaining optimal turbine meter calibration, an effective turbine meter proving facility must therefore be able to test meters at a wide range of Reynolds number and pressures.

Figure 4: Testing Turbine Meters in CO_2 at Triple Point

We shall explore the effect of different gases on Reynolds number. Substituting the appropriate properties of gases in equation (1), one can calculate the Reynolds numbers of various test gases in a meter run. The equivalent natural gas pressure which produces the same Reynolds number as the test gas stream in a meter run is known as the effective test pressure $P_{(eff)}$ of the test gas. Effective test pressure of a test gas can be determined by the following formula:

$$P_{(eff)} = \frac{Re_{(test\ gas)}}{Re_{(natural\ gas)}} \qquad (2)$$

where $Re_{(test\ gas)}$ is the Reynolds number of the test gas, and $Re_{(natural\ gas)}$ is the Reynolds number of natural gas. The effective test pressure of a test gas medium changes only slightly with the operating temperature and pressure. As a rule of thumb, the effective pressure of a test gas can be considered constant for operating pressure under 500 psia and temperature from 0 to 60ºF. For example, the effective test pressures of air and carbon dioxide were determined to be 1.024 and 2.102 respectively at 200 psia and 60ºF [*6*]. Based on these figures, one may conclude that while air produces a comparable Reynolds number to natural gas, it would be more advantageous to substitute the natural gas in a turbine meter test loop with carbon dioxide in order to produce Reynolds numbers twice as high at the same test pressure.

Similar considerations can be given to the density ratios of the gases used in the above example. Comparing air with natural gas under the same operating conditions, the density ratio is 1.67. The carbon dioxide to natural gas density ratio is 2.75. Based on this comparison, one can also come to the same conclusion that carbon dioxide is a better substitute than air as a meter proving medium when the density ratios of these gases are being considered.

Calibrating turbine meters in carbon dioxide gas presents several advantages: (1) carbon dioxide, being noncombustible, is safer to handle than natural gas; (2) comparing to both natural gas and air, the lower operating pressures needed to reach the target meter test Reynolds number require less compression; (3) the fact that the carbon dioxide meter proving loop can operate at a lower pressure means that time saving

