

# Uncertainty Analysis of a Multi-Viscosity Liquid Hydrocarbon Calibration Facility

T.M. Kegel

Colorado Engineering Experiment Station, Inc. (CEESI)  
54043 WCR 37, Nunn, Colorado, USA  
E-mail: tkegel@ceesi.com

---

## Abstract

In September 2015 CEESI began operation of a new multi-viscosity liquid hydrocarbon calibration facility. Calibrations can be made by comparison with either a prover or one or more master meters. Also, calibrations can be based on mass or volume flowrate. This paper documents the uncertainty analysis. It begins by deriving the four operating equations from first principles. Next each component of uncertainty is described and estimated. The estimates are combined expanded. Finally some examples from the CEESI Measurement Assurance Program are presented.

---

## 1. Introduction

CEESI decided to build this new facility for several reasons. First, the steadily increasing price of oil during the facility design process is expected to increase the cost associated with mis-measurement and create demand for calibration services. While the price has dropped recently it is expected to return. Second, increasing production of heavier oil will introduce non-linearities in many meters as a result of the higher viscosities and lower Reynolds numbers. Third, the newer technologies represent potentially unfamiliar meter performance that might require more detailed testing over a range of flowing conditions. One example is the discovery that a coriolis meter output is a function of Reynolds number [1].

A related comment is based on CEESI observations of the flow measurement market. Meter users are increasingly relying on surrogate fluid calibrations for liquid service, often based on water. A surrogate fluid is used in a laboratory as a substitute for the flowing product in the field. Such calibrations appear to be more economical based on comparing calibration quotations. They can result in mis-measurement if the meter operation in the field is not well characterized; an example is given later in the paper. A surrogate fluid calibration is acceptable if it covers the range of the relevant correlating parameter for the meter under test. For most liquid meters the Reynolds number ( $Re$ ) is the relevant correlating parameter. It is therefore the primary correlating parameter in the present facility.

## 2. Operation Briefly Described

Traceability to the SI is achieved with a ball prover (pipe prover) and three turbine master meters. The basic operating ranges are:

- Flowrate range: 80 - 3100 m<sup>3</sup>/hr.
- Viscosity range: 2 - 200 cSt
- Uncertainty range: 0.025% - 0.050%

A broad Reynolds number range is achieved based on the viscosity range. The viscosity range is achieved based on calibrating with three different liquids and varying the temperature.

Four basic calibration services are offered in this facility. First, a meter under test (MUT) can be calibrated directly against the prover. With the second service a MUT is calibrated against one or more master meters (MM). The master meters are maintained in calibration against the prover. Calibrations can be based on either mass or volume flowrate.

A more detailed description is contained in [2]

## 3. Operating Equations

In this section the calibration process operating equations are developed. The first case considers a pulse producing MUT or MM being calibrated against the prover.

The mass flowrate ( $\dot{m}$ ) through the meter equals the mass flowrate through the prover plus the mass flowrate into the trapped volume. The trapped volume term accounts for the change in oil density in the volume that connects meter and prover:

$$\dot{m}_M = \dot{m}_P + \dot{m}_{TV} \quad (1)$$

The subscripts correspond to the trapped volume ( $TV$ ), prover ( $P$ ) and meter ( $M$ ); the meter could be a MUT or MM. The mass flowrate is expressed as the product of volume flowrate ( $\dot{V}$ ) and density ( $\rho$ ). The trapped volume term is the product of a fixed volume ( $V$ ) and density change ( $\dot{\rho}$ ):

$$\dot{V}_M \rho_M = \dot{V}_P \rho_P + V_{TV} \dot{\rho}_{TV} \quad (2)$$

The time derivative terms are expanded:

$$\frac{\Delta V_M}{\Delta t_M} \rho_M = \frac{\Delta V_P}{\Delta t_P} \rho_P + V_{TV} \frac{\Delta \rho_{TV}}{\Delta t_{TV}} \quad (3)$$

