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# Laboratory Primary Standards

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Meter manufacturers and users utilize laboratories with primary flow standards to calibrate their working flowmeter standards. Such laboratory standards are designed to have the lowest practical measurement uncertainty so that this high accuracy can be passed on to the flowmeter being calibrated and subsequently to the flowmeter application. Laboratory standards are used to assess flowmeter performance under ideal conditions (generally field performance is not as good). Presently, the uncertainty of laboratory standards is typically less than 0.2% with a 95% level of confidence.* Laboratory flow standards exist for liquid flows from approximately 0.1 g/min to 10,000 kg/min and for gas flows from approximately $1x10^{-6}$ g/min to 100 kg/min. The low uncertainty requirement generally means that these devices are used in tightly controlled laboratory environments and are not portable. Laboratory flow standards can be grouped into certain general categories and examining their principles and methods of operation is useful for those seeking to establish a flow calibration laboratory or understand the laboratory calibration process. Laboratory standards are typically custom-built devices, unique in design, but some commercially built laboratory standards are available.

## *Primary Standards*

A primary standard is defined as a device or object used as the reference in a calibration that is acknowledged to be of the highest metrological quality and that derives its measurement without reference to some other standard of the same quantity.[1] For example, a flowmeter that has been calibrated against a flow standard, and is subsequently used to calibrate other flowmeters, is not a primary standard (it is a reference standard or transfer standard). A piston prover that has had all of the necessary lengths as well as its pressure, temperature, and time instrumentation calibrated can be a primary standard. It is desirable that the calibrations necessary for the primary standard be based on fundamental measurands (time, length, temperature, etc.) and not on some more complex derived quantities. It is important that the primary standard be compared to other primary standards to establish that it is working properly and to verify its uncertainty specifications. Other important characteristics of a primary standard are a well-established theory of operation or *basis equation* and a detailed uncertainty analysis. The uncertainty analysis is critical to assessing the uncertainty of the flowmeter calibrations performed with the primary standard. It is helpful if a primary standard

* All of the uncertainties herein will be expressed as 95% level of confidence values unless otherwise stated.

is conceptually simple and its proper operation easy to verify since it is often the arbiter of flow measurement disputes.

Most laboratory flow standards are systems in which the flow is diverted into a collection vessel for a measured period of time. The change in mass or volume in the collection vessel, divided by the collection time gives the flow. Such flow standards can be categorized as *gravimetric* or *volumetric* systems depending upon whether they use a weigh scale to measure the mass of collected flow or use a known volume to quantify the material collected. There is a significant difference in flow standards depending on whether they are designed for gas or liquid flows. Hence this chapter will be divided into one section pertaining to liquid and another for gas. Within these sections, the gravimetric and volumetric devices will be further divided. Methods that do not fall into these categories will be discussed separately.

## *Liquid Flow Standards*

### *Static Gravimetric Liquid Flow Standards*

A gravimetric flow standard for liquid is essentially a “bucket and stopwatch” system utilizing a weigh scale, and is illustrated in Figure 1. The system consists of a steady flow source and flow controls, a flow conditioner, a test section of piping which holds the meter under test, a flow diverter, and a collection tank mounted on a weigh scale. The diverter directs flow either to the collection tank, or to a supply tank and flow re-circulation system. To operate the system, the collection tank is drained and an initial tank mass (or tare mass) is measured. Steady state conditions of flow, temperature, and pressure are established through the meter under test and the connecting piping (this often takes 10 minutes or more). Flow is rapidly diverted into the collection vessel and a collection start time is measured. When the tank fills to some prescribed mass (collection times of 30 seconds or greater are recommended), the flow is diverted back to the re-circulation system and the stop time is measured. After a sufficient delay for settling, the final tank mass is measured. The change in tank mass (the mass of liquid collected) is divided by the collection time to obtain the mass flow. The mass flow can be converted to the volumetric flow if the density is known. Normally a relationship between the liquid temperature and its density is developed for this purpose, but an on line densitometer can be used instead. Due to weigh scale and time measurement uncertainty issues, a single gravimetric flow system is normally used over a 100 to 1 range of flows or less and to cover larger flow ranges, multiple, different sized gravimetric systems are used.

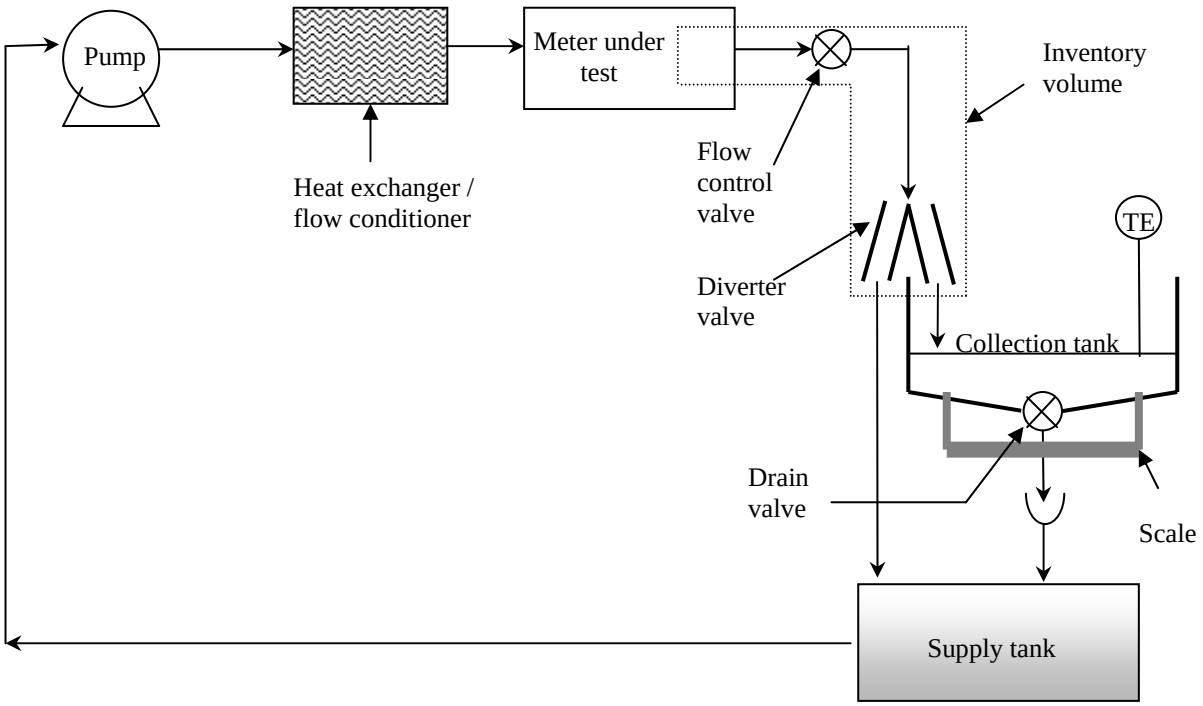


Figure 1. Schematic diagram of a static gravimetric liquid flow standard. Liquid is diverted into a collection tank mounted on a weigh scale for a measured time period. The symbol TE represents to a temperature sensor.

The method of operation described above constitutes a *static gravimetric* system since the mass is measured before and after the collection in a static manner (with flow diverted away from the tank and while the tank mass is not changing). The static gravimetric technique is conceptually simple and the results are easily verified and convincing.

The calibration of meters using such a system is based on the principle of conservation of mass applied to a control volume. The conservation of mass principle states that over a time increment, the change in the mass contained within a control volume is equal to the net mass which flows through the surface defining the control volume. For a flow standard, the control volume includes the collection vessel as well as the piping connecting the meter under test to the collection vessel (also known as the “inventory volume”). When applied to a flow standard, a convenient form of the conservation of mass equation gives the mass flow rate, $W_{grav}$, through the meter as:

$$W_{grav} = \frac{\Delta m_T}{\Delta t} + \frac{\Delta \rho_i \cdot V_i}{\Delta t} + W_{leak} \quad . \tag{1}$$

Here, $\Delta m_T$ is the mass of liquid collected in the tank during the collection time, $\Delta t$. The quantity $V_i$ is the inventory volume of the flow standard (see Figure 1) which includes the volume of the flowmeter being tested, the approach piping connecting the meter under test to the diverter, the tare volume in the prover, and tubing for pressure transducer connections. The quantity $\Delta \rho_i$ is the change in mean density of the liquid in the inventory volume during the collection time. It should be noted that the inventory volume may need to be treated as multiple sub-volumes due to non-uniformity of conditions throughout the inventory volume. The term $W_{leak}$ is included to represent leakage flows into or out of the system.

In a low uncertainty flow standard, buoyancy corrections must be made to the tank weight measurements since the tank and its contents are "floating" in the room air. The relationship for making the buoyancy correction is:

$$m_T = m_S \cdot \left( 1 + \frac{\rho_{air}}{\rho_{liq}} \right), \tag{2}$$

where $m_s$ is the mass of accumulated liquid as indicated by the scale, $\rho_{air}$ is the density of the room air, and $\rho_{liq}$ is the density of the collected liquid. Room temperature, pressure, and humidity measurements are needed to obtain the air density. Buoyancy corrections amount to about 0.1% if the calibration liquid is water.

The second term on the right hand side of Equation 1 accounts for "storage effects" in the inventory volume, $V_i$: if the density of the liquid in $V_i$ increases above some initial value (due for example to decreasing temperature), then liquid is effectively "stored" in the inventory volume and some of the mass which flowed through the meter under test does not reach the collection tank. Note that the liquid does not have to attain the same temperature *throughout* the system to make the storage effects term zero, rather the temperature distribution within the system must have reached *steady state* so that changes in density with respect to time are zero throughout the system. Steady state may be attained by allowing the temperatures to stabilize at a given flow condition before final flow collections are made. These effects can be made smaller by working with liquid temperatures that are close to room temperature. Further

reductions in uncertainty due to storage effects can be made by minimizing the ratio of the liquid mass in the inventory volume to collected mass. Storage effects can be quantified by making repeated flow collections and observing trends in the temperature and flow rate measurements over the time during which steady state is reached.

Critical issues regarding the design and use of the flow diverter have been discussed in written standards [2, 3] and will be repeated here. The goal of the diverter design is to redirect flow from the re-circulation path to the collection vessel. The motion of the diverter is detected with a sensor (optical or mechanical sensors are common) that generates the start and stop trigger signals for the timing system. If the diverter takes a long time to travel through the flow stream, there will be greater uncertainty as to the real start and stop times. Also, the diverter should not cause splashing and it should be a repeatable system, that is, it should travel at the same speed and along the same path each time that it is actuated, so that diverter corrections determined at one time are valid later. The position of the diverter valve should have no effect on the pressure and flow conditions upstream at the meter under test.

