

## LOWER UNCERTAINTY (0.015 % TO 0.025 %) OF NIST'S STANDARDS FOR GAS FLOWS FROM 0.01 TO 2000 STANDARD LITERS / MINUTE

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**Abstract – NIST has reduced the uncertainty of its 34 L and 677 L Pressure-Volume-Temperature-time (PVTt) primary flow standards from 0.05 % to 0.025 % ( $k = 2$ ) for air flow in the range from 0.01 slm\* to 2000 slm. Over the restricted range from 0.1 slm to 1000 slm, the uncertainty was reduced to 0.015 %. The reductions in uncertainty were primarily the result of accurately accounting for the water vapor present in the flowing air. Additional uncertainty reductions result from improved measurements of the pressure and of the collection tank volumes. The latter two improvements slightly reduced flow uncertainties for dry gases (e.g.,  $N_2$ , Ar, He, and  $CO_2$ ) from 0.03 % to 0.025 % in the wider range.**

### INTRODUCTION

The National Institute of Standards and Technology (NIST) 34 L and 677 L PVTt standards are used to calibrate gas flowmeters by measuring the mass of gas accumulated in a collection tank over a measured period of time. Diverter valves switch gas flowing through the meter under test from a bypass pipe into an evacuated collection tank and a timer is started. Once the tank pressure reaches an upper pressure set point (normally 100 kPa), the flow is switched back to the bypass pipe and the timer is stopped. The mass of the collected gas is calculated from the volume of the tank and measurements of pressure and temperature of the gas before and after the diversion to the collection tank using the virial equation of state. Dividing the mass change by the collection time gives mass flow. The volume of the collection tank was measured gravimetrically. To do so, 400 g of nitrogen (measured to  $\pm 4$  mg) was admitted into the collection tank. The volume was deduced from the equation of state along with pressure and temperature measurements. Specifics of the tank volume determinations, descriptions of the novel features of the NIST PVTt systems, and a detailed uncertainty analysis are given in a prior publication [1].

The 34 L and 677 L PVTt gas flow standards were placed in service for customer calibrations in 2002. Their best-in-the-world status was supported by an international key comparison and by hundreds of customer calibrations. Their low uncertainty has allowed customers to abandon expensive and difficult to maintain primary standards (such as piston and bell provers) in favor of working standard flowmeters while reducing uncertainty. The uncertainty reductions in NIST's PVTt standards described here reduce the uncertainty of thousands of flowmeters through customer's traceability chains.

Since the original uncertainty analysis was completed in 2002, a number of improvements have been made that reduce the maximum mass flow uncertainty from the original value of 0.05 % to 0.025 %. All uncertainties in this manuscript are expanded uncertainties with a coverage factor of  $k = 2$ . If the uncertainties fall on a normal distribution, 95 % of all measurements will fall within these uncertainty bounds. Figure 1 summarizes the reductions in the major uncertainty categories for the worst case, a 2000 slm flow in the 677 L standard. (Inventory uncertainties scale with flow and hence maximum uncertainty occurs at maximum flow.) The principal uncertainty improvement is due to the addition of a hygrometer to measure the dew point temperature of the compressed air used for calibrations. Additional

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\* slm = standard liter per minute, with standard pressure and temperature conditions of 101.325 kPa and 293.15 K.

improvements in pressure and temperature uncertainties result in reduced final gas density and tank volume uncertainties, slightly reducing the flow uncertainty for dry gases.

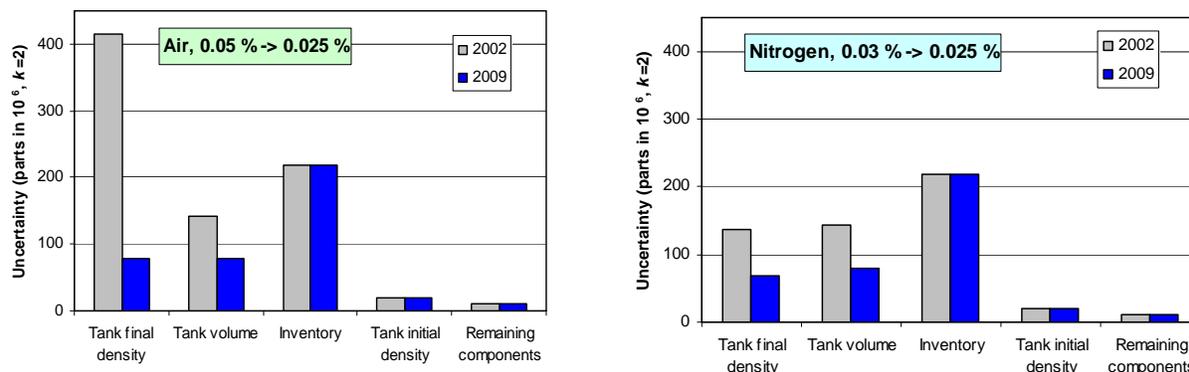


Figure 1 Uncertainty reductions for the worst case: the 677 L *PVTt* gas flow standard at its maximum flow of 2000 L/min. The largest reduction resulted from measuring the moisture content of air flows.

The addition of the hygrometer led us to incorporate the NIST property database Refprop 8.1 [2] directly into our data reduction software via a dynamic link library.\* (We had used polynomial fits in temperature and pressure to Refprop since 2003 [3], but this approach was impractical for air with varying water mole fraction.) Refprop 8.1 calculates the real gas critical flow factor which improves agreement among calibration results for critical flow venturis (nozzles) when they are calibrated in different gases (see Figure 8). If the ideal-gas critical flow factor is used, inconsistencies on the order of 600 PPM will result when calibrations using, for example nitrogen are compared with air at the pressures normally used during our calibrations.

