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Traceability Chain and Uncertainty of the U.S. National Flow Standard for High Pressure Natural Gas

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Abstract

In 2008, NIST and CEESI Iowa established an internationally recognized standard for calibrating meters used in high-pressure natural gas custody transfer. The facility initially covered 0.25 m^3/s to 10.5 m^3/s (18 kg/s to 780 kg/s at 7 MPa), with uncertainties of 0.23 % to 0.4 %. In 2019, a joint effort updated the traceability chain and reduced uncertainty using an 8-stage bootstrap process. Critical flow venturis (CFVs) were first calibrated in air against NIST's 677 L *PVTt* primary standard, then used to calibrate additional CFVs at higher pressures. These were subsequently applied to turbine meter calibrations in air and then in high-pressure natural gas using Reynolds number matching. The resulting turbine meter chain provided working standards for CEESI Iowa customer calibrations, achieving uncertainties of 0.16 % to 0.21 %. This manuscript describes the 2019 process, key lessons learned, and planned improvements.

1. Introduction

In 2008 NIST collaborated with CEESI (Colorado Engineering Experiment Station Inc.) to establish a high-pressure Natural Gas Flow Calibration Service (NGFCS). The NGFCS provides calibrations with low uncertainty for custody transfer natural gas flow meters used in the U.S. and internationally. Flow calibrations were traceable to the NIST 26 m^3 pressure-volume-temperature-time (PVTt) flow standard [1, 2] through a 5-stage bootstrap process. Critical flow venturis (CFVs) calibrated by NIST's low pressure 26 m^3 air flow standard were used in parallel arrays to calibrate other CFVs at high pressures and flows. These high-pressure and flow CFVs were subsequently used to calibrate the 9 turbine meter working standards (TMWS) that were used to calibrate custody transfer flow meters at the CEESI Iowa facility. This work in 2008 established flow measurement capabilities ranging from 0.25 m^3/s to 9 m^3/s (31,800 acfh[1] to 1,144,000 acfh) at expanded uncertainties ranging from U = 0.23 % to 0.40 %. Details regarding the 5-stage bootstrap process conducted in 2008 are available in the following references [3, 4, 5, 6]. In 2018, improvements in reference meter capabilities and the need for improved custody transfer measurements motivated a reduction in the uncertainty established in 2008.

2. Background

The CEESI Iowa flow facility is located at a custody transfer station in Garner, Iowa. The custody transfer station distributes dry, pipeline quality natural gas from the 1100 mm nominal diameter supply line to three downstream delivery points. During flow calibrations, natural gas is diverted and fed into the CEESI Iowa calibration facility. The diverted flow is measured by up to 9 305 mm (12 in) diameter turbine meter working standards (TMWS) each having a flow capacity from 0.25 m^3/s to 1.16 m^3/s (31,800 acfh to 148,000 acfh). Valves located upstream and downstream of each TMWS open or close selected flow paths to allow flow through any combination of the 9 TMWS. Accordingly, the flow capacity of the CEESI facility ranges from 0.25 m^3/s with a single TMWS operating at its minimum flow to 10.5 m^3/s when all nine TMWS operate in parallel at their full-scale flow. Flow exiting the array of TMWS enters a common header and then flows through a customer meter under test (MUT) installed in any one of 3 different line sizes depending on the flow. The natural gas exiting the MUT is then returned to the custody transfer station and transported to the delivery point.

In 2018, a project using an 8-stage bootstrap method to reduce the uncertainty of the CEESI Iowa facility for flows ranging from 0.3 m^3/s to 10.5 m^3/s (38,000 acfh to 1,330,000 acfh) at a nominal pressure of 7240 kPa (1050 psia) was initiated. For flows in this range the new expanded uncertainty is 0.16 % to 0.21 %.

3. 8-Stage Calibration Traceability Chain and Uncertainty Analysis

We implemented an 8-stage calibration process to establish a new traceability chain that reduces the uncertainty of CEESI Iowa's volumetric flow meter calibrations. Figure 1 shows the 8-

1 acfh (actual cubic feet per hour) is the volumetric flow rate at the gas's actual pressure and temperature

stage traceability chain that scales from the NIST low-pressure air flow standard to high-pressure, pipeline-scale natural gas flow.

8 Stage Traceability Chain

Stage	Reference Standard	Meter Under Calibration (MUC)	Fluid	MUC Meter Factor Exp. Unc.	Flow or Reynolds No. Range of MUC
1	NIST *PVTt* 677L PVTt	CFVs (Down) 21 × P = 0.2 to 0.8 MPa	Dry air at NIST	$U_r(C_d)$ = 0.055% to 0.075%	$Re = 0.11 \times 10^6$ to 0.53×10^6
2	21 CFV Array (Up) P = 0.2 to 0.8 MPa	CFV (Down) 2 × P = 0.2 to 0.65 MPa	Dry air at NIST	$U_r(C_d)$ = 0.075% to 0.090%	$Re = 0.55 \times 10^6$ to 2.1×10^6
3	2 CFV Array (Down) P = 0.2 to 0.8 MPa	CFVs (Up) 11 × P = 4.1 to 7.9 MPa	Dry air at CEESI Colorado	$U_r(C_d)$ = 0.082% to 0.095%	$Re = 3.6 \times 10^6$ to 9.1×10^6
4	11 CFV Array (Down) P = 4.1 to 7.9 MPa	Turbine Meter (Up) 1 × P = 4.6 to 7 MPa	Dry air at CEESI Colorado	$U_r(K)$ = 0.099% to 0.119%	$Re = 2.7 \times 10^5$ to 8.0×10^6
5	1 Turbine Meter (Down) $P \approx 7$ MPa	Turbine Meter (Up) 3 × $P \approx 7$ MPa	Natural Gas at CEESI Iowa	$U_r(K)$ = 0.134 % to 0.156 %	$Re = 1.24 \times 10^6$ to 1.08×10^7
6	4 Turbine Array (Down) $P \approx 7$ MPa	Turbine Meter (Up) 2 × $P \approx 7$ MPa	Natural Gas at CEESI Iowa	$U_r(K)$ = 0.115 % to 0.155 %	$Re = 5.09 \times 10^6$ to 2.24×10^7
7	2 Turbine Array (Down) $P \approx 7$ MPa	Turbine Meter (Up) 9 × $P \approx 7$ MPa	Natural Gas at CEESI Iowa	$U_r(K)$ = 0.145 % to 0.169 %	$Re = 6.12 \times 10^6$ to 2.47×10^7
8	9 Turbine Array (Down) … 1 to 9 $P \approx 7$ MPa	Custody Transfer Flowmeter (Down) $P \approx 7$ MPa	Natural Gas at CEESI Iowa	$U_r(Q)$ = 0.16 % to 0.21 %	Q = 0.3 m³/s (3.8×10^4 acfh) to 10.5 m³/s (1.34×10^6 acfh)