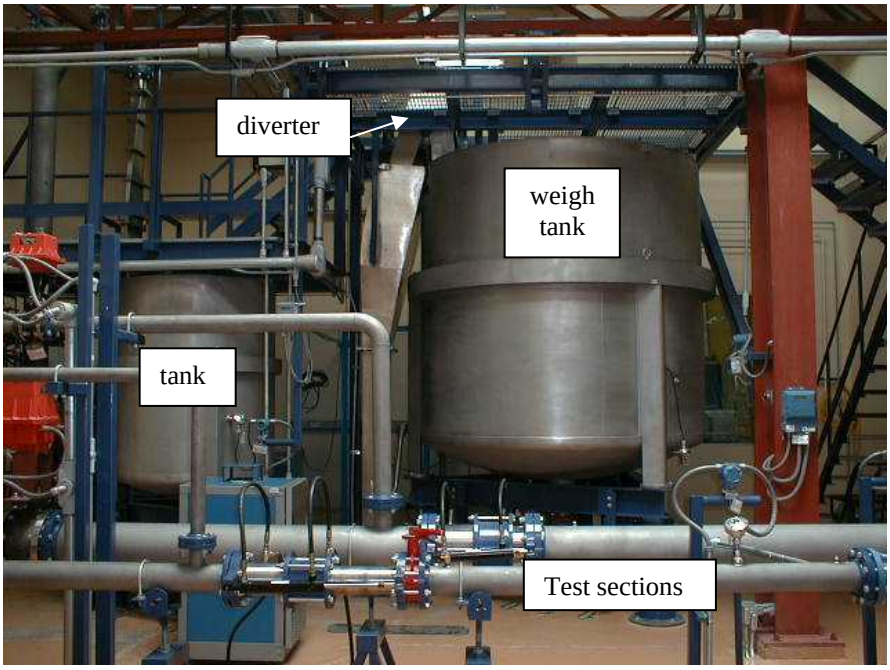


Figure 2. Two static gravimetric flow standards for water at Centro Nacional de Metrologia in Queretaro, Mexico. The standard uses a diverter and tank to collect a measured mass of water over a measured time.

A particular liquid diverter design is shown in Figure 3. The flow passes through a rectangular shaped nozzle or “fish tail” in order to form a narrow liquid sheet or waterfall that can be

traversed quickly by the diverter. The diverter is an enclosed splitter plate mounted on a pivot shaft. The liquid falls vertically through a short open space between the nozzle and the diverter so that the diversion does not cause a back pressure in the test section. The leading edge of the splitter plate should be sharp so that it does not cause splashing of the flow jet. The diverter may be actuated by electrical, mechanical, or pneumatic devices, but generally they should be fast acting so that the flow is switched in times of 0.1 second or less to minimize timing uncertainties. The design in Figure 3 permits the rectangular nozzle width to be varied so that the liquid jet remains full and does not splash over a wide range of flows.[4]

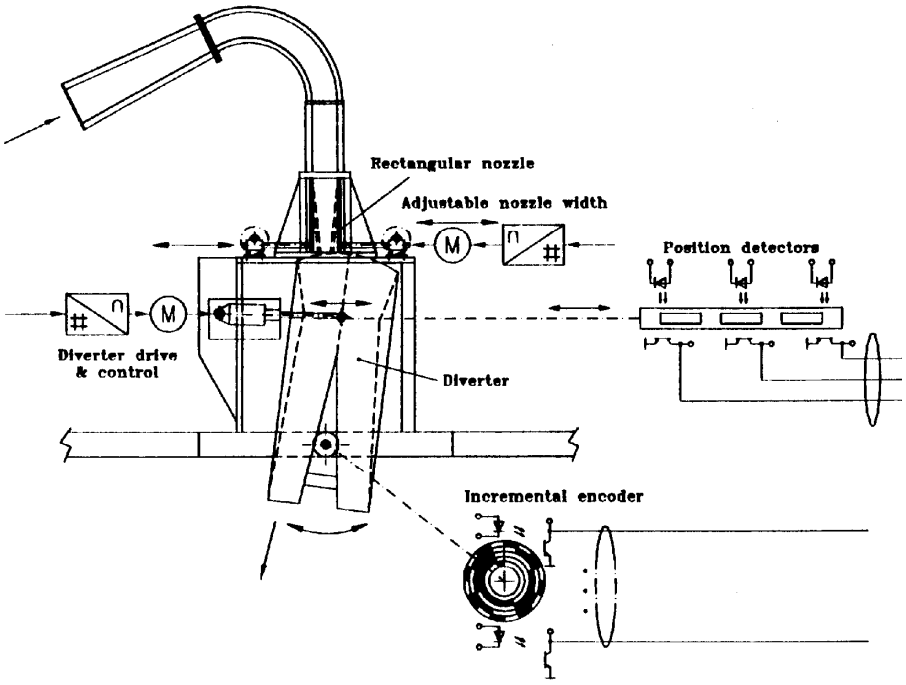


Figure 3. A "fishtail" and liquid flow diverter with adjustable nozzle width. Schematic from Poschel and Engel [4], Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany.

Measuring and correcting for timing errors introduced by the diverter is a topic of interest in the flow measurement literature. An idealized representation of the flow entering the collection tank versus time is shown in Figure 4. The idealized version applies if the flow jet has a symmetric velocity profile and the diverter moves at a constant velocity and without splashing across the liquid sheet. For this ideal diversion, starting and stopping the timer at the center of its travel across the jet will result in no diverter error, i.e. the areas of triangles A and B are equal as well as the areas of triangles C and D. Measurements of the velocity profile in the jet and of the diverter motion can be combined to give an estimate of the real shape of the flow versus time plot and subsequently the timing errors or uncertainties.[5] Methods for correcting

the collection time for diverter errors have been developed which involve collecting many short bursts of flow or making collections at the same flow but for widely varying collection times. Details of these methods can be found in the references.[2, 3]

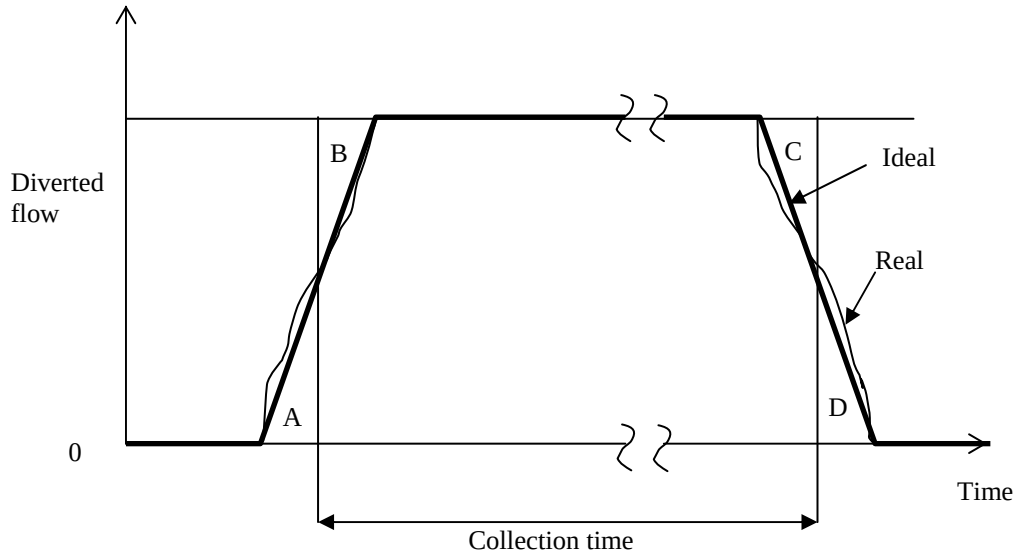


Figure 4. A representation of the flow diverted to the collection tank versus time. Departures of the real diverted flow from the ideal performance lead to flow measurement uncertainties.

Both meter users and calibration laboratories must be cognizant of flowmeter errors due to installation effects. Often a long straight run of piping upstream and downstream from the meter under test or flow conditioners are needed to provide a fully developed, symmetrical velocity profile through the meter under test. The effect of non-ideal velocity profiles on various flowmeter types has been the subject of a great deal of study and some of the results of this research are given elsewhere in this text. If the meter is tested in the laboratory under one velocity profile condition, and used in the meter application in a completely different velocity profile, the laboratory calibration may be of little value for predicting performance in the application. Therefore, the meter user should be cognizant of the piping and resulting profile differences between the two locations. The calibration laboratory should provide customers with actual velocity profile data at the test section or at least a complete description of the piping arrangement approaching and exiting the meter under test. It is important that the flow control valve not distort the velocity profile at the test section. For this reason, a designer should locate the flow control valve downstream from the meter under test or use a variable speed pump to reduce installation effects on the meter. It is also important that there be no vapor or air pockets in the test section piping due to their adverse impact on flowmeter performance.

Common components of uncertainty for a static gravimetric flow standard include: the weigh scale (calibration and resolution), the buoyancy correction to the mass measurements, the timer, the timing of the diverter, evaporation or splashing out of the collection tank or gas content of the liquid, the uncertainty due to storage effects in the inventory volume, fluid property measurements, the velocity profile at the meter under test, and the repeatability of the flow measurements. If volumetric flow is the quantity of interest, the uncertainty of the collected liquid temperature measurement and the density calculations must also be included. It should be noted that static gravimetric flow standards (and most other primary flow standards) give the average flow over the collection time, not instantaneous flows. Hence data from the meter under test must be averaged over the same time period as the collection otherwise, variations in the flow during the test can lead to calibration uncertainties. Uncertainty analyses for various implementations of this type flow standard give uncertainties from 0.01% to 0.1%. The uncertainty components listed above pertain to the measurement of flow by the standard. However, there will be other uncertainties related to acquiring the output from the meter under test that must be included in an uncertainty analysis of the flowmeter calibration. For instance, if one were calibrating an orifice plate, a differential pressure sensor is required, and hence the uncertainty of that pressure sensor needs to be considered when estimating the total uncertainty of the orifice plate.

