PROCESS VARIABLE STABILITY, DATA PROCESSING AND INSTALLATION AND ENVIRONMENTAL INFLUENCES DURING ULTRASONIC METER CALIBRATION

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Abstract: This paper is a synopsis of TCC's data acquisition methodology, processing protocols and supervisory system means, reference values and integrity procedures, presented together with a detailed description of the stability requirement of pressure, temperature and flows at the laboratory during ultrasonic meter calibration to minimise Type A contributions. TCC calibration data, including repeatability and short-term reproducibility values, taken from a meter calibration will be presented and used as baseline to illustrate the sensitivity of USM response to environmental and calibration variables. Monte Carlo simulation modeling will be used as replication tool. To provide a real-time illustration of TCC's operational capability, at the end of the presentation of this paper a calibrated meter will be verified live remotely by running the calibration laboratory from the conference room.

1. INTRODUCTION

The calibration process of an ultrasonic meter contains many critical components varying from the traceability, integrity, reliability and the reproducibility of the references values at the laboratory to the prevailing operating conditions and the environmental and installation effects during testing. Each component affects the meter response differently and some can even alter the intrinsic characteristic linearity of the ultrasonic meter performance

Particularly, the process conditions at the flow laboratory during calibration, such as flow and temperature stability, the operational control limits and environmental influences directly impact the meter performance and prove to be crucial for a correct meter validation.

This paper discusses the influence of some of those components on the meter calibration from the perspective of the Transcanada Calibration facility procedures and capabilities, with particular emphasis on the role played by the reference values, the stability of the operating conditions and the facility environmental influences.

2. TRACEABILITY AND DATA ACQUISITION

2.1 European Harmonized Reference Level

TransCanada Calibrations reference values has a direct tie to the Harmonized European natural gas cubic meter [1], [2] which was developed via key comparison of the reference levels of the independently realized traceability chains at the German PTB-Pigsar, Netherlands NMi-VSL and France LNE-LADG national metrology institutes.

The comparison method encompasses a weighted average of the three individual national realizations based upon the following metrological prerequisites:

- The independency of the realized traceability chains,
- The understanding and mutually acceptance of each individual system uncertainty budget and,
- The long term repeatability of the reference values, the degree of equivalence and the correlated permissible difference among the three systems as compared to the root square sum of the corresponding uncertainties

2.2 Reference Values Repeatability, Long Term Repeatability and Integrity

Between May 2005 and September 2005, NMi VSL-Flow with the assistance of TCC personnel, carried out a re-verification of the calibration status of the TCC's reference values.

The following discussion on the *quality of the TransCanada reference values* is founded on the results of the re-verification and the successive tracking information gathered during normal facility operation.

Repeatability and Agreement. The agreement and the repeatability of the reference values of the TCC turbine meters as compared against the European harmonized reference level are described in figure 1.

Figure 1 represents the error band of 3x6", 2x8", 1x10" and 3x12" travel master turbine meters and 2x16" sleeping standards turbine meters compared randomly against the harmonized values of 5x16",1x12" and 2x8" TCC turbine reference meters. The error bars across the facility's flow range fall within ± 0.06%, a value well within the expected combined meter and facility repeatability with a 95% confidence

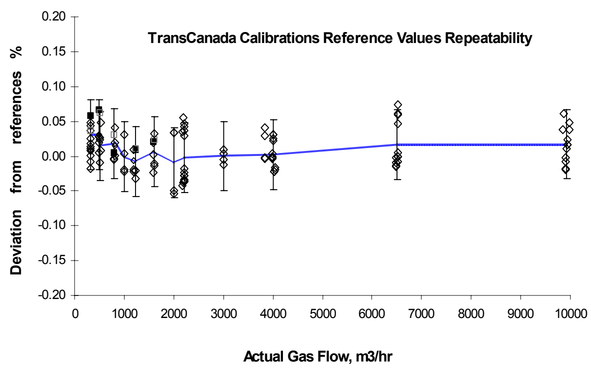

Fig No 1. Agreement and Repeatability of TCC's Reference Values.

