Constant Pressure Provers from the Standards Lab to the Shop Floor

Presented at NCSLI 2003

Harvey Padden

Bios International Corporation
10 Park Place, Butler, NJ, USA 07405
Phone: 973.492.8400 • Toll Free: 800.663.4977 • Fax: 973.492.8270
harvey.padden@biosint.com • www.biosint.com

PROVEN DryCal TECHNOLOGY

NVLAP Lab Code 200661

Bios
Driving a Higher Standard in Flow Measurement℠

Abstract

Metrological devices are continually evolving, in both usability and accuracy. Ruggedized and made simpler to use, precision instruments can now be implemented on the manufacturing floor. In essence, one generation's laboratory instrument becomes the next generation's field instrument.

For example, field-rugged primary gas flow measurement devices in the 1 sccm to 50,000 sccm flow range have long been needed for diverse applications, such as calibration of environmental air samplers at 1% accuracy, and the manufacture or field service of mass flow meters and flow controllers at 0.2% accuracy.

Historically, primary flow calibrators had the advantages of direct traceability, minimal drift mechanisms; however, they were large, delicate and slow to operate (a practical limit to dynamic range). More portable and user-friendly primary provers were highly desirable.

Here we trace the history of constant-volume provers and describe a version of the piston prover that has evolved to reduce the primacy/portability tradeoff. Using a viscous-sealed, virtually frictionless piston, this design achieves uncertainties below 0.2% while remaining small, fast and portable.

The analysis that follows shows that our goals have been met. In fact, a specification of ± 0.15% may be possible after further empirical verification.

1. Broad Objective: From the lab to the field

Perhaps ship's chronometers best exemplify the theme of this conference. The development of lab-accurate field-portable chronometers resulted in an explosion of commerce, forever changing the world. They did so by allowing accurate measurement of time, and hence longitude, far from the laboratory, in the only place where it mattered, on the open seas.

Essentially, the world's standard of living depends to a great degree upon the precision and reliability of its field metrology. Science progresses with our ability to perform measurements in the laboratory, but quality of life increases with our ability to perform measurements in the field.

Metrologists are all, in a sense, migrant workers. We cause precision to migrate from our laboratories outward and into the working world. Day-to-day, we do so by acting as the source from which field accuracy springs. In a long-term sense, though, we do so by migrating our technology outward, providing better and better instruments to those who use them in the field.

As the world's economies continue to expand, a primary motivating force is the continually increasing level of product and process sophistication. Standards of living increase in step with our ability to better control the processes by which we create products. The quality and yield of our industrial processes, as well as the level of products produced, is directly related to our metrological abilities at the point of manufacture.

Yesterday's laboratory instrument must evolve into tomorrow's field equipment. Operable by non-scientists with minimal training in relatively uncontrolled environments, they must be able to yield accurate results over long periods after transportation from their point of calibration.

Our efforts occupy one small part of this grand technological migration: Although quantifying the flow of a compressible fluid remains one of the most difficult metrological tasks, we sought to allow its reliable achievement under the difficult field conditions just discussed. Our approach was to migrate laboratory-standard primary piston provers into high-speed field devices

We achieved uncertainties comparable to those of the mercury-sealed provers found in most of the world's national laboratories, but with much faster operation. Sometimes things come full circle: Perhaps these viscous-sealed provers can eventually prove adequate for true laboratory service, greatly improving calibration productivity at the higher levels.

2. Specific objective: Portable Primary Calibrators

Our objective was to create portable primary for use in mass flow controller and mass flow meter manufacture and service, as well as for research, maintenance and calibration of secondary flow standards. To accomplish these ends, we sought the following characteristics.

2.1 Primary

Primary instruments possess the extremely desirable characteristic of being characterized by the most basic of quantities. In the case of piston provers, these are length and time. As flow is necessarily a derived unit, a dimensionally- characterized system is as close as possible to direct traceability from national dimensional standards. Malfunction is often much more easily detectable in a dimensionally derived device than in a secondary device.

2.2 Portable

It is very desirable for instruments to be readily movable from one location to another. Self-contained, wheeled units have a degree of portability. For our purposes, though, true portability can be regarded as the ability to be easily carried by any person. A realistic definition might be the size and weight of an airline carry-on bag, and operable in normal plant locations. Battery operation, while not a requirement, would further enhance portability.

Portability is greatly enhanced by a high turndown ratio, as fewer devices are needed to cover a given range. Portability also has the implicit requirement of ease of setup. A reasonable definition might be a setup time of less than several minutes.

2.3 Field-Rugged

A field-usable calibrator must be rugged. Portability inevitably results in shocks, bumps and even temperature extremes. Here is where primacy is extremely helpful in preventing calibration drift. Ideally, adjustments should be done in the electronics wherever possible, rather than by mechanical movement of the instrument's elements.

2.4 Minimal Training

A calibrator used in the field should not require specialized personnel or extensive training. Non-degreed skilled workers should be able to obtain accurate readings with only an hour or two of training. This characteristic is also important for high-level technical personnel who must master a large number of instruments or processes, such as field service engineers.

3. Predecessors: Primary Laboratory flow provers

Primary laboratory provers reach standardized uncertainties of less than 0.05% in the form of constant-volume provers and 0.1% in the form of bell and piston provers. However, such systems are historically large, expensive, and immobile, requiring extensive user training. The challenge has been to evolve such instruments into a form practical for field use. There are two basic types of laboratory primary calibrators: Constant-volume and constant-pressure.

3.1 Constant-Volume Provers (Rate of Rise, PVTt)

Constant-volume systems depend upon filling a very well characterized volume and observing its temperature and pressure. There are two basic methodologies: Rate-of-rise (ROR) and pressure-volume-temperature-time (PVTt).

By observing the rate of rise of the pressure (ROR), we can infer dynamic flow from the state equation. By measuring stable states at the beginning and end of a measurement period (PVTt), dynamic errors are reduced and intrinsic integration occurs, enhancing accuracy. Figure 1 shows a highly advanced constant-volume system now in use at NIST.