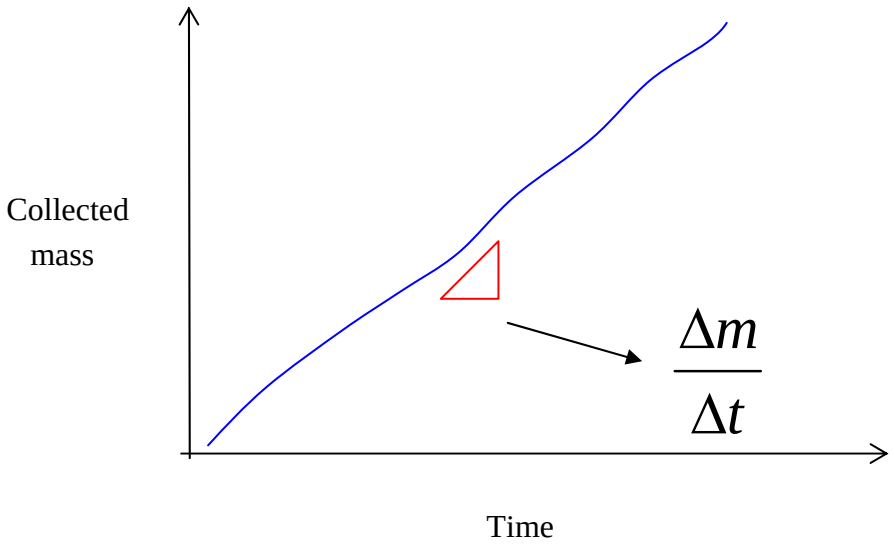


Figure 5. A rate of rise flow standard gathers mass versus time data and calculates the slope to obtain the flow.

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*Dynamic Gravimetric Liquid Flow Standards*

Another type of flow standard that uses similar equipment can be classified as a *dynamic gravimetric* system. In a dynamic system, continuous mass measurements of the collection tank are gathered as it is filled. In one implementation, known as a *rate of rise* system, time-stamped mass readings are gathered continuously. A numerically calculated slope of the liquid mass in the collection tank gives the mass flow during filling (see Figure 5). The method can suffer from waves in the collection vessel and impact forces caused by the incoming flow which may lead to unacceptable mass measurement uncertainties. For this reason, liquid rate of rise flow standards are normally used for the measurement of small flows (less than 10 g/min). Alternatively, one may choose to observe the *rate of fall* of mass in a tank that is the flow source. An important advantage of the dynamic gravimetric system is that a fast acting and well characterized diverter valve is not necessary since the collection of flow data does not need to coincide with the actuation of the diverter valve.

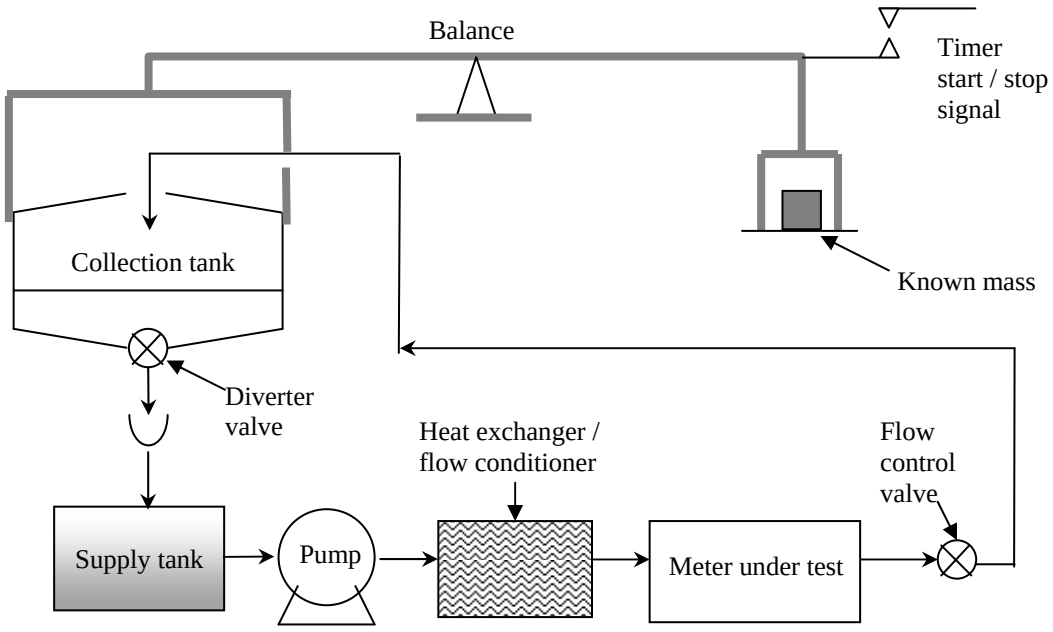


Figure 6. Schematic diagram of a dynamic gravimetric flow standard for liquid flow which uses a beam balance.

In another version of the dynamic gravimetric standard, the start and stop times are acquired when the mass indicates certain lower and upper values. A particular version of this system is shown schematically in Figure 6. Referring to the schematic, flow is pumped from a supply

tank, through flow controls, flow conditioners, the meter under test, and finally into a collection tank. Initially, the collection tank drain is left open so that flow returns to the supply tank from which the pump draws liquid. The collection tank is supported by one side of a beam balance and is not connected to the piping at the tank inlet or drain. To initiate a flow measurement, a certain lower mass value is placed on the opposite side of the balance from the tank and the drain valve is closed. When the mass of the tank and collected liquid causes the beam balance to tip, a start trigger signal generated by an electrical contact on the balance initiates timing. While the tank is filling, a certain upper mass value is placed on the opposite side of the beam balance. When the tank and contents attain the upper mass value and tip the weigh scale, a second trigger signal stops the timing. Uncertainty components related to the beam ratio and the action of the beam on the knife edge must be considered in this system. Also at issue in the uncertainty of the dynamic gravimetric standard are: 1) differences in the impact force of the falling liquid between the start and stop conditions, 2) extra liquid in the collection due to the rising level relative to the falling column, 3) the effects of waves in the collection tank, and 4) changes in the actuation time of the balance due to differences in mass between the start and stop conditions.[3, 6] An analysis of this system gives a flow uncertainty on the order of 0.10%.

*Volumetric* versions of the static and dynamic liquid flow standards are also possible. In these systems, a level sensor is utilized instead of a weigh scale to determine the mass of liquid collected. The level of liquid is measured and a predetermined relationship between the liquid level in the tank and the liquid volume allows one to calculate the volume of liquid collected. The temperature of the collected liquid is used to calculate its density, and the product of density and collected volume gives the mass of liquid collected, $m_T$. The volumetric standards will have an additional uncertainty component due to the effects of tank temperature on the level to volume relationship.

*Piston Displacement Provers*

A particular version of the dynamic volumetric flow standard called a piston displacement prover is shown schematically in Figure 7. In this system flow is pumped through flow controls and conditioners, the meter under test, and into a cylinder fitted with a sealed piston. The displacement of the piston along the cylinder is measured with a linear encoder that outputs a pulse for each small increment of piston position. In the piston displacement prover shown in Figure 7, a pair of three way valves is utilized to switch flow through the piston in alternating directions so that the piston is continuously travelling back and forth through the cylinder and

giving a flow measurement for each pass. One way versions of the system are also common (see below). For the piston displacement prover, multiplying the piston velocity by the liquid density, and the cylinder cross sectional area gives the mass flow. Some piston displacement provers are designed to be portable, enabling their use for field calibration.

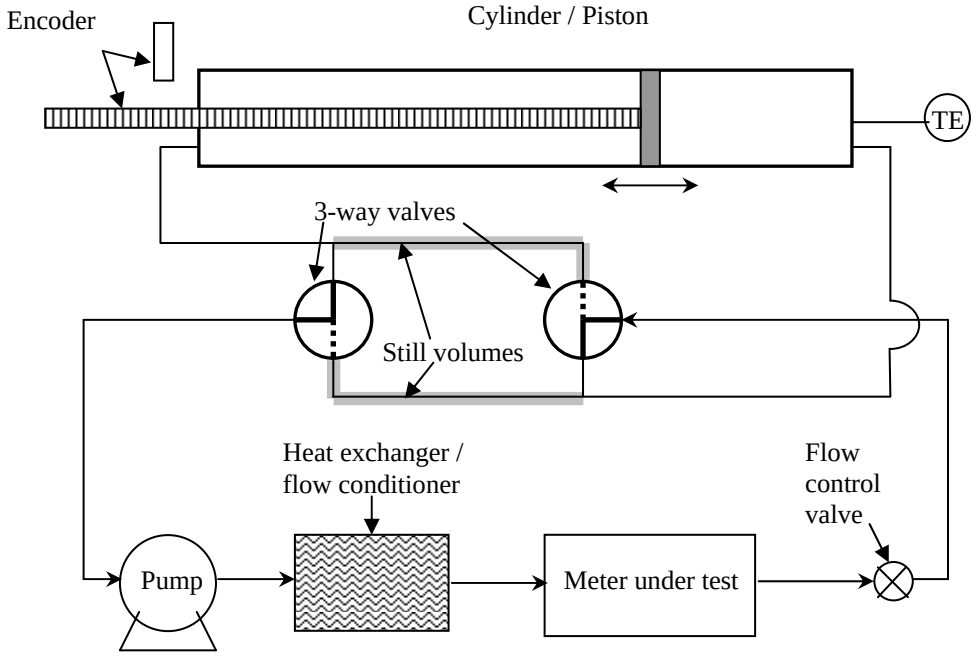


Figure 7. A schematic diagram of a piston displacement prover that uses two three-way valves to switch the direction of travel of the piston and measure flow in either direction.

There are two commonly used methods for obtaining the relationship between the position of the piston and the volume of liquid in the cylinder. One uses dimensional measurements of the cylinder diameter and calibrates the linear encoders (e.g., using a laser interferometer). The "water draw" method fills a separate collection vessel from the piston displacement prover. The number of pulses from the encoder is counted, and the quantity of collected liquid is measured by weighing or with a precisely calibrated volume. Care must be taken that thermal equilibrium is achieved during these tests so that storage effects are insignificant. Uncertainty analyses for the piston displacement prover are available, and uncertainties of 0.1% or better are attainable.[7]

Another version of the piston displacement prover uses a bypass valve to direct flow around the cylinder and piston assembly while the piston is returning to the end of the cylinder for a new collection (see Figure 8). Some piston displacement systems do not use a pump per se, but use a driven piston to pump the liquid through the meter under test.