Integrity. Each time that any meter is calibrated at TCC, the references values at the turbine are checked by a matched resolution ultrasonic meter, also traceable to the European harmonized reference values and positioned upstream.

The two meters are positioned in series in the reference run under the same controlled environment and each one calculates an error as compared with the Meter Under Test – MUT-, that is closely monitored for reference integrity.

The comparison criterion for the error difference is based on the individual standard uncertainty values identified during the commissioning and corroborated during the day to day operation.

Fig 2 represents the correlating statistics for the error difference at Reference Run No 8 (size 8") (turbine error minus ultrasonic error) compared against the maximum expected standard uncertainty values from both meters at 1S and 2S levels.

The control line at K=1 is derived from the combined uncertainties yielded by a Type A standard uncertainty of 0.05% and 0.075% for the turbine and the ultrasonic meter respectively for high flow calibrations (typically above 200 m3/hr) and 0.1% and 0.125% for the turbine and the ultrasonic meter respectively for low flows.

Figure 3 depicts similar approach for Reference Run No 2 (Size 16") with control lines at K=1 based on the combined uncertainties yielded by a standard uncertainty of 0.03% and 0.06% for the turbine and the ultrasonic meter respectively, for high flow calibrations (typically above 800 m3/hr)

In both cases, the scatter of the error differences values rests on the K=1 band in a very large proportion, a clear indication of the stability conditions prevailing during the tracking period and the long term stability of the reference values.

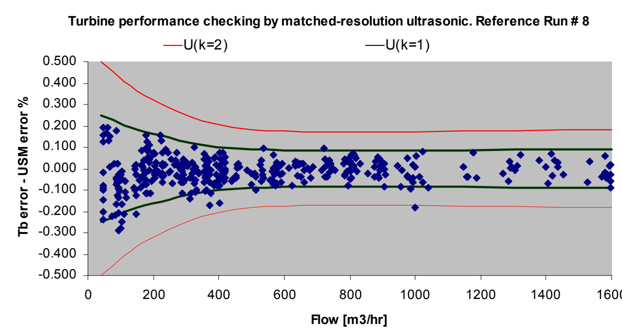

Fig No 2. Correlating Statistics between TCC' s turbine and Matching Ultrasonic Meter for Reference Run # 8.

The quality of each reference run is evaluated through lines band control as explained above besides periodic verification of the calibration status by checking with TCC's Traveling Reference Meters (TRM's*).*

Reproducibility. As with the repeatability, the long term stability of the reference values is a component of the facility uncertainty statement. The calibration capability status of the TCC reference values was checked during the facility re-verification procedure.

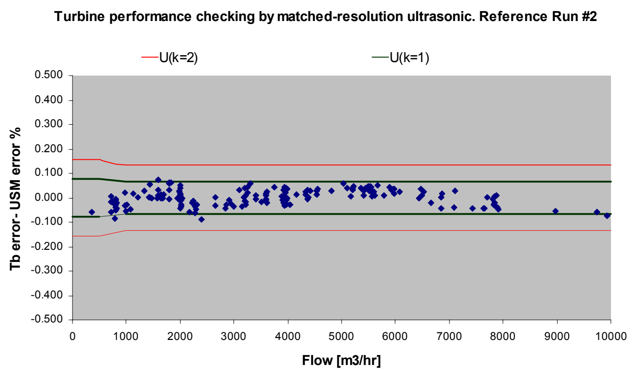

Fig No 3. Correlating statistics between TCC' s turbine and matching ultrasonic meter for Reference Run # 2.