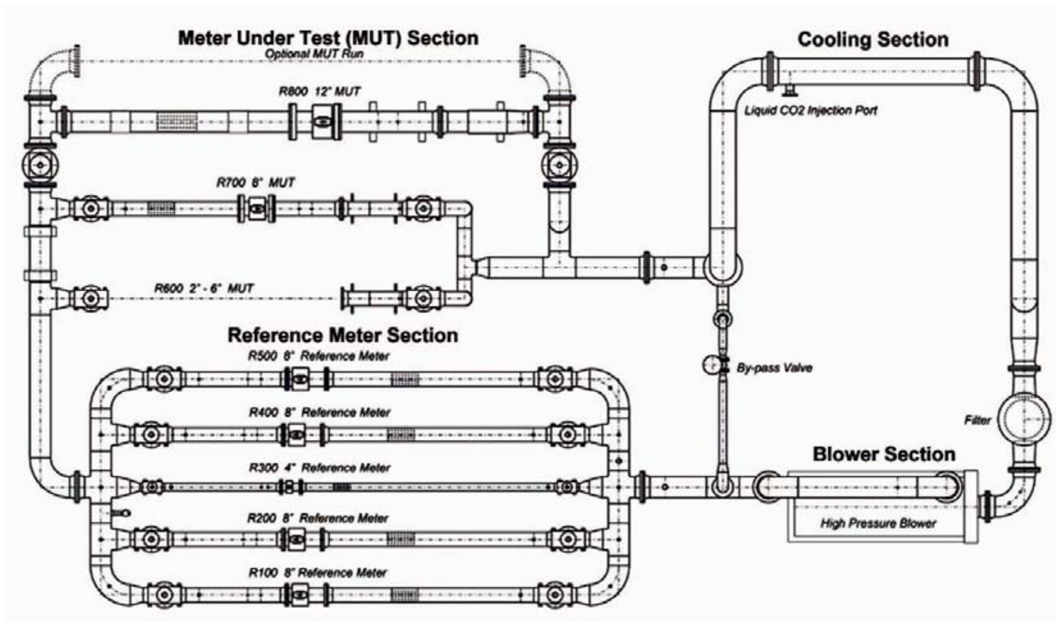

Figure 5: Terasen Triple Point Turbine Meter Testing Facility Schmatic

devices such as automated test meter clamps can be easily and inexpensively deployed; (4) because of the higher density of carbon dioxide, no density related correction would be necessary to improve the accuracy of calibration; (5) the triple point of carbon dioxide occurs much closer to ambient conditions than most gases, a property that allows the temperature of the flowing gas in the test loop to be controlled by direct injection of carbon dioxide in the liquid phase. Using this property of carbon dioxide and a temperature regulating process patented by Terasen, the temperature of the flowing gas in a meter test loop can be controlled to within ±1.8ºF (1ºC), between 40º to 104ºF (5º to 40ºC). This capability is unusual amongst large gas meter calibration facilities, few of which have variable operating temperature.

With these advantages in mind, Terasen Gas proceeded with funding a "proof of concept" test at the Southwest Research Institute's (SwRI) Meter Research Facility (MRF) in the fall of 2003. The purpose of this test was to validate the use of carbon dioxide gas as a calibration medium. The favorable results from this experiment led to the design and construction of the Triple Point Turbine Meter Testing Facility. A detailed account of this experiment was published in reference [*5*].

5. THE TRIPLE POINT FACILITY

Terasen Gas, a subsidiary of Kinder Morgan, supplies natural gas to more than 875,000 customers in the Province of British Columbia, Canada. Terasen Measurement tests, calibrates, and repairs electricity and gas meters, and provides asset management services throughout North America. The Triple Point Facility is located at Terasen Measurement's headquarters in Penticton, British Columbia, Canada. The Turbine Meter Section operates Triple Point as well as an atmospheric air prover. The staff is fully trained and equipped to test and repair turbine meters.

6. FACILITY DESCRIPTION

Triple Point is a closed loop facility designed specifically to calibrate turbine meters at their operating conditions. The most striking difference between Triple Point and other conventional high pressure meter testing facilities is its small footprint. The entire facility, including the control room and the liquid carbon dioxide storage tank, occupies an area less than 2,400 square feet. The absence of a heat exchanger to cool the circulating gas is due to the use of a patented compact cryogenic injection cooler. The Triple Point facility is self-contained. Since the test medium is carbon dioxide gas, the test loop does not rely on any high pressure natural gas pipeline feed to function.

The flow reference of the facility is provided by a bank of four 8-inch and one 4-inch Instromet X-Series master turbine meters. The test flow rate is controlled by adjusting the speed of a high pressure blower. Each master meter run is engaged independently by an array of isolation ball valves.

The test meter section consists of three meter runs of nominal sizes twelve, eight, and four inches. Each of the test runs is equipped with a set of hydraulic clamps to facilitate the mounting of test meters. These clamps enable the test technician to rapidly mount a meter-under-test (MUT) in order to maximize the productive time of the test facility. The typical preparation time for mounting a 12-inch turbine meter is less than twenty minutes. The fast test set-up time is the key to providing quick service for the facility's users.

All of the meter runs in Triple Point were built to AGA No. 7 standard. The reference and test runs are located in a building with environmental control. The liquid carbon dioxide storage, temperature control panels, liquid carbon dioxide injection system, and high pressure blower are located outdoors. Figure 5 shows the schematic layout of the Triple Point Facility.

7. OPERATING CAPABILITIES

The recommendations found in the new AGA-7 are based on a comprehensive research program into the characteristics of modern commercial turbine gas meters [*2, 3*, and *4*]. The research shows that these meters are quite sensitive to Reynolds number, particularly at lower flow rates and pressures. Based on this knowledge, Triple Point has been designed to operate over the range of measurement conditions in which turbine meters have been demonstrated to suffer from non-linearity.

