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Improvement and Analysis of Low Pressure Gas Flow Calibration System - Bell Prover

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Abstract

Bell Prover is the primary standard system for low-pressure gas by National Measurement Laboratory. When Bell Prover conducts calibration, the density of the gas inside the bell jar must be determined by the measurement of the pressure and temperature of the gas inside the bell jar. It is essential to accurately measure the representative temperature of the bell jar interior. After the system is redesigned in temperature control and temperature measurement methods, the half interval of the measurement error due to temperature stratification inside the bell jar is reduced from the original 0.1 ℃ drops to 0.05 ℃, and the relative expanded uncertainty of the entire system drops from 0.11 % to 0.09 %.

1. Preface

Flow measurement is different from length measurement or mass measurement. It cannot be directly conducted to obtain the measurement result and complete the traceability with only physical standards such as gauge blocks or weights. (Flow measurement is conducted by Bell Prover, a weighing system with a thermometer, pressure gauge, etc., and is traceable to the basic measurements, such as length, mass, time, temperature, and derived quantities such as pressure.) In a flow standard laboratory, the method adopted to establish the standard flow for the low-pressure gas flow calibration system is: Under good environmental control conditions, the compressed gas passes through the pressure regulating valve and the flow regulating valve to generate a stable flow process and fluid properties. With the introduction of a volume standard of pre-calibrated set volume and the measurement of the corresponding collection time, the temperature and pressure are simultaneously measured to calculate the gas density during the collection period. There are currently two designs for this method [1], Piston Prover and Bell Prover. This paper will discuss the improvement of the Bell Prover system. Please refer to Figure 1 for the schematic diagram of the system before improvement. The instruments on the system include Laser Doppler Scale, timer (HP34571A), pressure gauge (RUSKA 50743 and RUSKA 52280), and thermometer, etc. All the above instruments can be traced back to SI units. Please refer to Figure 2 for the traceability diagram.

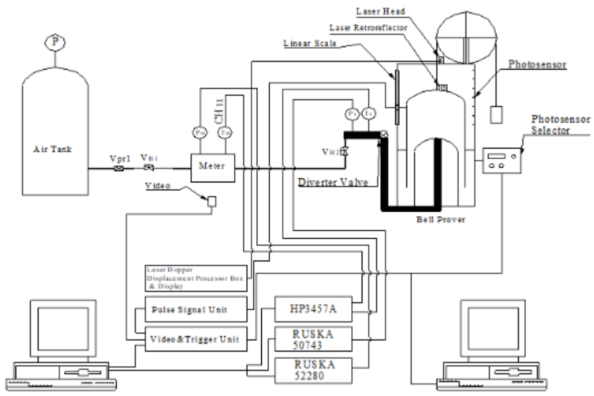

Figure 1: Bell Prover schematic diagram. [3]

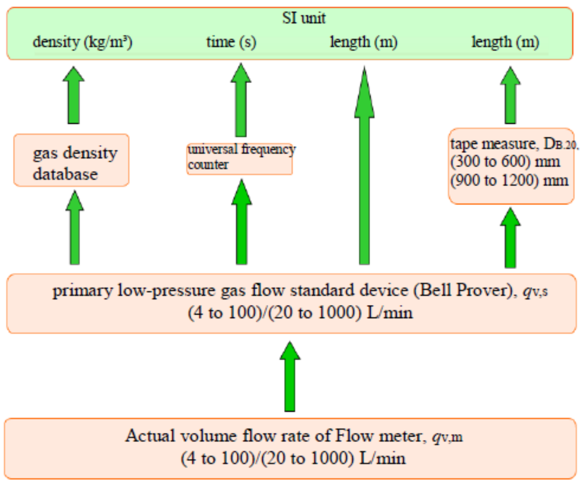

Figure 2: Bell Prover traceability diagram. [3]

The relative expanded uncertainty for the bell calibration system (1093) in the National Measurement Laboratory is analyzed by the recommended evaluation according to ISO "Guide 98-3:2008, Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement"[2]. The relevant information is summarized in Table 1. The key point of Bell Prover system improvement is to redesign temperature control and measurement method to lower the uncertainty, and reduce the system declared uncertainty from 0.11 % to 0.09 %.