Transients in the flow and pressure are a concern in all of the piston displacement provers. Operating the valves to direct flow into the cylinder or to alternate the direction of piston travel can cause abrupt pressure or flow spikes, and careful tuning of the mechanical systems is needed to minimize these effects and reduce their contribution to the uncertainty of the prover measurements and the flowmeter output. For the same reason, it is important to make the flow measurements over a range of piston positions well away from the travel endpoints so that the piston has reached a steady state velocity and pressure fluctuations are minimized. Another cause for concern in the prover system with two three-way valves is the two still volumes shown in Figure 7. Depending on the direction of piston travel, these two volumes alternately hold stationary liquid. Temperature differences between the room and the liquid in the still volumes can lead to temperature variations and uncertainties in the flow standard. It is also critical that checks for leaks past valves and the piston seals be routinely performed.

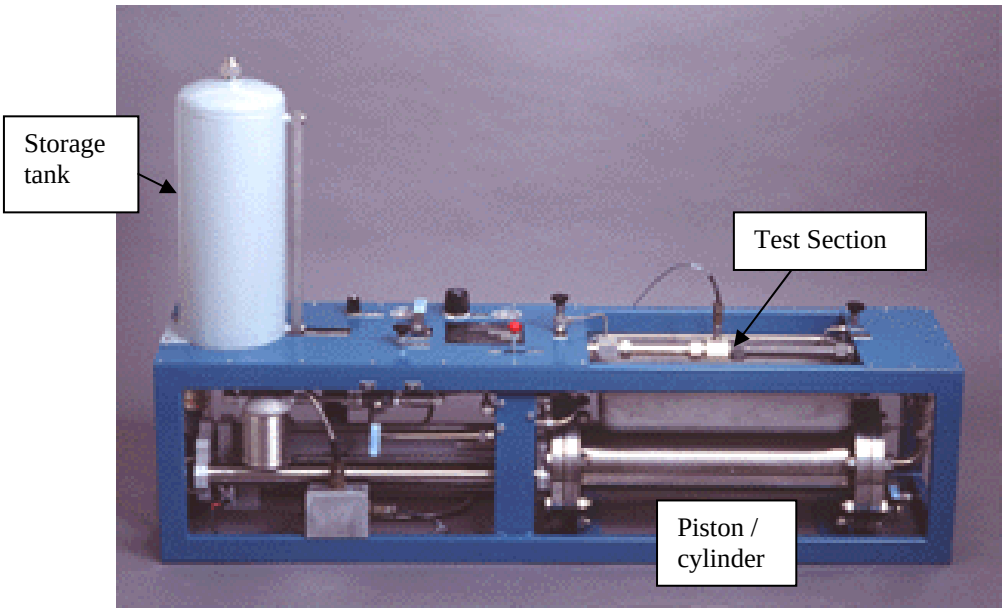


Figure 8. A piston displacement prover is one version of the dynamic volumetric liquid flow standard. Photo courtesy of Flow Technology Inc.

### *Gas Flow Standards*

Primary standards for gas flow measurements are largely equivalent in principle to those used to measure liquid flows. But certain inherent aspects make gas flows more difficult to meter and hence gas flow standards generally have larger uncertainties than liquid flow standards. For instance, due to their compressibility, both temperature and pressure measurements are necessary to determine the gas density. The equations of state for gases have greater

uncertainty than those for liquids: while the density of water is known to within a few parts per million, the density of dry air is known at about 100 PPM uncertainty. It is much more difficult to detect and find a gas leak than it is to find a liquid leak in a calibration system (gas leaks don't make puddles!). Gas cannot be collected in an open bucket, so the design of diverter valves and collection vessels is quite different. The mass of gas collected in a vessel is generally quite small compared to the mass of the vessel due to the low density of gas. Hence the resolution of the weigh scale in a gravimetric system becomes a much more significant issue for a gas standard than it is for a liquid flow standard.

In the following sections, the principles of the commonly used gas flow standards will be discussed following the same categories used previously for liquid flow standards: gravimetric, volumetric, static, and dynamic.

## Constant Pressure Gas Flow Standards

Constant pressure gas flow standards share the feature that the collection volume has a boundary that moves as the flow accumulates in (or is forced out of) the standard. These moving boundaries are designed to have low friction seals that cause only small pressure variations during the flow collection.

### *Piston Provers*

One of the oldest and most commonly used techniques for gas flow measurement is the piston prover. A piston prover (Figures 9 and 10) consists of a precision bore glass tube which contains a plastic piston slightly smaller in diameter.[8] A horizontal groove around the piston retains mercury that forms a low friction seal between the piston and the tube. A bypass valve is closed to initiate the collection of gas in the glass cylinder. As the piston rises by virtue of the small excess pressure (0.5 kPa) of the gas introduced at the bottom of the tube, it successively starts and stops a timer by blocking a pair of light beams, each beam passing through machined slits at the extremes of the measuring volume. Other sensor types can be used to initiate and stop the collection timer such as proximity switches. The volumetric flow is calculated by dividing the previously determined volume of the cylinder between the start and stop positions by the collection time. The temperature and pressure of the gas entering the collection volume are measured and used to calculate the density of the collected gas. The density is used to convert

the measured volumetric flow rate into a mass flow rate or to a volumetric flow at some reference temperature and pressure conditions. The piston prover is a dynamic volumetric flow standard because the fluid collection is initiated and terminated by the moving piston as it passes through a start and stop sensor used for timing purposes.

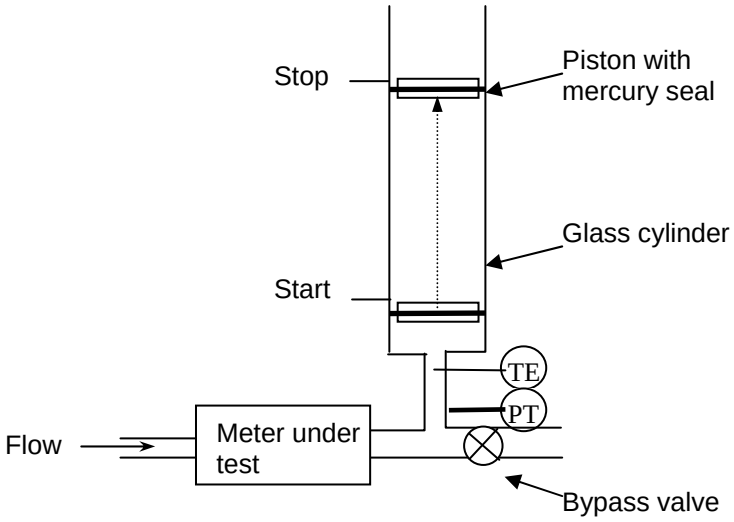


Figure 9. Schematic of a mercury sealed piston prover. The symbols TE and PT represent temperature and pressure sensors respectively.

Several variations on the piston prover technique are possible. There are versions of the piston prover which do not use a mercury seal, but simply have a close fitting graphite piston in the collection cylinder and accept a small leakage flow past the piston as a source of flow measurement uncertainty. Another version of the piston prover utilizes a continuous piston position measuring sensor (for instance a laser interferometer, an ultrasonic sensor, or a linear encoder) so that the velocity of the piston as it travels up the tube can be determined. This design is equivalent to the piston displacement prover for liquids described previously.[9] Some versions of this prover have a piston driven by a servo motor, and the motor speed is controlled based on a pressure measurement in the collection volume. [10]

The bubble meter is a low cost, but higher uncertainty alternative to the mercury sealed piston prover. In a bubble meter, a squeeze bulb is used to raise the level of a soap solution and generate a soap bubble at the bottom of a collection cylinder. The metered gas flow then pushes the soap bubble up the cylinder. The time to travel from a start to a stop position is generally measured by eye using a stopwatch, but some automatically timed versions have been developed.

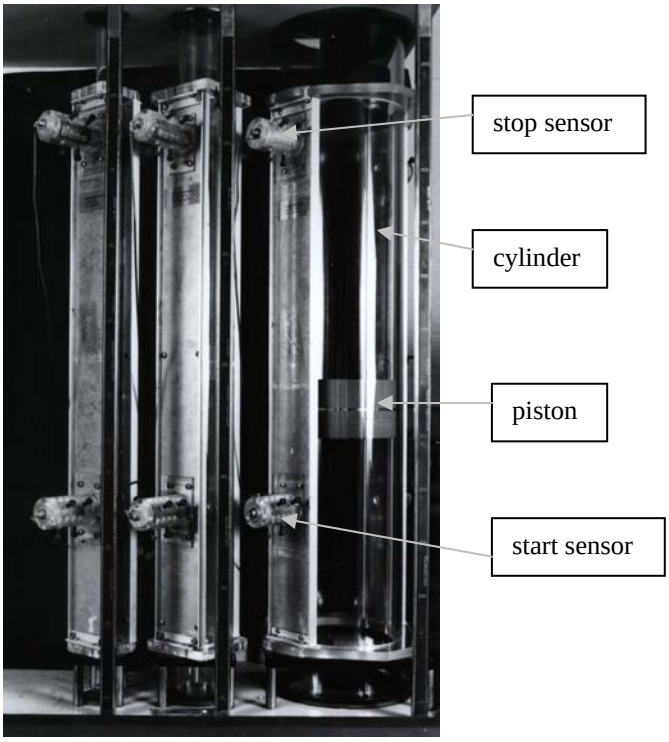


Figure 10. A set of three mercury sealed piston provers. The largest glass tube has the piston elevated and the mercury seal is visible.

Mass flow measurements made with a piston prover are subject to uncertainties in the determination of the gas density, collection volume, collection time, and other quantities.[8] A detailed list of uncertainty components and their magnitudes for a particular piston prover is given in Table 1. Regarding the uncertainty of the density of the gas in the collection volume, there are uncertainties in the measurement of the gas temperature due to instrument calibration, instrument drift over time, and due to temperature "sampling". The temperature sampling sub-component is due to the fact that the desired temperature is the average temperature of the gas in the full collection volume, but the temperature measured is generally the temperature of the gas flowing across a sensor in the piping leading to the glass cylinder. Differences between the temperature of the gas as it enters the glass cylinder and the temperature of the glass walls lead to a component of temperature measurement uncertainties. For many gas flowmeter tests, gas is expanded through a regulator, and sometimes it is expanded again through the meter under test. These expansions lead to temperature changes in the gas, hence it is common for there to be

significant differences between the gas temperature and the temperature of the piston prover glass walls. Some piston prover users utilize heat exchangers to keep the gas temperature close to room temperature and reduce these sampling uncertainty components. Also, as was the case for liquid flow standards, keeping the inventory volume to a minimum is desirable to reduce storage effects.