In the following sections, we will describe the improvements in more detail, explain the basis for the reduced uncertainty, and demonstrate the improvement by comparisons between the two *PVTt* standards.

## MOLECULAR MASS OF AIR

The source of “dry” air for the *PVTt* standards is a reciprocating compressor with a refrigeration drier. Before 2008, we periodically measured the dew point temperature of the compressed air using a chilled mirror hygrometer. On average, these measurements indicated a nominal dew point temperature of – 20 °C. This value of dew point is slightly below the lower limit of the hygrometer so that the uncertainty was not well characterized. Consequently, instead of using the measured dew point to calculate the moisture content, we used a more conservative approach. The air properties (*i.e.*, density, molecular mass, critical flow factor, and viscosity) used to compute calibration flow variables were determined while assuming the air was perfectly dry, and the differences between the properties of dry air and air with a – 20 °C dew point were treated as uncertainties.

For mass flow calculations using the *PVTt* primary flow standard the only necessary gas property is the gas density in the collection volume. For the range of moisture present in our compressed air (dew point of – 20 °C), the uncertainty in the compressibility factor, *Z*, is negligible (less than 20 PPM<sup>#</sup>) as a result of the undemanding range of conditions, *i.e.* 296.5 K and 0 kPa to 100 kPa. However, the moisture content was a significant uncertainty source for the molecular mass of the air, leading to an uncertainty of

\* Available for purchase at <http://www.nist.gov/srd/nist23.htm>.

# PPM = parts in 10<sup>6</sup>, 100 PPM = 0.01 %.

380 PPM for molecular mass, the main contributor to the 416 PPM air density uncertainty in the 2002 analysis.\*

In 2008, a chilled mirror hygrometer with a range of -50 °C frost point to 20 °C dew point temperature was added to the *PVTt* instrumentation. The manufacturer's uncertainty specification is 0.2 °C at the 95 % confidence level; however, we do not have our own calibration history yet. Therefore, we conservatively assume that the dew point temperature is measured within 0.4 °C with a 95 % confidence level. Since installing the hygrometer, we have observed dew point temperatures as high as -15 °C from our compressor. For this worst case, an uncertainty in the dew point temperature of 0.4 °C results in a 24 PPM uncertainty in the molecular mass of the air. In calculating this uncertainty we account for the relatively small uncertainty contributions (*i.e.*, less than 10 %) from the enhancement factor, the Hyland-Wexler equation used for determining the saturation pressure as a function of the dew point [4, 5], and the pressure head at the chilled mirror.

The uncertainty of the molecular mass of moist air includes two additional contributions, one from the uncertainty of the molecular mass of dry air at fixed CO<sub>2</sub> concentration (see Table 1), and another from the variable amount of CO<sub>2</sub> in the air. The uncertainty of the molecular mass of dry air was determined by Picard to be 32 PPM [6]. The mole fraction of CO<sub>2</sub> has a nominal value of 385 PPM [7] and is herein assumed to have an uncertainty of 25 PPM. The 25 PPM uncertainty accounts for differences in the mole fraction of CO<sub>2</sub> reported by different researchers as well as spatial and temporal variations in CO<sub>2</sub> levels. The uncertainty in the molecular mass of the air resulting from the uncertainty in CO<sub>2</sub> levels is 10 PPM. Combining the uncertainties attributed to water vapor (24 PPM), the molecular mass of dry air (32 PPM), and variations in the mole fraction of CO<sub>2</sub> (10 PPM) by root-sum-square (RSS) lead to an air molecular mass uncertainty of 41 PPM, a significant improvement over the 380 PPM in the 2002 uncertainty analysis [1].

Component	Molecular Mass (g/mol)	Mole Fraction (2009)
Nitrogen	28.01348	0.780854
Oxygen	31.9988	0.209406
Argon	39.948	0.009332
Carbon Dioxide	44.0098	385 × 10 <sup>-6</sup>
Neon	20.179	18.2 × 10 <sup>-6</sup>
Helium	4.0026	5.2 × 10 <sup>-6</sup>
	Average Molecular Mass	28.9653 <sup>#</sup>

Table 1 Molecular masses and mole fractions for dry air currently used (2009) for flow calibrations [6].

## COLLECTION TANK PRESSURE

In March 2004, the instrumentation for measuring the collection tank pressure was changed. To measure the approximately 20 Pa in the evacuated tank, two thermocouple gauges were replaced with two capacitance diaphragm gauges (CDGs). To measure the full tank pressure, a single pressure transducer was replaced with two resonant silicon pressure transducers (referred to as GPIB 10 and GPIB 11 in Figure 2) with a full scale pressure of 130 kPa. The original pressure instrumentation gave full tank pressure measurements with a  $k = 2$  uncertainty of 128 PPM and was also the largest contributor to the uncertainty of the tank's volume and thus to the uncertainty of the mass flow of pure gases.

\* Unless otherwise stated, uncertainties are given as  $k = 2$ , approximately 95 % confidence level values.

<sup>#</sup> Constituents with mole fractions below  $5 \times 10^{-6}$  have been omitted. Because mole fractions do not exactly sum to unity ( $\sum x_i \neq 1$ ), the molecular mass has been corrected using  $M = \sum x_i M_i / \sum x_i$ .