Table 1: Relative expanded standard uncertainty [3] for bell calibration system (1093).

	Bell Prover 1093
V_c	(200 to 600) dm^3
$\frac{V_c}{t}$	(20 to 1000) dm^3/min
$k(\frac{u_c(q_{m,s})}{q_{m,s}})$	0.11 %
k	1.96
effective degree of freedom	∞

2. Introduction of Principle and Uncertainty Evaluation for Bell Prover

2.1 Measurement principle

A typical flow measurement system consists of the pipelines to the flow meter to be calibrated, the flow meter to be calibrated, the pipelines to the standard, and the standard. There must be a long enough straight pipe upstream of the flow meter to be calibrated to prevent errors caused by installation effects.

So-called Control Volume is established at the inner edge of the pipeline between the outlet of the calibrated flow meter and the starting point of the collection volume by Bell Prover. According to the law of conservation of mass, the following equation can be written.

$$0 = \frac{\partial}{\partial t}\int_V \rho \cdot dV + \int_A \rho \vec{v} \cdot d\vec{A} \quad (1)$$

Wherein (1), ρ is the fluid density, V is the control volume, $\vec{v}$ is the fluid velocity, $d\vec{A}$ is the unit vector of the control surface. The mass flow rate $q_{m,s}$ is rewritten as the following equation (2).

$$\begin{aligned} q_{m,s} &= \frac{\pi \times \rho_S \times {D_S}^2 \times L_S}{4t} + \frac{\Delta\rho_{cv} \cdot V_{cv}}{t} + \frac{\rho_{cv} \cdot \Delta V_{cv}}{t} + q_{m,l} \\ &= \frac{\rho_S \cdot V_c}{t} + \frac{\Delta\rho_{cv} \cdot V_{cv}}{t} + \frac{\rho_{cv} \cdot \Delta V_{cv}}{t} + q_{m,l} \\ &= f(V_c, \rho_S, t, \Delta\rho_{cv}, V_{cv}, \rho_{cv}, \Delta V_{cv}, q_{m,l}) \end{aligned} \quad (2)$$

where V_c is the collection volume at the set point of the standard, D_S is the effective diameter corresponding to the collection volume at the set point of the standard, t is the corresponding collection time, V_{cv} is the control volume, ΔV_{cv} is the change after the control volume calibration, ρ_S is the gas density of the standard, ρ_{cv} is the gas density within the control volume, $\Delta\rho_{cv}$ is the change of gas density within the control volume at the moment of calibration start and end, and $q_{m,l}$ is the change of mass flow rate caused by oil adhesion during the calibration period.

2.2 Contributions to temperature measurement uncertainty

When Equation (2) is introduced to the recommended evaluation of uncertainty by the guideline [2], it can be obtained that:

$$\begin{aligned} \left(\frac{u_c(q_{m,s})}{q_{m,s}}\right) &= [(\frac{u(V_c)}{V_c})^2 + (\frac{u(\rho_s)}{\rho_s})^2 + (\frac{-u(t)}{t})^2 + \\ &(\frac{V_{cv}}{V_c}\frac{u(\Delta\rho_{cv})}{\rho_S})^2 + (\frac{u(\Delta V_{cv})}{V_c})^2 + (\frac{\Delta V_{cv}}{V_c}\frac{u(\rho_{cv})}{\rho_S})^2 + \\ &(\frac{\Delta\rho_{cv}}{\rho_S}\frac{u(V_{cv})}{V_c})^2 + (\frac{u(q_{m,l})}{q_{m,s}})^2]^{1/2} \end{aligned} \quad (3)$$