Assuming time intervals ( $\Delta t$ ) are synchronized:

$$\Delta t_M = \Delta t_P = \Delta t_{TV} \quad (4)$$

Combine Equations 3 and 4:

$$\Delta V_M \rho_M = \Delta V_P \rho_P + V_{TV} \Delta \rho_{TV} \quad (5)$$

Define the volume changes corresponding to  $\Delta t$ :

$$\Delta V_P = BPV \times C_{TSP} \times C_{PSP} \quad (6)$$

$$\Delta V_M = \frac{N \times MF}{NKF} \times C_{TSM} \times C_{PSM} \quad (7)$$

The base prover volume ( $BPV$ ) is the measured volume corrected to base conditions. The pressure and temperature based expansion of the steel is accounted for by the dimensionless factors  $C_{TS}$  and  $C_{PS}$ . The nominal collected MUT volume is the ratio of collected pulses ( $N$ ) to K-Factor ( $NKF$ ). The dimensionless MUT meter factor ( $MF$ ) is evaluated from a calibration history.

Define the trapped volume term as:

$$\varepsilon_{TV} = V_{TV} \Delta \rho_{TV} \quad (8)$$

Solve Equations 5, 6, 7 and 8 for meter factor:

$$MF = BPV \left( \frac{NKF}{N} \right) \left( \frac{\rho_P}{\rho_M} \right) \left( \frac{C_{TSP}}{C_{TSM}} \right) \left( \frac{C_{PSP}}{C_{PSM}} \right) + \varepsilon_{TV} \quad (9)$$

Define the density ratio:

$$\left( \frac{\rho_P}{\rho_M} \right) = \left( \frac{C_{TLP}}{C_{TLM}} \right) \left( \frac{C_{PLP}}{C_{PLM}} \right) \quad (10)$$

Combine Equations 9 and 10:

$$MF = BPV \left( \frac{NKF}{N} \right) \left( \frac{C_{TLP}}{C_{TLM}} \right) \left( \frac{C_{PLP}}{C_{PLM}} \right) \times \left( \frac{C_{TSP}}{C_{TSM}} \right) \left( \frac{C_{PSP}}{C_{PSM}} \right) + \varepsilon_{TV} \quad (11)$$

The second operating equation is applied when a MUT is calibrated against one or more master meters. The mass flowrate through the MUT (subscript  $MU$ ) equals the mass flowrate through the MM array (subscript  $MM$ ) plus the mass flowrate into the trapped volume:

$$\dot{m}_{MU} = \dot{m}_{MM} + \dot{m}_{TV} \quad (12)$$

Applying a process similar to that described by Equations 2-10 results in:

$$MF_{MU} = MF_{MM} \left( \frac{NKF_{MM}}{NKF_{MU}} \right) \left( \frac{N_{MU}}{N_{MM}} \right) \times \left( \frac{C_{TLMM}}{C_{TLMU}} \right) \left( \frac{C_{PLMM}}{C_{PLMU}} \right) \left( \frac{C_{TSMM}}{C_{TSMU}} \right) \left( \frac{C_{PSMM}}{C_{PSMU}} \right) + \varepsilon_{TV} \quad (13)$$

The equation development above is based on calibrating pulse producing volumetric meters such as turbine and ultrasonic meters. The last two operating equations are applicable to meters requiring mass flowrate. Equation 9 is modified:

$$MF = \left( \frac{BPV \times \rho_P}{m_{MI}} \right) \left( \frac{C_{TSP}}{C_{TSM}} \right) \left( \frac{C_{PSP}}{C_{PSM}} \right) + \varepsilon_{TV} \quad (14)$$

where  $m_{MI}$  is the meter indication of mass accumulated during the  $\Delta t_M$  time interval. Similarly, for a master meter calibration:

$$MF_{MU} = MF_{MM} \left( \frac{NKF_{MM} \times \rho_{MM}}{N_{MM} \times m_{MI}} \right) \times \left( \frac{C_{TSMM}}{C_{TSMU}} \right) \left( \frac{C_{PSMM}}{C_{PSMU}} \right) + \varepsilon_{TV} \quad (15)$$

#### 4. Uncertainty Components

Each component of Equations 11, 13, 14, and 15 potentially contributes uncertainty, they are discussed in this section and listed in Tables 1 and 2.

The uncertainty analysis is prepared and presented in compliance with the international standard [3]. In this paper the generalized standard uncertainty is symbolized by  $u$ . Numerical values are given in units of ppm or percent of a mean value. The Type B estimates are assumed to be represented by a rectangular distribution.