Figure 1. Schematic of the 8-stage traceability chain that establishes SI traceability for natural gas custody transfer flow measurements at the CEESI Iowa facility, in which stage-to-stage traceability is achieved using reference flow standards to determine the meter factors and associated uncertainties of stable working standards or calibrated flow meters.

In the staged calibration process shown in Fig. 1, reference standards calibrate flow meters (herein called meters under calibration, MUCs), and establish their meter factors, associated uncertainties, and applicable flow and Reynolds number ranges. In each successive stage, the MUCs from the previous stage serve as the reference standards for the current stage, thereby ensuring continuous SI-traceable calibration throughout the chain. The MUCs consist of critical flow venturis (CFVs) and turbine meters in Stages 1 through 7, and the customer custody-transfer flow meter in Stage 8. For critical flow venturis (CFVs), the meter factor corresponds to the discharge coefficient, while for turbine meters it corresponds to the K-factor. Each stage specifies the operating pressure, meter location (upstream or downstream), and working fluid.

We achieved a significant increase in both pressure and flow by operating multiple reference standards in parallel to calibrate a single MUC. At a given stage, multiple MUCs may be calibrated in this manner and subsequently used together in parallel as reference standards in the following stage. The first three stages employ arrays of CFVs to increase pressure capacity and flow range, enabling the calibration of a turbine meter in high-pressure air at relatively low flow rates. This air-calibrated turbine meter is then used to calibrate additional low-flow, small-diameter turbine meters in high-pressure natural gas at matched Reynolds numbers. These natural-gas-calibrated turbine meters are subsequently used in parallel to calibrate progressively larger turbine meters, ultimately achieving high-pressure, high-flow calibration capability suitable for custody-transfer applications.

The data-reduction equation for each stage is expressed as a function of variables measured in the current stage and the meter factor obtained from the previous stage,

$$MF_s = f\left(x_{s,1}, x_{s,2}, \ldots, x_{s,N}, MF_{s-1,1}, \ldots, MF_{s-1,M}\right), \quad (1)$$

where $x_{s,n}$ is the n[th] input quantity measured during stage s, and $MF_{s\text{-}1,m}$ is the m[th] meter factor established in the preceding calibration stage. Typical input quantities $x_{s,n}$ include pressure, temperature, and frequency, as well as thermodynamic properties such as the critical flow function, compressibility factor, molar mass, and gas composition.

In general, all $x_{s,n}$ values are treated as uncorrelated sources of uncertainty unless explicitly stated. An exception occurs for thermodynamic quantities that are used in sequential stages at the same nominal thermodynamic conditions for the same gas composition. For this special case, the variables are fully correlated with opposite sensitivity coefficients and identical uncertainties, so their contributions to the meter factor uncertainty identically cancel. For simplicity, we set tabulated values of uncertainty of the corresponding $x_{s,n}$ to zero.

The relative expanded uncertainty of the meter factor in stage s is

$$U_r(MF_s) = k u_r(MF_s), \quad (2)$$

where $k = 2$ is the coverage factor for an approximate 95 % confidence interval, and $u_r(MF_{s,m})$ is the relative, combined standard uncertainty at the 68 % confidence level, determined by propagation of uncertainty written as [7, 8]

$$u_r(MF_s) = \sqrt{\sum_{m=1}^{N} S_{x,n}^2 u_r^2(x_{s,n}) + \left[\sum_{m=1}^{N} S_{MF,m} u_r(MF_{s\text{-}1,m})\right]^2}. \quad (3)$$

The first term represents uncertainty contributions from variables measured in the current stage, which are combined in quadrature. The second term represents uncertainty contributions propagated from meter factors of the previous stage. These contributions are conservatively treated as fully correlated. Therefore, the products of the normalized sensitivity coefficients and the relative meter factor uncertainties are summed linearly before being squared in the overall uncertainty calculation.

The terms $S_{x,n}$ and $S_{MF,m}$ are the normalized sensitivity coefficients determined by

$$S_{x,n} = \frac{x_{s,n}}{MF_s} \frac{\partial f}{\partial x_{s,n}}, \quad (4)$$

and

$$S_{MF,m} = \frac{MF_{s\text{-}1,m}}{MF_s} \frac{\partial f}{\partial MF_{s\text{-}1,m}}, \quad (5)$$

respectively.

Across the seven calibration stages, a curve was fitted to the measured meter factors of CFVs and turbine meters as a function of Reynolds number. The relative uncertainty of the fitted values was determined by combining the standard uncertainty of the measurements in Equation (4) with the standard deviation of the fit residuals in a root-sum-of-squares approach. A coverage factor of 2 is applied to approximate a 95 % confidence interval,

$$U_r(MF_s^{FIT}) = k\sqrt{u^2(MF_s) + \sigma_{FIT,s}^2} \ . \qquad (6)$$

Here, $\sigma_{FIT,s,m}$ is the standard deviation of the fit residuals for stage s and the m[th] working standard.