The eight contributions to the uncertainty in Equation (3) include the relative standard uncertainty contributed by collection volume $\frac{u(V_c)}{V_c}$, the relative standard uncertainty pertaining to gas density measurement $\frac{u(\rho_S)}{\rho_S}$, the relative standard uncertainty pertaining to time measurement $\frac{u(t)}{t}$, the relative standard uncertainty due to the density change of the gas within the control volume at the moment of calibration start and end $\frac{V_{cv}}{V_c}\frac{u(\Delta\rho_{cv})}{\rho_S}$, the effect on the collection mass by the gas mass change within the control volume due to the change of control volume at the moment of calibration start and end $\frac{\Delta V_{cv}}{V_c}\frac{u(\rho_{cv})}{\rho_S}$, the relative standard uncertainty contributed by the control volume change $\frac{u(\Delta V_{cv})}{V_c}$, the relative standard uncertainty affected by the control volume measurement $\frac{\Delta\rho_{cv}}{\rho_S}\frac{u(V_{cv})}{V_c}$, and the relative standard uncertainty contributed by the adhered quantity $q_{m,l}$ on the control surface $\frac{u(q_{m,l})}{q_{m,s}}$. Among all contributing factors to the uncertainty, $\frac{u(\rho_S)}{\rho_S}$ has the largest contribution, about 0.047 % to the relative standard uncertainty. ρ_S has its main sources of uncertainty coming from the relative standard uncertainty $\frac{u(T_S)}{T_S}$and $\frac{u(P_S)}{P_S}$ contributed by temperature and pressure measurement. $\frac{u(T_S)}{T_S}$ is the measurement error due to the uneven distribution of bell jar interior temperature, which is the main point of improvement in the study. It is estimated that the maximum deviation half interval for temperature distribution is no more than 0.10 °C before improvement, while the maximum deviation half interval drops to 0.05 °C after improvement of the temperature control system and measurement method, and the contribution to uncertainty by lowering temperature makes $\frac{u(\rho_s)}{\rho_s}$ decrease from 0.047 % to 0.026 %.

Table 2: Evaluation of uncertainty by the density term $\frac{u(\rho_s)}{\rho_s}$.

$\frac{u(\rho_s)}{\rho_s}$ = 0.047 % ➔ 0.026 %	
$\frac{u(T_s)}{T_s}$	0.041 % ➔ 0.013 %
$\frac{u(P_s)}{P_s}$	0.0106 %
$\frac{u(R_u)}{R_u}$	ignored
$\frac{u(Z(P_s,T_s))}{Z(P_s,T_s)}$	0.015 %

R_u: Universal gas constant
Z: gas pressure

3. Methods

The objective of the study is to lower the expanded uncertainty of the system from 0.11 % to 0.10 % by improvement of temperature control and measurement method. The above methods will be described in the following.

3.1 Temperature control and measurement environment improvement

Please refer to the part labeled No. 1 in Figure 3. It is to solve the problem with excessively fast airflow at the outlet of the indoor air conditioner. After the system is improved, the ballast design is used to reduce the flow rate at the indoor air-conditioning outlet and reduce the influence of the uneven temperature distribution inside the bell jar caused by the direct airflow toward the calibration system. Refer to the part labeled No. 2 in Figure 3. To reduce the disturbance of the ambient temperature around the system when personnel entering, exiting or operating, the personnel operation area is isolated from the system by compartments. Refer to the part labeled No. 3 in Figure 3, where the heat exchange coil is added to bring the air source temperature closer to the laboratory environment temperature and lower the difficulty of the second temperature control. Refer to the part labeled No. 4. The second temperature control device is a fin-type heat exchanger, which allows the outlet gas of the part to be calibrated to go to thermal equilibrium the second time with the environment before entering the Bell Prover, and provides temperature control through the external heating and cooling of the fins. After the actual measurement, when the set temperature is 23 °C, the internal temperature of the compartment is controlled within ±0.5 °C. Please refer to Figure 4 for the actual measurement data.

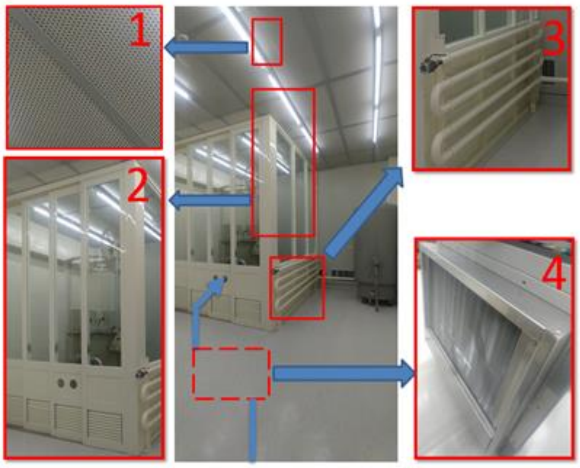

Figure 3: Temperature control improvement.