Pressure measurement uncertainties are due to calibration and sampling concerns (i.e. uncertainties caused by flow over the pressure tap or the location of the pressure tap being displaced from the glass cylinder). The mathematical expressions used to calculate the gas density from the temperature and pressure have uncertainties related to the quality of the mathematical fitting function and to the quality of the experimental data that is the basis of the fit.

Table 1. Summary of uncertainties for a piston prover operated by the NIST Fluid Flow Group in Gaithersburg, Md. The uncertainties are relative standard uncertainties (i.e. 67% level of confidence values). The italicized values are root-sum-squared totals of the indented sub-components.

| **Uncertainty Category** | **Uncertainty (%)** |
|---|---|
| *Gas Density* | ***0.053*** |
| Temperature | 0.037 |
| Pressure | 0.022 |
| Fitting Function | 0.029 |
| Experimental Data | 0.012 |
| *Collection Volume* | ***0.011*** |
| Cylinder Diameter | 0.009 |
| Collection Length | 0.001 |
| Thermal Expansion | 0.006 |
| *Collection Time* | ***0.058*** |
| Timer Calibration | 0.001 |
| Timer Actuation | 0.057 |
| Piston Rocking | 0.012 |
| *Leakage and Vapor Pressure* | ***0.010*** |
| *Storage Effects* | ***0.007*** |
| Combined Relative Standard Uncertainty | ***0.080*** |
| Expanded Relative Uncertainty (95% level of confidence) | ***0.160*** |

Generally, the volume of gas collected between the start and stop sensors is determined by making dimensional measurements of the glass tube inside diameter (at many locations along the cylinder length) as well as measurements of the length between the start and stop switches. There are uncertainties associated with both of these dimensional measurements which must be considered in the uncertainty analysis. The effects of temperature variations on the volume due to thermal expansion must be considered as well. Uncertainties in the measurement of the collection time can be categorized as timer calibration, timer actuation, and piston rocking. The sensors used for timer actuation do not start and stop the timer perfectly when the piston is at the ends of the collection volume. In addition, the piston can rock slightly within the cylinder and this is a source of uncertainty which can be considered a timing or volume uncertainty.

Uncertainties due to gas leaks between the meter under test and the piston must be considered. It is important that routine leak checks be performed to confirm that no significant leaks are present in the system. This can be done by raising the piston and holding it in the raised position by closing a valve upstream from the meter under test. The initial position of the piston is recorded, and over a period of hours, any movement of the piston is observed. Changes in the temperature and pressure of the gas trapped in the system cause gas density changes and may cause the piston to move even in the absence of leaks. To account for these effects, pressure and temperature measurements must be made at the beginning and end of the leak test. Then the following formula can be used to calculate the mass flow from any leaks:

$$W_{leak} = \frac{(\rho_1 - \rho_2)\cdot V_1 - \rho_2 \cdot \Delta V}{\Delta t}, \qquad (3)$$

where $\rho$ is gas density, $V$ is the trapped volume of the system, $\Delta V$ is the change in volume calculated from the piston position change ($V_2 - V_1$), $\Delta t$ is the length of time the leak test was conducted, and the subscripts 1 and 2 refer to initial and final values respectively. The first term of the numerator accounts for the effects of density changes in the gas. If the pressure and temperature conditions change insignificantly between the beginning and end of the leak test, the density change term will be negligible and the leak test is greatly simplified. This is because it is often fairly difficult to calculate a good value for the entire trapped volume, $V_1$, but easy to obtain $\Delta V$ since the cylinder dimensions and piston position change are readily available.

Another source of uncertainty for the piston prover is the vapor pressure of mercury or any other liquids that may be present in the flow standard. If there is any liquid in the flow standard, it will

evaporate and flow along with the metered gas to the collection volume. This is gas that has not passed through the meter under test, but does reach the collection volume and it is equivalent to a leak into the flow standard. The vapor pressure of mercury at room conditions is so small as to be negligible, but for the bubble meter and bell prover (covered in a subsequent section), the sealant vapor pressure must not be neglected. For the bubble meter, if a dry gas flow is being measured, the gas stream will pick up vapor as it passes over the soap solution at the bottom of the collection cylinder and over the solution coating the walls of the cylinder. Assuming it is a water based soap solution, a gas mixture saturated with water vapor at 23 ºC contains 2.7% water vapor by volume. Hence there is as much as 2.7% uncertainty in the flow measurement depending on the efficiency of the mass transfer from the liquid to the gas. Often it is assumed that the gas attains 50% relative humidity and thereby the uncertainty due to the sealant vapor pressure is reduced to half of the 2.7% figure. This level of uncertainty is sometimes deemed acceptable because normally the uncertainties in the bubble meter volume, the hand-measured collection time, and in the gas density are fairly large as well.

Another version of the piston prover, analogous to the piston displacement prover described in the liquid flow standards section, has been applied in gas as well. These piston provers are often designed to be transportable on a truck and are used to field check flow meter calibration in high pressure natural gas applications. Uncertainties ranging from 0.13% to 0.35% have been reported in the literature.[11]

*Bell Provers*

The bell prover system is based on the same principles described for the piston prover. The bell prover (Figure 11 and 12) consists of a cylindrical tank open at the top and a central “dry well”, which together form an annulus that is nearly filled with sealing oil. Into this annulus is placed an inverted cylindrical tank, i.e., the bell, open at the bottom and having a dome-shaped top. Its weight is nearly balanced by counterweights so that it can be raised or lowered by a small differential pressure (<1 kPa) to collect and measure a volume of gas. A smaller counterweight is mounted on a cam so that it provides a correction for buoyancy effects as the bell immersion in the sealing liquid changes. Rollers and guide rods provide lateral stability in the bell position as it moves upwards. Once flow conditions through the meter under test are deemed stable, a bypass valve is closed thereby directing gas into the bell. The volume of gas held within the bell between a start elevation and a stop elevation is carefully measured a priori.

During a flow calibration, the time required for the bell to travel between the start and stop positions is measured. The collection volume of the bell prover is divided by the collection time to obtain a volumetric flow. The mass flow or the standard volumetric flow can be calculated based on the temperature and pressure of the collected gas. The sealing liquid is generally low vapor pressure oil. Water has also been used, but this is an undesirable sealant because of its high vapor pressure and the resulting measurement uncertainties as discussed in connection with the bubble meter. Uncertainty analyses of flow measurements made with a bell prover fall within 0.06% to 0.20%.

Bell provers were first manufactured in the early 1900's, and they were originally used to check the gas volume measurements made with natural gas billing meters. The bell was raised to an initial position and then allowed to drop, discharging gas through a positive displacement gas meter. A length scale on the bell allowed the operator to count the number of cubic feet of gas discharged, and this was compared to the cubic feet of gas registered by the meter under test. Hence the bell prover was used to check or calibrate the volume registered by the gas meter and the time it took the bell to displace the volume (i.e. the flow) was not the quantity of interest. Now it is much more common to operate the bell prover as a flow measuring device rather than a volume measuring device.

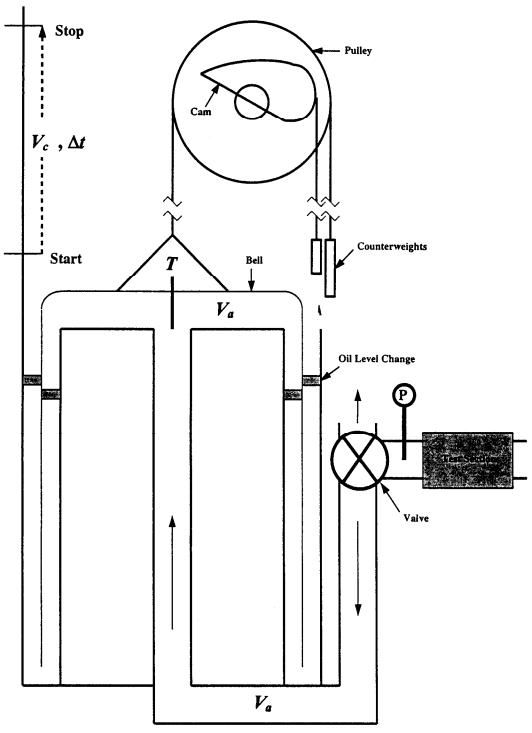


Figure 11. Schematic of a bell prover.

Measurement of the collection volume of a bell prover is greatly complicated by the fact that the liquid sealant level moves during bell usage for a variety of reasons. The slightly elevated internal pressure of the bell (needed for it to rise during a collection) causes the oil level to be lower inside the bell than outside. As the bell rises out of the oil during a gas collection, the metal walls of the bell displace less of the oil, and consequently the oil level falls. Also, oil adheres to the inner and outer surfaces of the bell as the bell rises, lowering the level of oil in the tank.[12] Using low viscosity oil minimizes this oil adherence effect. Closing the bypass valve causes pressure changes within the bell and leads to an oscillatory motion between the inner and outer bell oil surfaces. It is important that these oscillations fully decay before the timing start point of the bell travel is reached.[13] In addition, the bell should be well counterbalanced and travel smoothly so that pressure fluctuations within the bell during a collection are negligible. Significant pressure fluctuations lead to changes in the level of the sealing liquid and cause uncertainties in the bell collection volume.

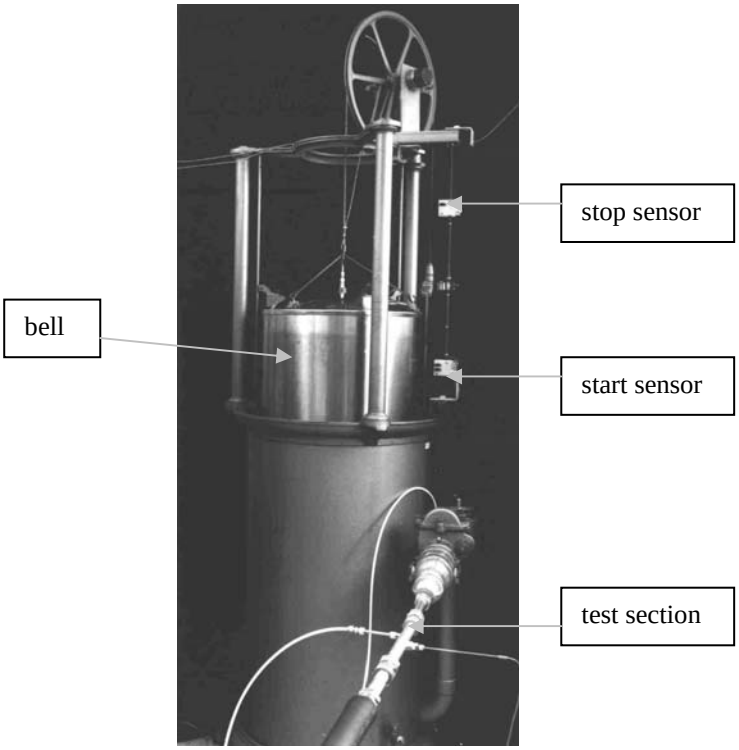


Figure 12. A partially elevated bell prover with a meter under test.