These generic equations were applied to every calibration stage. Although detailed uncertainty calculations are not included, the same methodology is used throughout, propagating current-stage measurements and meter factors from the preceding stage.

In summary, the 8-stage calibration process establishes a continuous, SI-traceable flow measurement chain from NIST low-pressure air standards to high-pressure, pipeline-scale natural gas custody-transfer meters. Each stage builds on the previous by propagating meter factors and uncertainties in a controlled and technically rigorous manner, ensuring traceability and quantified uncertainty throughout the chain. The following sections describe the calibration procedures, uncertainty propagation, and technical considerations for each stage in detail.

3.1 STAGE 1: Calibration of 21 CFVs using NIST's 677 L PVTt Standard in Low Pressure Air

In Stage 1, 21 CFVs with a nominal throat diameter d_1 = 5.207 mm (0.205 in) were individually calibrated in filtered dry air using NIST's 677 L *PVTt* flow standard [9, 10, 11, 12]. The *PVTt* method is a static volumetric technique [13] that determines the mass flow rate, $\dot{m}_{PVTt}$, by diverting a constant flow into an initially evacuated tank of known volume and measuring the resulting density difference over a measured time interval. Each CFV was calibrated individually at seven stagnation pressures ranging from 200 kPa to 800 kPa, in 100 kPa increments. At each setpoint pressure, $\dot{m}_{PVTt}$ was measured at least five times.

The Stage 1 discharge coefficients are defined

$$C_d = \frac{\dot{m}_{PVTt}}{\dot{m}_{th}} = \frac{4\dot{m}_{PVTt}\sqrt{R_u T_0}}{\pi d_1^2 C^* P_0 \sqrt{\mathcal{M}_{air}}} , \qquad (7)$$

where the theoretical mass flow is given by

$$\dot{m}_{th} = \frac{\pi d_1^2 C^* P_0 \sqrt{\mathcal{M}_{air}}}{4\sqrt{R_u T_0}} . \qquad (8)$$

Here, T_0 and P_0 are the stagnation temperature and pressure measured upstream of the CFV [14], C^* is the critical flow function evaluated at the stagnation conditions using REFPROP [15], $\mathcal{M}_{air}$ is the molar mass of dry air, and R_u is the universal gas constant defined in the following reference [16]. The discharge coefficient depends on the theoretical throat Reynolds number, defined as

$$Re_{th} = \frac{4\dot{m}_{th}}{\pi d \mu_0} = \frac{P_0 d_1 C^* \sqrt{\mathcal{M}_{air}}}{\mu_0 \sqrt{R_u T_0}} , \qquad (9)$$

where μ_0 is the dynamic viscosity evaluated at the stagnation conditions T_0 and P_0.

Table 1. Stage 1 uncertainty budget for CFV #10 at a representative calibration point: input quantities x, relative standard uncertainties $u_r(x)$, normalized sensitivity coefficients S_x, and percent contributions of each component to the overall uncertainty (Contrib). Nominal values of the input quantities are provided for reference.

Inputs, *x* [SI units]	**u_r(x) [%, *k*=1]**	**S_x [ ]**	**Contrib. [%]**	**Comment [ ]**
$\dot{m}_{PVTt}$ (9.9260 g/s)	0.0125	1	19.8	677 L *PVTt*
P_0 (200 kPa)	0.02	1	50.7	Pres. Cal. Records
T_0 (296 K)	0.03	0.5	28.6	Temp. Cal. Records
C^* (0.6854)	0	1	0.0	Correlated Unc. Stage 1 & 2
$\mathcal{M}_{air}$ (28.95 g/mol)	0	1	0.0	Correlated Unc. Stage 1 & 2
R_u 8.314 J/(molK)	0	1	0	Defined Constant
d_1 (5.207 mm)	0	2	0.0	Correlated Unc. Stage 1 and 2
$\sigma_{FIT,1,10}$	0.0027	1	0.9	Fit Residual Stdev.
		Total	**100 %**	
Output Quantities				**Comment**
$C_{d,1}^{FIT}$ = 0.9840				Equation (7)
$U_r(C_{d,1}^{FIT})$ = 0.056 %				Unc. Propagation

Figure 2 shows an example calibration curve for CFV #10, plotting the discharge coefficient versus the inverse square root of Re_{th}. The measured discharge coefficients are shown as circles (○), and the solid line (——) shows a 3rd degree polynomial fit to the data. Dashed lines (----) indicate the expanded uncertainty of the fitted curve. Procedures for calculating the uncertainty of the measured data and the fitted curve are described in Section 3, using Equation (2) for the measurements and Equation (6) for the fitted curve.

Table 1 illustrates the relative magnitudes of the input quantities and their uncertainties for a single calibration point. The table indicates the contribution of each input quantity to the overall Stage 1 uncertainty budget. Because all subsequent stages apply the same uncertainty-propagation methodology described in Section 3, we omit additional uncertainty tables in later stages for conciseness. For the 21 CFVs calibrated, the expanded uncertainties ranged from 0.055 % to 0.075 %, with the average uncertainty of the set below 0.06 %.

3.2 STAGE 2: Calibration of 2 CFVs using an Array of 21 Stage 1 CFVs in Low Pressure Air

In Stage 2, two CFVs each with a nominal throat diameter d_2 = 2.54 cm (1 in) were individually calibrated in dry air against an array of 21 Stage 1 CFVs [17]. Each Stage 1 CFV was equipped with a downstream valve that could be fully opened to allow normal flow or closed to block flow, enabling any combination of the 21 CFVs to be selected. The Stage 1 CFV array was installed upstream of the Stage 2 CFVs being calibrated. Flow from the CFV array passed through a perforated-plate flow conditioner followed by a reducer with an inlet diameter of 20.32 cm

(8 in) and exit diameter of 15.24 cm (6 in) before entering the Stage 2 CFV.