The *PVTt* mass flow measurement is not very sensitive to errors in the temperature and pressure of the evacuated tank, so the improvements in the vacuum gauges gave a negligible direct improvement to the flow standard uncertainty. Nonetheless, they have maintained a stable calibration within 1 Pa based on comparisons to other CDGs and reference ion gauges.

The pressure gauges are periodically calibrated against a piston pressure gauge with  $k = 2$  uncertainty of 34 PPM. The transducer outputs are corrected with a first order equation, i.e. the corrected reading =  $A0 + A1 \times$  reading, and this correction gives residuals with standard deviation of 8 PPM over the range of pressures of the full tank (40 kPa to 100 kPa). The zero offset and slope from the periodic calibrations of the transducers conducted during 5 years are plotted versus time in Figure 2. The zero offsets of both transducers drift at a rate of approximately 0.025 Pa/day. The initial zero drift rate was more than 0.05 Pa/day. The drift rate of the transducer slope also changed during the 5 years; initially it was  $8 \times 10^{-8}$ /day and now it is essentially zero.

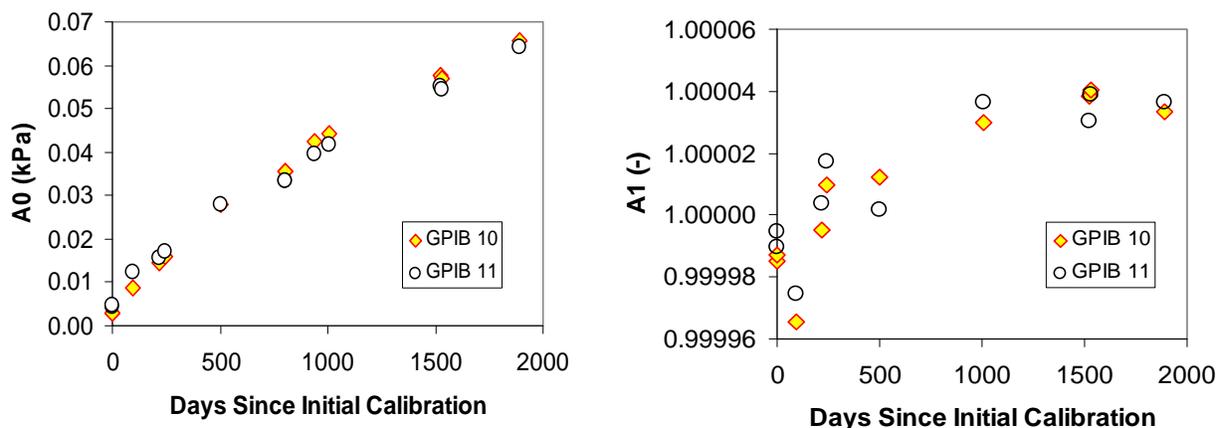


Figure 2. Zero offset ( $A0$ ) and slope ( $A1$ ) corrections for the two pressure transducers used to measure full tank pressure as a function of time since their initial pressure calibration performed on July 22, 2003.

The two transducers behaved in remarkably similar ways. Surely a portion of their correlated behavior can be traced to the fact that they were calibrated in parallel with the same piston pressure gauge. However, the shapes of the curves in Fig. 2 result from the transducers themselves and not from the pressure reference; other pressure transducers that were calibrated with the same reference have different aging characteristics.

The calibration drift of the pressure transducers is sufficiently predictable that one year after a calibration, they will read in error by  $0.035 \text{ Pa/day} \times 365 \text{ days} = 9 \text{ Pa}$  or 90 PPM of the normal full tank pressure. In January 2009, we adopted the practice of using the pressure from the CDGs each time the collection tank is evacuated for a new flow measurement to adjust the zero offset of the pressure transducers. With this approach, uncertainties due to drift in the pressure transducers was reduced to 20 PPM of the pressure in the full tank. Incorporating uncertainties due to the piston pressure gauge used for pressure calibrations, fit residuals, hysteresis, and thermal effects (see [1]) leads to a full tank pressure uncertainty of 30 PPM. Finally, the pressure measurement improvements reduced the full tank density uncertainty from 136 PPM (2002) to 84 PPM (2009) or less, depending on the gas in use. Pressure improvements also reduced the tank volume uncertainties as explained in the following section.

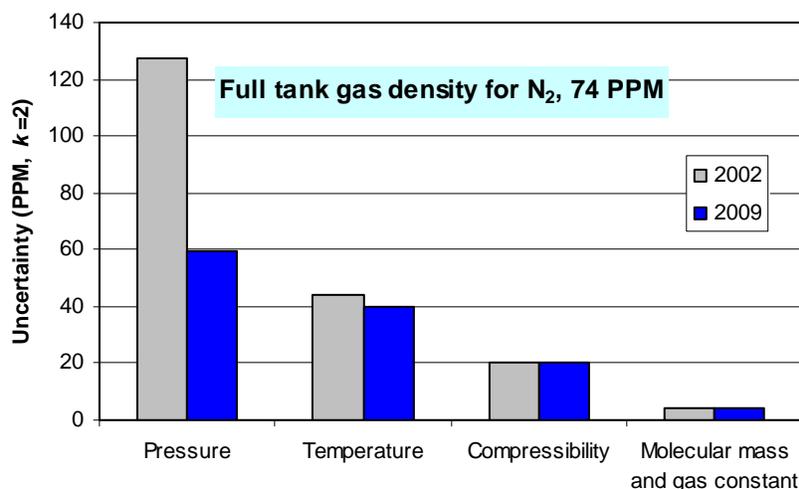


Figure 3. Improvements in final tank density are primarily due to reduced pressure uncertainty.