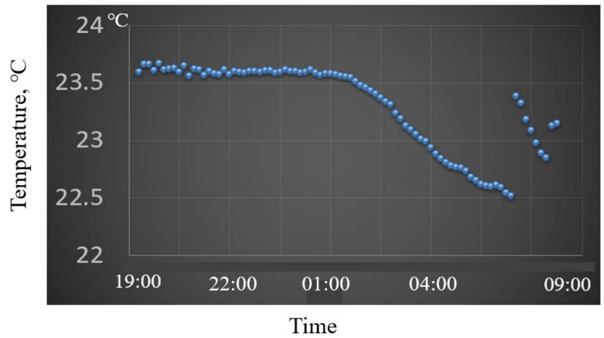

Figure 4: Actual measurement data for environment temperature.

3.2 Temperature measurement method improvement

Refer to Figure 5. The temperature measurement points in the original design are located at the top of the bell (temperature measurement point 1, T_{s1}), the upper layer of the sealing oil in the oil tank (temperature measurement point 2, T_{s2}) and the inlet of the incoming air (temperature measurement point 3, T_{s3}). A water bath heat exchanger is adapted to increase the air temperature before the air inlet at the outlet of the part to be calibrated. Because among the three temperature measurement points only point 1 is inside the bell jar, the minimum measurement distribution range can only reach the level of 0.1 °C in the half interval. During the calibration of Bell Prover, the gas temperature in the bell jar is affected by the ambient temperature, the temperature of the sealing oil outside the bell jar, and the temperature drop that occurs after air passing through the part to be calibrated. Thus, the originally designed temperature measurement method is difficult to obtain the representative temperature inside the bell jar. To effectively lower the system standard uncertainty, it is necessary to find a representative temperature measurement method.

Refer to Figure 6. To make the temperature measurement point closer to the air outlet inside the bell jar, this project developed a special mechanism to adopt a temperature probe that enters the bell jar from a three-inch air inlet and is placed along a U-shaped channel at the outlet of the interior airflow of the bell jar. Please refer to Figure 7 for the schematic diagram of the two temperature positions. Based on the need of routine calibration, this mechanism can allow the removal of the thermometer from the airflow channel and conduct calibration when the thermometer is sent for calibration.

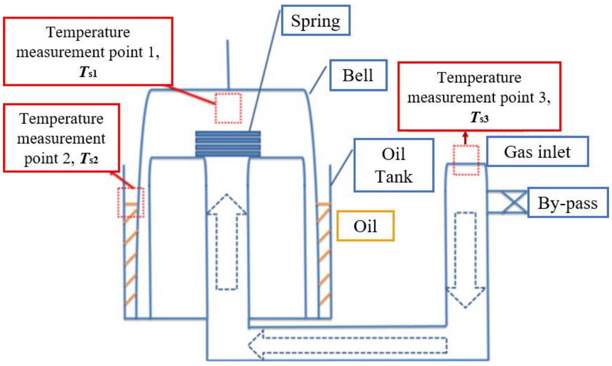

Figure 5: Schematic diagram for temperature measurement points of Bell Prover before improvement.

Figure 6: Thermometer placement mechanism in the bell jar.

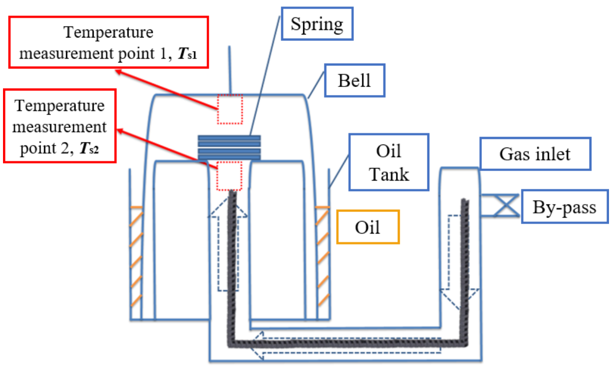

Figure 7: Schematic diagram of temperature measurement points of Bell Prover after improvement.

4. Experiment results and discussion

Refer to Figure 8. Through different conditions of intake air flow rate, the bell jar is ascending (from the beginning to the end of bell jar calibration) and then the exhaust is lowered (at the end the bell is returned to the beginning state), and the temperature is captured at the measurement point 1 (T_{s1}) and the measurement point 2 (T_{s2}) during the process.