##### 4.1 Prover Uncertainty

The prover uncertainty is made up of three components discussed in this section:

1. Base volume
2. Repeatability
3. Reproducibility

The base prover volume was determined from a water-draw process [4] with standard uncertainty is  $u = 96$  ppm. The repeatability of the prover was  $u = 30$  ppm during the water draw process, this value will be used to represent operational repeatability.

The reproducibility is estimated based on an industry standard [5] which suggests a typical five year reproducibility value of  $\pm 200$  ppm. Assuming a one year re-cali-

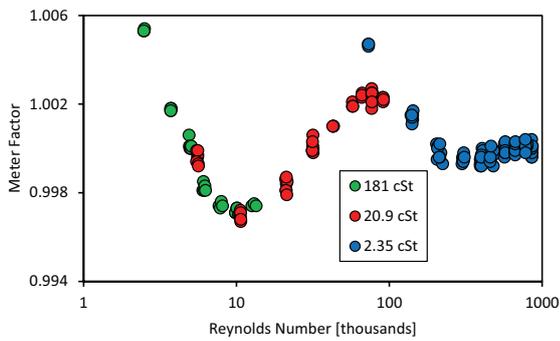


Figure 1: Calibration Data for Master Meter SN 393

bration interval, the annual linear change over time is 40 ppm. The corresponding Type B standard uncertainty is  $u = 40 \times 0.58 = 23$  ppm.

The original water draw was completed seven years ago, the previous and current *BPV* values differ by 43 ppm. The seven year time interval includes shipping and handling loads that will likely contribute more to reproducibility than the steady use of the prover. It is concluded that the seven year 43 ppm figure supports the 23 ppm value of reproducibility.

The combined standard uncertainty is  $u = 103$  ppm

#### 4.2 Master Meter Data

The facility operates with three DN400 (8 inch) helical turbine master meters. A turbine meter with helical blades is less sensitive to viscosity changes than a turbine meter with flat blades [6], an important consideration in the present facility design.

Each master meter is calibrated in comparison with the pipe prover at three viscosity values. Data from one of the three meters shown in Figure 1. While the data show some non-linearity the agreement between viscosities is very good. The outlying data point corresponds to low velocity. The resulting MF shift is attributed to bearing friction force that is overcome by flowing kinetic energy at higher velocity

Three components of uncertainty are assigned to the master meters. The first uncertainty component includes repeatability because each data point was repeated at least once. It also includes reproducibility because the flow-rate was changed between data points. The reproducibility time frame is relatively short, several hours at most. Finally, this component also accounts for the degree to which the curve fits the data.

The data for each meter is fitted to three curves corresponding to the three viscosities. The 95% confidence interval width about each curve fit is defined as  $\pm 2 \times \text{SEE}$  (standard estimate of error). Nine SEE values were averaged to estimate the standard uncertainty  $u = 100$  ppm. The nine values resulted from three meters and three viscosities.

A second component accounts for long term reproducibility, with the time frame measured in months. This component cannot currently be estimated because the system has only been operating for a short time. The standard uncertainty is estimated to be  $u = 150$  ppm.

The master meters were intended to be operated with a single curve fit over the entire *Re* range. An uncertainty component,  $u = 100$  ppm, was included to account for imperfect agreement between viscosity pairs. This approach was rejected but the uncertainty component has been retained.

The combined standard uncertainty is  $u = 206$  ppm

#### 4.3 Oil Density

Equations 14 and 15 require density values while Equations 11 and 13 require corrections for pressure and temperature. This section discusses the uncertainty components for each set of equations.

##### 4.3.1 Mass Calibration

The direct density measurement process begins with a representative sample. A clean dry 250 ml volumetric flask is placed on a scale and distilled water is added. The volume is calculated based on measured mass and published density data [7]. The flask is emptied dried and filled with calibration fluid. The density is calculated based on measured mass and the previously calculated flask volume.

The uncertainty in water density is  $\pm 1$  ppm. The volumetric flask is identified as Class A [8] with uncertainty of  $\pm 0.12$  ml. The current scale has resolution of 100 mg which contributes significant uncertainty. A new scale with resolution of 10 mg and repeatability of  $\pm 20$  mg will be purchased, the present analysis is based on the new scale. Uncertainty due to scale stability, reproducibility and calibration are not included because they are assumed to be fully correlated in the present measurement process. Uncertainties resulting from the volumetric flask and scale are included twice; once each for oil and water.

