Published in final edited form as:

Flow Meas Instrum. 2015 December ; 46(Pt A): 112–124. doi:10.1016/j.flowmeasinst.2015.10.010.

Hydrogen Field Test Standard: Laboratory and Field Performance

Jodie G. Pope and John D. Wright

Fluid Metrology Group, Sensor Science Division, Natl. Inst. Stand. and Technology

Abstract

The National Institute of Standards and Technology (NIST) developed a prototype field test standard (FTS) that incorporates three test methods that could be used by state weights and measures inspectors to periodically verify the accuracy of retail hydrogen dispensers, much as gasoline dispensers are tested today. The three field test methods are: 1) gravimetric, 2) Pressure, Volume, Temperature (*PVT*), and 3) master meter. The FTS was tested in NIST's Transient Flow Facility with helium gas and in the field at a hydrogen dispenser location. All three methods agree within 0.57 % and 1.53 % for all test drafts of helium gas in the laboratory setting and of hydrogen gas in the field, respectively. The time required to perform six test drafts is similar for all three methods, ranging from 6 h for the gravimetric and master meter methods to 8 h for the *PVT* method.

The laboratory tests show that 1) it is critical to wait for thermal equilibrium to achieve density measurements in the FTS that meet the desired uncertainty requirements for the *PVT* and master meter methods; in general, we found a wait time of 20 minutes introduces errors < 0.1 % and < 0.04 % in the *PVT* and master meter methods, respectively and 2) buoyancy corrections are important for the lowest uncertainty gravimetric measurements.

The field tests show that sensor drift can become a largest component of uncertainty that is not present in the laboratory setting. The scale was calibrated after it was set up at the field location. Checks of the calibration throughout testing showed drift of 0.031 %. Calibration of the master meter and the pressure sensors prior to travel to the field location and upon return showed significant drifts in their calibrations; 0.14 % and up to 1.7 %, respectively. This highlights the need for better sensor selection and/or more robust sensor testing prior to putting into field service. All three test methods are capable of being successfully performed in the field and give equivalent answers if proper sensors without drift are used.

Corresponding author: Jodie.pope@nist.gov.

¹Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

²Expanded uncertainty is the $k = 2$, corresponding to a 95 % confidence level. The standard uncertainty $k = 1$, corresponds to a 68 % confidence level.

1. Introduction

Today's fuel cell electric vehicles are typically refueled with pre-cooled hydrogen (H_2) gas from dispensers within 3 to 5 minutes using sequential gas releases from a bank of pressurized cylinders. The sequential releases generate large, rapidly-changing, gas flows (0 kg/min to 10 kg/min) spanning a wide pressure range (0.1 MPa to nominally 70 MPa) at gas temperatures down to -40°C . While there have been studies of high pressure hydrogen flow meters under steady flow conditions [1,2], measuring the flow under rapidly changing temperature, pressure, and flow conditions has received less attention. Prior research in our Transient Flow Facility (TFF) shows that coriolis mass flow meters can measure the totalized flow within 1 % under simulated H_2 dispenser conditions [3]. Therefore, it is feasible for well-designed commercial hydrogen dispensers to meet the proposed international requirement of 1.5 % accuracy for dispensing units [4].

Here, our attention turns to how state weights and measures inspectors will verify the accuracy of dispensers in the field. A similar effort is underway in the state of California in cooperation with the National Renewable Energy Laboratory [5]. What will be the analog of the 5 gallon test measures presently used to check gasoline dispensers [6]?

In this work, we tested three methods for field testing H_2 dispensers: 1) *gravimetric*; where the mass dispensed is determined by weighing a hydrogen pressure vessel (*i.e.*, tank) before and after filling it with H_2 , 2) *Pressure, Volume, Temperature (PVT)*; where the mass dispensed into the tank is determined from the tank's internal volume and gas density (ρ) change from before and after filling, and 3) *master meter (MM)*; where the mass dispensed is determined by integrating a well calibrated flow meter's measurements of the H_2 gas being blown-down (or withdrawn) from the filled tank. This work was performed in two parts: 1) a laboratory phase [7] and 2) a field phase. An uncertainty analysis is provided for each method. The desired uncertainty is 0.5 %, one third of the proposed requirement of 1.5 % for dispensing units. We constructed a prototype field test standard (FTS) to compare the three methods in terms of ease of use, time efficiency, and uncertainty. All three methods agree within the expected uncertainty of 0.57 % for all test drafts of helium (He) gas in the laboratory setting. Figure 1 shows these results for five test drafts of 0.5 kg, 1 kg, and 1.7 kg He gas. All three methods agree within 1.53 % for the test drafts of H_2 gas in the field setting. Figure 2 shows these results for three test drafts of 0.41 kg and four test drafts of 0.75 kg H_2 gas. A larger uncertainty was expected for the field tests than the laboratory tests due to the use of different pressure sensors that are suitable for use in H_2 gas. These sensors' calibrations drift over time. The disagreement in the field is more than the expected uncertainty due to excessive pressure sensor drift.

The purpose of the laboratory phase was to design, construct, and test a FTS in a controlled environment, *i.e.*, NIST's Transient Flow Facility (TFF) and using He as a surrogate gas for H_2 . The TFF allows us to: 1) evaluate each field test method without the time constraints that will be encountered in the field, 2) use a more-accurate pressure gauge that is incompatible with hydrogen, and 3) achieve more reproducible results under controlled environmental conditions. The purpose of the field test phase was to verify the laboratory results using H_2 gas in a more challenging setting; an outdoor H_2 dispenser.

2. Experimental Design

2.1 The Field Test Standard

The FTS consists of a 35 MPa (at 15 °C), 1 kg H₂ capacity storage tank that is mounted into a frame made from 2.5 cm² T-slotted aluminum with casters for mobility. The storage tank is a Type III cylinder; a seamless aluminum liner fully wrapped with a continuous filament made of carbon fiber in an epoxy reinforcement laminate [8]. The empty weight of the FTS is approximately 80 kg. Figure 3 shows the FTS in the horizontal position. For density measurements, the FTS is equipped with two, 46 cm long type K thermocouples (TCs) inserted at each end (to reduce stem conduction errors, TCs with a long insertion depth were chosen) and two analog pressure sensors; one with a 35 MPa range and one with a 1.4 MPa range. A plumbing and instrumentation diagram is shown in Fig. 4. A detailed description of the operating instructions and specifications can be found in the NIST technical publication NIST-TN 1888 [9]. Accompanying the FTS are 1) a 150 kg capacity weigh scale with 1 g resolution for gravimetric measurements, 2) a 3.7 m × 3.7 m tent with ventilated holes to protect the weigh scale from the environment, 3) a portable data acquisition (DAQ) system and laptop with acquisition software, 4) a 0.95 cm diameter, 3.05 m tall stainless steel vent stack with support stand for venting H₂ gas in the field, and 5) a hand truck with a tie down strap for moving the FTS securely while in the vertical position; the FTS must be in the vertical position during testing due to the position and orientation of pressure relief valves. The pressure relief valves were tested and found to be leak free. The DAQ box supplies power to the master meter and acquires data from the temperature and pressure sensors. All wires can be easily plugged into or unplugged from the DAQ box and coiled on the FTS frame to eliminate torquing of the scale during weighing. Figure 5 shows the weighing tent setup and the FTS on the scale with wind screens around it in the field setting. Figure 6 shows the FTS at the H₂ dispenser with accompanying DAQ box, laptop and vent stack. Elastomer materials are subject to H₂ embrittlement just as metals are [10,11,12], therefore all valves have H₂ compatible seating material. All plumbing on the FTS and the diaphragm in the pressure sensors is 316-stainless steel. The TC sheath material is Inconel¹.