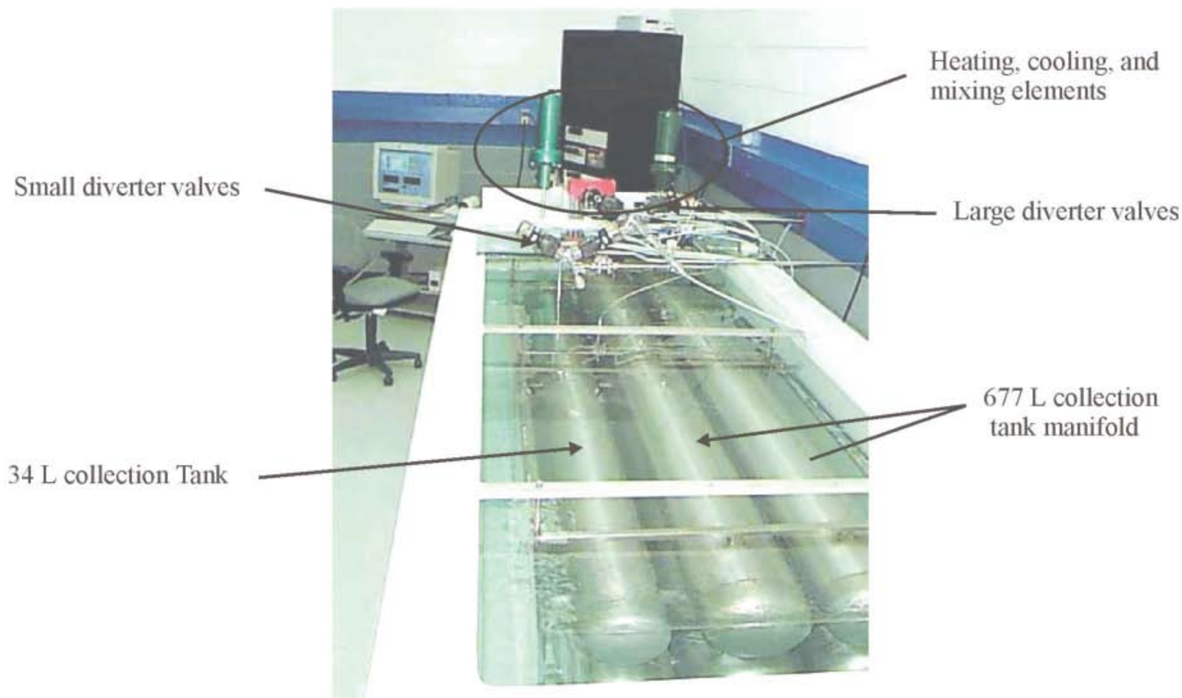

Figure 1 – NIST constant-volume system.

Somewhat portable versions of the constant-volume prover have been developed. Although these devices are intended for plant use, they are of limited portability and field-ruggedness. Figure 2 shows a self-contained ROR system that can be rolled about a plant location and operated by skilled technicians.

Figure 2 – ROR system.

3.2 Constant-Pressure Bell Provers

Constant-pressure provers have a long history as primary flow calibrators. At the national laboratory level, they reach standardized accuracies on the order of 0.2% in the form of bell and piston provers. A typical bell prover is shown in Figure 3. Essentially a very well calibrated cup inverted over a container of liquid, its contained volumetric flow can be well characterized by measuring its rate of drop or rise.

Figure 3– Bell prover.

Bell provers evolved into wet test meters (Figure 4), where compartments in hollow semi-immersed drums are sequentially filled, rotating the drum. These devices are somewhat portable and user-friendly, but require skilled application and are not well suited for regular shop use.

Figure 4 – Wet test meter.

3.3 Constant-Pressure Piston Provers

Piston provers may be the simplest primary flow measuring devices. An idealized piston prover would consist of a massless, frictionless, leak proof, shape-invariant and impermeable piston inserted within the flow stream and enclosed by a perfect cylinder (Figure 5). Inlet gas ordinarily flows through the bypass valve to the outlet. When a reading is to begin, the bypass valve closes and the incoming gas displaces a piston that moves through a cylinder. After the piston has been allowed adequate time to accelerate, the time needed to pass from one optical sensor to another is measured. To the degree that the volume of the device is well known, we can derive the flow from measured primary dimensions (length and time).

The time that the piston takes to move a known distance (which implies a known volume) then yields the volumetric flow as:

$$F = V / T = \pi r^2 h / T$$

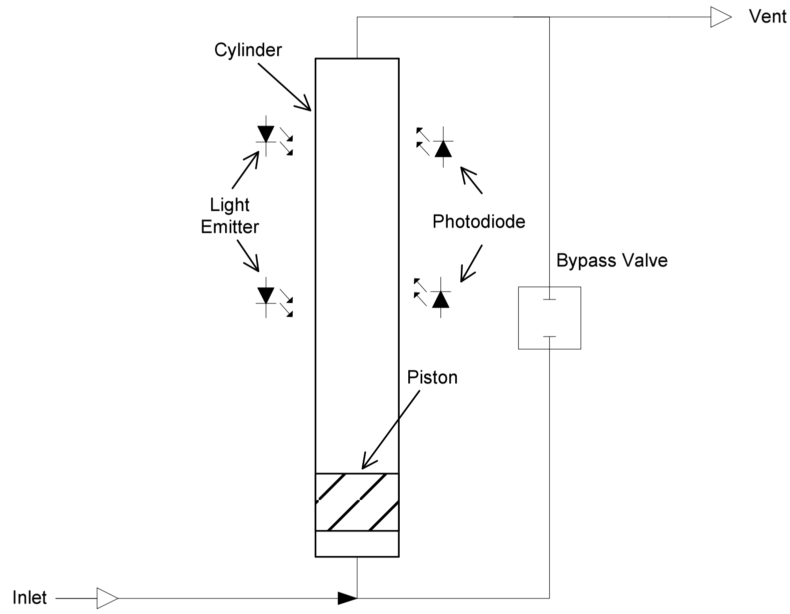

Figure 5 – Basic piston prover.

Several additional elements of the practical design must also be considered. Temperature and absolute pressure sensors must be added to obtain standardized readings. The light detectors are collimated to increase accuracy. Finally, there is unavoidable dead volume consisting of the inlet fitting and tubing, interior passages, the valve and the portion of the cylinder below the point at which timing begins (Figure 6).

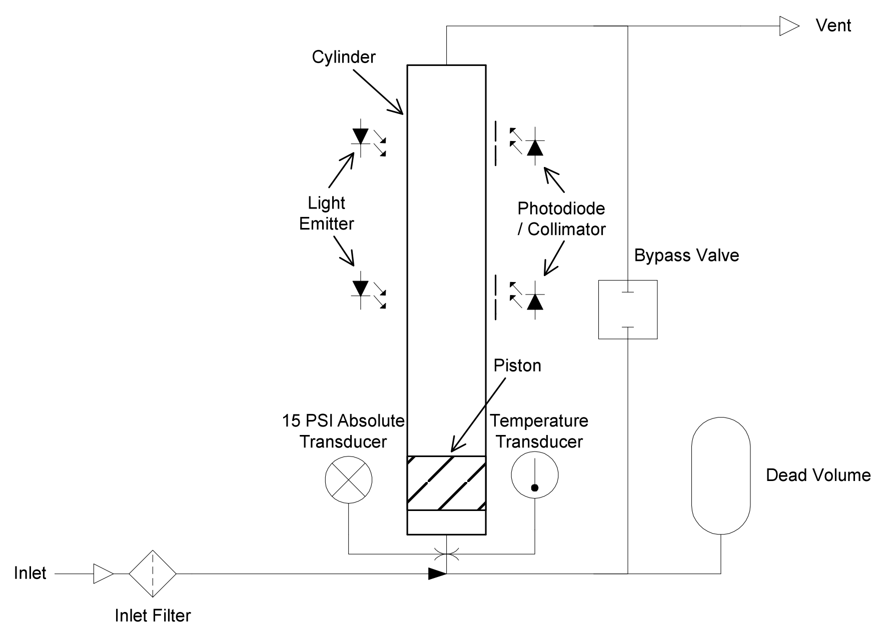

Figure 6- Standardized piston prover.