The combined standard uncertainty is  $u = 66$  ppm which includes uncertainties in the measurement of pressure and temperature.

##### 4.3.2 Volume Calibration

The corrections  $C_{TL}$  and  $C_{PL}$  account for the change in volume in response to changes in pressure and temperature. Uncertainties arise from the measurement of pressure and temperature as well as the basic equations. Equations 11 and 13 show the paired  $C_{TL}$  and  $C_{PL}$  values expressed as a ratios, correlation between meter and prover eliminates some uncertainty components. In particular the uncertainties in the underlying equations are assumed to be correlated and therefore contribute no uncertainty.

The uncertainties in pressure and temperature have a small effect on the uncertainties in  $C_{TL}$  and  $C_{PL}$  due to sensitivity coefficients. The sensitivity coefficient for thermal expansion ( $C_{TL}$ ) is:

$$\frac{\partial \rho}{\partial T} \approx \frac{\Delta \rho}{\Delta T} = 800 \left[ \frac{\text{ppm}}{\text{K}} \right] \quad (16)$$

The sensitivity coefficient for compressibility ( $C_{PL}$ ) is:

$$\frac{\partial \rho}{\partial P} \approx \frac{\Delta \rho}{\Delta P} = 0.86 \left[ \frac{\text{ppm}}{\text{kPa}} \right] \quad (17)$$

Combining the uncertainties in pressure and temperature (below) with the sensitivity coefficients above results in a combined standard uncertainty of  $u = 25$  ppm

#### 4.4 Measurements of Pressure and Temperature

Measurements are required for Equations 16 and 17 above, clearly temperature is more important than pressure. Temperature also affects viscosity which will be discussed below.

Pressures are measured with industrial grade transmitters. The manufacturer specification (0.04%) is assumed to represent the uncertainty. Further assuming a nominal measured value of 360 kPa (52 psi) is the standard uncertainty is:

$$u = \frac{0.04\%}{100\%} \times 0.58 \times 360 \text{ kPa} = 0.083 \text{ kPa} \quad (18)$$

Temperatures are measured by individually serialized RTDs. The values below are based on statistical analyses of RTDs already in use by CEESI.

1. Short term random variation,  $u = 25$  mK
2. Long term random variation,  $u = 15$  mK
3. Calibration standard,  $u = 12$  mK

Reference [9] lists uncertainty sources that are assumed to be included in Items 1 and 2 above.

The combined standard uncertainty is  $u = 31$  mK.

#### 4.5 Corrections For Pressure and Temperature of Steel

Equations 13 and 15 include terms ( $C_{TSP}$  and  $C_{PSP}$ ) that account for the change in prover volume ( $V_p$ ) with pressure and temperature. The sensitivity of  $V_p$  to temperature based on a known value of thermal expansion coefficient ( $\gamma$ ) is:

$$\frac{\partial V_p}{\partial T} \approx \frac{\Delta V_p}{\Delta T} = 33.5 \left[ \frac{\text{ppm}}{\text{K}} \right] \quad (19)$$

The sensitivity coefficient relating changes in  $V_p$  and  $\gamma$  varies with temperature because  $C_{TSP}$  is defined relative

to 15.4 °C (70 °F). Assuming a worst case temperature of 30 °C the dimensionless sensitivity is:

$$\frac{\partial V_p}{\partial \gamma} \approx \frac{\Delta V_p}{\Delta \gamma} = 4.87 \times 10^{-4} \quad (20)$$

The uncertainty in  $\gamma$  is usually determined experimentally for a particular application; general values are not published. Based on a recommendation of [10], a value of  $\pm 10\%$  ( $u = 5.8\%$ ) is assumed.

The sensitivity to of  $V_p$  to pressure based on a known value of Young's modulus ( $E$ ) is:

$$\frac{\partial V_p}{\partial P} \approx \frac{\Delta V_p}{\Delta P} = 10.9 \left[ \frac{\text{ppm}}{\text{kPa}} \right] \quad (21)$$

The dimensionless sensitivity coefficient relating changes in  $V_p$  and  $E$  is:

$$\frac{\partial V_p}{\partial E} \approx \frac{\Delta V_p}{\Delta E} = 1.56 \times 10^{-4} \quad (22)$$

The same approach is taken as described above for the temperature correction. An uncertainty of  $\pm 10\%$  ( $u = 5.8\%$ ) is assumed.