2.2 Laboratory Test Protocol

The Laboratory tests were carried out to mimic field tests as closely as possible. The smallest quantity verified is specified by the dispenser manufacturer and is termed the minimum measured quantity (MMQ) and is 0.5 kg for the tests presented here. The maximum quantity is limited by the H₂ storage tank capacity of approximately 1.7 kg He (1 kg H₂) at 34.5 MPa (5000 psi) and 15 °C. NIST Handbook 44 [13] recommends three consecutive test drafts of approximately the same size of the MMQ and the greater of 10 times the MMQ or 1 kg. We performed five test drafts for the collection of 0.5 kg, 1.0 kg, and 1.7 kg He gas. The small collection tank limited us from testing 10 times the MMQ. A coriolis mass flow meter was installed upstream of the FTS tank to aid in delivering the same total mass to the tank to assess the draft-to-draft repeatability (Fig. 7). The pressure and temperature in the tank was monitored continuously during the fill. If the temperature had reached 80 °C (85 °C is the maximum design temperature of the pressure vessel), the fill would have been halted by the operator [14].

NIST's TFF served as the 35 MPa gas source to fill the FTS. We used flexible compressed natural gas hoses (0.64 cm diameter) that can be easily connected to and disconnected from the FTS to fill the FTS tank and to blow-down the gas into the TFF low pressure tanks. The TFF high capacity compressor re-pressurizes the high pressure tanks so the measurement can be repeated.

Table 1 gives the target mass (m) of gas and the corresponding pressures $P(m)$ at 20 °C that were collected during the laboratory tests and the field tests. We calculated the uncertainty for each measurement method based on the propagation of uncertainty as described in [15], Section 4 in this paper, and in [7]. The expanded² uncertainties are included in Table 1 ($k = 2$).

2.3 Field Test Protocol

The FTS cannot travel with H₂ gas inside of it due to Department of Transportation regulations; therefore, the FTS travels with approximately 700 kPa of He gas inside the collection tank. Upon arrival at the field location, the FTS was filled with H₂ to approximately 20 MPa and then vented until the pressure was again 700 kPa. This was repeated three times prior to a test draft, resulting in H₂ purity of 99.99 %. The 0.01 % impurity results in 0.006 % uncertainty in the mass measurement via the *PVT* method for the first test draft. Sequential drafts use > 99.9997 % pure H₂ resulting a negligible *PVT* mass measurement errors.

The field tests were conducted in the same manner as the laboratory tests. The main differences were 1) the collection tank inlet was replaced with a standard 35 MPa hydrogen nozzle receptacle [16] and 2) the H₂ gas was released to the atmosphere via the vent stack instead of collecting it for reuse. This is primarily for gas purity concerns. H₂ Fuel cell electric vehicles must have *pure* H₂ to function properly [17]. The pressure and temperature was continuously monitored in the FTS tank during filling and blow-down of the collected gas. The hydrogen station operator disabled the dispenser readout during tests; we conducted these tests to evaluate the FTS, not the dispenser. Therefore, the tank pressure was used to aid in delivering the same quantity of gas during repeated test drafts.

The purpose of the FTS is to measure the mass of gas that is delivered into a vehicle. The mass dispensed into a vehicle as determined by the dispenser is the mass measured by the dispenser's meter minus the mass in the refueling hose at the end of a fill. Because we are comparing various field test methods, the gas in the dispenser's hose is not a concern for these tests.

We followed 7 steps in the laboratory and the field to collect mass flow measurements with the FTS by all three methods:

- 1) Weigh the FTS with all sensor wires disconnected, coiled and attached to the frame and record atmospheric conditions for an initial tank mass measurement for the gravimetric method.

- 2) Plug the sensors into the DAQ box and make temperature and pressure measurements for an initial mass measurement for the *PVT* and master meter methods.
- 3) Connect plumbing from the gas source to the FTS inlet and fill the tank to the target mass. During the fill, temperature and pressure measurements are monitored and archived.
- 4) Wait for thermal equilibration of the tank and conduct final temperature and pressure measurements for a final mass determination for the *PVT* method.
- 5) Disconnect the inlet plumbing; re-coil all sensor wires and attach them to the FTS frame, and weigh the FTS for a final mass measurement for the gravimetric method.
- 6) Connect the outlet plumbing from the FTS to the TFF low-*P* tanks (laboratory) or the vent stack (field) and connect the temperature and pressure sensors and power for the coriolis master meter. Blow-down the gas through the master meter by opening the regulator at the FTS outlet. The master meter transmitter displays the totalized mass through the meter and therefore automated acquisition is not necessary.
- 7) Following the blow-down through the master meter and after thermal equilibrium is reached; measurements are again made to determine the mass left in the tank for the master meter method.

3. Results

3.1 Method Comparison

All three methods performed in the laboratory with the FTS agree within 0.57 %. Figure 1 shows the difference between the three methods and their average for 0.5 kg, 1 kg, and 1.7 kg He test drafts. The gravimetric method generally reads higher than the *PVT* and MM methods, on average by 0.28 %. The master meter and the *PVT* methods use the same measurement for the starting mass in the FTS, therefore, errors in their results are correlated.

All three methods performed in the field with the FTS agree within 1.53 %. Figure 2 shows the difference between the three methods and their average for 0.41 kg and 0.75 kg H₂ test drafts. The *PVT* method has the largest uncertainty because 1) the pressure sensors drifted at some point during the field tests and 2) the temperature gradient in the collection tank was slightly larger than expected when the gas density measurements were made. The master meter and scale also had drift problems that are detailed in Section 4.

3.2 Temperature and Pressure Profiles while Dispensing

The dispenser used to test the FTS is a type D dispenser, *i.e.* there is no pre-cooling of the gas and the TFF operates like a type-D filling station. Therefore, to safely fill our Type III cylinder, the mass flow was controlled such that the temperature in the tank stayed well below 80 °C (353.15 K), the temperature at which the carbon fiber and epoxy wrapping may start to weaken.

The ambient temperature plays a significant role in how fast the FTS tank can be safely filled. Figure 8 shows pressure/mass flow rate and temperature profiles for the test draft fills of 1 kg and 1.6 kg helium gas in the laboratory. The room temperature was approximately 16 °C the day the 1 kg draft was collected and 18 °C the day the 1.6 kg draft was collected. The lower room temperature allowed for a larger average pressure ramp rate (PRR) and a fill time of only 6 minutes. A 1.6 kg draft at the same PRR would require 9.6 minutes. However, because the room temperature was higher, the PRR was lower and a longer fill time of approximately 25 minutes required in order not to exceed the temperature rating of the tank.