## TANK VOLUMES

The change of pressure and vacuum transducers necessitated re-measuring the collection tank volumes because the network of tubing connecting the sensors to the tanks and the internal volumes of the gauges themselves are part of the collection volume. Re-measuring the volume provided an opportunity for further reduction in the  $PVTt$  uncertainty. As explained in reference [1], the 677 L volume  $V_{grav}$  was measured gravimetrically by putting a known mass of gas in the unknown volume and measuring the resulting density change according to

$$V_{grav} = \frac{m_c^f - m_c^i}{\rho_T^f - \rho_T^i} - V_{extra} , \quad (1)$$

where  $m_c^f - m_c^i$  is the difference between initial and final masses of a weighed gas cylinder divided by the density change (i.e.,  $\rho_T^f - \rho_T^i$ ) of the gas in the collection tank (with small corrections for extra connecting tubing,  $V_{extra}$ ). The improved uncertainty in the final tank density measurement,  $\rho_T^f$ , explained in the previous section decreased the uncertainty of  $V_{grav}$ .

Eight volume measurements were performed on the 677 L tank, two with ultra high purity (UHP) nitrogen (99.999 %  $N_2$ ) and six with UHP argon. The average of the eight measurements was 677.936 L and the standard deviation of their mean was 10 PPM. Based on the propagation of uncertainty analysis the  $k = 2$  uncertainty for the 677 L volume was reduced from 142 PPM (2002) to 81 PPM (2009), primarily due to improvements in the pressure measurements (see Figure 4).

As a check, we compared the 2002 measurements of the collection tank volumes to the 2004 measurements. To do so, we measured the volume of the old and new piping and pressure instrumentation networks while they were separated from the collection tanks. These volume measurements were performed for each piping network using the volume expansion method [1] and a reference volume of 0.53775 L. The volume difference between the two piping networks was 0.0485 L. When this difference was applied, the old and new volume measurements for the 677 L tank agreed within 41 PPM, well within our expectations based on the uncertainty analyses (see Figure 5).

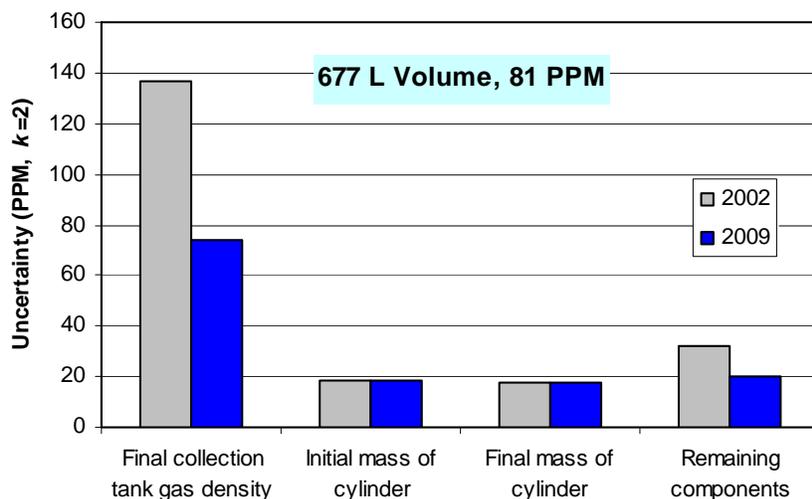


Figure 4. Uncertainty of the 677 L volume measurements in 2002 and 2009. Most improvement is due to pressure instrumentation effects on final gas density.

In 2002, the gravimetric method was used to determine the volume of the 677 L tank and that result was used in a volume expansion method to obtain the 34 L tank volume. The uncertainty for the 34 L tank volume was larger than the 677 L uncertainty (232 PPM versus 142 PPM). When the new pressure instruments were installed and the volumes re-measured in March 2004, the gravimetric method was used for both the 34 L and 677 L volumes. The uncertainty in the mass of the pressurized cylinder was 4 mg and this constituted a significant uncertainty for a single filling of the 34 L volume with nitrogen ( $0.004 \text{ g} / 38.6 \text{ g} = 103 \text{ PPM}$ ). In order to reduce the significance of the mass uncertainty component, the mass change of the cylinder was increased by 1) using a gas with relatively high density (argon), and 2) filling the unknown volume twice and applying the equation:

$$V_{\text{grav}} = \frac{m_c^f - m_c^i}{\Delta\rho_1 + \Delta\rho_2} - V_{\text{extra}} \quad (2)$$

where  $\Delta\rho = \rho_T^f - \rho_T^i$  and the subscripts 1 and 2 represent the two independent fillings of the unknown volume. With this procedure, the uncertainty of the gravimetric measurements of the 34 L volume fell to 58 PPM.

The average of four measurements of the tank volume was 34.0815 L and the standard deviation of their mean was 10 PPM. Using the difference between the old and new piping networks, the 2004 and 2002 volume measurements for the 34 L tank differed by 29 PPM. The  $k = 2$  uncertainty of the 34 L volume uncertainty was reduced from 232 PPM to 116 PPM.