With a maximum flow rate of 230,000 ACFH (6,510 m3/hr), Triple Point is capable of testing the full flow range of an extended-range 12-inch (300 mm) turbine meter. The test loop supports the maximum volumetric flow rate at an operating pressure of 116 psia (8 bars). With the test loop operating at the maximum design pressure of 232 psia (16 bars), the flow rate is reduced to approximately 120,000 ACFH (3,400 m3/hr). The upper limit of the operating pressure and flow rate is defined by the mass flow capacity of the high pressure blower. The maximum Reynolds number generated by the test loop is well over 9 million. The facility's operating capabilities are shown in Figure 6. A summary of Triple Point's operating specifications is shown in Table 2.

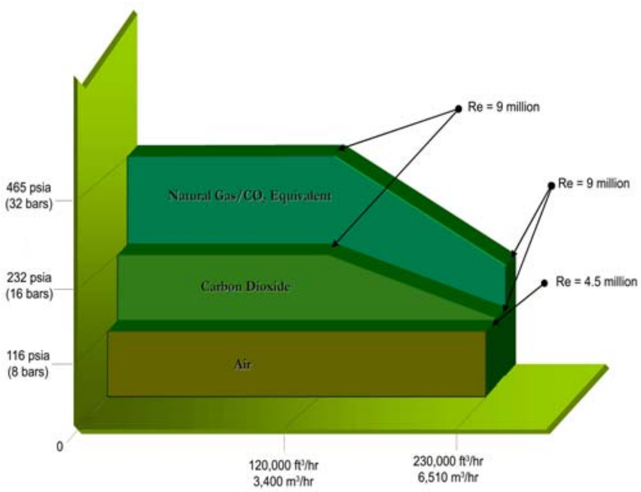

Figure 6: Triple Point Calibration Capacity

The facility was commissioned in the summer of 2005. After a year of vigorous evaluation and testing, Triple Point was recognized by the Canadian government (Measurement Canada) in August 2006 as an approved provider of high pressure test data for turbine gas meters in Canada.

8. TRACEABILITY

Since carbon dioxide is not a traditional calibration gas for metering devices, one of the first concerns regarding traceability was to establish its suitability for use as a test medium. Prior to construction of Triple Point, a research program was conducted at the Meter Research Facility (MRF) at Southwest Research Institute. Six turbine meters of 4-inch, 8-inch, and 12-inch (100, 200 and 300 mm) diameter from two different manufacturers were tested in both carbon dioxide and natural gas over the widest available range of matching Reynolds numbers. The results of this dual fluid work have been published in reference [5]. To summarize, the research shows that the calibration results for all six of the meters agreed within 0.15 %. A typical result is shown in Figure 7.

As can be seen, the correspondence of the K-factors with the different gases is almost identical when plotted against Reynolds

Specifications

1.	**Type of Meter**	Gas Turbine Meter
2.	**Meter Size**	2" to 12"
3.	**Flange Rating**	ANSI 150, 300, 600
4.	**Test Medium**	Carbon Dioxide
5.	**Flow Range**	
	4",8", and 12" meter	2,700 to 230,000 ACFH
	2" and 3" meter	700 to 10,000 ACFH
6.	**Operating Pressure**	Atmospheric to 240 psig
7.	**Pressure Stability**	± 1.0 psig
8.	**Operating Temperature**	40 to 104ºF (±2ºF)
		± .5°F stability during test
9.	**Reynolds Number**	100,000 to 9,000,000
10.	**Measurement Uncertainty**	±0.27 of deviation (GUM method) Confident level 95% (k = 2)
11.	**Traceability**	NMI (Netherlands)
12.	**Government Recognition**	Measurement Canada

Table 2: Triple Point Specifications

number, with both tracking non-linearity in the meter's performance well. From this evidence, it was concluded that carbon dioxide can reliably be used to calibrate natural gas meters.

The reference meters at Triple Point have been calibrated at three facilities operated by the Nederlands Meetinstitut (NMi) in the Netherlands: Silvolde on atmospheric air, Utrecht on 7.6 bar natural gas, and Bergum on 18 bar natural gas. At these locations, data for the meters was taken in the range of Reynolds numbers over which they are being used at Triple Point. Thus, the reference meters are traceable to the European harmonized cubic meter.