The ambient temperature varied in the field from 20.2 °C to 23.3 °C during the collection of three test drafts of approximately 0.41 kg H₂ gas. This allowed us to fill the FTS tank within 3 minutes for all test drafts of this quantity with average PRRs ranging from 4.5 MPa/min to 7 MPa/min. During the collection of approximately 0.75 kg H₂ gas, the ambient temperature varied from 16.3 °C to 24.5 °C. The PRRs varied from 2.8 MPa/min to 7.0 MPa/min. The quickest test draft of 0.75 kg H₂ was performed at 18.5 °C and took less than 5 minutes. The longest test draft was performed at 24.5 °C and took less than 12 minutes. The test draft taken during the cooler ambient temperature was faster and the internal gas temperature stayed approximately the same compared to the test draft taken at the higher ambient temperature. Figure 9 shows the FTS collection tank temperature and pressure during these two test drafts.

The internal temperature of the gas stayed well below 80 °C during all test drafts in the laboratory and field demonstrating the PRR could have been higher resulting in shorter fill times.

4. Description of the Three Mass Measurement Methods

4.1 PVT method

The mass dispensed (m_{PVT}) into the FTS is calculated by:

$$\Delta m_{PVT} = \rho_2 V_2 - \rho_1 V_1; \quad (1)$$

where ρ_1 and ρ_2 are the initial and final gas densities, and V_1 and V_2 are the initial and final volume of the FTS tank, respectively. The gas density is given by:

$$\rho = \frac{PM}{zRT}; \quad (2)$$

where P is the gas pressure, M is the gas molar mass, R is the universal gas constant, T is the gas temperature, and z is the compressibility factor. The NIST properties database REFPROP [18] is used for density calculations. The FTS tank volume is a function of T and P and is given by:

$$V = V_{ref} [1 + \lambda \Delta P] [1 + 3\alpha \Delta T]; \quad (3)$$

where V_{ref} is the FTS tank volume at 20 °C and 101 kPa, $\lambda = 2.4 \times 10^{-7} \text{ kPa}^{-1}$ is the pressure expansion coefficient, $\alpha = 3.0 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ is the linear thermal expansion coefficient, and T and P are the difference of the temperature and pressure from the reference values, respectively. The thermal expansion coefficient of the pressure vessel was provided by the manufacturer. The pressure expansion coefficient was calculated from manufacturer's values of the tank volume at 100 kPa and at 43 MPa. An expanded uncertainty of 20 % was assigned to each of these values because we are relying on manufacturer's data. Inserting Eqns. 2 and 3 into Eqn. 1 gives the governing equation for the mass dispensed via the *PVT* method:

$$\Delta m_{PVT} = \frac{V_{\text{ref}} M}{R} \left[\frac{P_2}{z_2 T_2} [1 + \lambda \Delta P_2] [1 + 3\alpha \Delta T_2] - \frac{P_1}{z_1 T_1} [1 + \lambda \Delta P_1] [1 + 3\alpha \Delta T_1] \right]. \quad (4)$$

4.1.1 Tank volume determination—We used the volume expansion method [19] to measure the volume $V_{\text{ref}} = 39\,530 \text{ cm}^3$ at a pressure of 101 kPa with expanded uncertainty of 0.17 %.

4.1.2 Pressure measurements—For the laboratory tests, a resonant silicon gauge pressure transducer calibrated by the NIST Thermodynamic Metrology Group and two intrinsically safe analog sensors were used for pressure measurements. The resonant silicon gauge sensor has a higher accuracy than the analog sensors that use piezoelectric technology for sensing and is therefore called the 0.01 % pressure sensor. The analog pressure sensors were calibrated against the 0.01 % pressure sensor. The two analog sensors have ranges of 35 MPa (5000 psig) and 1.4 MPa (200 psig). The higher ranged sensor is used for measurements when the FTS tank is “full” and the lower ranged sensor is used when the FTS tank is nearly “empty”. The 0.01 % pressure sensor is not intrinsically safe and therefore cannot be used for field tests with H_2 .

All sensors were calibrated the week prior to traveling to the field test site and upon return to NIST. The calibration upon return of the low and high range pressure sensors' showed a 0.5 % shift in the low range sensor over its measurement range and a 1.7 % to 1.57 % shift in the high range sensor at approximately 16 MPa and 31 MPa, respectively. These pressure sensors demonstrated the tendency to drift in the laboratory as much as 0.065 % and 1.34 % for the low and high ranged sensor, respectively over a period of 90 days. Therefore, we knew drift was a possibility, however, we did not expect drift of this magnitude over the period of the field tests (< 1 week). The shift in the sensors' calibration is taken as the upper limit of a rectangular distribution and root-sum-squared with the uncertainty of the working calibration standard (0.006 %) and the standard deviation of the fit residuals from the calibration. Therefore the standard uncertainty in the pressure measurement made with the

analog sensors is $\sqrt{\left((0.006\%)^2 + (0.13\%)^2 + \left(0.5\% / \sqrt{3}\right)^2\right)} = 0.32\%$ for the low range

$$\begin{aligned} \text{sensor and } \sqrt{\left((0.006\%)^2 + (0.071\%)^2 + \left(1.57\% / \sqrt{3}\right)^2\right)} &= 0.91\% \quad \text{to} \\ \sqrt{\left((0.006\%)^2 + (0.071\%)^2 + \left(1.7\% / \sqrt{3}\right)^2\right)} &= 0.98\% \quad \text{for the high ranged sensor.} \end{aligned}$$

4.1.3 Temperature measurements—Four Inconel sheathed, ungrounded type K TCs were purchased for use in the FTS; two are spare and two were inserted into each end of the FTS tank (Fig. 3) and used for temperature measurements during the tests. A National Instruments¹ TC DAQ card was used to acquire the TC measurements. Before the two sensors were installed in the FTS, all four were calibrated against the Fluid Metrology Group's reference temperature standards. The standard uncertainty from the calibration is 0.01 %. The FTS is designed for use outdoors under a wide range of temperature conditions; therefore, an assessment of the cold junction compensation by the TC DAQ card was made. The details of this assessment can be found in a prior publication that describes only the laboratory tests [7]. However, the field tests were carried out under very similar temperature conditions as the laboratory tests and therefore this added uncertainty can be ignored in this case. The atmospheric temperature ranged from 288 K to 295 K in the laboratory and from 290 K to 298 K in the field.

The TCs did not show a significant drift in their calibration after returning to NIST from the H₂ dispenser site (< 200 mK or ≈ 0.07 %), however, the temperature gradient in the FTS tank during the density measurements in the field tests was greater than during the laboratory tests (because we waited for thermal equilibrium in the lab but not in the field). Hence there is a larger uncertainty component for the field test measurement for spatial non-uniformity. The difference in the two sensors that measure the internal FTS tank gas temperature varied from 0.11 °C to 7.45 °C during the density measurements following a 20 minute wait after filling and after blowing the gas down (Table 2). Because the average measurement of the two TCs was used for density calculations in the FTS tank, the largest deviation in sensor reading from the average (1.24 %) was used, considered to have a rectangular distribution, and root-sum-squared with the other uncertainty components. Therefore, the standard uncertainty in the temperature measurements ranges from

$$\begin{aligned} \sqrt{\left((0.01\%)^2 + \left(0.07\% / \sqrt{3}\right)^2 + \left(1.24\% / \sqrt{3}\right)^2\right)} &= 0.72\% \quad \text{to} \\ \sqrt{\left((0.01\%)^2 + \left(0.07\% / \sqrt{3}\right)^2\right)} &= 0.042\% \quad \text{for field and laboratory tests, respectively.} \end{aligned}$$