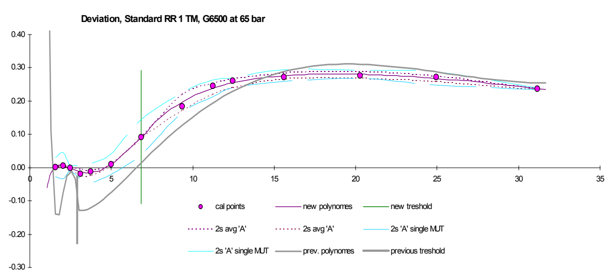

Fig No 4. Long term Stability of TCC's reference values after six years in operation for reference run # 1

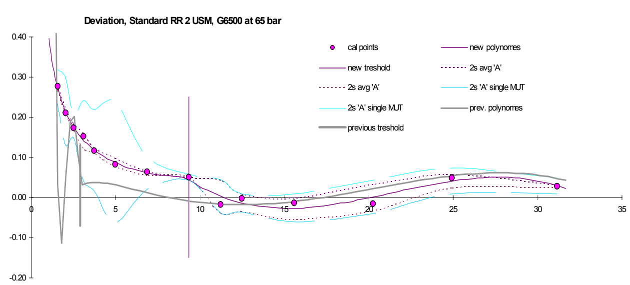

Fig No 5. Long term stability of TCC's reference values after six years in operation for Reference run # 2

During commissioning at 2001, a reproducibility value of 0.1% was considered on the base of NMi VSL-Flow previous experience.

A stable value drifting not more than 0.1% was observed for the average reference value of all reference meters for the evaluation period as represented by figure No 4 and figure No 5. Both pictures depict the graphical correlation found between the polynomial corrections applied to two different TCC reference meters during the five years re-verification interval.

2.3 Data Acquisition Impact

At TransCanada Calibrations the data acquisition system calculates the average error and the standard deviation on a running basis. Implicit on this methodology is the fact that a maximised sampling time is required to limit the Type A uncertainty contribution [3] during calibration, particularly of an ultrasonic meter under dynamic conditions influence.

The statistical approach of the required number of samples needed to achieve a type A uncertainty contribution of less than 0.1% is calculated as;

$$N = \frac{4s^2}{U^2} + 1 \qquad (1)$$

with s the standard deviation in the individual samples and U is the uncertainty of the end result (U at 2s level).

Designed to minimise the facility impact on the performance of ultrasonic meters during calibration and with ultrasonic meters (16") providing checking to the turbine reference meters, at TCC the averaging time required for calibration was estimated through the following reasoning:

Ultrasonic meters have a much wider bandwidth than turbine meters and are able to measure flow fluctuations up to about 1 kHz. Therefore, the actual flow velocity including the turbulent fluctuations is measured. When being tested, these turbulent fluctuations have to be eliminated from the final result.

A minimum required length of a 16" pipe was considered for reducing the turbulence in a normal "fully developed" flow to levels of less than 0.1% (as a function of number of vortices passed and their Gaussian distribution in the pipe). From the analysis, an equation relating velocity V in m/s with time Tav, in seconds was deducted as:

$$T_{av} = 400 \bullet D / V \qquad (2)$$

Where for a 16” meter (D = 0.4 m) at a flow velocity of 1 m/s, the averaging time would be at least 160 seconds and at 0.5 m/s, 320 seconds as the time needed to reduce the uncertainty 0.1%

Three hundred seconds were selected as the testing time at TCC where from equation (1) the type A uncertainty is quantified as:

$$U = 2S/\sqrt{N-1} = 1/\sqrt{299} = 0.07\%$$

with a 0.5 % standard deviation.