Similar terms ( $C_{TSM}$ ,  $C_{PSM}$ ,  $C_{TSU}$ , and  $C_{PSU}$ ) account for changes in meter volume with pressure and temperature. Traditionally meter volume changes have not been calculated. The terms are included in the current analysis in anticipation of future applications. Zero uncertainty is currently assigned.

When the uncertainties in pressure and temperature are combined with the sensitivity coefficients the standard uncertainty is  $u = 31$  ppm.

#### 4.6 Oil Viscosity

Viscosity is measured over a temperature range in a laboratory using a rotary viscometer. Three components of uncertainty are included:

1. Calibration standard
2. Random effects from calibration data
3. Display resolution

The combined standard uncertainties are:

$$u = 0.62\%, \eta < 10 \text{ cSt}$$

$$u = 0.21\%, \eta \geq 10 \text{ cSt}$$

The uncertainty in viscosity ( $\mu$ ) directly affects the uncertainty in Reynolds number which in turn contributes uncertainty to meter factor. The sensitivity coefficient is proportional to the slope of  $MF$  vs  $Re$ . The worst case is assumed to correspond to  $Re = 125,000$  in Figure 1.

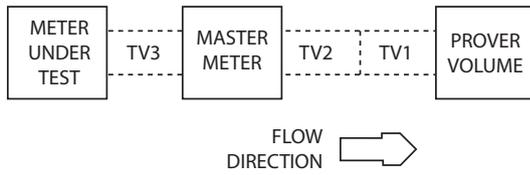


Figure 2: Trapped Volume Locations

A 4.6% change in  $Re$  results in a 0.023% change in  $MF$ :

$$\frac{\partial MF}{\partial \mu} = \frac{\partial MF}{\partial Re} \approx \frac{\Delta MF}{\Delta Re} = \frac{0.23\%}{4.6\%} = 5.00 \times 10^{-3} \quad (23)$$

Accounting for the sensitivity coefficient, the worst case standard uncertainty is  $u = 31$  ppm.

#### 4.7 Pulse Counting

Three components are assumed when the MUT pulses are counted:

- resolution,  $u = 5$  ppm
- time base stability,  $u = 1$  ppm
- triggering error,  $u = 18$  ppm

The combined standard uncertainty is  $u = 19$  ppm

#### 4.8 Trapped Volume

The pipe and fittings required to direct flow from the MUT exit to the prover inlet comprise what are called “trapped volumes”. The general layout is illustrated in Figure 2. Three trapped volumes are identified:  $TV_1$  and  $TV_2$  are included when a MUT or MM is calibrated against the prover while  $TV_3$  is included when a MUT is calibrated against one or more MM.

At the beginning of a data point the trapped volume contains calibration fluid that did not flow through the MUT but does flow through the prover. At the conclusion of a data point the trapped volume contains calibration fluid that flowed through the MUT but does not flow through the prover. A change in liquid density during a data point results in mass storage or discharge. The trapped volume contributes no uncertainty if the liquid density remains constant.

Trapped volumes are typically addressed in one of two ways. The first approach is to apply a correction based on measurements of pressure temperature and volume. The uncertainty in the correction is calculated based on estimate uncertainties in the measurements. Inexpensive pressure and temperature sensors are usually adequate because the sensitivity coefficients are quite small. This process is applied to CEESI gas flow primary standards

An alternate approach is taken with the oil facility uncertainty analysis. No correction is made, instead the worst case values of  $\varepsilon_{TV}$  are estimated and treated as uncertainty components. The contributed uncertainties are reduced by controlling temperature. The facility operating proce-