4.1.4 Expanded uncertainty in the PVT method measurement—The expanded uncertainty in the PVT measurement with coverage factor k can be calculated by:

$$\left[\frac{U(\Delta m_{PVT})}{k \Delta m_{PVT}} \right]^2 = \sum_{i=1}^9 S_{x_i}^2 \left(\frac{u(x_i)}{x_i} \right)^2; \quad (5)$$

where the x_i are the 9 measurands in Eqn. 4: V_{ref} , P_1 , P_2 , T_1 , T_2 , z_1 , z_2 , α , and λ and where S_{x_i} is the normalized sensitivity coefficient for each variable. The values of S_{x_i} are calculated by:

$$S_{x_i} = \frac{\partial \Delta m_{PVT}}{\partial x_i} \frac{x_i}{\Delta m_{PVT}}; \quad (6)$$

The full uncertainty budget for this method has been published previously [7] and therefore will not be repeated here. Table 1 gives the expanded uncertainty for each measurement method in the laboratory and in the field. Table 3 compares the contributions of uncertainty components of the *PVT* method in the laboratory setting to that in the field for a test draft of approximately 0.5 kg. In the laboratory, the largest contributors to the uncertainty are 1) the volume of the FTS tank followed by 2) the compressibility factor z_2 and 3) the final gas temperature. However, in the field the larger uncertainty pressure sensors are used and the temperature spatial gradient in the tank during density measurements is relatively large. Therefore, the tank temperature and pressure when “full” become the dominating uncertainty components.

4.1.5 Feasibility of the *PVT* method in field tests—There are two reasons why the *PVT* method was not ideal for our field tests. First, the commercially-available, intrinsically-safe pressure sensors have significant calibration drift, making their measurements too unreliable for the 0.5 % uncertainty goal for the mass measurement. The highest ranged pressure sensor is the largest contributor to the uncertainty in the mass determined by the *PVT* method. As mentioned in section 4.1.2, the sensor demonstrated a drift of up to 1.7 % during its use in the week-long field tests. This calibration shift leads to an overall uncertainty in the mass measurement of 1.83 %.

The second disadvantage, shared with the master meter method, is that quasi-thermal equilibrium must be reached in the FTS before accurate temperature and pressure measurements can be made. Because field tests are repeated a minimum of three times at the MMQ and at the maximum capacity of the FTS tank [13], there are two times (for each test draft) when thermal equilibrium is necessary: 1) following the release of the previous test draft, and 2) following the fill of the current test draft. Figure 10 illustrates the process for three test drafts. This process is repeated a second time for the other quantity of gas to be collected. The time to wait depends on the atmospheric temperature and the resulting temperature of the gas inside the FTS during a fill or blow-down. The wait time will increase as the temperature difference between the gas inside the tank and the atmosphere increases. The factors that influence this difference are 1) the rate of the fill (or pressure ramp rate (PRR)), 2) the pressure blow-down rate (PBDR), and 3) the atmospheric conditions.

The average PRR affects the FTS tank temperature because the tank heats up due to gas compression while being filled. In general, the less mass dispensed into the tank and the lower the PRR, the less the FTS tank heats when being filled. Figure 11 shows the PRRs used in the laboratory and field tests and the resulting difference in the tank gas temperature

before the start of the fill and immediately after the fill is stopped; *i.e.* as soon as the dispenser is shut off.

The PBDR affects the FTS tank temperature in a similar manner as the PRR. In general, the smaller amount of mass blown-down and the lower the PBDR the less the FTS tank will cool due to expansion of the gas leaving the tank. Figure 12 shows the PBDRs used in the laboratory and the field and the difference in the FTS tank internal temperature before blowing the gas down and immediately after the blow-down. We blew the H₂ gas down slower than the He gas because H₂ gas diffuses into elastomer materials in the FTS tank when it is under *high* pressures and it is necessary to release it slow enough for the H₂ molecules to diffuse out of the elastomers without damaging them. In the laboratory, we could blow the He gas down at faster rates.

It was shown in our original publication on the laboratory tests [7] that a 20 minute wait time following a blow-down and subsequent fill results in less than a 0.1 % error in the dispensed mass measurement. Because of the thermodynamic similarity between He and H₂ [18], we made the assumption that H₂ would behave likewise. In the field, we waited 20 minutes before taking density measurements in the FTS tank following each fill and blow-down. After this wait time, the temperature gradient in the tank following a fill was a few degrees higher than in the laboratory and approximately the same as in the laboratory following a blow-down. Figure 13 shows the difference between the two temperature sensors in the FTS tank immediately following multiple fills (A) and blow-downs (B) and after waiting 20 minutes for the field and laboratory test drafts of approximately 0.75 kg H₂ and 1 kg He.

The FTS tank temperature gradient is larger following the 20 minute wait period for the collection of H₂ gas than immediately after the collection (Fig. 13A). This could be explained by the larger PRRs used for H₂ test drafts compared to He and possible improved gas mixing in the tank as it is filled; the temperature gradient develops once filling is halted. The larger thermal gradient following the collection of H₂ after a 20 minute wait compared to He can also be explained by the larger PRRs used.

Typically the temperature of the gas in the FTS tank immediately following the blow-down of 0.75 kg H₂ gas has an approximate 6.5 K higher thermal gradient compared to 1.7 kg He (Fig. 13B). This can be almost completely explained by the existence of a thermal gradient in the FTS tank prior to the beginning of the blow-down as is shown in Table 2.

Because we did not wait for thermal equilibrium in the FTS tank in the field, like in the laboratory tests, we can only make predictions on what the equilibrium pressure and temperature will be and hence the error in the dispensed mass measurement. A simple lumped heat transfer model was used:

$$T = e^{\left(\frac{-t}{\tau}\right)} (T_0 - T_{\infty}) + T_{\infty}, \quad (7)$$

where t is the time, T is the temperature at time t , T_0 is the initial temperature at time zero, T_{∞} is the temperature of the environment at the time of the test draft, and τ is the time constant. Once the temperature profile in the tank as a function of time is calculated and

assuming the mass in the tank is that measured by the gravimetric method, Eqn. 4 is used to predict the tank pressure. Therefore, the mass dispensed can be calculated as a function of time and compared to the calculated equilibrium value. Figure 14 demonstrates how Eqn. 7 is used to predict the temperature as equilibrium is reached. Figure 14A shows the FTS tank temperature and pressure during the blow-down of H₂ test draft #3 (the pre-fill conditions for test draft #4) and the fill for test draft #4. This test draft was chosen for the example because it has the largest differences in the two temperature sensors during the density measurements (Table 2).

Following the blow-down and the fill we let 20 minutes elapse and we recorded and averaged the tank gas temperature and pressure for approximately 1.5 minutes. These averages are used to calculate the pre-fill and post-fill gas density. There are 20 minute gaps in the data because we used this time to weigh the FTS tank for the gravimetric measurements. The bottom graph in Fig. 14B show the predicted temperature behavior in the FTS tank via Eqn. 7 and the percent difference in the calculated mass dispensed from the value calculated at thermal equilibrium. Despite the disagreement between the two TCs, at 20 minutes the difference in the dispensed mass calculation is less than 0.1 % as expected from the laboratory tests. When determining the 20 minute wait time, the added uncertainty in the density measurement was considered. If the pressure sensor did not drift, the expanded uncertainty in the *PVT* method would increase from 0.22 % in the laboratory to 0.47 % in the field, within the 0.5 % target. Figure 15 shows the equivalent of Fig. 14B for the blow-down and fill of 1 kg He gas in the laboratory.