The Stage 2 discharge coefficient is defined as,

$$C_{d,2} = \frac{\dot{m}_2}{\dot{m}_{th,2}} , \qquad (10)$$

where the mass flow $\dot{m}_2$ is calculated from the Stage 1 CFV array as the sum of each CFV's theoretical mass flow $\dot{m}_{th,1,m}$ multiplied by its fitted discharge coefficient $C_{d,1,m}^{FIT}$,

$$\dot{m}_2 = \dot{m}_{CFVarray,1} = \sum_{m=1}^{21} \delta_m \dot{m}_{th,1,m} C_{d,1m}^{FIT} . \qquad (11)$$

with $\delta_m = 1$ if the mth Stage 1 CFV is open, and $\delta_m = 0$ if it is closed. The theoretical mass flows $\dot{m}_{th,2}$ in Equation (10) and $\dot{m}_{th,1,m}$ in Equation (11) are expressed in terms of their stagnation pressures, temperatures, and critical flow functions, with a functional form analogous to Equation (8), adjusted for the Stage 2 measurement conditions. The resulting Stage 2 discharge coefficient can then be expressed as,

$$C_{d,2} = \frac{P_{0,u} C_u^*}{P_{0,d} C_d^*} \sqrt{\frac{T_{0,d}}{T_{0,u}}} \sum_{m=1}^{21} \delta_m \frac{d_{1,m}^2}{d_2^2} C_{d,1m}^{FIT} , \qquad (12)$$

where the subscripts "u" and "d" denote the locations where upstream and downstream P_0, T_0, and C* are evaluated, and the Stage 1 CFV discharge coefficients are scaled by the squared ratio of CFV diameters $(d_{1,m}/d_2)^2$.

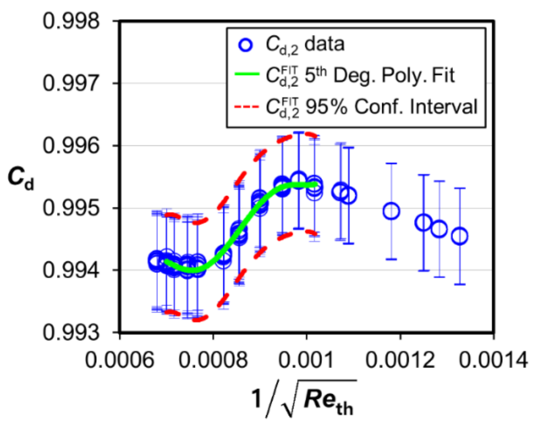

Figure 3. Calibration data of a Stage 2 CFV showing measured ($C_{d,2}$) and fitted ($C_{d,2}^{FIT}$) discharge coefficients plotted versus the inverse square root of the CFV theoretical Reynolds number for air flow.

The Stage 2 CFVs were calibrated at a minimum of 16 set points covering Reynolds numbers from 5.6×10^5 to 2.2×10^6, or mass flows from 0.2 kg/s to 0.8 kg/s. Figure 3 shows an example calibration curve for a Stage 2 CFV. The measured discharge coefficients are denoted by the circles (○), and the solid line (—) is a 5th degree polynomial fit to the measured $C_{d,2}$ values. The fitted calibration curve $C_{d,2}^{FIT}$ is limited to theoretical Reynolds numbers ranging from $Re_{th} = 8 \times 10^5$ to 2.04×10^6, and the dashed lines (----) indicate the expanded uncertainty of the fitted curve.

3.3 STAGE 3: Calibration of 11 CFVs using an Array of 2 Stage 2 CFVs

In Stage 3, 11 CFVs were calibrated: ten with a nominal diameter of 9.55 mm (0.376 in) and one with a nominal diameter of 6.99 mm (0.275 in), where d_3 denotes the nominal diameter of a Stage 3 CFV. Each Stage 3 CFV was individually calibrated in dry air at the CEESI Nunn facility using one or both of the Stage 2 CFVs.

The calibration was performed at sixteen flow rates in descending order, followed by eight repeat flow rates in ascending order, at pressures between 4.1 MPa and 7.9 MPa. The complete calibration sequence was then performed again on a subsequent day.

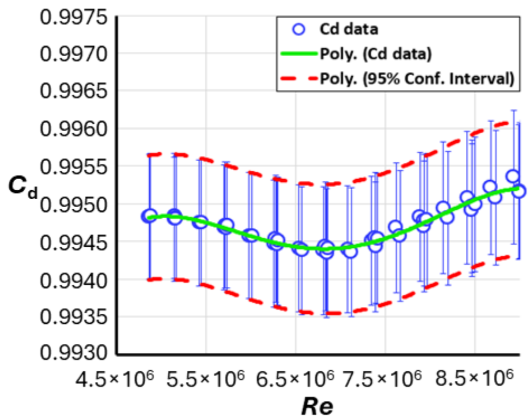

Figure 4. Calibration data of a Stage 3 CFV showing measured ($C_{d,3}$) and fitted ($C_{d,3}^{FIT}$) discharge coefficients plotted versus the CFV throat Reynolds number for air flow

The discharge coefficient of the Stage 3 CFVs is,

$$\begin{aligned} C_{d,3} &= \frac{\dot{m}_3}{\dot{m}_{th,3}} = \frac{\dot{m}_{CFVarray,2}}{\dot{m}_{th,3}} \\ &= \frac{1}{\dot{m}_{th,3}} \sum_{m=1}^{2} \delta_m \dot{m}_{th,2,m} C_{d,2m}^{FIT} , \qquad (13) \\ &= \frac{P_{0,d} C_d^*}{P_{0,u} C_u^*} \sqrt{\frac{T_{0,u}}{T_{0,d}}} \sum_{m=1}^{2} \delta_m \frac{d_{2,m}^2}{d_3^2} C_{d,2m}^{FIT} \end{aligned}$$

with the valve selector $\delta_m = 1$ if the mth Stage 2 CFV is open, and $\delta_m = 0$ if it is closed. The mass flow $\dot{m}_3$ is determined by the Stage 2 CFV array (analogous to Equation 11 for Stage 2 mass flow), and $\dot{m}_{3,th}$ is based on Equation 8 (adjusted for Stage 3 operating conditions). The Stage 3 CFV discharge coefficient has the same functional form as that in Stage 2 (see Equation 12), but with the upstream and downstream subscripts flipped due to the reversed orientation of the reference CFV array and the CFV being calibrated, as shown in Fig. 1.