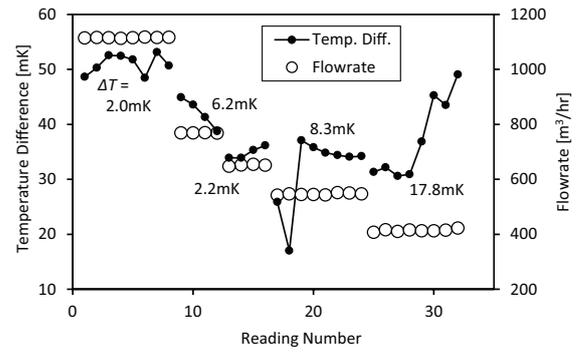


Figure 3: Typical Temperature Data

dures include limits to the temperature change allowed during a data point. For  $TV_2$  and  $TV_3$  the temperature tolerance is  $\pm 0.1^\circ\text{C}$ . For  $TV_1$  the  $\pm 0.05^\circ\text{C}$  is less because the same fluid passes through  $TV_1$  when the prover reverses direction.

Typical temperature data in Figure 3 consist of 32 readings at five flowrates. The temperature difference ordinate values represent the differences between master meter and prover inlet. The  $\Delta T$  labels represent the temperature change between the first and last reading. The temperature difference increases slightly with flowrate, this is attributed to heat exchanger residence time. It is noted that the temperature difference does not contribute to the TV, only if it changes with time. The  $\Delta T$  values decreases with increasing flowrate, temperature control improves as the oil is more quickly distributed throughout the loop. That having been said, all the five  $\Delta T$  are well below the  $\pm 50$  mK ( $\pm 0.05^\circ\text{C}$ ) tolerance

The trapped volume uncertainty results are:

$$\begin{aligned} u_{TV1} &= 16 \text{ ppm} \\ u_{TV2} &= 16 \text{ ppm} \\ u_{TV3} &= 37 \text{ ppm} \end{aligned}$$

## 5. Meter Under Test Example

The extensive calibration of a DN250 (10 inch) ultrasonic meter is described as an example of system operation. It also represents an example of typical meter under test.

Data were obtained using each master meter and three different viscosity values. Data are plotted in Figure 4, the legend entries identify the master meter (M1, M2, M3) and viscosity in centistokes (cS). It is suggested that the data be divided into three regions:

- laminar region ( $180 < Re < 2500$ )
- transition region ( $2,950 < Re < 29,000$ )
- turbulent ( $29,000 < Re < 1,260,000$ )

The laminar  $Re$  range corresponds well to the traditional fluid mechanical definition. The “transition” region extends to  $Re = 29,000$  which is much larger than generally defined. In the present analysis the transition region is

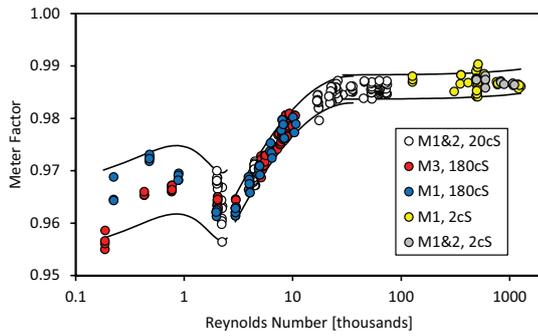


Figure 4: Calibration Data for a DN250 Ultrasonic Meter

based on non-linear MUT operation. The fluid mechanical definition would result in a much narrower  $Re$  range. The MUT linearity improves in the turbulent region.

The solid lines identify statistical intervals in each region centered on curve fits. The interval widths intended to contain 95% of the data, listed below are the interval widths ( $\pm 2s$ ). The  $2s/\sqrt{5}$  are also given to allow MUT data evaluation based on one common industry standard [4]

- laminar region,  $2s = 0.673\%$ ,  $2s/\sqrt{5} = 0.301\%$
- transition region,  $2s = 0.260\%$ ,  $2s/\sqrt{5} = 0.116\%$
- turbulent region,  $2s = 0.235\%$ ,  $2s/\sqrt{5} = 0.105\%$

The data represents a good opportunity to demonstrate potential problems with surrogate fluid calibration. Assuming this meter was calibrated using water over the 0.15 - 7.6 m/s (0.5 - 25 ft/s) range the corresponding  $Re$  range is 44,000 - 2,200,000. The water calibration would 1) not quantify the non-linear performance and 2) over state MF by as much as 2.5%.