4.2 Gravimetric Method

The dispensed mass (m_{grv}) into the FTS is calculated by:

$$\Delta m_{grv} = m_2 - m_1, \quad (8)$$

where m is the true mass and the subscripts 1 and 2 denote the mass of the FTS pre-filling and post-filling, respectively.

The scale indicated mass (m_a) is buoyancy corrected to determine the true mass via the equation: $m = m_a + \rho_{air}V$; where ρ_{air} is the density of the air surrounding the tank, a function of atmospheric pressure, temperature, and relative humidity (P , T , RH) and the molar mass of air. V is the volume of the FTS tank. Therefore:

$$\Delta m_{grv} = m_{a2} + \rho_{air2}V_2 - [m_{a1} + \rho_{air1}V_1]. \quad (9)$$

Inserting Eqn. 3 for the volume of the FTS tank into Eqn. 9 leads to the governing equation for mass determination for the gravimetric method:

$$\Delta m_{grv} = m_{a2} - m_{a1} + V_{ref} [\rho_{air2} [1 + \lambda \Delta P_2] [1 + 3\alpha \Delta T_2] - \rho_{air1} [1 + \lambda \Delta P_1] [1 + 3\alpha \Delta T_1]]. \quad (10)$$

4.2.1 Uncertainty in the gravimetric measurement method—The uncertainty in the gravimetric measurement can be calculated by:

$$\left[\frac{U(\Delta m_{grv})}{k\Delta m_{grv}} \right]^2 = \sum_{i=1}^{11} S_{x_i}^2 \left(\frac{u(x_i)}{x_i} \right)^2, \quad (11)$$

where the x_i are the 11 measurands in Eqn. 10: m_{a1} , m_{a2} , V_{ref} , P_1 , P_2 , T_1 , T_2 , ρ_{air1} , ρ_{air2} , α , and λ and where S_{x_i} is the normalized sensitivity coefficient for each variable. The values of S_{x_i} are calculated with Eqn. 6 by replacing $m_{PV\bar{T}}$ with m_{grv} .

The weigh scale used in these measurements has resolution of 1 g and that is the largest contributor to the uncertainty in the gravimetric measurement. Calibration of the scale against NIST standard masses introduces a gain correction factor that differs by only 0.02 % from unity. The weigh scale was calibrated after it was set up at the field location. Checks of the calibration throughout testing showed drifts in and out of calibration with a maximum of 0.031 %. No significant drift was observed in the laboratory setting. This is treated conservatively as a rectangular distribution leading to an added uncertainty of 0.018 % during field use due to scale drift. The weigh scale drift could possibly be caused by wind currents that were present in the field and not in the laboratory setting.

An atmospheric monitor was used to measure the air density with uncertainty of 0.32 % ($k = 1$). Because the temperature and pressure measurements inside the FTS tank that were discussed in detail in Section 4.1 are only used for determining the FTS tank volume for buoyancy corrections, their combined contribution to the overall uncertainty budget is $< 10^{-4}$ %. Table 4 compares the contributions of uncertainty components of the gravimetric method in the laboratory setting to that in the field for a test draft of approximately 0.5 kg. Scale drift is the only reason why this method has an increased uncertainty in the field compared to in the laboratory.

4.2.2 Importance of buoyancy corrections—The conventional correction factor for buoyancy effects used by scale manufacturers to turn apparent mass readings into true mass readings is $1 - \rho_{air} / \rho_{stainless\ steel}$, where the conventional values for the density of air and stainless steel are 1.2 kg/m³ and 8000 kg/m³, respectively at $P = 101.325$ kPa, $RH = 50$ %, and $T = 293.15$ K. The density of stainless steel is used because the masses used to calibrate scales are generally made of stainless steel. If the air or the weighed object density is not the conventional values, additional buoyancy corrections must be made for measurements of the lowest uncertainty.

In the laboratory and field tests, environment T , P , and RH measurements were made simultaneously with the gravimetric measurements in order to make buoyancy corrections. Buoyancy corrections become more significant if the environmental conditions change between weighing the empty and full FTS tank before and after taking a test draft. The magnitude of the changes in environmental T , RH , and P during a test draft in the laboratory and the field were similar. In the laboratory, the maximum change observed was 1.5 K, -2.6 %, and -300 Pa. In the field, the maximum change observed was 1.62 K, -4.4 %, and -26 Pa. If these buoyancy corrections were ignored during our 0.5 kg He and the 0.41 kg H₂ test drafts, mass measurement errors of 0.029 % and 0.032 % would result, respectively.

To estimate the maximum importance of making buoyancy corrections in the field, we considered extreme environmental conditions. The day time T , RH , and barometric P during the winter and summer seasons were investigated for multiple locations within the United States. Of the locations we considered, the location with the highest daytime air density is Anchorage, Alaska in the winter. The location with the lowest daytime air density is Alma, Colorado in the summer. Phoenix Arizona was also investigated and found to have the next lowest daytime air density in the summer. Table 5 gives the parameters for these locations. Figure 16 shows the error in the gravimetric measurement if buoyancy corrections are not made in these locations. The error has been calculated for the non-conventional environmental conditions with 1) no change in conditions between weighing the “empty” and “full” FTS and 2) assumed changes in T , RH and barometric P of 5 K, -5% , and -300 Pa, respectively. These changes are reasonable estimates of what will be encountered during field tests and therefore give an estimate of the error in gravimetric measurements if they are not buoyancy corrected. These corrections become more significant as the atmospheric density increases from the conventional value, as in Anchorage AK, where the error is as large as 0.17% with the mentioned changes in environmental conditions.

4.3 Master meter method

Following the fill of the FTS tank, the gas is blown down through a coriolis master meter. The mass that filled the FTS tank (m_{MM}) is calculated by:

$$\Delta m_{MM} = \Delta m_{CM} + \Delta m_{FTS} + \Delta m_{CV}, \quad (12)$$

where m_{CM} is the mass totalized by the coriolis master meter, m_{FTS} and m_{CV} are the change in mass after blow-down compared to before filling in the FTS tank and in the connecting volume between the FTS tank and the master meter, respectively (mass post blow-down – mass pre-filling). The connecting volume is less than 9 cm^3 , less than 0.022% of the FTS tank volume and therefore, mass measurements in it can be neglected without significant measurement uncertainty.

4.3.1 Calibration of the master meter—The master meter is a coriolis meter with two 0.15 cm diameter flow tubes. The meter was calibrated under steady state conditions on NIST's $PVTt$ system [20]. The master meter is used as received from the manufacturer and therefore corrections are not made to its readings, which agree with the $PVTt$ standard within 0.36% under steady flow conditions. Furthermore, the meter zero was verified under a no flow condition using the manufacturer's software prior to use every day in the laboratory and in the field. It never failed verification and therefore, we never performed a zero calibration. Figure 17A shows the results from this steady state calibration. The 0.36% can be treated as the boundary value in a rectangular distribution so the meter has a base standard uncertainty of 0.21% .