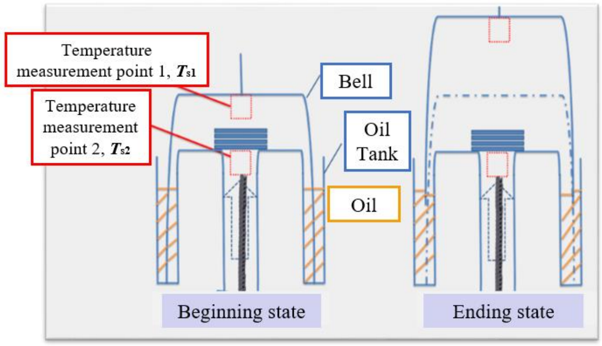

Figure 8: Schematic diagram for the bell jar ascending and descending.

Refer to Figure 9. In the example of the sonic nozzle in the part to be calibrated, it is placed upstream and gets connected with the Bell Prover. Under the condition when the maximum system intake air flow rate is 1000 L/min, it is found that the temperature difference between T_{s1} and T_{s2} measured during the bell jar ascending is up to 0.4 °C. It is estimated that the air inlet temperature is affected by the rapid expansion of the outlet air of the part to be calibrated, resulting in the lower air inlet temperature. Although it is heated by the wall of the gas channel, when the air passes through T_{s2}, it is still a cooler gas. At the end of the ascending process and the bell jar starts descending, T_{s2} temperature probe gradually reaches thermal equilibrium with the exhaust gas. When the bell jar returns to its initial state, it is found that the temperature difference between T_{s1} and T_{s2} is smaller than 0.05 °C. This phenomenon means that the temperature inside the bell jar has been fully uniform during the exhaust process.

To reduce the above-mentioned stratification inside the bell jar, the second temperature control, and ambient temperature control equipment labeled as No. 4 in Figure 3, number 4 can be used to raise the temperature of the outgoing cooling air at the nozzle to be calibrated close to the ambient temperature. Please refer to Figure 10 for the measurement result. Under the condition that the maximum system operating volume flow rate is 1000 L/min, when the bell jar is ascending, the largest temperature difference between T_{s1} and T_{s2} is 0.019 °C; under the condition that the minimum system operating volume flow rate is 10 L/min, when the bell jar is ascending, the largest temperature difference between T_{s1} and T_{s2} is 0.044 °C. It is found that the temperature difference between T_{s1} and T_{s2} at 10 L/min is relatively large, and although inlet air temperature control and ambient temperature control are implemented to reduce stratification, there still remains some temperature stratification. This is because under this condition the airflow rate at T_{s2} position in the bell jar is so low that it cannot make the air inside the bell jar fully mixed; however, the objective of the project has been achieved for the temperature difference due to uneven gas distribution in the bell jar to be less than 0.05 °C. Please refer to Table 3 for all flow rate experiment data. After the calculation by Equation (3), when the half-interval of the temperature deviation caused by the gas distribution inside the bell jar is 0.1 ℃, the relative expansion uncertainty of the system is 0.11 %； when the temperature deviation caused by the gas distribution inside the bell jar is 0.05 ℃, the relative expansion uncertainty of the system is 0.09 %. Please refer to Table 4 for the evaluation results after improvement.

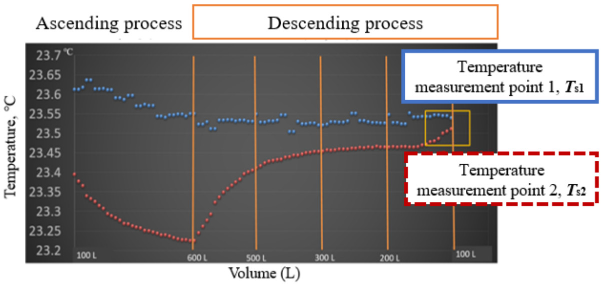

Figure 9: Temperature measurement data inside the bell jar (1000 L/min).