Various methods are documented in the flow literature for determining the collection volume of a bell prover.[8, 14, 15] In the “bottling” procedure, a volume standard is repeatedly discharged into the bell collection volume until it is filled, and the volume is totaled. Typically the volume standard is an immersion type cubic foot bottle or a Stillman cubic foot standard. Bottling has

the disadvantage of errors caused by gas density changes (due to temperature differences) between the volume standard and the bell prover during the gas transfer. It is generally accepted that the "strapping" procedure delivers a collection volume value with lower uncertainty. In this method, measurements of the outside diameter of the bell are made at many elevations. Measurements of the volume occupied by the metal bell walls and any length scales attached to the bell walls are made. Also, measurements of changes in the oil level due to adherence of the oil to the bell walls are gathered. The degree of ellipticity of the bell must be assessed for the volume uncertainty analysis. Geometrical treatment of the dimensional measurements yields the collection volume.[8] The uncertainty categories of a bell prover flow standard are largely the same as those given for the piston prover, with additional components related to the collection volume, such as oil film adherance.[8]

*Liquid Displacement Method*

The apparatus necessary for implementing the liquid displacement method is a sealed tank filled with a low vapor pressure liquid (usually mineral oil) plus a liquid gravimetric flow standard. During operation of the standard, gas flows through the meter under test to the oil filled tank. The incoming gas displaces oil from the tank and pushes it through a pipe to the gravimetric flow standard. A measurement of the liquid mass flow, as well as temperature and pressure measurements made at appropriate locations in the system, permits calculation of the gas flow at the test section. The liquid displacement method takes advantage of the relative simplicity of a liquid diverter valve as compared to a gas diverter. Also the greater density of a liquid relative to a gas makes the gravimetric liquid flow measurement low in uncertainty.

Many of the uncertainties in the liquid displacement method have been discussed previously in the section about gravimetric liquid flow standards. Extra uncertainty components arise related to the measurements of temperature and pressure throughout the system. For instance, it is necessary to obtain a good average temperature for the gas accumulating in the tank, but the presence of temperature gradients within the tank and the rest of the system may complicate that effort and lead to uncertainties due to storage effects. One analysis for a flowmeter calibration using a liquid displacement flow standard gave an uncertainty of 0.06%.[16]

**Constant Volume Gas Flow Standards**

The flow standards described in the following sections share the common characteristic that they use a tank of carefully measured and essentially constant volume to accumulate the gas flow being measured.

*Pressure-Volume-Temperature-time*

Pressure-Volume-Temperature-time (PVTt) systems have been used as primary gas flow standards by national laboratories for more than 30 years.[17, 18] A PVTt system generally consists of a flow source, valves for diverting the flow, a collection tank, a vacuum pump, various pressure and temperature sensors, and a critical flow venturi or back pressure regulator (see Figures 13 and 14). The critical flow venturi isolates the meter under test from the pressure variations in the downstream piping and tank. The critical flow venturi is necessary to maintain stable temperature and pressure conditions at the test section even though extreme pressure variations occur downstream due to the operation of the diverter valves and pressure changes as the collection tank is filled.

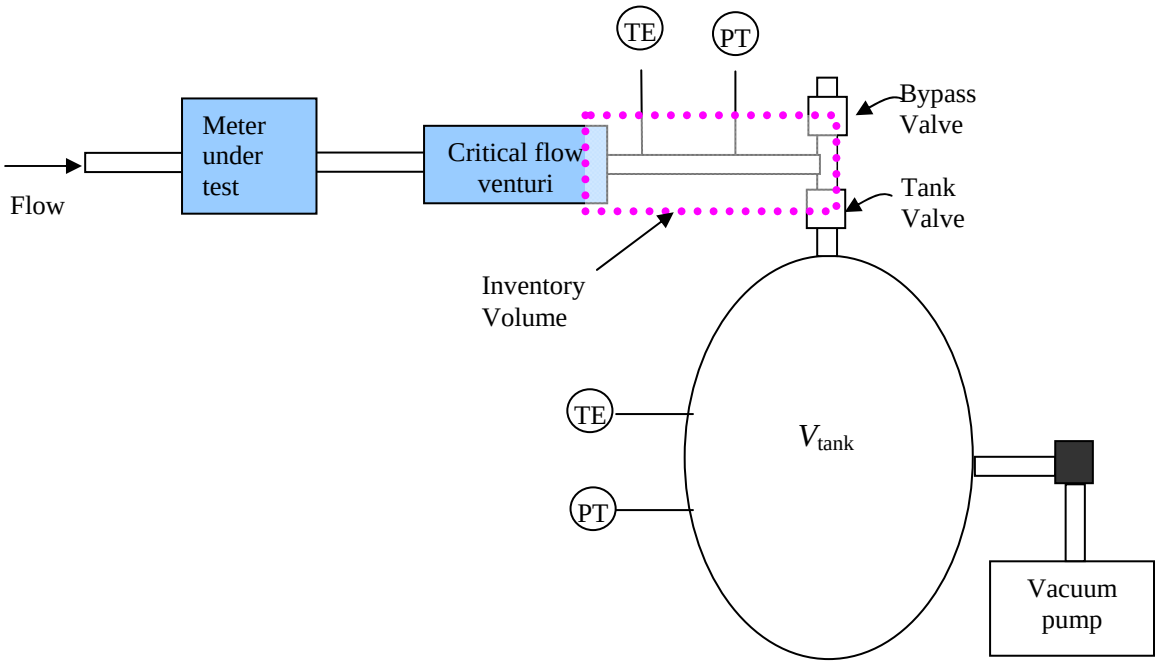


Figure 13. Arrangement of equipment in a PVTt system.

The process of making a PVTt flow measurement entails the following steps.

1) Establish a stable flow through the meter under test with flow through the bypass valve.
2) Evacuate the collection tank volume ($V_{tank}$) with the vacuum pump.

3) Wait for pressure and temperature conditions in the tank to stabilize and acquire initial values for the tank ($P_{tank1}$ and $T_{tank1}$). These values will be used to calculate the initial density and the initial mass of gas in the tank ($m_{tank1}$).
4) Close the bypass valve and obtain a start time ($t_1$). At the same time, acquire the pressure and temperature in the inventory volume ($P_{inv1}$ and $T_{inv1}$). These values will be used along with the equation of state for the gas and the inventory volume ($V_{inv}$) to obtain an initial mass in the inventory volume ($m_{inv1}$).
5) As soon as the bypass valve is fully closed, open the tank valve.
6) Wait for the tank to fill to a prescribed upper pressure, and then close the tank valve, obtain the stop time ($t_2$), and open the bypass valve. At the same time, acquire the inventory volume pressure and temperature ($P_{inv2}$ and $T_{inv2}$) and hence the final mass in the inventory.
7) Wait for stability and then acquire $P_{tank2}$ and $T_{tank2}$ and hence $m_{tank2}$. The average mass flow during the collection time can be calculated from the following equation:

$$W_{PVTt} = \frac{(m_{tank\,2} - m_{tank1}) + (m_{inv2} - m_{inv1})}{t_2 - t_1}, \tag{4}$$

or, expanding the mass calculations:

$$W_{PVTt} = \frac{(\rho_{tank2} \cdot V_{tank} - \rho_{tank1} \cdot V_{tank}) + (\rho_{inv2} \cdot V_{inv} - \rho_{inv1} \cdot V_{inv})}{t_2 - t_1}, \tag{5}$$

where $\rho$ is the gas density determined via a real gas equation of state:

$$\rho = \frac{P}{Z \cdot R \cdot T}, \tag{6}$$

where $Z$ is the compressibility (a function of temperature, pressure, and composition), and $R$ is the gas constant (universal gas constant divided by the gas molecular weight).

The process described above can be performed in a “blow down” mode also, where initial and final values of the mass in a tank that is the *source* of flow instead of the collector of flow are utilized. Such a system has the advantage that a small compressor can be used to charge a large

pressure vessel over a long period of time allowing one to achieve very large flows relatively inexpensively. The blow down method has the disadvantage that it is more difficult to maintain stable pressure and temperature conditions at the meter under test since the high-side pressure of the flow control throttling process is changing continuously as the tank discharges.

The bypass and tank valves can be operated with valve overlap, i.e. where one valve begins to open before the other is fully closed, or with zero overlap, where one is completely closed before the other begins to open (as described above).[19] With zero overlap, there is no question about lost or extra mass occurring during the diversion. For instance, if the tank is at an initial pressure less than atmospheric, when both valves are partially open, flow can enter the tank from the room instead of through the meter under test. Zero overlap avoids this possibility. For a zero overlap system it is important that any valve design be fast acting. There is a short period of time during the actuation of the diverter valves during which both valves are closed (the "dead end" time) and the mass of gas which passed through the critical venturi accumulates in the inventory volume. The mass accumulation leads to a pressure rise in the inventory volume that will depend on the mass flow, the size of the inventory volume, and the dead end time of the diverter valves. The pressure in the inventory must not be permitted to reach a high enough level that the flow at the venturi is no longer critical, lest pressure perturbations reach the meter under test and disrupt the steady state flow conditions at the meter.