Traceability of the pressure and temperature transmitters used at the facility is maintained by comparing them periodically to reference equipment which has been calibrated and certified by Measurement Canada.

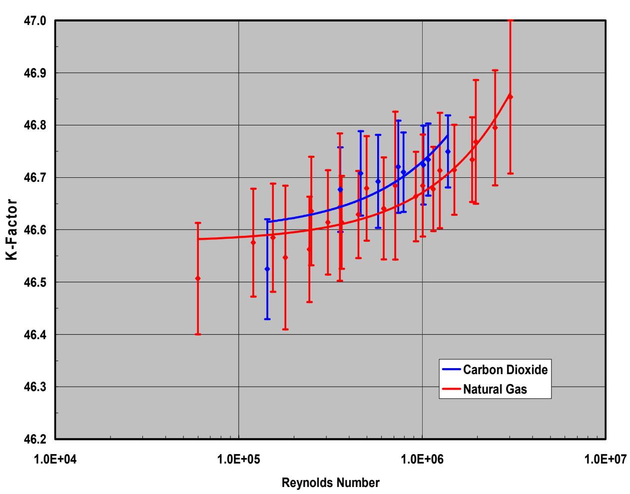

Figure 7: Dual Fluid Test Results at SwRI

9. MEASUREMENT UNCERTAINTY

In order to satisfy the Canadian Government's regulatory requirements for recognizing the test data produced by the facility [*7*], Triple Point has undergone a very comprehensive process of producing a measurement uncertainty analysis document [*8*]. The measurement uncertainty analysis was modeled after the *ISO GUM* [*9*] recommendations. All of the measurement uncertainty contributing factors in the Triple Point calibration process were identified, and their impacts to the overall uncertainty explained. Being a brand new facility, some of the longer term measurement statistics were not available at this early stage of development. In those cases, worse case figures were used for the analysis. The expanded uncertainty of the calibration facility was determined to be ±0.27% with a confidence level of 95% (k =2). This uncertainty figure is expected to improve as more test data becomes available to replace the worse case estimates presently used. The current uncertainty figure is well better than the ±0.33% required for government recognition of high pressure meter calibration facilities in Canada.

10. INTER-FACILITY COMPARISONS

It is necessary for high-pressure gas meter calibration facilities to compare their results with those from other accepted test facilities in order to demonstrate that calibrations are valid. At Triple Point, this obligation is currently being met in two ways.

First, the six meters used in the dual fluid research program have been retained and used to compare the facility's measurements with those made in 2003 at the MRF. The test data agreement between Triple Point and the 2003 dual fluid test was excellent and well within the level of measurement uncertainty expected of the two facilities.

Secondly, Triple Point has participated in inter-facility round-robin comparison and will continue to do so when opportunities arise. Arrangement is being made to design and fabricate an artifact specifically for routine inter-facility comparisons between participants of the program. This work is expected to be completed in 2007. Test results will be published once they are available.

11. ACCREDITATIONS

Accreditation of a meter calibration facility by a recognized organization is an assurance that the quality management system of the facility meets the standard of the organization issuing the accreditation. Terasen Measurement is pursuing accreditation by Measurement Canada as well as ISO 17025 for Triple Point. This will be integrated with Terasen's existing ISO 9001 and Measurement Canada accreditations currently established for the other facilities at the Penticton site.

12. CONCLUSION

Triple Point is a new facility which has been designed specifically to address the need for high quality commercial turbine meter calibration. Gas metering errors are costly. Using a patented carbon dioxide process, the facility is capable of testing turbine meters over a wide range of Reynolds numbers as recommended by the AGA No. 7 report, thereby providing accurate meter calibration data appropriate for the users' operating conditions. The facility has been recognized by the Canadian government as an approved high pressure turbine meter calibration facility since 2006. On-going efforts are being made to maintain and improve the high quality test data produced by the facility.

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