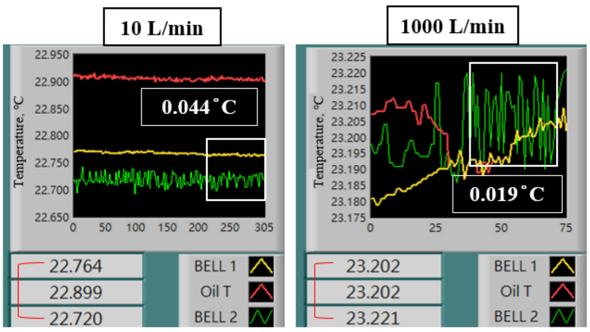

Figure 10: Temperature difference measurement data ($|T_{s1}$-$T_{s2}|$) inside the bell jar.

Table 3: Experiment data.

Flow rate (L/min)	**$\|T_{s1}$-$T_{s2}\|$ (℃)**
10	<0.05 ℃
50	<0.05 ℃
100	<0.05 ℃
300	<0.05 ℃
500	<0.02 ℃
750	<0.02 ℃
1000	<0.02 ℃

Table 4: Evaluation results for system relative uncertainty.

Symbol	Source of uncertainty	Estimator		Type	Standard uncertaint y	Relative standard uncertainty	Sensitivity coefficient	y_i
		x_i	*unit*		$u(x_i)$	$u(x_i)/x_i$	c_i	$\|c_i\|u(x_i)/x_i$
A_{eff}	Effective area	0.807207	dm³/mm			0.008%	1	0.008%
α_s	Thermal expansion coefficient	0.000018	1/℃	B	0.000001		3	0.0003%
α_l	Temperature effect	0.000001	1/℃	B		0.0001%	4.5	0.0005%
T_a	Temperature Control	296.15	K	B	0.87		0.000036	0.0031%
L_{20}	Length measurement	124.3	mm				1	0.0068%
ρ_s	Gas density of standard system	1.19229	g/dm³					0.026%
T_s	Temperature measurement	296.15	K		0.038		0.00338	0.013%
	calibration			B	0.02			
	curve fitting			B	0.012			
	stability of temperature sensor			B	0.006			
	temperature distribution			B	0.029			
P_s	Pressure measurement	101.325	kPa		0.0107		0.010	0.0106%
M	Molar mass of Air	28.9646	g/mol	B		0.019%	1	0.0190%
R_u	Universal gas constant	8.314471	J·mol⁻¹K⁻¹	B		0.0002%	1	0.0002%
Z_s	Compressibility	0.99966				0.0011%	1	0.001%
t	Collection time	60	s			0.0043%	1	0.0043%
$\Delta\rho_{CV}$	Variation of gas density in control volume					0.020%	1.5	0.030%
ρ_{CV}	Gas density in control volume	1.19229	g/dm³	B		0.026%	0.01	0.0003%
ΔV_{CV}	Variation of control volume			B	0.0007		0.1446	0.010%
$q_{m,l}$	Oil film adherence(SP 250-49)	10	cm³	B	5.8		0.000002	0.002%
$(\frac{u_c(q_{m,s})}{q_{m,s}})$								0.043%
$(\frac{U_{95}(q_{m,s})}{q_{m,s}})$								0.085%

5. Conclusions

This research focuses on the improvement of the experiment environment and temperature measurement methods, which reduces the relative expanded uncertainty of the system from 0.11 % to 0.09 %, better than the original project objective at 0.10 %. The conclusions are as follows：

5.1 Temperature control and measurement

Installation of compartments and ballast air conditioning system can reduce the disturbance of external factors to the ambient temperature around the calibration system. The ambient temperature of the compartment where the calibration system is located is controlled at about ±0.5 ℃, which facilitates the operator to grasp the temperature control of the system.

5.2 Temperature control and measurement

Measuring the temperature of the top inside the bell jar and the bottom inside the bell jar, as compared to the average temperature of the top inside the bell jar, the oil temperature and the air inlet temperature before the improvement, proves to be more representative, and provides the operator with a more desired basis for temperature control.

References

[1] Gas Flow Standard Facility, China Metrology Press, 2005.

[2] ISO/IEC Guide 98-3:2008, Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM:1995).

[3] Instrument Calibration Technique for Low Pressure Gas Flow Calibration System–Bell 1093 Calibrating Meter, 07-3-76-0010, 12th Edition, Center for Measurement Standards/ITRI, 2015.