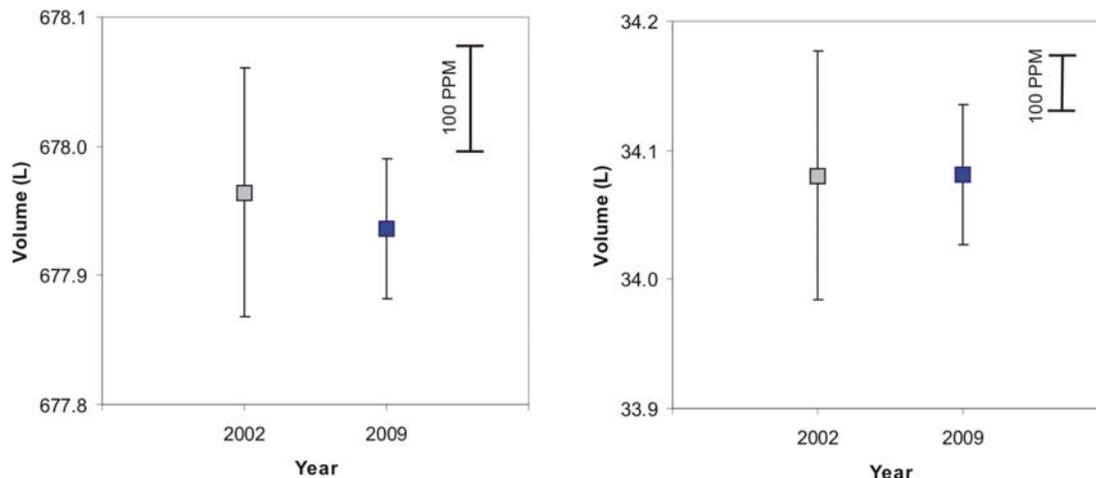


Figure 5. Volumes of the 677 L and 34 L collection tanks, measured in 2002 and 2009, with their  $k = 2$  uncertainty bars.

### UNCERTAINTY DEPENDENCE ON FLOW

Figure 6 presents the results from our propagation of uncertainties model as a function of flow for the 34 L and 677 L flow standards. This plot captures two flow dependent components: 1) uncertainties related to the inventory volume and 2) leaks. The flow dependent components cause the uncertainty to increase above baseline levels of approximately 150 PPM at high and low flows. The 150 PPM baseline uncertainty is traceable to the tank volume and final gas density uncertainties (both traceable to pressure). If the crossover flow between the two standards is 50 slm, the  $k = 2$  uncertainty for the mass flow is  $< 250$  PPM from 0.01 slm to 2000 slm. Note that the 677 L standard can be used at crossover flows lower than 50 slm, but the collection times grow inconveniently long.

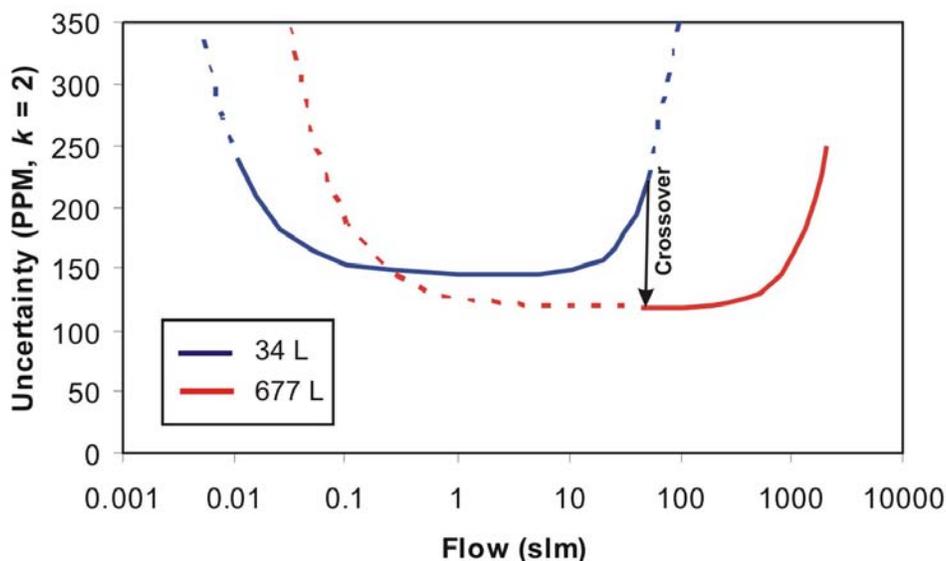


Figure 6.  $PVTt$  uncertainties versus flow. Dashed lines indicate possible, but normally unused ranges. For both systems, inventory uncertainties dominate at high flows, leaks dominate at low flows, volume and density measurements establish baseline uncertainty in mid-range flows.

## Inventory Uncertainties

The inventory volume lies between the meter under test and the diverter valves. As discussed in reference [1], changes in the density of gas in the inventory volume between the start and stop times add the term

$$\dot{m}_I = \frac{V_I(\rho_I^f - \rho_I^i)}{t^f - t^i}, \quad (3)$$

to the *PVTt* mass flow equation, where  $\dot{m}_I$  is the mass flow correction for the inventory volume,  $V_I$  and  $\rho_I$  are the inventory volume and density respectively,  $t$  is time, and the superscripts  $i$  and  $f$  indicate initial and final values. The NIST *PVTt* standards use a density matching technique that leads to  $\rho_I^f = \rho_I^i$  and hence  $\dot{m}_I = 0$ . However there are uncertainties in the matching technique due to 1) spatial variation of the pressures and temperatures in the inventory volume and 2) trigger pressure differences [1]. These uncertainties are difficult to quantify. In 2002 the inventory volume uncertainty estimates were validated by 1) comparisons between the 34 L and 677 L systems and 2) multiple diversions during a single flow measurement (see sections 4.1 and 4.2 in reference [1]). In the absence of new information about the uncertainty due to the inventory volume, we have used the same model as in 2002, in which uncorrelated inventory uncertainties scale with the flow and are zero at the minimum flow of each tank. The inventory uncertainties begin contributing significantly to the flow uncertainty at about 10 slm for the 34 L system and 250 slm for the 677 L system. Figure 1 separates the uncertainty contributions for the maximum flow (2000 slm) in the 677 L standard where inventory uncertainties are largest.