Of course, the ideal prover does not exist, and instruments have evolved for many decades. Piston provers originally took the form of soap films that blocked a calibrated burette, with their transit time measured manually. A cup of soap solution was raised into contact with the lower lip of a graduated burette, the top of which was connected to a suction source. The transit time of the soap film bubble that resulted was measured with a stopwatch, and the flow calculated.

These were later partially automated for lab use, and then miniaturized for applications at the 1% volumetric level, such as calibration of environmental samplers. Modern soap film calibrators use optical bubble detection and an internal computer. The accuracy of any practical soap film device is limited by:

- Vapor pressure of water
- Shape variation of the bubble
- Permeability of the bubble
- Fluid viscosity changes with evaporation, variation of cylinder working diameter from dried and prior-reading bubble solution

The above-described uncertainties limit the usefulness of soap film devices. Vapor pressure alone can account for ±1.5% uncertainty if not compensated for. Soap-film devices are still of value when the insertion pressure must be as low as possible, such as measurement of a very highly unregulated source.

Soap-film provers later evolved into automated systems with solid, mercury-sealed pistons (Figure 7). These are still the most common primary flow calibrator at the national lab level.

Mercury-sealed provers remedy many of the shortcomings of soap film calibrators. A rigid piston has the advantage of shape-invariability and impermeability. In a laboratory calibrator used with high-stability flow sources, the piston mass can be made to cause minimal uncertainty. However, there is still the problem of sealing the piston. The best solution to date had been the use of a mercury piston ring to fill the gap between the piston and the cylinder. Its friction is very low and its vapor pressure is acceptable. Piston speeds must be kept low to avoid loss of the mercury seal, limiting maximum flow rates and increasing measurement cycle time. A mercury seal also has the disadvantage of toxicity.

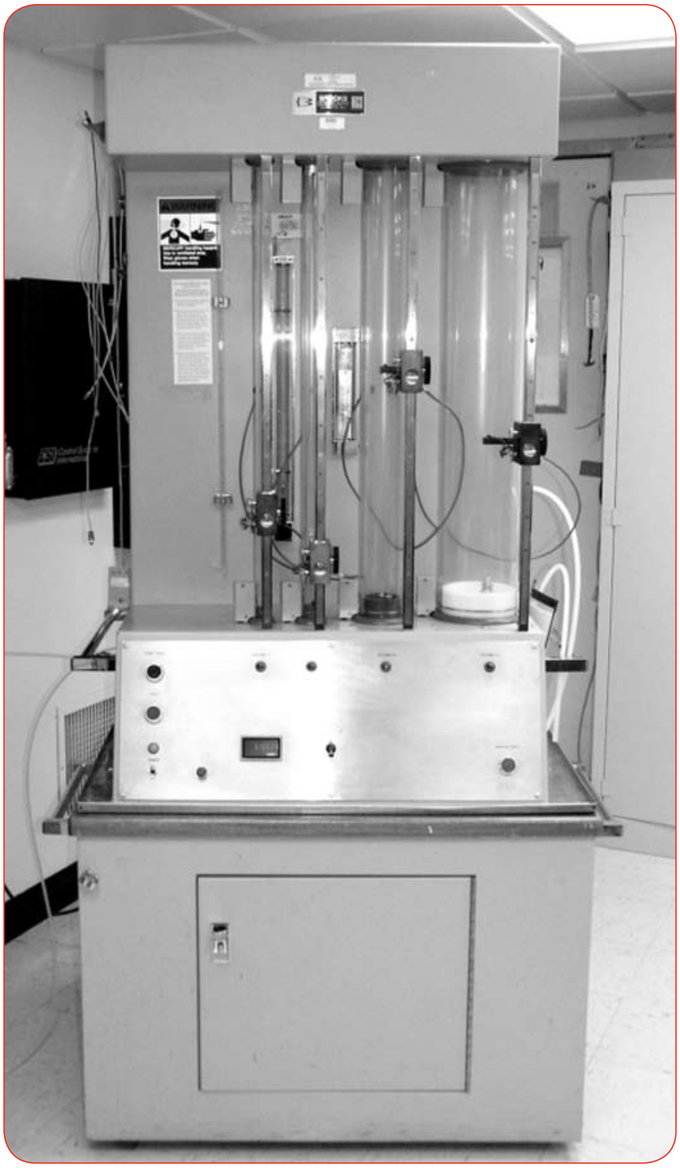

Figure 7 – Mercury-sealed piston prover.

4. Predecessors: Portable primary flow provers

The laboratory soap-film calibrator was succeeded by three evolutionary lines, as shown in Figure 8. We have already discussed the mercury-sealed branch. This design reached its peak with standardized devices using a multiplicity of distance-measuring techniques: Direct optical, encoder, ultrasonic and laser interferometer. Standardization was added by incorporating pressure and temperature sensors. These provers were not suitable for portability because of mercury toxicity and the need for a long distance of piston travel.

