Laminar flow

Innovation in Industrial and Environmental Hygiene

AN ENHANCED FLOW MEASUREMENT AND CONTROL SYSTEM FOR PERSONAL SAMPLING PUMPS

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A miniaturized electronic laminar flow meter has been developed for inclusion in a compact personal sampling pump. This development, for the first time, provides both an internal secondary flow standard with high resolution readout and the sensor means for enhanced flow-feedback control of the pump drive mechanism. The design and performance of the Escort ELF™ Pump from MSA resulting from this basic improvement are described.

Personal sampling pumps for industrial hygiene exposure monitoring have become widely used. Field calibration often requires that auxiliary equipment be carried to verify flow rate integrity. For many applications, a continuous reading flow indicator integral to the pump design is either legislated, e.g., for coal mine dust sampling,[1] or at least desirable to provide user confidence that the pump is sampling at the proper flow rate.

The traditional integral flow indicator has been a ball-in-tube rotameter. Part 74.3, Title 30 of the Code of Federal Regulations for coal mine dust sampling requires that the flowmeter be calibrated at 1.6, 1.8, and 2.0 liters per minute (LPM) to guarantee accuracy of reading to within ±5% at those flows. For rotameters with the wide range of 0.5 to 4.0 or even 5.0 LPM, it has become much more difficult to meet this requirement. Rotameter scale length has necessarily followed the miniaturization trend of pump design and gradually shrunk from as much as 4 inches to as low as 1.5 inches in more recent designs. Visual parallax alone makes it extremely difficult to align the ball and tube markings to within the ±0.024 inch (±5%) resolution required for a 1.5 inch scale length at 1.6 LPM.

Clearly a need exists for a wide range, high accuracy flow display for compact personal sampling pumps. The design rationale is described and statistical performance data are presented for a newly patented pump[2] which incorporates an electronic laminar flow (ELF) measurement and control scheme to meet this need.

PUMP FLOW CONTROL: HISTORY AND RATIONALE

The preferred and usual method of automatically controlling any process variable is to make a direct measurement of that variable and use that measurement to make an appropriate adjustment of a process input, typically an energy source, to bring the controlled variable into compliance with the process requirements.

A baking oven, for example, might require control at 200°C ±5°C. Because both the ambient temperature and the number of loaves of bread may vary, the process load is variable and the oven cannot, therefore, be adequately controlled using a single setting of the fuel input or electrical wattage to the oven. Thus such a process is usually controlled by incorporating a thermocouple or other temperature sensor within the oven and transmitting the sensor signal to a comparator module where its signal is compared to a setpoint which duplicates the ideal sensor signal. The difference signal between the two values, plus or minus, is then fed to an automatic control module where the decision is made whether to maintain, increase, or decrease the existing wattage setting (or fuel valve setting). The control mechanism might be as simple as an on-off relay or as sophisticated as proportional control plus integral and derivative action corrections. In either case, the objective is to bring the measured value of the control condition into compliance with the process requirements.

The analogy of temperature control of a baking oven to flow control of a compact personal sampling pump is, however, tenuous at best. The technology needed to include a very small, low power flow sensor capable of feedback control of a d.c. powered pump drive mechanism with simultaneous flow rate display capability has either not been available or has been considered too costly to implement at a competitive price.

For these reasons most state-of-the-art personal sampling pumps incorporate an inferential electronic flow control system wherein the pump and drive mechanism is characterized in a laboratory setting by noting flow rate and vacuum load (pneumatic parameters) vs. motor voltage and current drain (electrical parameters). As an over-simplified explanation of this technique, any increase in vacuum load will cause an increase in motor current drain and tend to decrease flow rate. A current sensor, however, senses this change and activates a compensation circuit (as determined by the laboratory characterization) to increase the motor voltage to maintain the same approximate flow rate. A temperature compensation circuit provides additional correction to maintain the flow setpoint. This feed forward technique can work well in a well designed pump system, as in the MSA FLOW-LITE™ series of personal sampling pumps. However, both normal and abnormal wear and tear affect the pump's pneumatic vs. electrical parameters; therefore, pump calibration must be checked frequently. Recalibration of this type of control system usually involves tedious adjustment and "fine tuning" of three separate potentiometers.

In still another patented flow control scheme,[3] the pressure swings across an adjustable needle valve are sensed by a pressure switch and converted to an electrical signal whose difference from setpoint provides a corrective signal for the motor control circuit. The control signal in this case is produced directly by the flow itself. This technique also works quite well, but is affected by altitude changes non-linearly.[4]

Neither the inferential technique nor the pressure switch scheme provide a signal which can be readily used to display flow rate.