## Leaks

The 34 L *PVTt* standard was designed for use at a minimum flow of 1 slm, however, the actual lower flow limit is determined by time constraints and by leaks. (In this discussion, we do not distinguish between actual leaks and so-called “virtual leaks” or “out-gassing.”) We have successfully used the 34 L system to calibrate flowmeters at flows of only 0.01 slm. Unfortunately, a single flow measurement at this flow takes 28 hours, even if one fills the tank to 50 kPa instead of the normal 100 kPa.

We routinely measure leaks into the collection and inventory volumes by evacuating them and observing the rate of rise of density over several hours. Typical values from these tests are  $1 \times 10^{-6}$  slm for the 34 L tank and  $8 \times 10^{-6}$  slm for the 677 L tank. Because of these leaks, not all of the gas entering the evacuated tank flows through the meter under test: some of it enters from the room or comes from the collection tank walls. In Figure 6, the leaks are treated as an uncertainty, a fixed flow error added to the propagation of uncertainties result. (However, in some low flow tests, we carefully measure the leak rate before and after each calibration and include it as a correction rather than an uncertainty.) Leaks become significant uncertainty contributors at flows less than 1 slm for the 677 L standard and less than 0.1 slm for the 34 L standard.

## GAS PROPERTIES REVISITED

The need to handle moist air prompted us to change the way we calculate fluid properties. In the past we used polynomial curve fits to the Refprop property database. However, we presently calculate all fluid properties by directly using Refprop 8.1 via a dynamic link library (Refprop.dll) that communicates with our Labview data acquisition programs and our Excel data reduction spreadsheets. The most common meter types tested at NIST are critical flow venturis (nozzles) and laminar flowmeters. For these meter types, the gas properties needed for the calibration process are: molecular mass, density, viscosity, and critical flow factor. The most notable changes between the old and new property calculations are in 1) molecular mass and density (explained in the section “Molecular Mass of Air”) and 2) in the critical flow factor used with nozzles.

Version 8.1 of the Refprop.dll gives the real critical flow factor,  $C_R^*$ , whereas in the past the Fluid Metrology Group used the ideal critical flow factor,  $C_I^*$ , which is calculated from the specific heat ratio [3]. The difference between  $C_I^*$  for dry air and  $C_R^*$  for air with dew point temperature of  $-17\text{ }^\circ\text{C}$  over the typical pressure range for customer calibrations (200 kPa to 700 kPa) is shown in Figure 7a. The difference between  $C_I^*$  and  $C_R^*$  for nitrogen is also shown in Figure 7a. Figure 7b shows the difference in density for nitrogen introduced by the 2009 property calculations (negligible) and the density change between the 2002 dry air calculations and the 2009 moist air calculations (also for a dew point temperature of  $-17\text{ }^\circ\text{C}$ ).

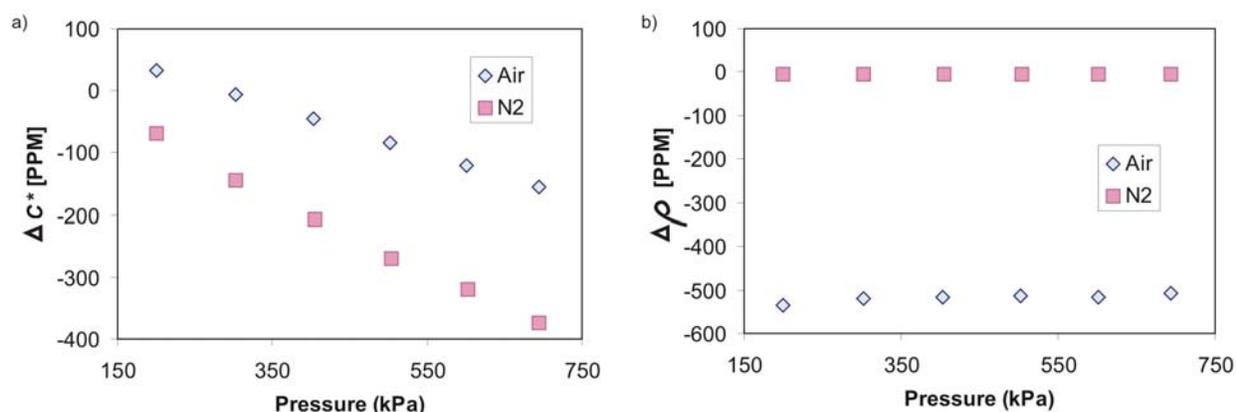


Figure 7. Changes in the critical flow factor and density resulting from adding the hygrometer and changing the property calculation algorithm.