Often the terms “calibration” and “proving” are interpreted to be two words for the same process. Calibration characterizes a meter over a broad range of conditions, typically covering a wide  $Re$  range. Calibrations are conducted in a laboratory where temperature, viscosity and flowrate can be independently varied, tightly controlled and measured with low uncertainty. Proving is a field operation that cannot achieve the same level of control. Figure 4 illustrates the non-linearity with Reynolds number; it is unlikely that field conditions could be varied enough to provide a similar characterization. Proving a meter in the field can provide reasonable assurance of consistent measurement at a single  $Re$  value.

## 6. Measurement Assurance Testing

CEESI maintains measurement assurance programs (MAP) to support all measurement processes. A good MAP definition [11] is reproduced below:

“A quality assurance program for a measurement process that quantifies the total uncertainty of the measurements (both random and systematic components of error) with respect to national or des-

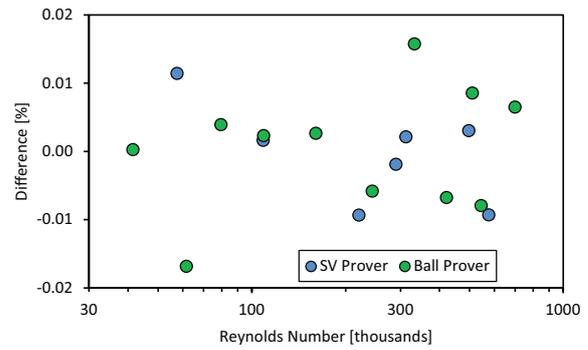


Figure 5: Comparing Two Provers

ignated standards and demonstrates that the total uncertainty is sufficiently small to meet the user’s requirements.”

This section contains a brief discussion of four tests that support the facility MAP.

### 6.1 Case 1

The facility has recently been expanded with the addition of a small volume prover (SVP) and set of smaller master meters. The calibration capability is not included in the present uncertainty analysis, it will be published in the future. Currently the traceability chains of the two provers are independent: the ball prover waterdraw was completed by a contractor while the SVP waterdraw was completed by the manufacturer .

An indirect inter-comparison test was completed by calibrating a master meter in both provers [2]. The data analysis began with a polynomial fit of  $MF$  vs  $Re$ , the results are shown in Figure 5. The abscissa is the MM  $Re$ , the ordinate is the difference between a data point and the curve fit. The analysis indicates that 95% of the data fit within  $\pm 160$  ppm. These data support the reproducibility of the system because the data were taken on separate days.

The trapped volume between MM exit and SVP inlet is very large, a quick estimate suggests that the trapped volume uncertainty could be as large as 0.05%. Clearly the data of Figure 5 do not reflect that uncertainty. Perhaps the TV uncertainty can be reduced based on these data plus the small temperature variations of Figure 3.

One data point was excluded from the curve fit: for  $Re = 23,984$  the difference is -0.39%. This point corresponds to the lowest flowrate. It is suggested that either the pipe prover or the trapped volume can contribute large uncertainty.

### 6.2 Case 2

The master meters were calibrated by the manufacturer prior to shipping. The two calibrations are shown in Figure 6, the solid lines represent averages. Note that the manufacturer used four viscosity ranges while CEESI used three.

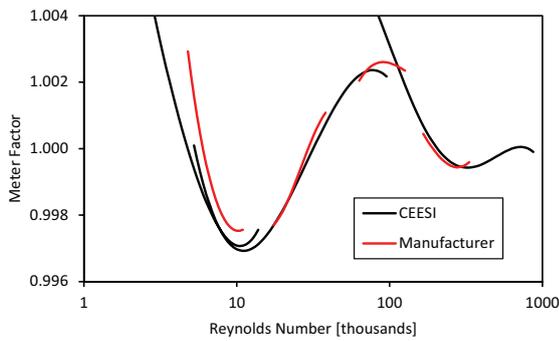


Figure 6: Master Meter Calibration Data

The differences indicated over two  $Re$  ranges (4700 - 6300 and 72,000 - 100,000) are significant resulting from low flow operation of the meters. Neglecting these ranges the fitted curves are in agreement to within  $\pm 140$  ppm. These data provide support that the uncertainty analysis is not excluding systematic effects. Also confidence in the analysis is increased based on agreement between two independent traceability chains.