Figure 4 shows an example calibration curve for a Stage 3 CFV. The measured discharge coefficients are denoted by the circles (○) and plotted versus the throat Reynolds number. The solid line (—) is a 4th degree polynomial fit to the measured $C_{d,3}$ values. As shown in the figure the fitted calibration curve $C_{d,3}^{FIT}$ extends from $Re = 4.9 \times 10^6$ to 9.0×10^6. The dashed lines (----) are the expanded uncertainty of the calibration curve, which ranged from 0.082 % to 0.095 %.

3.4 STAGE 4: Calibration of Low Flow Turbine Meter (LFTM) in High-Pressure Air

In Stage 4, we calibrated a meter package consisting of an ultrasonic flow meter (USM) and a turbine meter (TM) installed in series. The calibration used the 11 Stage 3 CFVs arranged in a parallel array as the reference. Each CFV was equipped with a downstream valve that can be fully open or closed, allowing any combination of 11 CFVs to be used. The meter package has a nominal diameter of $D_{TM} = 10.16$ cm (4 in) and a total length of 30 D_{TM} (pipe diameters). The USM served only as a check meter and was not included in the analysis.

The first 20 D_{TM} of the meter package served to condition the flow, consisting of 10 D_{TM} of straight pipe, a CPA 55E perforated-plate flow conditioner, and another 10 D_{TM} of straight pipe. The USM was installed immediately downstream of the flow conditioning section, with the TM located 10 D_{TM} further downstream and used for all calibration measurements.

To house the Stage 3 CFV array, a pipe section 8 D_{array} in length with nominal diameter D_{array} =25.4 cm (10 in) was installed downstream of the meter package. A reducer transitions between the meter package and this larger-diameter section. A CPA 50E perforated-plate flow conditioner is located midway along the piping, and the CFV array is installed at the downstream end, exhausting into the laboratory at atmospheric pressure.

The calibration procedure was performed at 11 flow rates, ordered from high to low. Each calibration was repeated twice, with at least five measurements per flow point. Each successive volumetric flow was obtained by closing an additional CFV. The transfer package was calibrated at two different line pressures, 7 MPa (1010 psia) and 4.6 MPa (667.2 psia) to assess small pressure-dependent effects on the *K*-factor that are not fully captured by Reynolds number scaling.

The turbine meter *K*-factor is defined as

$$K_{TM,4} = \frac{f_{TM}}{Q_{TM}}, \tag{14}$$

where Q_{TM} is the volumetric flow through the meter and f_{TM} is resulting blade frequency. The volumetric flow through the turbine meter is

$$\begin{aligned} Q_{TM} &= \frac{\dot{m}_4}{\rho_{TM}} = \frac{\dot{m}_{CFVarray,3}}{\rho_{TM}} \\ &= \frac{Z_{TM} R_u T_{TM}}{P_{TM} \mathcal{M}_{air}} \sum_{n=1}^{11} \delta_m \dot{m}_{th,3,m} C_{d,3,m}^{FIT} , \\ &= \frac{\pi Z_{TM} T_{TM} P_0 C^*}{4 P_{TM} \sqrt{T_0 \mathcal{M}_{air} / R_u}} \sum_{n=1}^{11} \delta_m d_{3,m}^2 C_{d,3,m}^{FIT} \end{aligned} \tag{15}$$

with the valve selector $\delta_m = 1$ if the m[th] Stage 3 CFV is open, and $\delta_m = 0$ if it is closed. The mass flow rate $\dot{m}_4$ is determined by the Stage 3 CFV array (analogous to Equation 11 for Stage 1 mass flow). The theoretical mass flows, $\dot{m}_{th,3,m}$ are expressed in terms of stagnation pressure, temperature, and the critical flow function, with a functional form analogous to Equation (8), adjusted for the Stage 4 measurement conditions. The density, $\rho_{TM} = P_{TM}M_{air}/(Z_{TM}R_u T_{TM})$ is the density evaluated by measuring the respective pressure P_{TM} and temperature T_{TM} at the turbine meter. The compressibility factor Z_{TM} is determined using REFPROP [15] at P_{TM} and T_{TM}.

The resulting turbine meter *K*-factor is then given by

$$K_{TM4} = \frac{4 f_{TM} P_{TM} \sqrt{T_0 \mathcal{M}_{air} / R_u}}{\pi Z_{TM} T_{TM} P_0 C^* \sum_{m=1}^{11} \delta_m d_{3,m}^2 C_{d,3,m}^{FIT}} . \tag{16}$$

where $d_{3,m}$ are the diameters of the Stage 3 CFVs, T_0 and P_0 are stagnation temperature and pressure determined upstream of the CFV array, and $C_{d,3,m}^{FIT}$ are the fitted Stage 3 discharge coefficients. The turbine meter Reynolds number is calculated by

$$\begin{aligned} Re_{TM4} &= \frac{4\dot{m}_4}{\pi D_{TM4} \mu_{TM}} = \frac{4\dot{m}_{CFVarray,3}}{\pi D_{TM4} \mu_{TM}} , \\ &= \frac{4}{\pi D_{TM4} \mu_{TM}} \sum_{n=1}^{11} \delta_m \dot{m}_{th,3,m} C_{d,3,m}^{FIT} , \\ &= \frac{P_0 C^* \sqrt{\mathcal{M}_{air}}}{D_{TM,4} \mu_{TM} \sqrt{R_u T_0}} \sum_{m=1}^{11} \delta_m d_{3,m}^2 C_{d,3,m}^{FIT} , \end{aligned} \tag{17}$$

where $d_{3,m}$ are the diameters of the Stage 3 CFVs, T_0 and P_0 are upstream CFV array stagnation temperature and pressure, and $C_{d,3,m}^{FIT}$ are the fitted Stage 3 discharge coefficients.