In experiments independent from those used to produce Fig. 1, we used the PVT system to assess the uncertainty in the master meter due to the transient conditions produced when blowing the gas down from the FTS tank. Figure 17B shows the agreement between the two methods for these experiments prior to field tests ($< 0.19\%$) and after field tests ($< 0.33\%$). The 0.19% can be treated as the boundary value in a rectangular distribution so the meter

has added standard uncertainty due to usage during transient flow of 0.11 %. The steady-state uncertainty root-sum-squared with the transient uncertainty leads to an overall standard uncertainty for the totalized mass according to the master meter of 0.24 % in the laboratory. The cause of the apparent offset of 0.14 % in the calibration results shown in Fig. 17B is not known. Possible causes are exposure to H₂ gas and transport. The meter was not exposed to pressures greater than 1034 kPa during the H₂ gas blow downs. The shift increases the standard uncertainty of the master meter to 0.28 %; therefore, the expanded uncertainty is outside of the 0.5 % target.

4.3.2 Uncertainty in the master meter method—The uncertainty in the master meter measurement can be calculated by:

$$\left[\frac{U(\Delta m_{MM})}{k\Delta m_{MM}} \right]^2 = \sum_{i=1}^3 S_{x_i}^2 \left(\frac{u(x_i)}{x_i} \right)^2, \quad (13)$$

where the x_i are the 3 measurands in Eqn. 12: m_{CM} , m_{FTS} , and m_{CV} and where S_{x_i} is the normalized sensitivity coefficient for each variable. The values of S_{x_i} are calculated with Eqn. 6 by replacing m_{PVT} with m_{MM} .

Taking the partial derivative of Eqn. 12 for each component shows that the sensitivity coefficients are directly proportional to the fraction of total mass each component represents. The closer the mass in the FTS tank is following the blow-down through the master meter to that before the FTS tank was filled, the less m_{FTS} contributes to the overall uncertainty. The largest change in this mass during the laboratory tests was 18.7 g of He, which represents a 288 kPa (42 psi) change at constant temperature of 290 K. The uncertainty in the m_{FTS} measurement in the laboratory setting is less than 0.12 % with the FTS tank volume being the largest contributor. The largest change in this mass during the field tests was 7.9 g of H₂, which represents a 241 kPa (35 psi) change at constant temperature of 290 K. The uncertainty in the m_{FTS} measurement in the field setting is less than 0.83 % with the temperature measurement dominating the uncertainty due to spatial non-uniformity. Regardless if the m_{FTS} measurement was made in the laboratory or the field the normalized sensitivity coefficient is < 0.04 and thus the contribution to the overall uncertainty in the master meter method is < 0.3 %. Table 6 compares the contributions of uncertainty components of the master meter method in the laboratory setting to that in the field for a test draft of approximately 0.5 kg.

4.3.3 Effect of measurement errors in m_{FTS} —Measurements are repeated multiple times for field tests. Therefore, gas will be blown-down from the FTS tank before it is filled for the next test multiple times. As a consequence, the temperature of the gas left in the tank following the blow-down is initially cold, but will warm to the environmental temperature. Because the temperature and pressure sensors have response time lags, the density measurements made following the release of gas have errors from the un-steady conditions. Due to time constraints in the field it is difficult to wait for thermal equilibrium. Therefore, it is necessary to estimate the contribution of unsteady conditions to the uncertainty of the master meter method.

m_{FTS} is zero if the mass in the FTS tank following the blow-down through the master meter is equal to the mass in the tank before filling, and hence, there is no need to make density measurements for the master meter measurement method. However, it is impractical to achieve this condition. The measurement error added by not waiting for thermal equilibrium and not having $m_{\text{FTS}} = 0$ was quantified as follows. The FTS was filled with 1 kg He. Helium was blown-down from the FTS tank and measurements were made from the temperature and pressure sensors continuously following the blow-down (Fig. 18A). Readings from the sensors were averaged every minute while thermal equilibrium was reached and the mass calculated. This is the starting mass in the FTS for the master meter method. This data was used to simulate the conditions in the FTS following a fill and blow-down through the master meter, however, it was altered to not match the pre-fill conditions: temperature was increased by 5 K and pressure by 173 kPa (25 psi), 345 kPa (50 psi), or 690 kPa (100 psi). Figure 18A illustrates the temperature and pressure profile for the 345 kPa increase case. The mass dispensed into the FTS tank (m_{MM}) was calculated using the average density measurements while the tank gas was not at thermal equilibrium and compared to the calculated m_{MM} value at equilibrium. Figure 18B shows the added measurement error as a function of wait time and as a function of not returning to the pre-fill tank pressure. Neglecting meter drift, to keep the master meter measurement uncertainty below 0.5 %, the added uncertainty should not be larger than 0.04 %. This requires wait times of 20 minutes if the starting pressure is within 173 kPa of the ending pressure. This wait time increases to 1.5 hours if the pressure change is as large as 690 kPa. Therefore, for measurements that meet the desired uncertainty and reasonable wait times, the starting (or pre-fill) pressure should ideally be kept within 173 kPa of the ending (or post blow-down) pressure.

5. Summary

All three methods incorporated into the FTS (*PVT*, gravimetric, and master meter) agree within 0.57 % and 1.53 % in the laboratory and field settings, respectively. All methods 1) allow a gaseous dispenser to perform as it would while filling the compressed gas tank of a small vehicle and 2) can be successfully performed in the field and give equivalent answers. However, not all methods are equally practical in the field.

The lowest uncertainty measurement is the *PVT* performed in the laboratory with a 0.01 % pressure sensor (resonant silicon gauge). However, we were unable to find commercially-available, high accuracy pressure sensors for use with H_2 ; therefore, the uncertainty in this method increased to 1.83 % due to sensor drift in the field; exceeded the 0.5 % target. As shown in Section 4.1.5, waiting for 20 minutes for thermal equilibrium following a fill or blow-down is adequate to achieve mass measurements with less than 0.5 % uncertainty if the pressure measurements are as accurate as in the laboratory setting. The wait time depends on 1) the rate the tank was filled or blown-down (vented) and 2) the heat transfer from the FTS tank to the environment. If a tank with better heat transfer characteristics were available, less time would be needed for thermal equilibrium and the FTS could make faster measurements. Because of the wait time required for acceptable thermal equilibrium, this measurement method takes the longest amount of time to complete, approximately 8 h for six test drafts, compared to the other two methods that require approximately 6 h for six test

drafts. (The time for 6 test drafts assumes it takes 30 minutes to fill the FTS with 1 kg H₂, 20 minutes to reach thermal equilibrium, 10 minutes to weigh the FTS, and 10 minutes to blow-down the FTS through the master meter.)

The gravimetric method takes less time than the *PVT* method, and if atmospheric conditions are close to the conventional conditions, buoyancy corrections account for < 0.04 % of the measurement uncertainty. The magnitude of the added measurement uncertainty will depend on: 1) the mass being weighed, 2) the deviation of densities from the conventional values, and 3) the change in environmental conditions between weighing the “empty” and the “full” FTS. In the field tests, the buoyancy correction was as large as 0.032 %. An environmental monitor can account for environmental changes between weighing the “empty” and “full” FTS (Section 4.2.2). Aside from buoyancy corrections, the scale with the capacity needed to weigh the FTS has 1 g resolution making it the largest uncertainty contributor in this measurement.