3. ULTRASONIC METER TESTING AT TRANSCANADA

At TransCanada the comparison process is completed at line conditions by correcting the readings from the reference meters to the conditions of the tested ultrasonic meter.

$$\frac{qmut}{qref} = \frac{Pref}{Pmut} \cdot \frac{ZmutTmut}{Zref \cdot Tref} - \frac{1}{qref} \cdot \frac{ZmutTmut}{Pmut} \cdot \frac{d}{dt}\left(\frac{P_v \cdot V}{Z_v \cdot T_v}\right) \quad (3)$$

$$Error = \frac{qmut\_ind}{qmut} - 1 \quad (4)$$

The relationship is presented in equation 3, where, under stable operating conditions and no installation and/or thermal effects, the corrections applied due to pressure, temperature and compressibility ratio are minimal. Additionally, a reduced distance between the meter under test (MUT) and the reference meters together with the enclosed and thermal isolated conditions inside the facility reduce dramatically the pressure and temperature drift and the packing effect and its impact on the meter error, particularly for low flows.

Tables 1 and 2 illustrate the calibration result for a 12” USM with the standard uncertainty in the sample mean for Error, Q and process variables defined as [4]:

$$u_{\bar{x}} = \frac{s}{\sqrt{n}}$$

Where $u_{\bar{x}}$; Standard uncertainty s; sampled standard deviation and n; number of values (100)
The mean error is the deviation of the calibrated ultrasonic meter as compared with the reference values. The bandwidth defined by the error standard uncertainty will have a confidence level of about 68 % associated with it. To a 95% confidence level, the error $u_{\bar{x}}$ will be multiplied by a factor of around 2.

3.1 Repeatability and Short and Long Term Reproducibility

Operationally, the combined facility and ultrasonic meter repeatability is affected by the following conditions:

- drifting beyond tolerances of the flow and process pressure and temperature,
- Unstable flow and process conditions
- Stability of the facility reference readings

Tables No 1, 2 and 3 depict the baseline results for flow and temperature and error stability for a 12” ultrasonic meter after being corrected and validated respectively at the TransCanada Calibration facility.

The results of Table 1 represent the mean error and the error standard uncertainty as a function of the variability of the ultrasonic meter gas flow and the gas temperature at the meter conditions based on reference run No 2 (tandem of 16” Ultrasonic and turbine meters)

TABLE 1. 12" USM ***CALIBRATION*** STABILITY PARAMETERS

Date: 10/13/2005				REFERENCE RUN # 2
Flow	Ultrasonic $u_{\bar{x}}$	USM Temp. $u_{\bar{x}}$	Mean Error	Error $u_{\bar{x}}$
m3/hr	m3/hr	Deg C	%	%
7841	1.67	0.0003	-0.02	0.02
5946	1.22	0.0008	0.00	0.02
3959	0.85	0.0003	-0.01	0.02
1985	0.47	0.0011	0.01	0.02
809	0.40	0.0008	-0.01	0.04
422	0.31	0.0060	-0.01	0.05

To illustrate the combined short term ultrasonic meter and facility repeatability and the reference agreement, the same meter was validated the following day using reference run No 3 (Size 16”) and the results are presented in table 2.

As expected, the error mean value lies within the predicted bandwidth as the random contributions for variability of Q and T are maintained.

The long term response of the system was evaluated again on March 25 2006 (five months later) again at this time using reference run No 3. The results are presented in table No 3.

TABLE 2. 12" USM ***VERIFICATION*** STAB. PARAMETERS

Date: 10/14/2005			REFERENCE RUN # 3	
Flow	**Ultrasonic** $u_{\bar{x}}$	**USM Temp.** $u_{\bar{x}}$	**Mean Error**	**Error** $u_{\bar{x}}$
m3/hr Flow	**m3/hr**	**Deg C**	**%**	**%**
7804	1.92	0.0005	-0.01	0.02
5907	1.54	0.0005	-0.03	0.02
4037	0.94	0.0004	-0.01	0.02
2009	0.57	0.0000	0.00	0.02
805	0.46	0.0005	0.01	0.04
431	0.24	0.0020	0.02	0.05