The *K*-factor showed a small (~ 0.09 %) difference between the two line pressures, reflecting minor pressure-dependence. A linear pressure correction was applied in the *K*-factor versus Reynolds number calibration fit, collapsing the data from both pressures into a single curve. Figure 5 shows the measured *K*-factors (○) and the 4th degree polynomial fit (—) plotted versus Reynolds number. The fit extends from $Re = 2.7 \times 10^5$ to 8.0×10^6. Dashed lines (----) indicate the expanded uncertainty of the calibration curve ranging from 0.099 % to 0.119 % depending on the Reynolds number.

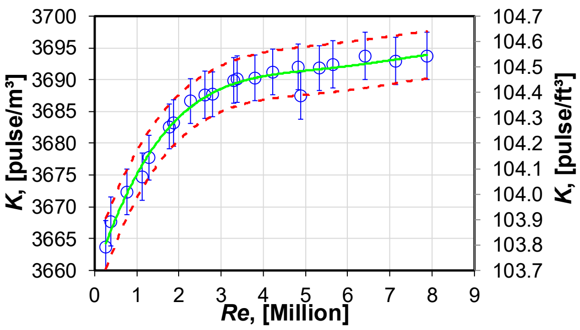

Figure 5. Calibration data of the Stage 4 turbine meter showing measured data (K_{TM4}) and fitted (K_{TM4}^{FIT}) *K*-factors plotted versus the Reynolds number for air flow.

3.5 STAGE 5: Calibration of 3 Low Flow Turbine Meters (LFTMs) in High Pressure Natural Gas

In Stage 5, the 102-mm (4 in) diameter turbine meter package calibrated in high-pressure air at the CEESI Nunn facility was used to calibrate 3 102-mm diameter Low Flow Turbine Meters (LFTMs) in natural gas at the CEESI Iowa Facility. The 3 102-mm LFTMs were installed on a "skid", a compact prefabricated assembly containing inlet and outlet headers and shut-off valves. The skid is designed to hold up to four 102 mm diameter turbine meters, and the shut-off valves allow flow through all turbine meter simultaneously (parallel operation) or through any single turbine meter individually. For Stage 5, the 3 uncalibrated LFTMs were installed in the low flow skid, with the fourth slot empty and valved shut. The low flow skid was then installed upstream of the Stage 4 reference turbine meter, which had been calibrated in high-pressure air. Calibration data were collected over a three-day period, with at least five repeated measurements per flow rate.

The Reynolds number and K-factor of a Stage 5 LFTM are defined as

$$Re_{\text{TM5}} = \frac{4\dot{m}_5}{\pi D_{\text{TM5}} \mu_{\text{TS5}}} \,, \tag{18a}$$

$$K_{\text{TM5}} = \frac{f_{\text{TM5}}}{Q_{\text{TM5}}} = \frac{\rho_{\text{TM5}} f_{\text{TM5}}}{\dot{m}_5} \,, \tag{18b}$$

where ρ_{TM5} is the density, Q_{TM5} is the volumetric flow rate, and f_{TM5} the resulting rotor blade frequency at the meter. The mass flow rate based on the Stage 4 reference turbine meter is $\dot{m}_5 = \rho_{\text{TM4}} Q_{\text{TM4}}$ with the volumetric flow expressed as $Q_{\text{TM4}} = f_{\text{TM4}}/K_{\text{TM4}}^{\text{FIT}}$. Substituting these relationships into Equation (18a) and (18b) yields the following expressions for the Stage 5 Reynolds number and K-factor,

$$Re_{\text{TM5}} = \frac{4\rho_{\text{TM4}} f_{\text{TM4}}}{\pi D_{\text{TM5}} \mu_{\text{TM5}} K_{\text{TM4}}^{\text{FIT}}} \,, \tag{19a}$$

$$K_{\text{TM5}} = \frac{\rho_{\text{TM5}}}{\rho_{\text{TM4}}} \frac{f_{\text{TM5}}}{f_{\text{TM4}}} \frac{1}{K_{\text{TM4}}^{\text{FIT}}} \,. \tag{19b}$$

Figure 6 shows the calibration data for one of the Stage 5 LFTMs. Blue circles (○) indicate discrete data points, with error bars representing the expanded uncertainty at each point. The solid line (──) shows the fitted calibration curve, while dashed lines (----) indicate the expanded uncertainty of the fitted Stage 5 LFTM calibration curve, which ranged from 0.115 % to 0.155 %, depending on the Reynolds number.

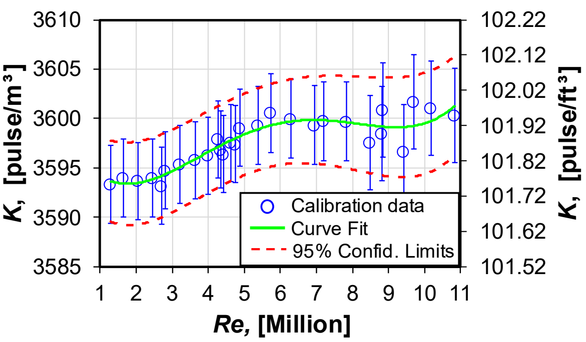

Figure 6. Calibration data of the Stage 5 turbine meter showing measured data (K_{TM5}) and fitted ($K_{\text{TM5}}^{\text{FIT}}$) K-factors plotted versus the Reynolds number for natural gas flow.