The only direct flow measurement and control scheme heretofore capable of electronic display was the mass flow sensor system.[5] While this scheme provided extremely tight flow control, the flow signal required linearization (or a look-up table with a microprocessor) for display. Moreover, power consumption of the constant temperature anemometer type flow sensor system made it difficult to further reduce the overall pump package size.

The effort to provide direct volumetric flow measurement and control in a personal sampling pump was stalemated for many years by component size, power, performance, complexity and cost restraints. As the technology of silicon diaphragm strain gauge pressure sensors has advanced, however, these restraints have been eliminated. It is now possible to build a miniature high performance volumetric flow sensor that is cost-competitive with the rotameters used in so many personal sampling pumps.

For a number of years MSA has used a variety of flowmeters during production calibration which incorporate both a laminar flow element to create a linear pressure drop with flow and a pressure sensor to convert this pressure drop and display it as a volumetric flow reading. It was apparent to MSA's designers that a miniaturized version of the laminar flow meter could provide the key to an enhanced performance sampling pump.

LAMINAR FLOW METER: THEORY AND PRACTICE

The inherent linearity and stability of the laminar flowmeter is well known and documented in a multitude of references.[6,7,8,9] These documents describe a flowmeter device that obeys a modified form of Poiseuille's law of viscous flow (as opposed to turbulent flow). The Poiseuille law states that the pressure drop, P_1-P_2 , across a tube of length L and diameter D, carrying a flow at an average velocity V of fluid with a viscosity μ, follows the Poiseuille-Hagen equation:

$$P_1 - P_2 = \frac{32\mu VL}{D^2}$$

It has been found empirically that the Poiseuille equation applies only to relatively small diameter tubes at low velocities, i.e., where the Reynolds number is less than 1600. The Reynolds number, N_{Re}, equals $DV\rho/\mu$ where ρ = density of the fluid. This dimensionless number is often thought of as the "turbulence factor" since its value defines the relative state of flow. At a condition of viscous or laminar flow the flow lines are straight and parallel and the flow profile across the tube is parabolic. As the Reynolds number increases above 4000 the flow lines become turbulent with the formation of eddy current vortices. The flow profile also flattens. Laminar flow is also termed viscous flow because the resistance to flow (pressure drop) is primarily a function of the drag of one layer of fluid on the adjacent layer starting with the static layer at the wall. It should be noted that density is not included in the laminar

(Poiseuille) flow equation, but does play a major role in turbulent flow formulae, e.g., orifice flow equations, where the back pressure is proportional to ρV^2. In practice flow patterns are seldom ideal and laminar flow equations at Reynolds numbers up to 1600 often include a small correction term for turbulent flow. Thus the equation for a flowmeter based on Poiseuille's law may include a non-linear second term for maximum accuracy, e.g., $\Delta P = a\mu V + b\rho V^2$, where a and b are empirically derived constants. Some manufacturers of laminar flow elements place maximum recommended pressure drops on their devices in order to keep Reynolds numbers low enough that the turbulent flow term can be ignored.

The rangeability data for various gases reported in one laminar flow element manufacturer's literature[10] indicate compliance to Poiseuille's law generally within ±1% or at least as good as available viscosity data. Reference 7 gives some guidelines for construction of laminar flow elements including smooth, uniform flow paths and a ratio of length to flow diameter of 100 or more. Such restrictions and the associated need to provide multiple parallel flow paths to increase flow range contribute to the relatively large size of commercial laminar flow elements.

A laminar flow sensor was chosen because of its insensitivity to changes in altitude. Although barometric pressure affects density, it is not a factor in the linear term of the ΔP equation above. Viscosity is a factor but pressure's effect on viscosity is <0.01% per psi.[9] A number of other design criteria were also set. For example, the flow sensor system could not add more than 4 inches w.c. to the pump load at 4.0 LPM flow. A tubular type laminar flow element to meet this requirement at a Reynolds number below 200 (another design criteria) would be much too massive. Luckily, porous elements also exhibit a Poiseuille flow characteristic as evidenced in a unique pneumatic flow controller design.[11] After evaluating a number of porous elements of varying shapes, sizes, and porosities, a closed-end cylinder, 1 inch long by $\frac{1}{4}$ inch OD of 20 micron porosity stainless steel, was selected for the laminar flow element. A low power miniature differential pressure sensor with a range of 4 inches w.c. was selected to monitor the pressure drop from the outside to the inside of the porous cylinder. Several identical flowmeters were constructed from these elements and tested. When powered by a well regulated d.c. supply, the zero and span stability was found to be excellent. Multipoint flow calibration showed typical linearity to be better than ±1% f.s. Further testing at temperature extremes of -5 to +55°C in an environmental chamber showed that some correction for temperature was warranted and a temperature compensation circuit was added to provide this correction.