TABLE 3. 12" USM ***VERIFICATION*** STAB. PARAMETERS

Date: 3/22/2006			REFERENCE RUN # 3	
Flow	**Ultrasonic** $u_{\bar{x}}$	**USM Temp.** $u_{\bar{x}}$	**Mean Error**	**Error** $u_{\bar{x}}$
m3/hr	**m3/hr**	**Deg C**	**%**	**%**
7659	2.04	0.0010	-0.04	0.02
6083	1.38	0.0010	-0.04	0.02
4010	1.74	0.0004	-0.02	0.02
2025	0.42	0.0000	-0.02	0.02
826	0.51	0.0010	-0.01	0.04
403	0.28	0.0010	0.05	0.01

Clearly, the stability and fine tuning of the reference values coupled with not environmental influences permit the repeatability values observed in the verification results of table No 3

3.2 USM Sensitivity to Operational Variables

It is apparent that the larger the variability of the operational data, the larger the uncertainty about the true mean error value with impact in the repeatability. The following are key considerations on USM sensitivity to operational variables.

3.2.1 Impact of Correction for Pressure and temperature on Mean Error Bias and Repeatability

The facility installation and the flow conditioner used for calibration (if present) normally introduce a minimum pressure drop with an associated temperature reduction. However; their incidence on the meter calibration result must be quantified and proved to be negligible.

The first term of the right side of equation (3) accounts for the correction applied to the readings of the reference values; strictly, only the operational differences between the reference meter and the ultrasonic meter under test should affect the ratio for pressure and temperature corrections. However, under poorly controlled flow conditions and environmental influences, the amount corrected can be altered from "minimum" base conditions.

Table 4 represents the pressure and temperature factors accounted during the Ultrasonic Meter verification performed on March 22/2206 (Table 3).

TABLA 4. PRESSURE AND TEMPERATURE CORR. FACTORS

Flow	**Δ P**	**Δ T**	**P Ratio**	**T Ratio**
	Ref - MUT	Ref - MUT	Ref/MUT	MUT/Ref
m3/hr	kPa	^{o} C		
403	-0.23	0.090	0.99996	0.9997
827	1.30	0.007	1.00021	1.0000
2026	8.15	0.080	1.00131	0.9997
4010	31.42	0.162	1.00511	0.9995
6083	72.12	0.298	1.01181	0.9990
7658	113.20	0.452	1.01875	0.9985

Exactly the same patterns for pressure and temperature ratio were observed from the test on October 13 and 14 2005; a result confirming the flow and process controlled conditions at the facility.

Table 5 represent the baseline stabilityb data obtained at the higher velocity during the testing performed on October 13 2005. To prove the validity of a model after equations (3) and (4), a MonteCarlo simulation [5] was completed based on the calibration results of table 5. The output corresponds to the results for mean error and standard uncertainty by running the model. A perfect agreement is observed between the values obtained during the meter testing (Table 1) and the simulation.

To recreate the conditions of temperature influence due to external factors, a simulation was completed with gas temperature variation of 1ºC caused at the condition of the ultrasonic meter (heat transfer due to environmental effects can also affect the measurement transducers due to conduction and radiation).

Inversely proportional to the temperature, the meter error can show deviations beyond 0.3% from the baseline, depending on temperature offset, as a result of environmental influences affecting the temperature correction factor.

This effect will be prevalent at low velocities particularly in case of large dead (enclosed) volume between meters and drastic ambient conditions affecting the gas flow temperature and the temperature transducers.

TABLE 5. BASELINE FOR STABILITY OF CALIBRATION VARIABLES AT TCC

VARIABLE	VALUE	Stand Uncert.	ASSUMPTION
Q_USM (m3/hr)	7841.034579	1.669949612	7841
Q_Tur_raw (m3/hr)	7703.751398	1.200067458	7703
P_USM (Kpa-a)	6146.104345	0.049203636	6146
Dp (kPa)	124.5918194	0.0154994	124
Z_Turb	0.902814489		
Z_USM	0.903820719		
T_turb (Deg C)	29.2717448	0.000260406	302
T_USM (Deg C)	28.73234928	0.000258744	301
Enclosed Volume (m3)	1.29		

SIMULATION OUTPUT: METER ERROR AND SYSTEM REPEATABILITY

VARIABLE	Mean %	Stand Uncert.
Meter Error	-0.02412356	0.02661127

A second simulation was also performed for instability of the gas temperature at the ultrasonic meter conditions. As per table No 1, for the highest flow, the absolute standard temperature uncertainty is ± 0.0003 ºC and the overall (including flow and pressure stability conditions) impact on the repeatability of the mean error is ± 0.04% (at 95% confidence).