The master meter method met the measurement accuracy requirement of 0.5 % in the laboratory. However, the meter drifted during the field tests resulting in an increased expanded uncertainty of 0.56 %. If the change in mass in the FTS tank (m_{FTS}) is less than 2 % of m_{CM} , density measurements can be made within 20 minutes following the blow-down through the coriolis master meter. As discussed for the *PVT* method, the wait time could be decreased if better heat transfer existed between the collection tank and the environment. The master meter method has a significant disadvantage; the meter cannot be easily verified in the field. The meter used in these experiments was carefully handled and was tested extensively under transient flow conditions. The need for field verification could be circumvented by using two master meters in series. This allows the operator to check for consistent measurements and will flag calibration drift, but will increase the component cost of the FTS. If the two meters in series used different sensing technology, they are unlikely to be subjected to the same drift or sensitivity to temperature and vibration.

The tests described here indicate that all three methods can achieve 0.57 % or less uncertainty for a H₂ field test standard for 0.5 kg of gas. The uncertainty is < 0.57 % for larger masses of gas. The laboratory tests and uncertainty analyses give guidance on the importance of proper measurements for each method. The field tests show the importance of sensor selection and sensor verification before and after field tests. We have also gained insight on the relative performance regarding completion time and ease of use of the three methods.

Acknowledgements

The authors wish to thank 1) Michael Moldover of the National Institute of Standards and Technology for his advice and support, 2) Ernest Chaput, Fred Humes, Patrick Woodell, and Joette Sonnenberg of the Applied Research Center in South Carolina for allowing us access to their facilities and their invaluable help and support with the field tests, 3) Robert Burgess, Michael Peters, Kevin Harrison, and William Buttner of the National Renewable Energy Laboratory for helpful design discussions, and 4) The National Institute of Standards and Technology Office of Weights and Measures for providing funding and specifically Juana Williams for her assistance in arranging and performing the field tests.

References

1. Morioka T, Ito M, Fujikawa S, Ishibashi M, Nakao S. Development and Evaluation of the Calibration Facility for High Pressure Hydrogen Gas Flowmeters. *Flow Measurement and Instrumentation*. 2014; 39:19–24.
2. Nakao, S. Development of the Critical Nozzle Flow Meter for High Pressure Hydrogen Gas Dispenser at a Hydrogen Gas Station.. *FLOMEKO 2005 Conference Proceedings*;
3. Pope JG, Wright JD. Performance of Coriolis Meters in Transient Gas Flows. *Flow Measurement and Instrumentation*. 2014; 37:42–53.
4. International Recommendation: Compressed Gaseous Fuel Measuring Systems for Vehicles. International Organization of Legal Metrology; p. 14OIML R 139 Edition 2007(E) section 3.1.1
5. Schnepf, KL.; Kashuba, MJ. Hydrogen Dispenser Testing and Certification Update. Oct. 2014 http://cafcfp.org/sites/files/Hydrogen_Dispenser_Testing_Update_CDFA_DMS_Final.pdf
6. Specifications, Tolerances, and other Technical Requirements for Weighing and Measuring Devices. Section 3.30: Liquid-Measuring Devices. NIST Handbook 44, 2013 Edition
7. Pope, JG.; Wright, JD. Hydrogen Field Test Standard: Laboratory Performance. 9th International Symposium for Fluid Flow Measurement; Arlington, VA.. April 14th – 17th, 2015;
8. Dynecell Type 3 Cylinder Operation Manual S-OP-020 Rev D. Mar.2012
9. Pope, JG. Hydrogen Field test Standard, Operating Instructions & Specifications. National Institute of Standards and Technology; 2015. Technical Note: NIST-TN 1888
10. San Marchi, C.; Somerday, BP. Technical Reference on Hydrogen Compatibility of Materials; Nickel Alloys: Solid Solution Alloys, Ni-Cr Alloys. Sandia National Laboratories; Livermore CA.: code 5110
11. San Marchi, C.; Somerday, BP. Technical Reference on Hydrogen Compatibility of Materials; Austenitic Stainless Steels: Type 316. Sandia National Laboratories; Livermore CA.: code 2103
12. San Marchi, C.; Somerday, BP. Technical Reference on Hydrogen Compatibility of Materials; Non-metals: Polymers. Sandia National Laboratories; Livermore CA.: code 8100
13. Specifications, Tolerances, and other Technical Requirements for Weighing and Measuring Devices. Section 3.39: Hydrogen Gas-Measuring Devices – Tentative Code. NIST Handbook 44, 2013 Edition.
14. Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles. Mar 16.2010 SAE TIR J2601.
15. Guide to the expression of uncertainty in measurement. International Organization for Standardization; Geneva, Switzerland: 1993.
16. WEH Company USA. <http://www.weh.us/refueling-systems-hydrogen.html>
17. Hydrogen Fuel Quality for Fuel Cell Vehicles. Sep 20.2011 SAE J2719.
18. Lemmon, EW.; Huber, ML.; McLinden, MO.; REFPROP 23: Reference Fluid Thermodynamic and Transport Properties. NIST Standard Reference Database 23. Version 9. National Institute of Standards and Technology; Boulder, CO.: 2010.
19. Wright JD, Johnson AN, Moldover MR. Design and Uncertainty Analysis for a PVTt Gas Flow Standard. *J. Res. Natl. Inst. Stand. Technol.* 2003; 108:21–47.
20. Wright, JD.; Johnson, AN. NIST Lowers Gas Flow Uncertainties to 0.025 % or Less. Vol. 5. NCSL International Measure; 2010. p. 30-39.

Fig. 1. Comparison of the three test methods for the test draft of 0.5 kg, 1 kg, and 1.7 kg of He gas. The error bars are the $k = 2$ expanded measurement uncertainty corresponding to a confidence level of 95 %. The average of all three methods is used as the reference value (difference = 0).

Fig. 2. Comparison of the three test methods for the test draft of 0.41 kg and 0.75 kg of H_2 gas. The error bars are the $k = 2$ expanded measurement uncertainty corresponding to a confidence level of 95 %. The average of all three methods is used as the reference value (difference = 0).

Fig. 3.
Portable FTS in horizontal position.

Fig. 4. FTS plumbing and instrumentation diagram. There are two check valves and one ball valve (valve #1) at the FTS tank inlet. One of the check valves is incorporated into the H₂ dispenser receptacle. The ball valve can be used to control the inlet flow. There is one check and one ball valve (valve #2) at the inlet for purge gas. The FTS tank must be purged of all H₂ gas before vehicular transport. The tank outlet has one ball valve (valve #3) upstream from a non-venting regulator that is used to control the flow through the master meter when blowing the tank down. Valve #4, a ball valve, and pressure relief valve #2 protects the low ranged pressure sensor when the tank is pressurized above 1.4 MPa.

Fig. 5.
The weighing tent and the FTS on the scale inside the tent at the H₂ dispenser location.

Fig. 6.
The FTS at the H₂ dispenser with accompanying DAQ box, laptop and vent stack.

Fig. 7.
Schematic of FTS filling and blow-down setup in the laboratory.

Fig. 8.

Pressure, mass flow, and temperature for the FTS tank during the test draft of A) 1 kg and B) 1.6 kg He. In (A), at approximately 4 min, one high P tank was depleted and a second one opened to finish the collection. In (B), all four of the TFF high P tanks were used for the collection. At approximately 10 min, 18 min, and 24 min a high P tank was closed and another opened. The temperature trace is the average of the two TCs in the FTS tank.