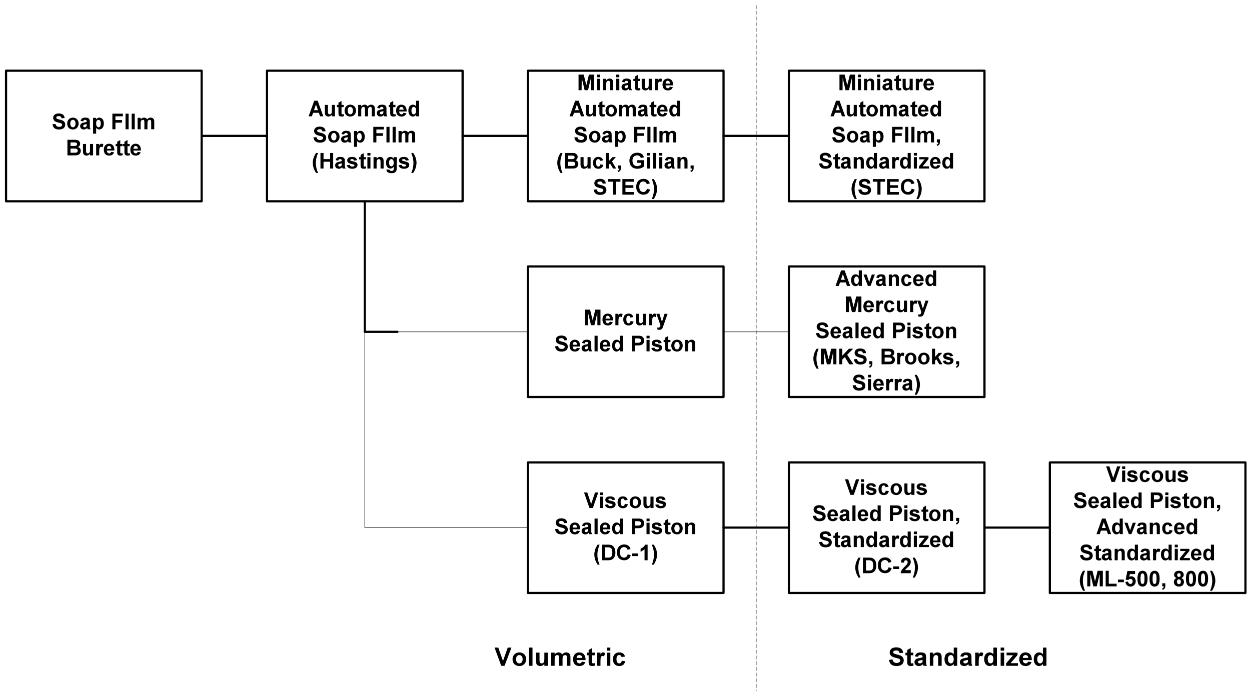

Figure 8 - Piston prover evolution

4.1 Soap-Film Evolutionary Branch

Soap-film instruments did not disappear after the invention of the mercury-sealed prover. Rather, they evolved into miniaturized devices suitable for a number of field uses.

4.1.2 Portable Volumetric Soap-Film Devices

After the development of automated laboratory film provers, the first evolution in portable provers was the development of small volumetric semi-automatic devices for use in calibrating personal and environmental air samplers (Figure 9). Bubbles were generated by a movable ring that was manually lifted by an external actuator and then timed automatically.

As previously noted, these devices are susceptible to very significant vapor pressure errors. Care must also be taken not to allow the soap film to increase viscosity through evaporation, or to allow the tube's diameter to be reduced by dried solution.

4.1.2 Portable Standardized Soap-Film Devices

The final evolution in soap-film technology was the standardization of the simple volumetric calibrator. Pressure and temperature sensors were added, as in the mercury-sealed provers.

Our challenge was to migrate the soap film and mercury-sealed technologies into devices suitable for field use without seriously compromising accuracy. To miniaturize the instrument, we needed high piston velocities and small measurement distances. Sealing the piston using the viscosity of the gas under test was a critical innovation. The required close clearances are very difficult to achieve. However, they permit minimal piston rocking, allowing the piston to be directly detected with great accuracy. The small cylinder diameters allow simple LED/photodiode detectors. The small size also minimizes temperature variations within the cylinder, enhancing standardization accuracy. Operation can be totally automated.

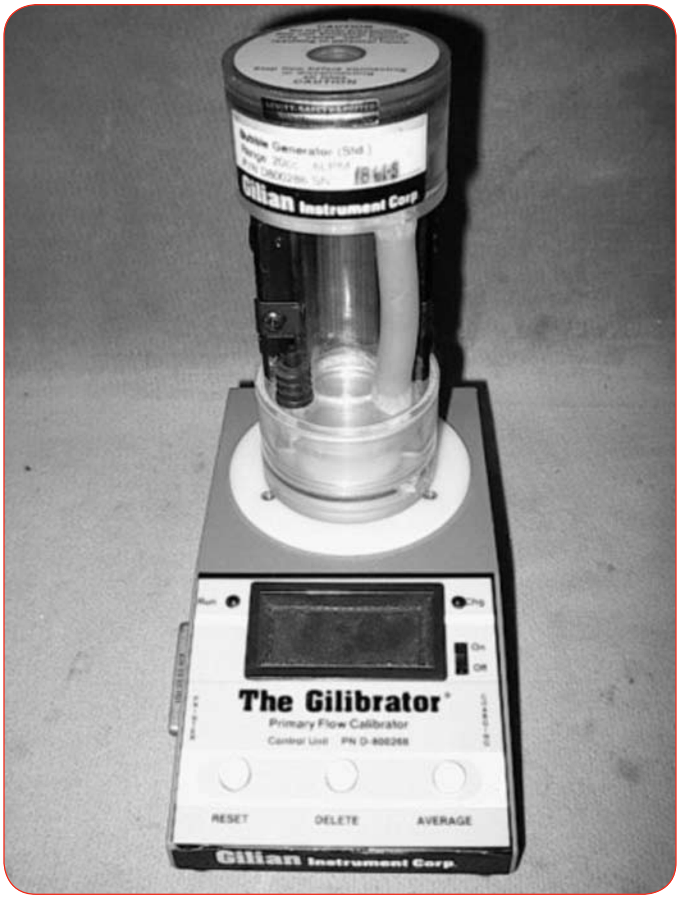

Figure 9 – Portable soap-film calibrator

4.2 Viscous-Sealed Evolutionary Branch

The clearance-sealed prover uses a piston and cylinder fitted so closely that the viscosity of the gas under test results in a leakage small enough to be insignificant. For reasonable leakage rates, such a gap must be only a few microns. As a practical matter, the piston and cylinder are made of graphite and borosilicate glass (Figure 10) because of their low, matched temperature coefficients of expansion and low friction[1].

Figure 10 – Viscous-sealed piston and cylinder.

[1] U.S. Patent No. 5,440,925

Such a device comes close to the ideal. The piston is shape invariant, impermeable and virtually frictionless. There is no vapor pressure from a soap film or sealant. The instrument can utilize high piston speeds, resulting in a measurement repetition rate rapid enough to be considered quasi-continuous.

Such an instrument has unique considerations. Static uncertainties are similar to those of mercury-sealed provers. The small size reduces piston rocking and temperature stratification errors, but dynamic uncertainties resulting from a significant underdamped piston mass, the effects of enclosed dead volume and from leakage must be controlled.

4.2.1 First generation Viscous-sealed provers

The early viscous-sealed provers had a volumetric accuracy of 1%. They consisted of interchangeable volumetric measuring cells that plugged into a base unit. A standardizing base unit was later offered, with overall standardized accuracy of 1.4% (Figure 11). Later one-piece designs serve the same accuracy region with enhanced portability.

4.2.2 Advanced Viscous-Sealed Provers

Approximately 20,000 first-generation provers have been produced over a twelve-year period. This extensive experience was used as a basis for the development of far more advanced instruments.