THE ELF PUMP

Features

It was clear that the electronic laminar flow (ELF) sensor just described could be integrated in a compact pump design to provide not only a high resolution flow display but the measurement required for direct flow control and easy calibration.

Customer input derived over many years in the personal sampling pump market dictated careful attention to other design criteria. The result of the design effort is a compact (2"x4"x3$\frac{7}{8}$"), lightweight (19 oz), highly durable quiet personal sampling pump with an operating range of 1.0 to 3.0 LPM accurate to ±2.5% of setpoint over a wide range of environmental conditions. The package has also been designed to seal against dust and water entry to meet an Ingress Protection (IP) rating of 66 per IEC Standard 529, thus facilitating water washdown and spray during and after asbestos sampling. A high visibility 3 digit LCD display alternately shows elapsed running time and sample flow rate. The metal-filled plastic case provides both EMI/RFI and electrostatic shock protection.

These and other features are covered in the following sections.

Description

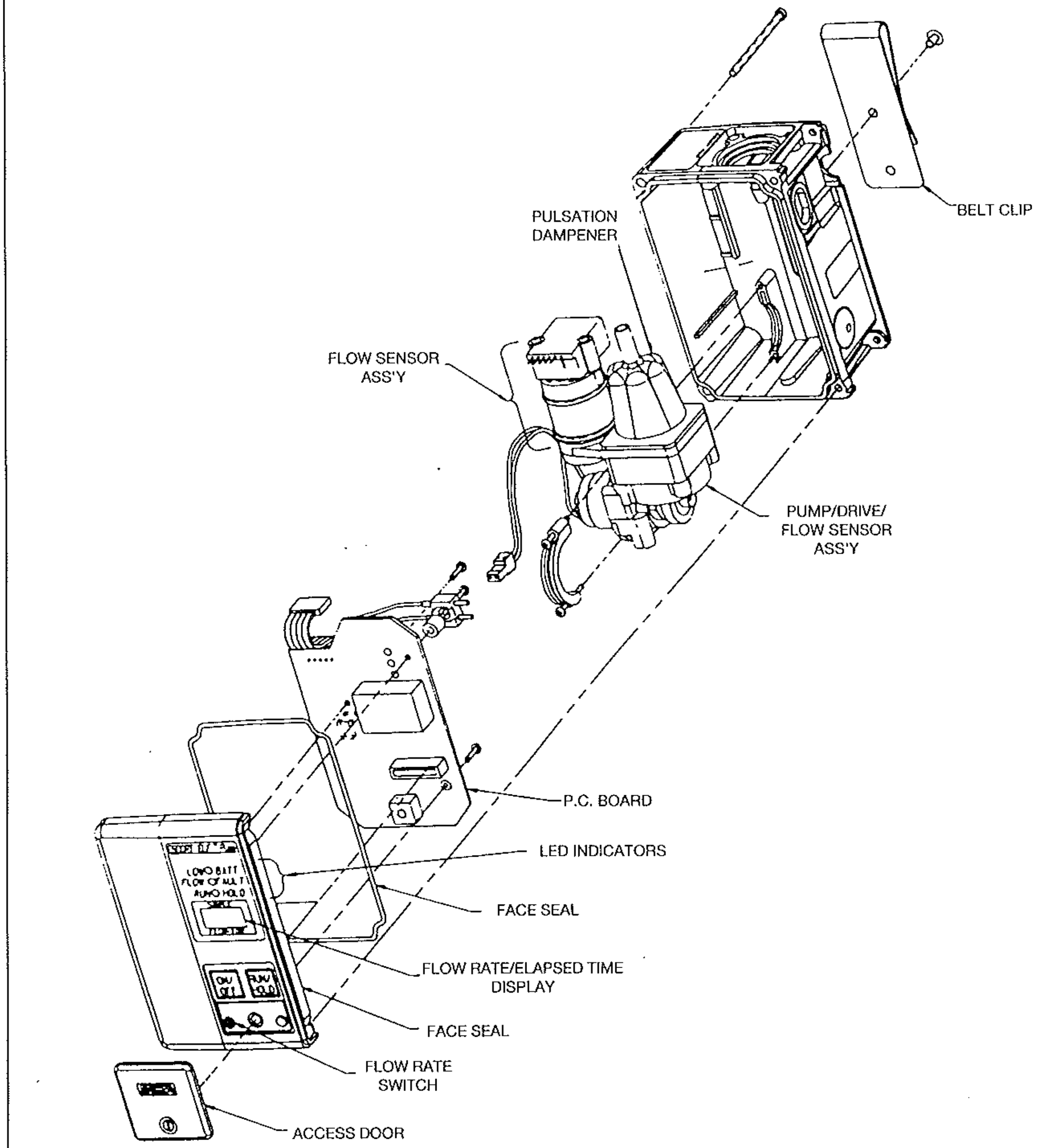
The Escort ELF Sampling Pump can be used with a variety of personal and area sampling devices to collect such airborne contaminants as: asbestos fibers, silica, coal and wood dusts, toxic gases, vapors, fumes and mists.