TABLE 6. 12" USM TEMPERATURE STABILITY INFLUENCE ON ERROR REPEATABILITY

Temperature Stability $u_{\bar{x}}$ ° C	Error SD (U=2S) %
0.0003	0.05
0.0335	0.06
0.0669	0.08
0.1000	0.10
0.1334	0.13
0.1668	0.15
0.2000	0.18
0.2333	0.20
0.2660	0.23

AGA report # 9 and the ISO standard (in preparation) for ultrasonic metering under custody transfer conditions, specify maximum repeatability values of ± 0.2%. Using the simulation model, the temperature instability was gradually modified while maintaining stable the flow and the pressure at the conditions of the ultrasonic meter. Table No 6 depicts the results.

A temperature variability of ± 0.23 ºC during the meter testing can add up to ± 0.2% in the error repeatability at 95% confidence. The temperature influence can be particularly notorious in case of short testing time when stable conditions are not achieved easily.

3.2.2 Flow Impact on Mean Error Bias and Repeatability

It is apparent that the flow control and the environmental influences on the gas flow impact the most both the bias and the stability of the error reported by the ultrasonic meter. The following are the critical factors associated with flow influence during ultrasonic meter calibration:

- *The flow control scheme:* is critical during the ultrasonic calibration, particularly with reference meters at the facility with a larger response time than that of the ultrasonic meter (as is the case of turbine meters).

- *The reference values traceability:* the procedures developed to trace back the reference values to a primary standard is reflected in the amount corrected on the readings of the meters used to calibrate the ultrasonic meter and hence the bias correction applied.

- *Packing Effect:* In a stable and quasi-stationary flow condition, the mass accumulation between both meters (the term following the minus sign in the right hand of equation 3) should be negligible. However, under conditions of heat transfer between the ambient and gas temperature the change in density in the trapped volume between both meters can propitiates transient effects affecting the expected material balance in the system. This effect is particularly critical in case of long, exposed pipe between the references and the ultrasonic meter tested.

- *The flow averaging time:* the time required to average out turbulence conditions at the ultrasonic meter must be sufficiently long to attain a sampling that statistically meets the stability criteria for desired uncertainty

- *Valve leakage:* Critical valves connecting the calibration system can leak in to or out of the active flow loop and alter the mass balance between the two meters. Again, this effect is particularly critical at low flows.

Flow Control Scheme.

At TCC the control and testing process is performed via two station servers with the critical task of flow computation, calibration procedures, reporting and archiving.

On the other hand switching, control of valves and safety procedures are handled by a station PLC via a serial port with modbus slave protocol.

At TCC the flow control and stabilization during the calibration process are achieved through adequate manipulation of three levels of flow control: an external 800 ND control valve, an internal 200 ND vernier control valve and the individual throttle valve downstream of the meter tested. Control level of 0.1% of opening for both 800 ND and 200 ND is achievable.

Again, from the results of table 1 as a baseline, a MonteCarlo simulation was performed to estimate the impact of the variability of the gas flow and gas temperature at the ultrasonic meter condition on the estimated error repeatability.

Highly sensitive to small variations in flow stability, the error standard deviation can approach easily to values beyond the recommended by industry for repeatability, as presented in the simulation results in table 7.