Fig. 9. Pressure and temperature profiles for the FTS tank during the test draft of approximately 0.75 kg H_2 in ambient temperature of A) 24.5 °C and B) 18.5 °C. The temperature trace is the average of the two TCs in the FTS tank.

Fig. 10.

Illustration of the number of times thermal equilibrium must be reached for the *PVT* method in the FTS during three repeats of the collection of a specified amount of gas.

Fig. 11.
Relationship between the pressure ramp rate (PRR) and the increase in internal tank temperature during filling.

Fig. 12.

Relationship between the pressure blow-down rate (PBDR) and the decrease in internal tank temperature during blow-down.

Fig. 13.

The internal FTS tank gas temperature gradient following a fill (A) and the blow-down (B) of approximately four test drafts of 0.75 kg H₂ gas and five test drafts of 1.7 kg He gas. Measurements were made immediately after the fill or blow-down halted and after waiting approximately 20 minutes.

Fig. 14.

A) Measured T and P profiles (solid symbols) and B) predicted T profiles (lines) of the sensors in the FTS collection tank following a blow-down of 0.41 kg and a fill of 0.75 kg H_2 gas. The red and blue boxes in (A) correspond to the same colored boxes in (B). An approximate 20 minute period of recording is missing after the blow-down and the fill (the time we waited for quasi-thermal equilibrium). The bottom graph shows the percent difference in the dispensed mass (dashed line) from the calculated equilibrium value as a function of time.

Fig 15.
Temperature profiles in the FTS tank following the blow-down and fill of 1 kg He gas in the laboratory. The traces begin following a 20 minute wait after the blow down and fill so they can be better compared to those in Fig. 14B.

Fig.16.

The symbols show the error in mass measurements of 0.75 kg and 0.41 kg at 4 locations in the United States if no buoyancy corrections are made. The upward arrows represent error for non-conventional atmospheric conditions with no change (NC) in conditions between weighing the “empty” and the “full” FTS. The downward arrows represent the error if the non-conventional conditions change by 5 K, -5 % *RH* and -300 Pa.

Fig. 17.

A) Difference between the master meter and NIST's PVT_t primary standard during steady flows. B) Difference between the master meter and PVT measurements made by blowing the collected gas down from the FTS tank before (blue stars) and after (red crosses) the H_2 field test.

Fig. 18.

A) P and T profile of the FTS tank gas following the blow-down of 1 kg He gas. B) Added uncertainty in the master meter method measurement for not waiting for thermal equilibrium during m_{FTS} measurements.

Table 1

Target mass (and corresponding pressure) collections for laboratory tests (He) and field tests (H₂) and the expanded uncertainty of each measurement [7].

Gas	m [kg]	$P(m)$ [MPa]	Gravimetric U [%]	PVT U [%]	Master Meter U [%]
He	0.5	8	0.57	0.21	0.45
H ₂	0.5	17	0.61	1.83	0.56
He	1	17	0.29	0.22	0.46
H ₂	1	35	0.34	1.73	0.56
He	1.7	30	0.17	0.25	0.47

Table 2

Internal temperature and pressure of the FTS collection tank during density measurements in the field. Measurements were made 20 minutes following the end of a fill or blow-down.

Test Draft [#]	FTS Tank Status []	Tank Bottom T [K]	Tank Top T [K]	Tank P [MPa]	T Tank [K]
1	Empty (Post H ₂ purity established)	290.83	294.52	1.05	3.69
	Full	308.89	312.96	16.10	4.07
2	Empty	289.56	294.40	1.17	4.84
	Full	310.01	314.16	16.14	4.16
3	Empty	295.78	296.96	1.18	1.18
	Full	314.90	319.22	15.64	4.32
4	Empty	296.00	303.45	1.41	7.45
	Full	327.45	331.65	30.31	4.21
5	Empty	289.08	289.19	1.23	0.11
	Full	313.43	316.82	31.39	3.39
6	Empty	284.46	287.66	1.09	3.19
	Full	314.55	318.70	31.03	4.15
7	Empty	286.42	288.43	1.15	2.02
	Full	315.41	319.76	30.44	4.35

Table 3

Comparison of the magnitudes of uncertainty components for the *PVT* method in the laboratory and field setting. Analysis is for 0.5 kg gas collected.

<i>m</i> via <i>PVT</i> Method Uncertainty Components	Nominal Values	% Contribution in the Laboratory	% Contribution in the Field
V_{ref} [cm ³]	39530	65.7	0.62
Tank <i>P</i> initial [kPa]	841	<0.1	<0.1
Tank <i>P</i> final H ₂ gas [kPa]	17235	0.38	84.99
Tank <i>T</i> initial [K]	295	0.16	0.16
Tank <i>T</i> final [K]	300	17.7	13.89
Coefficient of linear expansion (α) [1/K]	3.0×10^{-6}	<0.1	<0.1
Pressure expansion coefficient (λ) [1/kPa]	2.4×10^{-7}	5.5	0.14
Compressibility factor z_1	1.00	0.1	<0.1
Compressibility factor z_2	1.04	10.5	0.16

Table 4

Comparison of the magnitudes of uncertainty components for the gravimetric method in the laboratory and field setting. Analysis is for 0.5 kg gas collected.

m via Gravimetric Method Uncertainty Components	Nominal Values	% contribution in the Laboratory	% contribution in the Field
m_a initial [kg]	79.7	48.9	48.5
m_a final [kg]	80.2	48.9	48.5
ρ_{air} initial [kg/cm ³]	1.2×10^{-6}	1.1	1.1
ρ_{air} final [kg/cm ³]	1.2×10^{-6}	1.1	1.1
V_{ref} [cm ³]	39530	<0.1	<0.1
Tank P initial [kPa]	160	<0.1	<0.1
Tank P final H ₂ gas [kPa]	8160	<0.1	<0.1
Tank T initial [K]	303	<0.1	<0.1
Tank T final [K]	293	<0.1	<0.1
Coefficient of linear expansion (α) [1/K]	3.0×10^{-6}	<0.1	<0.1
Pressure coefficient (λ) [1/kPa]	2.4×10^{-7}	<0.1	<0.1
Scale drift [kg]	.025	0	0.87

Table 5

Daytime environmental conditions at several United States locations and the difference in air density from the conventional value of 1.2 kg/m³.

Location	Air T [K]	Barometric P [kPa]	RH [%]	ρ_{air} [kg/m ³]	Difference from conventional value [%]
Phoenix, AZ (summer)	314	100	20	1.104	−7.97
Anchorage, AK (winter)	267	98.4	73	1.283	6.89
Alma, CO (summer)	297	64	21	0.748	−37.66
Gaithersburg, MD (winter)	295	99.1	41	1.168	−2.69

Table 6

Comparison of the magnitudes of uncertainty components for the master meter method in the laboratory and field setting. Analysis is for 0.5 kg gas collected.

m via Gravimetric Method Uncertainty Components	Nominal Values	% contribution in the Laboratory	% contribution in the Field
m_{CM} [kg]	0.5	99.92	99.79
m_{CV} [kg]	1.7×10^{-6}	<0.01	<0.01
m_{FTS} [kg]	0.008	0.08	0.21