The changes in gas properties have led to an improvement in the agreement of critical flow venturi calibrations performed in different gases. In our past calibration results where we used  $C_I^*$  and assumed that air was perfectly dry, the calibration coefficient for the same nozzle calibrated in air and nitrogen differed by as much as 600 PPM. This result was in conflict with nozzle theory, which predicts that  $C_d$  for these two gases plotted versus the Reynolds number should differ by no more than 100 PPM. By using Refprop to compute  $C_R^*$  and accounting for moisture in the air, the agreement between discharge coefficient,  $C_d$ , versus the Reynolds number falls within 120 PPM (see Figure 8). The uncertainty bars in the figure (400 PPM) include the uncertainty of the  $PVTt$  standard, the uncertainty of the pressure and temperature sensors associated with the nozzle, and the reproducibility of the six individual measurements at each flow.

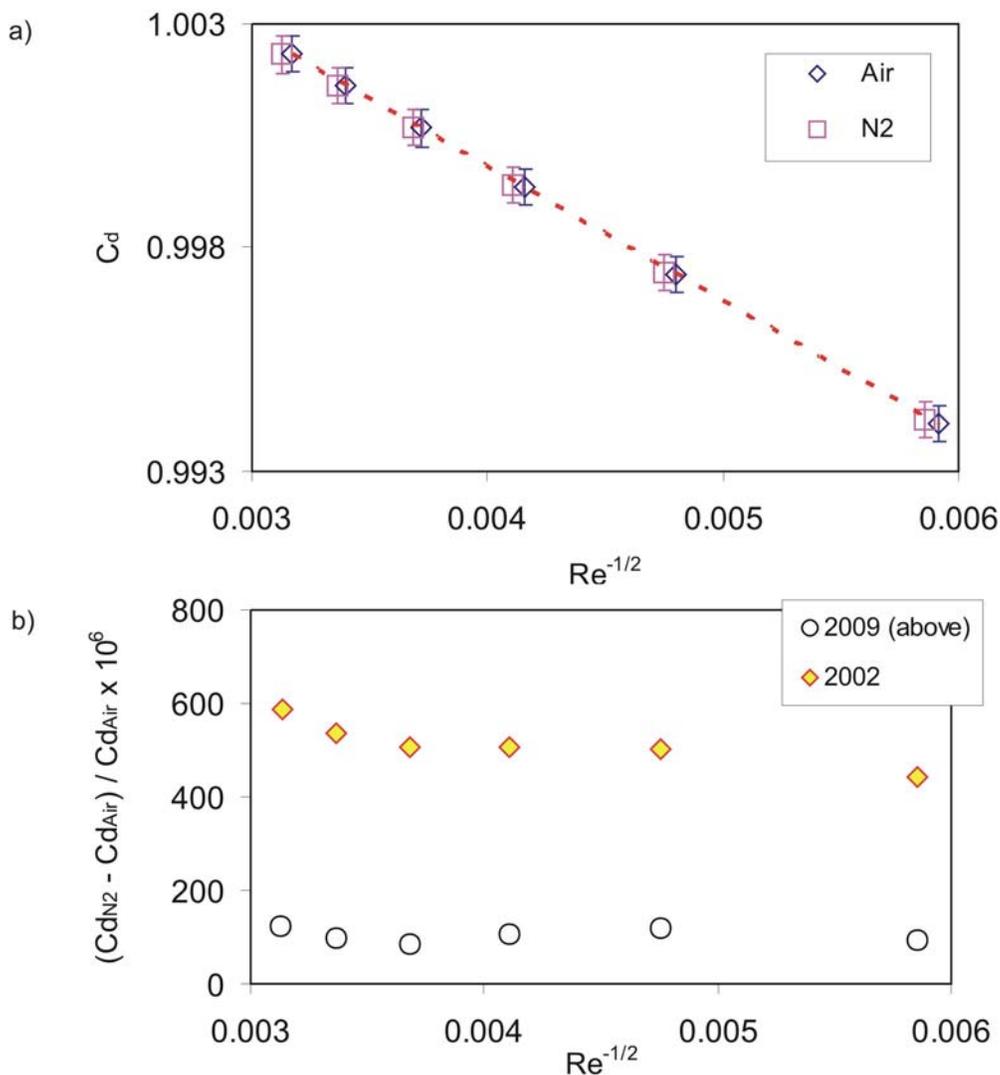


Figure 8. a) Discharge coefficient versus  $Re^{-1/2}$  for a 1.12 mm critical flow venturi calibrated with air and nitrogen on the 677 L *PVTt* standard. b) Deviations from dashed line in a). Using the 2009 property calculations, the discharge coefficients for air and N<sub>2</sub> differ by approximately 120 ppm; in contrast, they differ by as much as 600 PPM using the 2002 property calculations.

### COMPARISON OF THE 34 L AND 677 L STANDARDS

The two flow standards were compared with each other using two critical flow venturis with throat diameters of 1.12 mm and 0.648 mm. The two nozzles were calibrated on both flow standards using six flows of nitrogen and air each. At each flow, three flow measurements were made on two different occasions. A sample of the comparison results for the 1.12 mm nozzle in air is shown in Figure 9.