TABLE 7. 12" USM TEMPERATURE AND GAS FLOW STABILITY INFLUENCE ON ERROR REPEATABILITY

Temperature Stability $u_{\bar{x}}$	**USM Gas Flow** $u_{\bar{x}}$	**Error SD (U=2S)**
° C	**m3/hr**	**%**
0.0003	1.6699	0.06
0.1002	3.4460	0.11
0.2000	5.2233	0.18
0.3000	7.0000	0.27

A deficient flow control system and/or not enough stabilization time during testing can generate high gas flow instability and an increase in the type A uncertainty contribution during calibration

Finally, a material unbalance created by the packing effect is simulated with an increase in the volume trapped between both meters resulting in a simultaneous reduction in the gas volume sensed by the ultrasonic meter. From equation 4, a direct relationship between gas volume at the USM and error can be established such that any percent change in the volume produces the same change in the error reported by the calibration.

As an example, from the baseline represented in table 5, a decrease of 0.1% in the gas flow at the MUT from 7841.03 m3/hr to 7833 m3/hr maintaining the same gas flow input for the reference meter, results in an error of -0.12% whereas the decrease of 0.5% results in an error of -0.52%.

A similar effect can occur in case of gas leaking in or leaking out at the downstream piping of the reference meters due to gas inflow through critical valves. A positive or negative error effect will be expected depending on the valves affecting the material balance.

TCC performs a documented valve leakage test on any valve that is moved from the open to closed position during calibration. This must be done to ensure that the possibility of gas leakage past a valve is not adding or subtracting from the total gas measured by the meter under test and is not going unmeasured by the reference meter.

Additionally, total leakage across the valve considered to be critical to the calibration process is measured and validated on a regular basis.

4. REAL TIME DEMONSTRATION

The 12" ultrasonic meter calibrated and verified as per the results presented at section 3 will be tested on line at the end of the conference session. The calibration laboratory capabilities and the meter error and system repeatability, evaluated at a single velocity, will be demonstrated remotely via Internet.

5. CONCLUSIONS

The bias correction applied to a customer's ultrasonic meter as a result of the calibration has a direct link with the procedures developed to establish traceability and to maintain the calibration status of the references values.

The closeness among reference meters readings (fig 1) validates the rigorousness of the calibration procedures whereas the repeatability values endorse the quality of the facility installation, the meters and the data acquisition methodology, under facility operating conditions

The maintenance of the calibration status of the reference values is critical to retain its traceable condition and to provide integrity to the meter calibration.

The adjusted ultrasonic meter output represents a baseline that agrees with the facility reference values within the combined meter and facility repeatability.

Under controlled conditions of variability for the operational input parameters and no installation or thermal effects on the ultrasonic meter, the expected repeatability of the mean error should be within the error uncertainty bandwidth to a 95% confidence level.

Under TCC's data acquisition methodology and within the laboratory's environmental controlled conditions, a maximum operational stability range is defined for each variable affecting the USM response during calibration, setting the expected Type A uncertainty contribution within the limits imposed by the facility uncertainty budget.

Temperature and flow instability have the largest effect on the ultrasonic meter repeatability

Temperature effects during ultrasonic meter calibration can affect the meter linearity due to over or under correction introduced by the temperature ratio

Any material unbalance created by gas packing and leaking or deficient flow control during ultrasonic meter testing can seriously impact the meter linearity and the bias correction applied to the ultrasonic meter.

6. FINAL REMARKS

The meter log files captured during meter calibration make available:

- Evidence to the customer on the operational conditions prevalent during the calibration.

- A tool to extrapolate the calibration results to the field attending the laws of similarity between both the laboratory and the field

- Information used to document the meter's operational characteristics and also to diagnose the operational conditions existing in the facility during meter calibration. For instance, real gas temperature stability at the ultrasonic meter during calibration can be quantified via the meter reported speed of sound stability from the meter's diagnostic log file

- A meter specific performance baseline relating the diagnostic data to the corrected meter output (laboratory corrected value). Used to validate the volumetric output of the meter in the field installation where no reference exists.

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