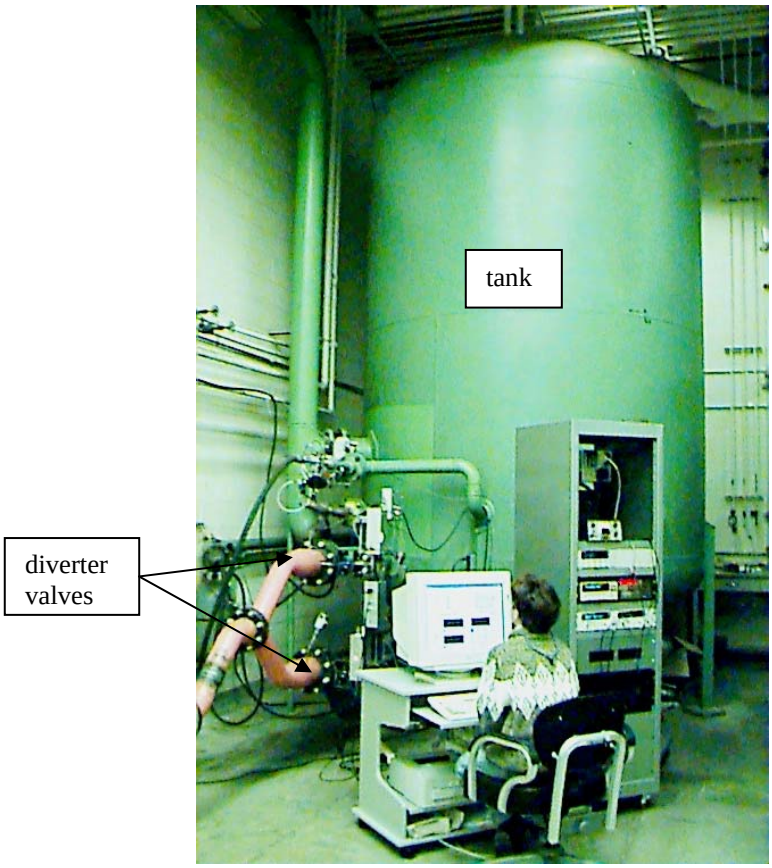


Figure 14. A PVTt flow standard for flows up to 80,000 liters/min located at NIST, Gaithersburg, MD.

For a zero overlap diverter, the time at which the bypass valve first reaches the fully closed position is the time after which all of the mass flowing through the meter under test remains in the system defined by the inventory and tank volumes. Prior to this instant, some of the flow is still exiting the inventory volume via the bypass valve. Actually, any time during the start dead end interval could be used as the start time as long as the initial inventory pressure and temperature values are read at the same time as that used for $t_1$. The time at which the bypass valve first reaches the fully closed position is convenient since a trigger signal is available. At the completion of a collection, as before, any time during the stop dead end period is acceptable, but the time that the tank valve first reaches fully closed is often chosen for convenience.

Obtaining accurate measurements of the inventory temperature and pressure can be difficult and high time resolution instruments may be required to reduce “sampling uncertainties” and reach acceptable flow measurement uncertainties. As the bypass valve closes, pressure will begin to rise in the inventory volume and flow work will cause the temperature of the gas in the

inventory volume to rise. The work necessary to push additional gas into an already pressurized volume, i.e., work associated with the pressure at the inlet or outlet of a control volume, is called flow work. It is the product of the mass flow, pressure, and specific volume of the gas.[20] If the inventory volume is small and the flow is large, the temperature and pressure changes caused by flow work can be quite rapid and dramatic. To measure accurate values for the initial and final masses of gas in the inventory volume, fast temperature and pressure sensors are necessary. Slower sensors are acceptable in the collection volume since it is common to wait thirty minutes or more for temperature conditions in the tank to equilibrate. The inventory volume will also accept the discharge from a critical flow venturi, and therefore will contain a flow jet with shocks and corresponding spatial variations in temperature and pressure. Therefore, obtaining an accurate average for the inventory temperature and pressure is not trivial and leads to another source of sampling uncertainty. The significance of these uncertainties can be greatly reduced by designing the inventory volume to be a small fraction of the collection volume (1/1000 or less).

The volume of the PVTt collection tank and of the inventory volume can be determined by dimensional measurements (for a volume of simple geometry) or by gravimetric means. In one gravimetric method, the tank is weighed empty, filled with distilled water, and weighed full. Care must be taken that no air bubbles are trapped within the tank. The temperature of the water is measured so that the water density can be calculated. The change in mass (with buoyancy corrections) along with the water density is used to calculate the volume of the tank. A similar gravimetric process can be used with gas instead of water. The tank is evacuated with a vacuum pump and initial temperature and pressure measurements are gathered so that an initial gas density in the tank is available via an accurate equation of state. A second tank with an isolation valve is filled to high pressure with pure gas and the mass of the second tank is measured. The second tank is discharged into the collection volume and after stabilizing, final temperature and pressure measurements give the final density in the collection tank. The second tank is re-weighed so that the mass of gas discharged into the collection tank is known. The collection volume can be calculated via:

$$V = \frac{m_2 - m_1}{\rho_2 - \rho_1}, \qquad (7)$$

where $V$ is the collection volume, $m$ is the mass of the second tank, $\rho$ is the gas density in the collection volume, and the subscripts 1 and 2 refer to initial and final values. The gas gravimetric method has the advantage that it can be used in complex shapes where bubbles could not be eliminated were the liquid gravimetric approach used. However, the uncertainty of pressure instrumentation enters the process, and the resolution of the weigh scale must be good since the mass of gas is generally quite small compared to the mass of the second tank.

Equations 5 and 6 are the *basis equations* for the mass flow calculation in a PVTt system and hence are the foundation for a propagation of uncertainty analysis for a PVTt flow standard.[21] Analyses of PVTt flow standards give uncertainties ranging between 0.05% and 0.25%. Uncertainty components include: the collection volume, the inventory volume, the tank pressures (both initial and final values), the tank temperatures, the inventory temperatures and pressures, the collection time, leaks, and the gas equation of state. The average temperature of the gas in the collection tank can be difficult to obtain with low uncertainty. The flow work phenomenon leads to reduced temperatures when the tank is evacuated and elevated temperatures when the tank is filled. Hence there is heat transfer to the surroundings and temperature gradients within the tank, which make gathering a good average temperature non-trivial. It is common for a fan to be placed within the tank to give mixing and speed the return of the gas temperature to equilibrium with the surroundings. At least one facility has used a water jacket to achieve greater heat transfer and speed the return to thermal equilibrium.[18] For facilities used over a large flow range, the time resolution of the sensors in the inventory volume and of the data acquisition system can be a significant source of uncertainty at high flows. As previously discussed, if the inventory conditions are changing rapidly, it becomes more important that the pressure and temperature measurements be coincident with the start and stop timing trigger signals. The inventory conditions may also have significant uncertainties caused by non-uniformity of the pressure and temperature within the inventory volume.

*Rate of Rise*

Rate of rise systems are dynamic volumetric, constant volume flow standards that utilize equipment very similar to that used in a PVTt system. Rate of rise standards are commercially available from several manufacturers. As for the liquid rate of rise systems, the principle is to collect the flow in a carefully measured volume, and continuously measure the mass of gas in

the volume as it fills. The rate of change of the mass measurements is the mass flow. For a volumetric gas rate of rise system, the mass of gas in the volume is calculated by measuring the rates of change of the average temperature and pressure of the collected gas, using the gas equation of state to convert the gas conditions to a density rate of change value, and finally multiplying the gas density rate of change by the collection volume. In equation form:

$$W_{rate\ of\ rise} = \frac{\Delta m}{\Delta t} = V \cdot \frac{\Delta \rho(P,T)}{\Delta t}. \qquad (8)$$

The mass flow can be calculated using numerical finite difference equations, or a first order least squares regression can be performed on a long record of time and mass data and the slope gives the mass flow. The advantage of the rate of rise method over the PVTt approach is that there is no need to make the difficult pressure and temperature measurements in the inventory volume during the valve switching processes. The flow can be diverted and the pressure and temperature spikes resulting from the valve changes can be allowed to settle before rate of rise data are used.

The rate of rise method is documented for very small flows in an American Vacuum Society Standard.[22] The standard points out the concern that there may be significant pressure differences between the collection tank pressure and the pressure at the pressure sensor due to the resistance of the connection between them. These differences will be most pronounced at low pressures and can be reduced by using connections that are large in diameter and short in length. The rate of rise method has been refined considerably since the time the standard was written, and recent implementations incorporate actuated valves and account for the temperature changes induced in the collected gas by flow work (i.e. they do not measure the rate of change of pressure only).

The rate of rise method is best suited for small flows since the uncertainties of the method increase unless the filling times are long (requiring a large collection volume). Since the tank is filled from a higher pressure source, flow work is performed on the gas already in the tank, causing the collected gas temperature to increase. The magnitude of the flow work is proportional to the flow of gas into the collection volume. For a small flow, the heat added to the gas can be balanced by the heat losses through the tank walls to the surroundings, and the temperature gradients within the gas are relatively small. But for large flows, the gas temperature will rise considerably, and obtaining a low uncertainty average temperature is

complicated by temperature gradients near the tank walls and where the relatively cold incoming gas jet enters the hot gas. Gas flow across the pressure taps, large scale gas motions (such as a large vortex) which set up pressure gradients, the kinetic energy (impact pressure) of the incoming jet, and differences between the pressure within the jet and rest of the tank lead to average pressure uncertainties. All of these sources of pressure uncertainty can be reduced by maintaining a small rate of change of pressure with respect to time during the filling process. Rate of rise uncertainty analyses typically fall between 0.1% and 1%.

*Dynamic Gravimetric Gas Flow Standards*

The rate of rise method can be implemented using a weigh scale to measure the change of mass of the collection volume.[23, 24] The inclusion of a scale eliminates the need for pressure and temperature measurements in the collection volume to calculate density, the need for an equation of state for the gas, as well as the need to accurately determine the volume of the collection tank. Such dynamic gravimetric gas flow standards generally operate in a blow down mode as shown in Figure 15. To operate the flow standard, the gas cylinder is filled and flow is established through the meter under test by adjusting the set point on a pressure regulator. Continuous time-stamped measurements of mass (buoyancy corrected) are gathered. The time rate of change of these mass measurements is calculated numerically to obtain the mass flow.