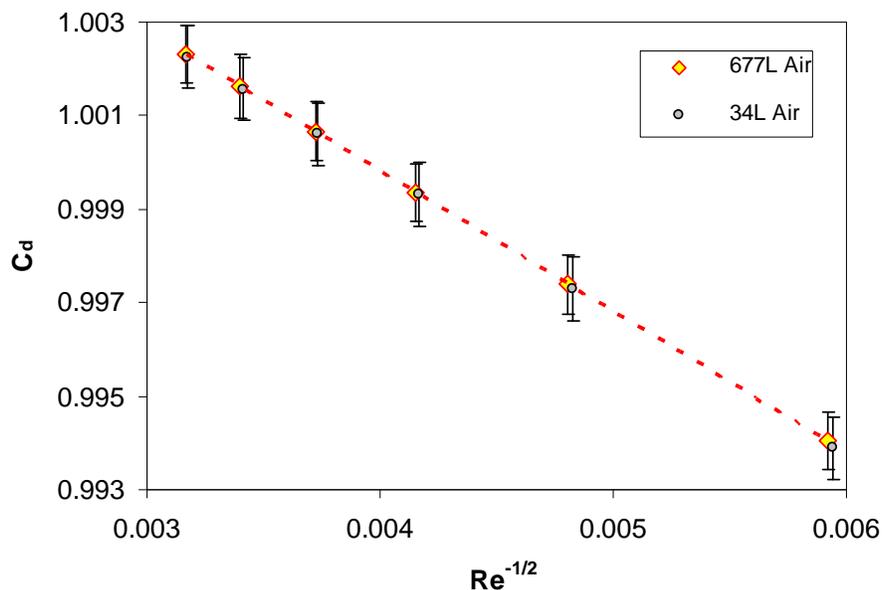


Figure 9. Comparison of the 34 L and 677 L *PVTt* standards using the discharge coefficient of a 1.12 mm nozzle calibrated with air. Each point is the average of six individual flow measurements.

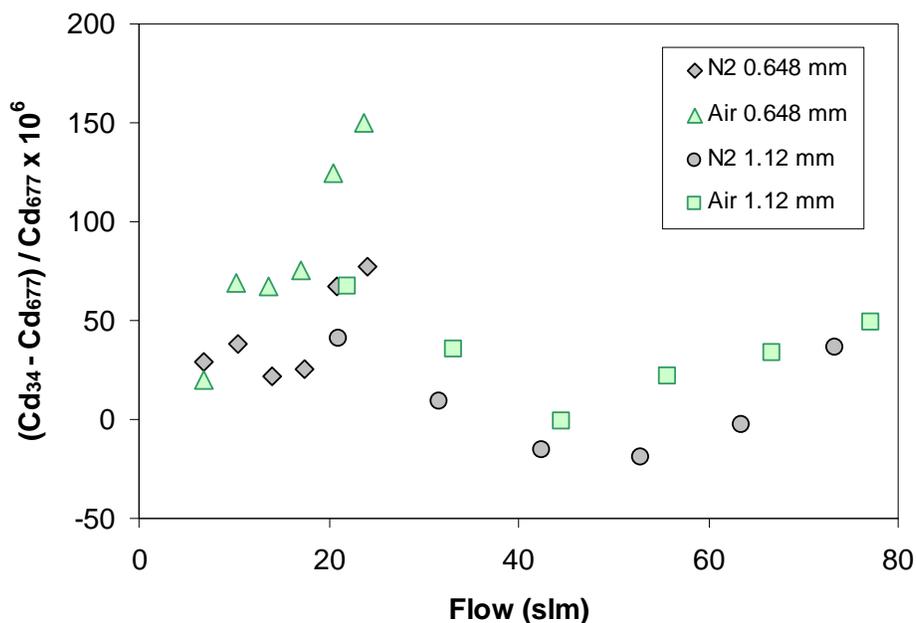


Figure 10. Difference in discharge coefficients measured with the 34 L and 677 L *PVTt* standards for two nozzles calibrated in nitrogen and air.

The difference between a second order polynomial best fit through the 677 L results and the 34 L points is plotted in Figure 10, along with results from three other data sets resulting from testing the two nozzles in nitrogen and air. Except for two data points, the results show differences between the two standards of < 80 PPM. Although there are many correlated uncertainties between the two flow standards, the agreement is well within the propagation of uncertainties analysis (Figure 6) and validates the < 0.025 % uncertainty specifications. This is true despite our usage of the 34 L system at flows larger than the 50 slm crossover flow.

## SUMMARY AND CONCLUSIONS

Adding an optical hygrometer and improved pressure instrumentation to the NIST 34 L and 677 L *PVTt* gas flow standards reduced the uncertainty for air, nitrogen, and other gases. The  $k = 2$  uncertainty was reduced to 0.025 % or less for flows between 0.01 slm and 2000 slm (see Figure 6). For reasons of time efficiency, the normal crossover flow between the two standards is 50 slm. However, if the crossover flow is moved to 10 slm and the flow range is restricted to 0.1 slm to 1000 slm, the uncertainty is only 150 PPM. Comparisons of the two calibration standards support this uncertainty specification (see Figure 10).

The flow range for the 34 L standard has been extended downwards by two orders of magnitude to 0.01 slm. At such low flows, the collection times are long (28 h) and leaks are a significant concern. For customers requiring accurate calibrations at flows below 0.01 slm, we will measure and correct for leaks instead of treating them as an uncertainty as we have done here.

A NIST properties database (Refprop.dll) was incorporated into our data acquisition and reduction programs to calculate the properties of moist air. Refprop 8.1 also calculates  $C_R^*$  (instead of  $C_I^*$ ), leading to much better agreement between nozzle discharge coefficients measured in air and nitrogen (see Figure 8).

Recently, we used the 34 L tank and the rate of rise (RoR) method [8] to measure flows between 0.001 slm and 0.1 slm with great success. Comparisons between the *PVTt* and RoR methods between 0.025 slm and 0.1 slm agreed within 200 PPM. Therefore, we expect to apply the 34 L and 677 L standards to customer calibrations over six decades of flow in the near future.

## ACKNOWLEDGEMENTS

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