Mass Flow Expression for an Array of Reference Turbine Meters

As illustrated in Figure 1, for the subsequent stages, reference turbine meters are installed in parallel and are used either to calibrate additional turbine meters required for SI-traceability scale-up (Stages 6 and 7) or a customer flow meter (Stage 8). The total mass flow through a parallel array of reference turbine meters can be expressed as

$$\dot{m}_{\text{TMarray}} = \sum_{m=1}^{N} \delta_{\text{m}} \dot{m}_{\text{TM}_\text{m}} = \sum_{m=1}^{N} \delta_{\text{m}} \rho_{\text{TM}_\text{m}} Q_{\text{TM}_\text{m}} \,, \tag{20}$$

where $\delta_{\text{m}} = 1$ if the turbine meter flow valve is open permitting flow, and $\delta_{\text{m}} = 0$ if the valve is closed. At each reference turbine meter, ρ_{TMm} is the fluid density and Q_{TMm} is the volumetric flow through that meter. Substituting $Q_{\text{TMm}} = f_{\text{TMm}}/K_{\text{TMm}}$ where f_{TMm} is the meter rotor frequency and K_{TMm} is the turbine meter K-factor, gives

$$\dot{m}_{\text{TMarray}} = \sum_{m=1}^{N} \frac{\delta_{\text{m}} \rho_{\text{TM}_\text{m}} f_{\text{TM}_\text{m}}}{K_{\text{TM}_\text{m}}^{\text{FIT}}} \,. \tag{21}$$

The parameter N is the number reference turbine meters in the parallel array: $N = 4$ in Stage 6, and $N = 2$ in Stage 7, and $N = 9$ in Stage 8.

3.6 STAGE 6: Calibration of 2 Medium Flow Turbine Meters (MFTM) in High Pressure Natural Gas

In Stage 6, the 3 LFTMs from Stage 5 and the air-calibrated turbine meter from Stage 4 were installed in the low flow skid (LFS) and operated in parallel. These meters were used as references to individually calibrate two 194 mm (8 in) medium flow turbine meters (MFTMs) in high-pressure natural gas. Valves on the LFS allowed any combination of the reference meters to be used, providing flexible flow configurations. The two MFTMs were also installed in a skid, which allowed them to be operated individually or together in parallel. The MFTS skid was installed upstream of the LFTS skid in the CEESI Iowa calibration building. Calibration data were collected over five separate days, with at least five repeated measurements at each flow rate.

The Reynolds number and K-factor of a Stage 6 MFTM are calculated by applying the fundamental definitions from Stage 5 (Equations 18a and 18b), adjusted for Stage 6 (*i.e.*, all variables are changed from "5" to "6"), using the mass flow determined from the parallel array of reference LFTMs (Equation 22) of a Stage 6 MFTM is defined as

$$Re_{\text{TM6}} = \frac{4}{\pi D_{\text{TM6}} \mu_{\text{TM6}}} \sum_{m=1}^{4} \frac{\delta_{\text{m}} \rho_{\text{LFTM}_\text{m}} f_{\text{LFTM}_\text{m}}}{K_{\text{LFTM}_\text{m}}^{\text{FIT}}} \,, \tag{22a}$$

$$K_{\text{TM6}} = \left[\sum_{m=1}^{4} \delta_{\text{m}} \frac{\rho_{\text{LFTM}_\text{m}}}{\rho_{\text{TM6}}} \frac{f_{\text{LFTM}_\text{m}}}{f_{\text{TM6}}} \frac{1}{K_{\text{LFTM}_\text{m}}^{\text{FIT}}} \right]^{-1} , \tag{22b}$$

where the subscript LFTM represents the calibrated Stage 4 and 5 turbine meters, $N = 4$ is the number of reference turbine meters in the skid, $\delta_{\text{m}} = 1$ if the shutoff valve of a reference meter is open and $\delta_{\text{m}} = 0$ if it is closed, and the subscript TM6 is synonymous with MFTS.

The Reynolds versus K-factor data is shown in Fig. 7 for one of the Stage 6 MFTS. Blue circles (○) are discrete measurements at different Reynolds numbers, with the error bars showing the expanded uncertainty. The solid line (──) shows the calibration curve fit extending from $Re = 5.09 \times 10^6$ to 2.24×10^7 with expanded uncertainties for ranging from 0.115 % to 0.155 % depending on the Reynold number.

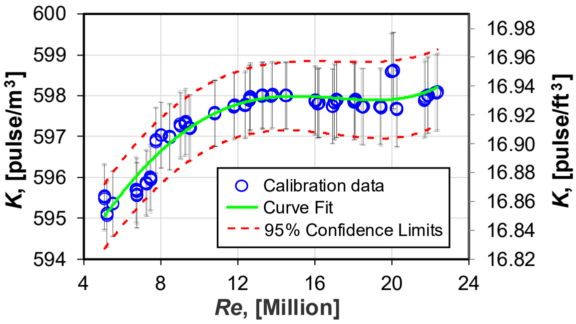

Figure 7. Calibration data of the Stage 6 MFTS showing measured data (K_{TM6}) and fitted (K_{TM6}^{FIT}) K-factors plotted versus the Reynolds number for high pressure natural gas flow.

3.7 STAGE 7: Calibration of 9 High Flow Turbine Meters (HFTMs) in High-Pressure Natural Gas

Each of the 9 high-flow turbine meters (HFTMs)has a nominal diameter of 304 mm (12 in) and serves as the working standards for the CEESI Iowa facility, where they are used to calibrate customer flow meters. These HFTMs are installed in a parallel array with shutoff valves, allowing any combination of meters to operate depending on the required flow rate. This flexible arrangement ensures that these working standards can cover a wide range of flow conditions.

To calibrate the HFTMs, two medium-flow turbine meters (MFTMs) with nominal diameters of 194 mm (8 in), previously calibrated in Stage 6, were employed as reference standards. The MFTMs were installed in skid downstream of the HFTMs. Each HFTM was calibrated individually against the reference MFTMs, with calibration data collected over nine separate days. At each flow rate, at least five repeat measurements were recorded to ensure accuracy and repeatability.