We began by producing experimental laboratory provers .We fabricated two each of three sizes of measuring cells for use with a common control base. We calibrated the cells by dimensional means. We then performed a rigorous uncertainty analysis stating that our primary laboratory master volumetric provers have an expanded (2X) uncertainty of approximately 0.07% [1].

Figure 11 – First-generation portable viscous-sealed piston prover.

4.2.3 ML-500

We developed our commercial ML-500 standardized primary flow calibrator from the experimental laboratory devices. Using the same basic design as the laboratory master provers, these devices have a shorter measuring path and include standardization using internal temperature and pressure sensors.

We retained the modular concept used in our earlier machines: Three sizes of cells are used interchangeably with a universal base. In the new designs, each cell contains everything that must be calibrated, except for the crystal time base and the resonant pressure transducer. The base contains these and the computer, which performs all of the control and data-processing functions. These include data logging, communications, interval operation and other features.

Because the devices are fast and automatic, we were able to easily collect extensive statistically valid data for each flow we tested. Again, we performed a rigorous uncertainty analysis of the ML-500 devices. The analysis resulted in a conservative specification of ± 0.35% [2].

4.2.4 ML-800

Next, we wished to develop a prover the 0.2% range. The production version of the ML-500 was used as a starting point. The cylinder was lengthened to increase the volumetric repeatability, but the biggest improvements were in the standardization system. A special high-accuracy, high-speed transducer system was added to permit unique dynamic standardization techniques to be developed (Figure 12).

Each cell consists of a machined base containing the inlet and outlet fittings, bypass valve, temperature sensor and pressure tap. The bypass valve is of a self-relieving, low pressure, large area design. It latches in either the open or closed position to minimize introduction of heat into the flow stream. The pressure tap is located at the entrance to the measuring cylinder to maximize accuracy.

The base serves as a mounting for the vertical measuring cylinder/piston assembly, which uses a clearance-sealed piston to minimize friction. The effective cylinder diameter is neither the piston diameter nor the cylinder diameter: Rather, it is an intermediate value.

Detector slits are mounted directly to the cylinder's outer surface for maximum repeatability. A support structure is also attached to the base. It holds infrared light emitters and detectors, as well as the cell's electronic circuitry. Each cell contains all signal processing circuitry, A/D conversion and an EEROM for calibration data. In this way, complete calibration (with the exception of the computer's time base) can be performed on each cell individually.

Figure 12– DryCal ML-800 (shown with MFC)

5. Current State of Development: ML-800 Unceratainty Analysis

The ML-800 represents the current state of the viscous-sealed prover art. Therefore, close examination of its uncertainty is in order. This subject was treated in detail in a previous publication [3]. Here, we will present a synopsized version.

5.1 Special Dynamic Considerations

5.1.1 Dynamic Uncertainty Contributions

Traditionally, standardization of constant-volume devices has been treated in a static manner. Pressure and temperature were measured in the inlet piping by low-speed transducers, accepting the resultant uncertainties. Yet, correlation of the average inlet temperature to that of the measured gas was always questionable.

More recently, evidence has been presented of dynamic pressure variations in bell provers [4], as well as in dry piston provers. We cannot treat standardization in a static manner. The ML-800 contains provision for dynamic standardization of temperature and pressure.

5.1.2 Pressure

To a first order, pressure only needs to be measured at the beginning and end of the timed measurement period. From the Ideal Gas Law, flow will be given by:

$$F = F_I \left[\frac{P_2}{P_A} + \left(\frac{P_2 - P_1}{P_A} \right) \frac{V_D}{V_M} \right]$$

Where:

F = Flow
F_I = Uncorrected flow
P_A = Ambient (or standardizing) pressure
P_1 = Pressure at start of timed period
P_2 = Pressure at end of timed period
V_D = Dead volume
V_M = Measured volume

Uncorrected, the measured volume contains an error equal to the difference in internal pressure at the start and the end of the measuring period, amplified by the ratio of dead volume to measurement volume, as well as that of the pressure within the cylinder at the end of the timed period. The DryCal is a high-speed device. As a result, the internal pressure changes rapidly and can significantly affect measurement uncertainty.

5.1.3 Temperature

One of the largest potential error sources in standardization of provers is in the measurement of a truly representative standardization temperature. If the incoming flow stream varies in temperature from that of the prover, we must find means of assessing the effective measurement temperature.

Our best solution is measurement of both the inlet flow stream and the temperature of the slug of gas ejected from the cylinder after measurement. Since the ejection time is generally less than a second, the ejected slug will tend to be representative of the measurement temperature.

Now our problem is similar to the pressure standardization dilemma: We need a dynamic temperature measurement technique of very high speed and very high accuracy. To this end, we employed near-microscopic thermistors (about 100 micron diameter) at the end of a probe such that the still-air time constant was approximately 100 microseconds. We located the thermistor on the centerline of the cylinder and immediately beneath it.

5.2 Uncertainty Contributions

It was not necessary to measure all of the uncertainty sources individually. Many of them affect only repeatability. As these are automatic high-speed provers, it was simple to collect adequate statistical data to include them in Type A analysis. However, as the type A repeatability data was scaled for the differing measurement paths of these devices, we will treat all readings as type AB or Type B.

5.2.1 Effective Piston Diameter

The effective piston diameter is midway between the cylinder and piston diameters. This subject was analyzed in detail in our previous publication [1]. The uncertainty values shown in Table 1 were calculated. Later work indicated that these values are probably too conservative. However, we shall let them stand pending further investigation.

Table 1 - Effective Diametric Uncertainties

Diameter (cm)	Annular Gap (microns)	Max Error (ppm)	Factor (U-shaped)	u (ppm)
0.95	7.3	772	2.121	364
2.4	8.4	352	2.121	166
4.44	11.8	266	2.121	125

5.3.2 Measured Piston Diameter

The main precaution to be observed in measuring the piston diameter is to avoid deflection of the graphite piston by a measuring device. To avoid this problem, diameter is measured with a laser micrometer. Several readings are averaged to enhance accuracy.

Assuming a coverage factor of two, the uncertainty of the readings is 0.51 microns. Dividing by the piston diameters, we obtain uncertainties of 16, 6 and 33 ppm for the small, medium and large provers respectively. Since the volume is affected by the square of the diameter, the sensitivity factor is 2.

5.2.3 Measurement Length Calibration

The length of the timed stroke is determined by measuring the location optical detectors using a depth micrometer to move the piston. The location of each detector was measured separately. A number of readings were taken for each detector. Each reading reproduced the others within the digital micrometer's resolution of 0.0001 inches. Including the micrometer's rated accuracy and dividing by 1.732 for a rectangular distribution, we calculated the uncertainties of Table 6. The sensitivity factor is 1.