### 6.3 Case 3

The ultrasonic meter data of Figure 4 contains two regions with overlap. The first is  $3500 < Re < 10,000$  where the averages agree within  $\pm 0.050\%$ . The second is  $50,000 < Re < 110,000$  where the averages agree within  $\pm 0.036\%$ .

The agreement quantifies reproducibility of the facility because data were obtained on different days with different fluids. The agreement values are larger than Case 1 or Case 2 because the reproducibility of a turbine meter is better than an ultrasonic meter.

Table 1: Prover based uncertainty components

Component	Volume [ppm]	Mass [ppm]
Base Prover Volume	96	96
Prover Repeatability	30	30
Prover Reproducibility	23	23
Corrections for Prover Steel	31	31
Trapped Volume	23	23
Volume Correction Prover	25	
Volume Correction MUT	25	
Density		79
Combined	116	136

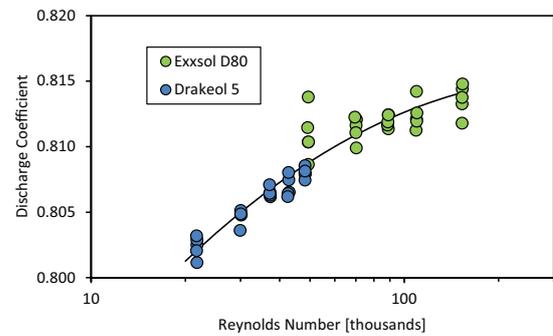


Figure 7: Cone Meter Calibration Data

### 6.4 Case 4

This Case refers to a DN200 (8 inch) cone type meter with  $\beta = 0.75$  [12]. Figure 7 shows the data obtained at the transition between two different calibrations which occurs at  $Re \approx 48,000$ . As with Case 3 the agreement, estimated to be  $\pm 0.06\%$  quantifies reproducibility of the facility.

## 7. Summary

The uncertainty analysis of a new calibration facility has been presented. The facility operates with three calibration fluids of different viscosities, temperature control allows for additional variation in viscosity. Calibrations can be performed against primary (pipe prover) or secondary (master meter) standards reporting either mass or volume units. The analysis begins by deriving the measurement model and identifying potential uncertainty components. The estimated uncertainty for each component is described, the resulting values are tabulated. Several calibration examples are summarized.

Table 2: Master meter based uncertainty components

Component	Volume [ppm]	Mass [ppm]
MM Volume	116	116
MM Repeatability	100	100
MM Reproducibility	150	150
MM Viscosity Correction	100	100
Viscosity Measurement	31	31
MUT Pulses	19	19
MM Pulses	19	19
Trapped Volume	37	37
Volume Correction Prover	25	
Volume Correction MUT	25	
Density		79
Combined	245	255

## References

1. Mills, C. et al, "Flow Measurement of High Viscosity Fluids," North Sea Flow Measurement Workshop, 2013.
2. Johansen, W.R. et al, "The Development and Performance of a Low Uncertainty Flexible Multi-Viscosity Calibration Facility," FLOMEKO, 2016,
3. JCGM 100: Evaluation of measurement data - Guide to the expression of uncertainty in measurement, 2008.
4. API MPMS 4.9.1: Proving Systems - Methods of Calibration for Displacement and Volumetric Tank Provers, Part 1 - Introduction to the Determination of the Volume of Displacement and Tank Provers, 2005.
5. API MPMS 4.8: Proving Systems - Operation of Proving Systems, 2002.
6. Anderson, K., "Helical Turbine Meters For Liquid Measurement," 87th International School of Hydrocarbon Measurement, 2012.
7. Lemmon, E.W., Huber, M.L. and McLinden, M.O., NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP).
8. ASTM E288: Standard Specification for Laboratory Glass Volumetric Flasks, 2003.
9. ASTM E1137: Standard Specification for Industrial Platinum Resistance Thermometers, 1997.
10. Doiron, T., "Uncertainties Related to Thermal Expansion in Dimensional Metrology," *NCSLI Measure*, 2006.
11. Belanger, B, "Measurement Assurance Programs, Part I: General Introduction," NBS Special Publication 676-1, 1984.
12. Melendez, G. et al, "Wedge Meters with Low Reynolds Number Flow," FLOMEKO, 2016.