The expressions for the Reynolds number and K-factor for the Stage 7 HFTMs are

$$Re_{TM7} = \frac{4}{\pi D_{TM7}\mu_{TM7}} \sum_{m=1}^{2} \frac{\delta_m \rho_{MFTM_m} f_{MFTM_m}}{K_{MFTM_m}^{FIT}}, \qquad (23a)$$

$$K_{TM7} = \left[\sum_{m=1}^{2} \delta_m \frac{\rho_{MFTM_m}}{\rho_{TM7}} \frac{f_{MFTM_m}}{f_{TM7}} \frac{1}{K_{MFTM_m}^{FIT}} \right]^{-1}, \qquad (23b)$$

where the subscript TM7 is synonymous with HFTM. These equations are analogous to Equations (22a) and (22b), but applied to Stage 7 reference MFTMs.

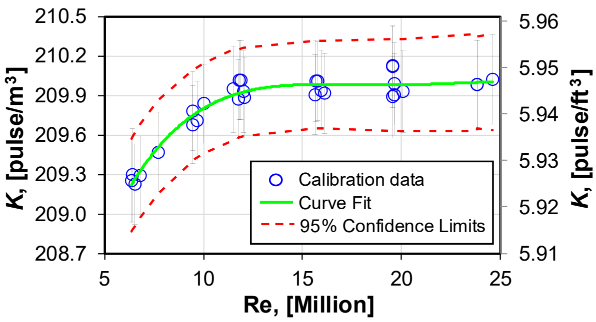

Figure 8. Calibration data of the Stage 7 HFTSs showing measured data (K_{TM7}) and fitted (K_{TM7}^{FIT}) K-factors plotted versus the Reynolds number for natural gas flow.

A plot of the *R*eynolds number versus K-factor for one of the HFTMs is shown in Figure 8. Blue circles (○) indicate discrete measurements made at different Reynolds numbers, with the error bars showing the expanded uncertainty. The solid line (—) shows the calibration curve fit, and the dashed lines (----) indicate the expanded uncertainty of the Stage 7 HFTM calibration curve, which ranged from 0.145 % to 0.169 %, depending on the Reynold number.

3.8 STAGE 8: Calibration of a Custody Transfer Flow Meters in High-Pressure Natural Gas

In stage 8, the 9 HFTMs are used to calibrate custody transfer flow meters in high-pressure natural gas. Depending on the flow rate, any combination of 1 to 9 HFTMs may be operated in parallel. This configuration provides a facility flow range of 0.25 m³/s to 10.5 m³/s (38,000 acfh to 1,330,000 acfh) and allows redundancy, as the same flow can be measured through different HFTMs to ensure reliability. This stage does not include testing but is used to estimate the expanded uncertainty of the volumetric flow rate at a customer meter when the flow rate is measured upstream with the working turbines. To conservatively estimate this uncertainty, the contribution from the working turbine calibrations, and the instrumentation are combined with the values estimated from historical data on short term random effects (repeatability), long term random effects (reproducibility), and changes in the stored mass in the connecting volume between the reference meters and the meter being calibrated. This analysis provided expanded overall uncertainties in volumetric flow for a typical custody transfer ultrasonic flow meter from 0.16 % to 0.21 %, depending on the flow. Both the improved expanded uncertainty and the previous uncertainty are shown in Figure 9.

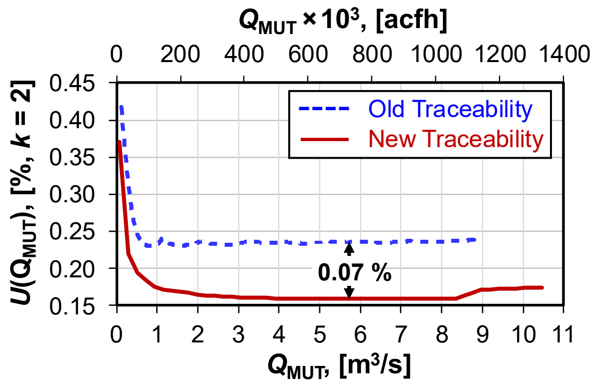

Figure 9. Expanded uncertainty new 8 stage traceability chain and old traceability chain of a calibrated ultrasonic flow meter in high-pressure natural gas verses volumetric flow rate (Q_{MUT}).

4. Lessons Learned and Process Changes to be implemented for 2026 testing

The 8-stage test plan is being repeated in 2026 to verify the calibrations and help monitor the long-term stability of the provided measurements. The 2026 iteration will have updates based on the lessons learned in 2019.

After the 2019 process and during subsequent use, the LFTM (nominal diameter 102 mm) that was calibrated in high-pressure air and then used as a reference standard to calibrate 3 additional turbine meters in high-pressure natural gas did not maintain the desired long term calibration stability. The air-calibrated LFTM employed a dual rotor design, and it is hypothesized that the additional mechanical complexity of this configuration contributed to its long-term instability. The 2026 effort to repeat the complete eight-stage process will use a new 102 mm single-rotor turbine meter.

The ultrasonic flowmeter that was included in the transfer standard package with the Stage 4 102m turbine was not used in the analysis. The 2026 analysis will try to leverage the use of an additional meter of a different design to reduce the random effects associated with the step from air calibrations to a natural gas application.

The uncertainty due to changes in stored mass between the HFTMs (nominal diameter 305 mm) and the customer meter was treated as an uncertainty component in the 2019 analysis. For the 2026 testing, the changes in stored mass will be measured to improve the measurement and reduce the uncertainty.

5. Conclusion

The 8-stage process, extending traceability from the NIST *PVTt* through four levels of CFVs and three levels of turbine meters to provide high-pressure, large-scale natural gas calibrations for custody transfer, was successful and achieved expanded relative uncertainties as low as 0.16 %.This process scaled the flow rate from 0.04 kg/sec to 680 kg/sec (0.09 lbm/s to 1490 lbm/s), achieving a ratio of 16,400:1, and scaled pressure from 0.8 to 7.6 MPa (120 to 1100 psi), achieving a 9:1 ratio relative to the initial NIST measurements. A repeat of the process is underway in 2026 and will provide valuable information on the stability of the process and potentially lead to improved measurement.

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