Table 2 – Measurement Length Calibration Uncertainties

Size	Detector	Tolerance (micro in.)	Distance (inches)	u (ppm)
S	Lower	105	5	12
S	Upper	115	5	13
M	Lower	105	4	15
M	Upper	115	4	17
L	Lower	106	4	15
L	Upper	56	4	8

The measurement length calibration is performed once the entire measuring cell is fabricated. The piston is positioned using a depth micrometer. The trip points actually detected by the mating optics and electronics are then used to determine the stroke length and its reproducibility.

5.2.4 Measurement Length Drift

Collimating slits attached to the glass cylinder's exterior mask the optical detectors. The effective width of the sensing slit is the actual slit width increased by the image of the emitter at the slit, reduced by any adaptive enhancement. Therefore, we use an adaptive measurement scheme. Before each cycle, a reading of the ambient light level is taken for each photodiode with the light emitters turned off. Then a reading is taken with the light emitters turned on. An average of the two levels is then set as the trip level for that cycle. This is shown in Figure 13.

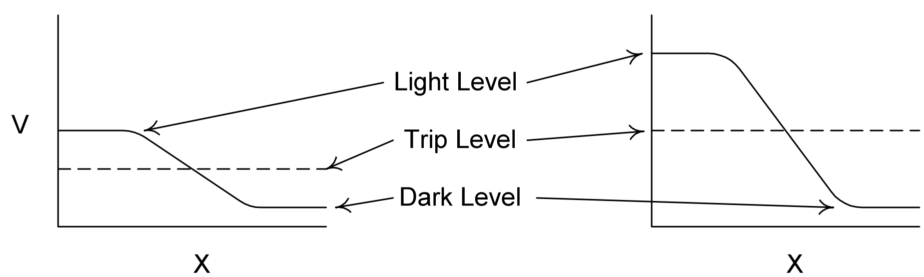

Figure 13 - Adaptive Detection

With our 4096 bit A/D converter, it is simple to assure that we have at least 20 bits of signal. This will reduce the geometric piston location uncertainty by a factor of 40:1, with a rectangular distribution. The individual uncertainty is multiplied by the square root of two to represent the two independent detectors. The resulting uncertainties are shown in Table 3

Table 3 - ML-800 Detector Drift Uncertainties

Size	Slit Image (inches)	Separation (inches)	Variation (ppm)	u Total (ppm)
S	0.014	5	135	110
M	0.014	4	169	138
L	0.0013	4	158	129

5.2.5 Thermal Expansion

The graphite piston and the borosilicate glass cylinder have similar thermal coefficients of expansion of 7 ppm/K. Expansion is in three dimensions, so the sensitivity factor is 3. Over our temperature range of 7°K, allowing for three degrees of freedom and for a rectangular distribution, we have a resulting uncertainty of 85 ppm.

5.2.6 Time Base Calibration

The time base is derived from a crystal rated at (and measured to) ±0.005%, or 50 ppm. Applying the appropriate factor for a rectangular distribution, u = 50/1.732 = 29 ppm with a sensitivity factor of 1.

5.2.7 Pressure Standardization

Pressure is measured by a combination of a resonant barometric transducer and a strain gauge dynamic trim transducer. Both uncertainties must be accounted for.

5.2.7 Temperature Standardization

We designed the circuit so that the self-heating of the probe would be insignificant with respect to our required accuracy. We then amplified the output with a precision instrumentation amplifier so that A/D quantization would be minimal.

We fitted the in-circuit voltage results to the data at several points over the design temperature range of 15 °C to 30 °C. Using a second-order polynomial (easy to program into the instrument's microcontroller), we were able to get a fit that resulted in very little error.

Finally, we measured the drift of ten probes over a one-month period, aging the devices at 200 °C (Figure 14). This drift should far exceed the drift over a one-year period at room temperature.

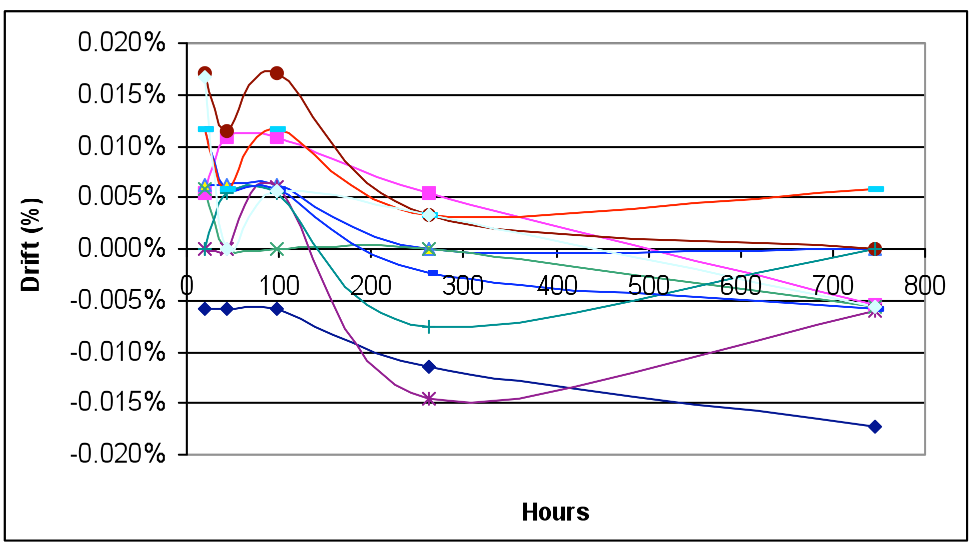

Figure 14 – Thermistor Drift

The combined results are contained in Table 4, with the total error remaining quite small.

Table 4 – Thermistor Uncertainty

Source	Worst Case Error (ppm)	Divisor	u (ppm)
Curve Fit	77	1.732	44
Quantization	69	1.732	40
Self-Heat	79	1.732	46
Calibration	100	1.732	58
Drift	170	1.732	98
Net			136

5.2.8 Piston Leakage

Leakage is, of course, very significant in determining the lower flow limit of the cells. For this reason, all ML-800 cells are calibrated for leakage and for the uncertainty of leakage, with the average leakage value added to each reading as a tare value. Statistical tests of leakage repeatability exhibited a standard deviation of 12 percent. Therefore, 12 percent of the leakage value divided by the flow is used as a flow-dependent uncertainty. For the small, medium and large cells, these uncertainties are 0.006, 0.01 and 0.12 ccm. Although we actually screen for leakage uncertainty, we will use the above values for illustrative purposes.

5.2.9 Repeatability of Readings (Piston oscillations, rocking, detector trip point, quantization)

Extensive statistical data was collected for Type A analysis of the earlier ML-500 provers. We tested several of each size cell, taking 100 readings at each of 5 flows logarithmically spaced throughout the cells' ranges. We then calculated the standard deviation of each flow rate's 100 readings for each measurement point. Again, for conservatism, no attempt was made to remove flow generator and room temperature effects from the data. We averaged the readings for each flow point for each cell. Since we have yet to conduct the same level of Type A data collection for the ML-800, we used a type AB approach to estimate the ML-800 repeatability. We divided the ML-500 data by the ratio of ML800/ML-500 measurement path lengths (Table 5). The resulting uncertainties are shown in Table 6.