A limitation common to all gravimetric gas flow standards is the resolution of the weigh scale. The mass of the pressure vessel is large compared to the mass of gas used during the course of a flow measurement. Hence it is necessary to discern small changes of mass using a scale with a relatively large full scale capacity. Fortunately weigh scales are available with resolutions better than one part per million. But for very low flows, long test times may be necessary to obtain adequate gas mass changes. At very large flows, the time resolution of the scale output may become a problem. Another source of uncertainty in the dynamic gravimetric standard is the connecting tube between the gas cylinder and the meter under test. This tube is generally a pig tail shape or some otherwise flexible connection so that it imparts negligible forces to the gas cylinder which would cause false indications of mass change. It is useful to have the pressure regulation upstream from the connecting tube so that the tube does not experience changes in pressure and any Bourdon tube type stresses. Also, the availability of zero displacement type weigh scales, in which the pan is maintained in the same position despite changes in the mass placed on it, minimizes the changes in force from the connecting tube. A protective cover eliminates mass errors due to air flow from room ventilation systems. But

discharging gas from the cylinder will cause temperature changes in the cylinder and will set up convection currents along the cylinder exterior. These air currents will lead to mass uncertainties. Uncertainties reported for the dynamic gravimetric method range from 0.13% to 0.60%.[25]

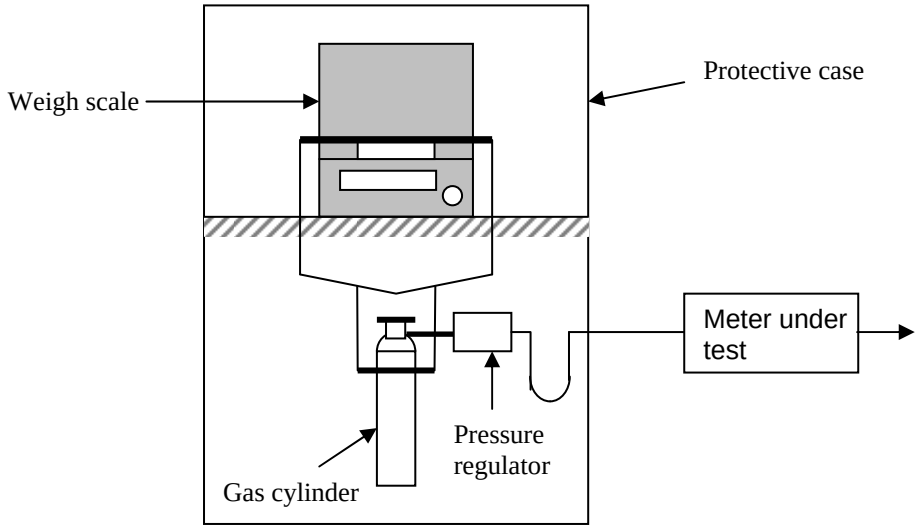


Figure 15. Schematic of a dynamic gravimetric gas flow standard.

*Static Gravimetric Flow Standards*

Among high quality gas flow laboratories, the most widely implemented approach is the static gravimetric method. This method is similar to the PVTt method in equipment and in operation, but initial and final gas mass determinations are made by placing the collection vessel on a weigh scale rather than by calculating density from pressure, temperature, tank volume, and the gas equation of state. Although it is fairly time consuming to obtain each flow measurement, and is not so easily automated, the static gravimetric method is widely used due to its potential for low uncertainties. The basis equation for flow calculation is:

$$W_{grav} = \frac{\left(m_{\text{tank2}} - m_{\text{tank1}}\right) + \left(\rho_{\text{inv2}} \cdot V_{\text{inv}} - \rho_{\text{inv1}} \cdot V_{\text{inv}}\right)}{t_2 - t_1}, \qquad (9)$$

where the variables are the same as those previously defined. The potential for lower uncertainty arises because uncertainties in the tank pressure, tank temperature, tank volume, and the gas equation of state are replaced by the uncertainty of the tank mass measurement. In a

case where there is a diverter valve and a separate tank isolation valve so that the tank can be disconnected and weighed, there will be two inventory volumes which must be treated separately, each with their own pressure and temperature measurements. A corresponding extra term in the numerator of Equation 9 then is necessary since the initial densities in the two inventory volumes will differ. The tank mass measurements must be buoyancy corrected, hence temperature, pressure, and humidity measurements in the environment housing the collection tank and an equation of state for the room air are necessary. Also, if significant changes in the external tank volume occur due to changes in the internal pressure, these volume changes are needed for the buoyancy correction. Depending on the procedure used to calibrate the weigh scale, corrections to the tank mass measurements for the local value of the gravitational constant may be required. Pressure and temperature measurements from the inventory volume are still required (to obtain density) and uncertainties related to the inventory volume and collection time are the same as those discussed for the PVTt method.

As for the dynamic gravimetric method, the weigh scale resolution is often a technical challenge for the static gravimetric method. The problem arises because a heavy pressure vessel is used to collect a small mass of gas. A weigh scale that has a large enough full scale capacity for the heavy tank may have difficulty measuring the small mass of gas collected. Ever improving scale performance has helped drive down this source of uncertainty. However at low flows, it may be necessary to collect gas for hours or even days to obtain a large enough mass of gas for the scale to measure well. One approach to this difficulty is to set up a tare weight on a two-pan balance, i.e. counterbalance the collection tank with a similar empty tank.[26] Another approach is to immerse the collection tank in liquid, so that the buoyancy forces imposed by the liquid counterbalance the mass of the vessel to give a small apparent mass and allow the usage of a scale with a small range and high resolution.[27, 28] Unfortunately, convection currents in the suspending liquid can exert forces on the collection tank and lead to repeatability problems and measurement uncertainty. The same concern applies to a lesser extent for systems that measure the mass in air. Evacuation cools the tank walls and filling heats the tank. Hence significant temperature differences exist between the tank and the room air at certain times in the calibration. Upward or downward convection currents along the exterior of the tank can cause significant mass measurement errors, and it becomes necessary to measure the mass in a vacuum chamber or wait for thermal equilibrium between the tank and the room.

Published uncertainty analyses for static gravimetric flow standards give uncertainties ranging from less than 0.01% to 0.25%.[11, 24, 29, 30, 31] The uncertainty components of a static gravimetric flow standard can be broken into three major components: mass uncertainty, time uncertainty, and inventory volume uncertainty. Uncertainties in the *mass measurement* include the weigh scale calibration uncertainties (including uncertainty of the reference mass values, local gravitational constant value, scale linearity, and reproducibility), uncertainty of the buoyancy corrections to the mass measurement (due to uncertainties in the tank displacement volume, in room temperature, pressure, humidity, and in the room gas equation of state), and uncertainties in the mass measurements caused by electromagnetic forces or forces imposed by flow over the exterior of the collection vessel. Uncertainties in the *time measurement* include the timer calibration uncertainties as well as uncertainties related to the triggering of the timer and the synchronization of the triggering with the actual closure of valves. Finally the uncertainty in the mass change in the *inventory volume(s)* must be considered. This category includes the uncertainty in the volumes used, in the measurement of temperature and pressure within these volumes, and uncertainty due to the equation of state used to calculate density. Uncertainties caused by leaks must not be overlooked. There may also be significant uncertainties caused by using an equation of state for a pure gas when there has been inadequate purging of a gas previously used in the system. Also, so called sampling uncertainties in the inventory temperature and pressure measurements should be considered as covered in the discussion of the PVTt uncertainty components.

### *Primary Flowmeters*

Based on the definition of a primary standard, it is possible for what we typically think of as a flowmeter to be a primary standard. The requirements are that we have a proven basis equation for the flowmeter operating principle and that we use traceable calibrations of fundamental quantities like mass, length, and time, not a flow calibration by a separate primary standard. Hence devices like the laminar flowmeter, critical flow venturi, or ultrasonic time of travel flowmeter could be used as primary flow standards, at appropriate uncertainties. The reason they usually are not is that the uncertainties of the flow measurement are generally unacceptably large without a flow calibration by another primary flow standard like those described in previous sections. For instance, using the laminar flowmeter example, the

uncertainties of the dimensional measurements of a tiny flow tube and of the viscosity of the gas are relatively large and would lead to flow uncertainties of several percent without a flow calibration. However, the commonly used gravimetric and volumetric flow standards previously described have practical range limitations: very large collection tanks are expensive, and systems for very small flows have unreasonably long collection times. Therefore, flowmeters are sometimes used as primary standards. One example of a flowmeter used as a primary standard is given below (since it is presently the most established example), but certainly others are possible.

*Critical Flow Venturis*

A critical flow venturi is a converging-diverging nozzle operated with sufficient pressure drop across it, such that sonic velocities are reached at the venturi throat. If inviscid, one dimensional flow of an ideal gas is assumed, an equation for the mass flow through the critical flow venturi as a function of the upstream gas pressure and temperature, the critical flow venturi throat diameter, the upstream pipe diameter, and properties of the gas can be derived. An assumption in this derivation is that the velocity of the gas is sonic across the entire throat cross section. In reality, there are departures from this assumption in both the core region and in the boundary layer along the venturi wall. Efforts to model the flow through a critical flow venturi (and particularly the boundary layer region) and to arrive at accurate theoretical predictions of the venturi discharge coefficient have been active areas of flow metrology research for several decades.

For large critical flow venturis, low uncertainty throat diameter measurements are possible. Also, in large critical flow venturis, the boundary layer becomes a relatively small portion of the flowing area so that the uncertainty of the theoretical predictions of discharge coefficient become relatively small. Theoretical discharge coefficients may be based on analytical or computational solutions to the equations of flow with appropriate assumptions. Hence by using theoretical discharge coefficients and fundamental calibrations of length, pressure, and temperature, the critical flow venturi can be used as a primary flow standard with useful levels of uncertainty.

The use of critical flow venturis as primary standards has been validated experimentally by showing differences smaller than 0.05% between calculated and calibrated discharge

coefficients (under certain conditions).[32] An uncertainty analysis for the use of a critical flow venturi as a transfer standard is available[33] and this serves as a good starting point for analyzing the uncertainty of a critical flow venturi primary standard. The uncertainties can be broken into the following categories: discharge coefficient, pressure, temperature, gas properties, and throat diameter. The uncertainty of the discharge coefficient will depend on the size of the critical flow venturi and the sophistication of the theoretical model used. It is extremely important to thoroughly evaluate the literature on this subject to establish conservative operating conditions and corresponding levels of uncertainty. It is important that the approach conditions to the nozzle are carefully designed to make installation effects (flow profile effects) on the discharge coefficient negligible. The pressure and temperature used in the flow equation are the stagnation values and therefore have corrections related to the flow velocity and gas properties. Again, a well designed approach pipe will minimize the uncertainties from these sources. Other pressure and temperature uncertainties due to calibration, pressure tap effects, radiation, stem conduction, and sampling must be considered. Other uncertainty topics include the gas properties (critical flow function, specific heat ratio, composition) and the universal gas constant. Finally, the uncertainty of the measured throat diameter must be included. It is quite difficult to measure a low uncertainty throat diameter if the throat is small, but for large critical flow venturis the measurement can be accurate enough to give a useful flow measurement uncertainty. One must also consider the effects of material thermal expansion on the throat diameter. Considering these uncertainty components, it is practical to achieve 0.5% uncertainty or better for a large critical flow venturi primary standard with the largest sources of uncertainty being the theoretical discharge coefficient and the throat diameter.

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