Table 5– ML-500/ML-800 Measurement Path Lengths

Measurement Path Lengths (inches)					
Small Cell		Medium Cell		Large Cell	
ML-500	ML-800	ML-500	ML-800	ML-500	ML-800
2.4	5.0	2.0	4.0	1.5	4.0

Table 6– ML-800 Prover Repeatability (Type AB)

Measurement Path Lengths (inches)								
Small Cell			Medium Cell			Large Cell		
Flow Rate (ccm)	Observed ML-500 u (ppm)	Projected ML-800 u (ppm)	Flow Rate u (ppm)	Observed ML-500 u (ppm)	Projected ML-800 u (ppm)	Flow Rate u (ppm)	Observed ML-500 u (ppm)	Projected ML-800 u (ppm)
4	730	350	50	730	365	250	710	266
11	470	226	190	470	235	1000	350	131
42	450	216	690	450	225	3500	290	109
160	470	226	2600	470	235	13300	390	146
600	470	226	9000	470	235	50000	980	368

5.3 Uncertainty Statements

Since we wish to characterize the ML-800 over its range, we will first calculate the flow-independent uncertainty and then calculate the total uncertainty over a range of tested flows for each cell size.

5.3.1 Flow-Independent Uncertainty

The flow-independent sources are summarized in Table 7.

Table 7– Flow-independent Uncertainties (Type B)

Source	Small u (PPM)	Medium u (PPM)	Large u (PPM)
Diameter Measurement	16	6	33
Annular Gap Adjustment	364	166	125
Stroke Measurement	38	45	60
Static Pressure Correction	321	321	321
Dynamic Pressure Correction	104	104	104
Temperature Correction	136	136	136
Detector Drift	110	138	129
Thermal Expansion	85	85	85
Combined (RSS)	829	505	442

5.3.2 Flow-Dependent Uncertainty

Flow-dependent uncertainties consist of the statistical data from the repeatability studies of 5.2.9 root-sum-squared with the leakage uncertainties of 5.2.8. The total flow-dependent uncertainties are shown in Table 8.

Table 8 – Flow-Dependent Uncertainty (Type A)

Small		Medium		Large	
Flow (~sccm)	u (ppm)	Flow (~sccm)	u (ppm)	Flow (~sccm)	u (ppm)
4	1540	46	513	229	768
10	590	174	253	916	223
38	259	632	227	3207	120
147	229	2382	235	12185	147
550	226	8245	235	45807	368

5.3.3 Total Uncertainty

Finally, we can combine the flow-independent uncertainties of Table 7 with the flow-dependent uncertainties of Table 8 and multiply by 2 to obtain the expanded uncertainties of Table 9.

Table 9 – ML-800 Prover Expanded Uncertainty (2X, Standardized)

Small		Medium		Large	
Flow	U	Flow	U	Flow	U
4	0.350%	46	0.144%	229	0.177%
10	0.204%	174	0.113%	916	0.099%
38	0.174%	632	0.111%	3207	0.092%
147	0.172%	2382	0.111%	12185	0.093%
550	0.172%	8245	0.111%	45807	0.115%

The expanded uncertainties can be visualized more easily in graphical form in Figure 15, Figure 16 and Figure 17. We have added a line representing the average of five readings to each, derived by dividing the repeatability by the square root of five before inclusion with the other errors.

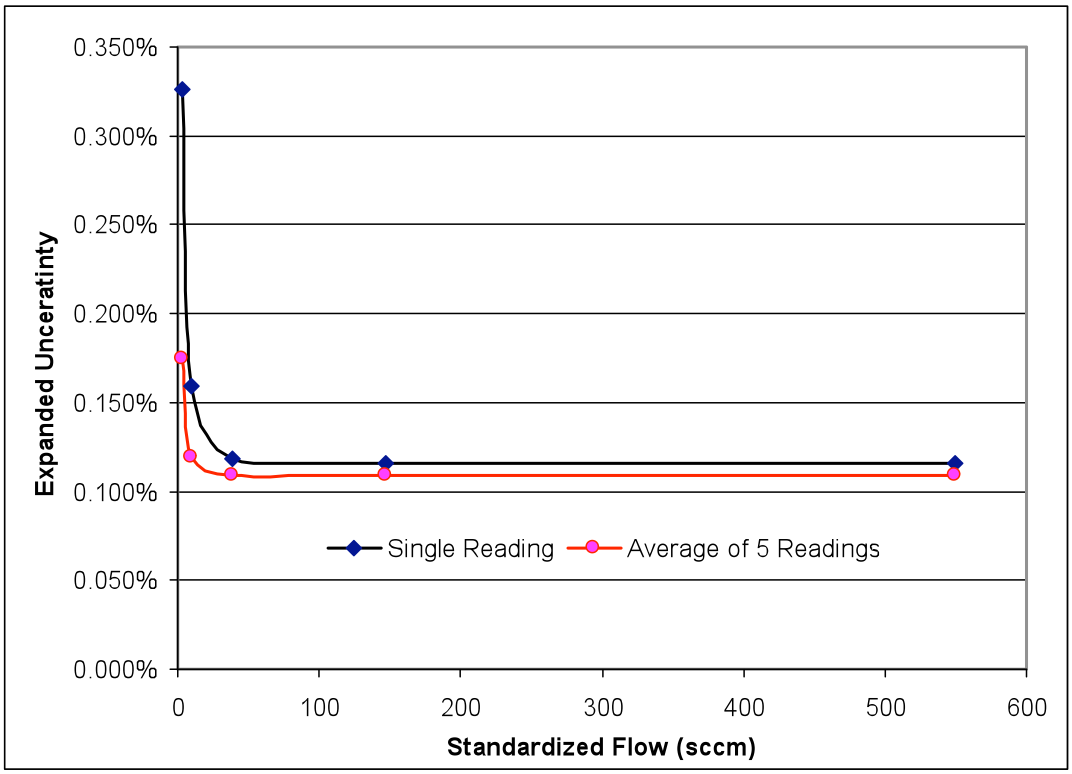

Figure 15 - Standardized ML-800 Small Cell Expanded Uncertainty (2X)

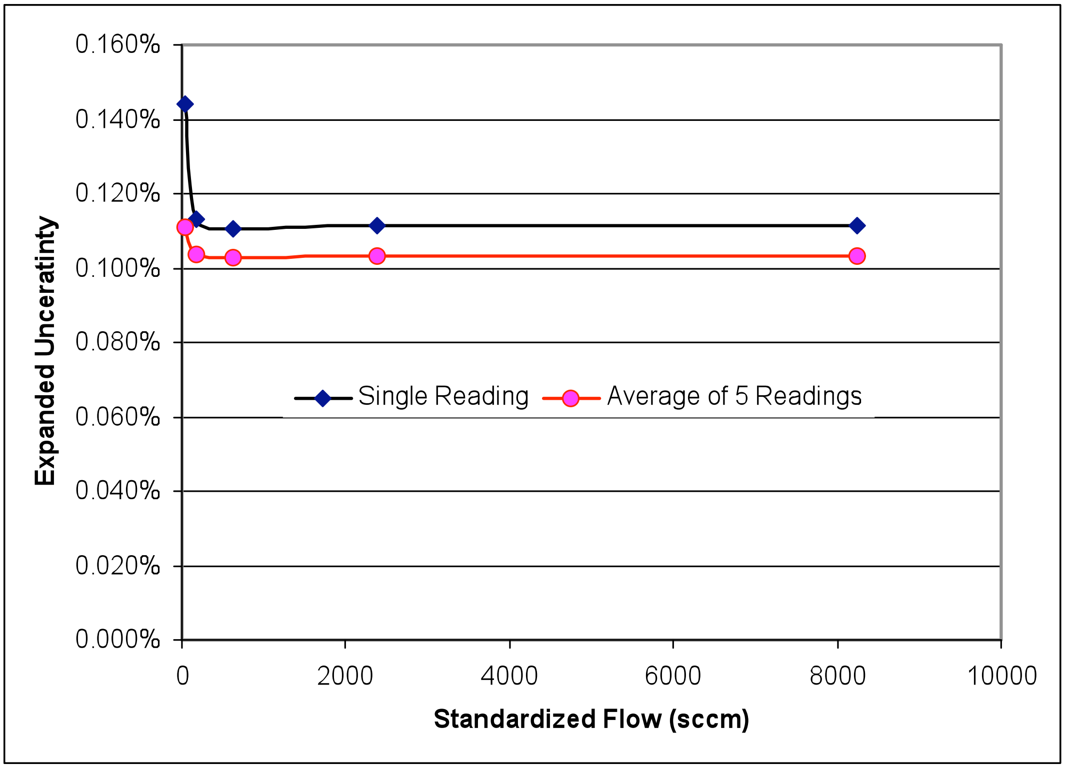

Figure 16 - Standardized ML-800 Medium Cell Expanded Uncertainty (2X)

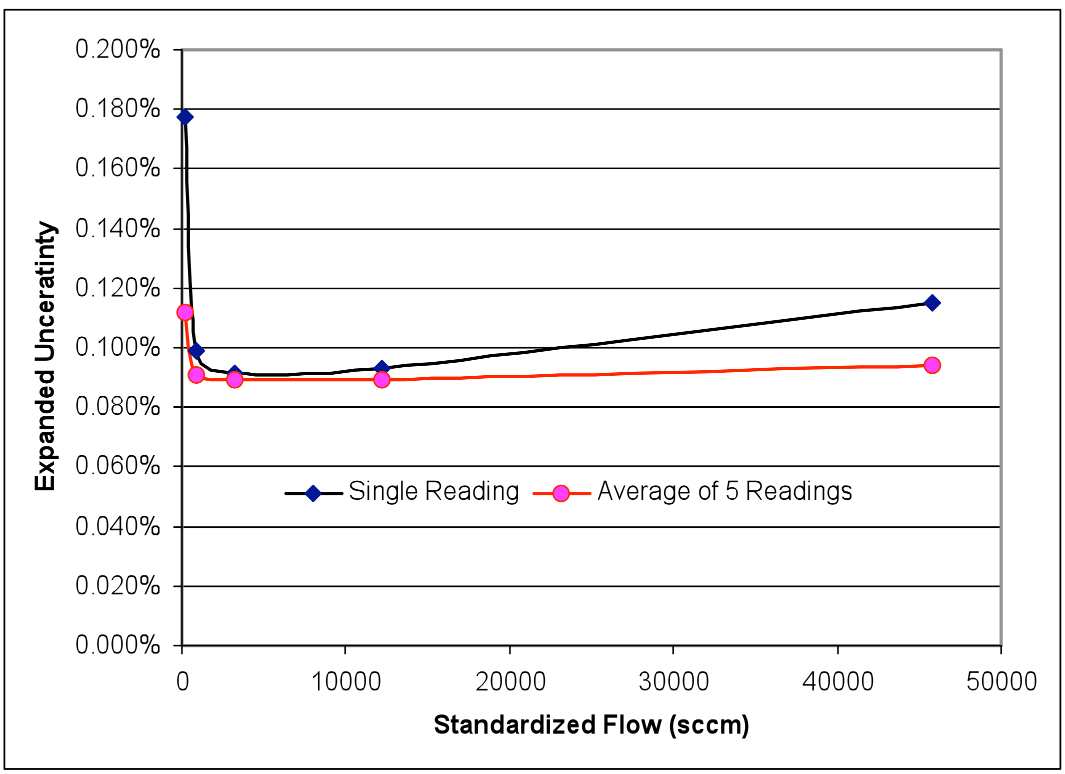

Figure 17 - Standardized ML-800 Large Cell Expanded Uncertainty (2X)

6. Conclusions and Observations

Field-portable primary provers have evolved to a level that rivals the accuracy of laboratory instruments. Now, the work of verification and application must begin. Preliminary inter-laboratory comparisons have shown very encouraging results, supporting the preceding uncertainty analysis. More comparisons will be performed for further verification.

No instrument performs in isolation. Rather, its effective uncertainty includes interactions with the device under test. Because high-speed viscous-sealed provers have dynamic pressure effects, applications must be investigated for suitability, and proper methodologies developed.

Overall, however, the goal that was stated in this paper's title appears to have been achieved. Laboratory provers are ready for shop-floor use.

Reference:

1. H. Padden, Uncertainty Analysis of a High-Speed Dry Piston Flow Prover, Measurement Science Conference, Anaheim, CA, 2002 (contact author at padh@biosint.com for reprints)
2. H. Padden, High-Speed Prover Systems For Cost- Effective Mass Flow Meter And Controller Calibration, NCSLI International Conference, San Diego, CA, 2002
3. H. Padden, Development of a 0.2 % High-Speed Dry Piston Prover, Measurement Science Conference, Anaheim, CA, 2003
4. T. O. Maginnis, Simple Dynamic Modeling of Expanding Volume Flow Calibrators, Measurement Science Conference, Anaheim, CA, 2002

Bios

Bios International Corporation
10 Park Place
Butler, NJ, USA 07405

Phone: 973.492.8400
Toll Free: 800.663.4977
Fax: 973.492.8270

www.biosint.com