The Escort ELF Pump provides enhanced flow regulation for many types of sample collection media, including filter discs, charcoal tubes and other sorbent tubes, impingers and reagent filter discs.

Exceptionally compact, lightweight and quiet in operation, the Escort ELF Pump promotes rapid user acceptance. Engineered for use in "hostile" environments, the unit can be sprayed with water while operating without being damaged.

The state-of-the-art electronic laminar flow sensor, consisting of a laminar flow element and pressure sensor, provides constant flow (volume) control, with ±2.5% regulation of flow rate (from 1.0 to 3.0 LPM) and automatic compensation for changes in battery voltage, temperature, altitude and sample load.

FIGURE 1. Exploded View of Escort ELF Pump (Less Inlet Filter and Battery Pack)



The circuit board, labelled P.C. Board in Figure 1, is assembled with surface-mount devices (SMD) which provide an extremely compact module.

The internal diaphragm pump provides vacuums comparable to heavier, bulkier pumps. Normal flow range of the Escort ELF Pump is 0.5 to 3.0 LPM, covering most industrial hygiene applications. Note that both the inlet pulsation dampener and the flow sensor are integral parts of the pump and drive assembly. This modular construction facilitates assembly and maintenance procedures.

The stainless steel-filled plastic case provides protection against electromagnetic or radio-frequency interference (EMI and RFI, respectively). The unit is assembled with stainless steel screws. A belt clip allows the unit to be worn at the waist.

Four gaskets seal the case, making the unit resistant to water spray and dust while running. This feature is especially important to asbestos abatement workers who pass through decontamination showers while wearing the unit. The gaskets are located between: the main body of the pump and front face; battery pack connection and main body; the inlet filter and tubing connector; and the access door and front face.

A special Teflon* filter prevents water and dust from being drawn into the pump mechanism, thus increasing service life (see Figure 2). A transparent view window over the filter on the inlet lets the user judge whether replacement of the inlet filter is warranted.

The Escort ELF Pump includes separate LED's to indicate flow blockage and low battery voltage.

The state-of-the-art mechanical design of the Escort ELF Pump is highly efficient, allowing the use of a compact rechargeable NiCad battery pack. Its compact size helps keep the overall weight of the pump low.

Battery operating time varies, depending on the selected flow rate and the pneumatic load imposed by the chosen sampling device, but in most cases the Escort ELF Pump will operate for a full eight-hour shift before recharging is necessary (see Figure 3).

FIGURE 2. Inlet Filter Assembly

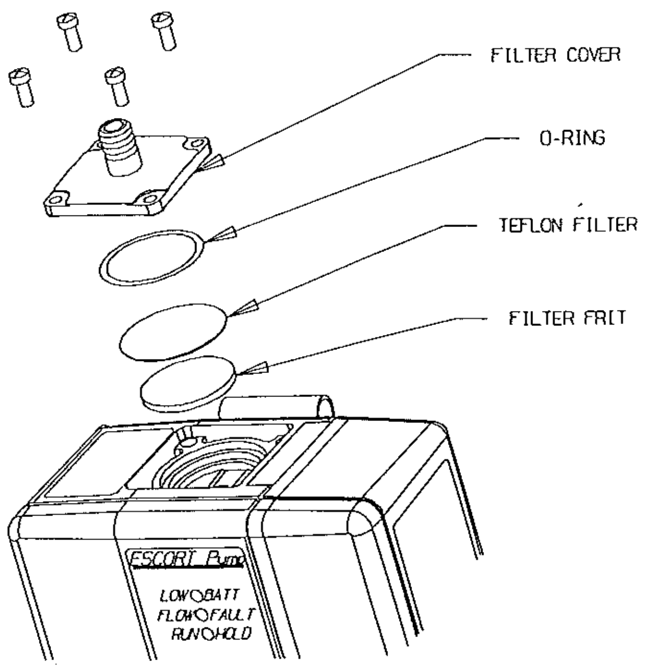
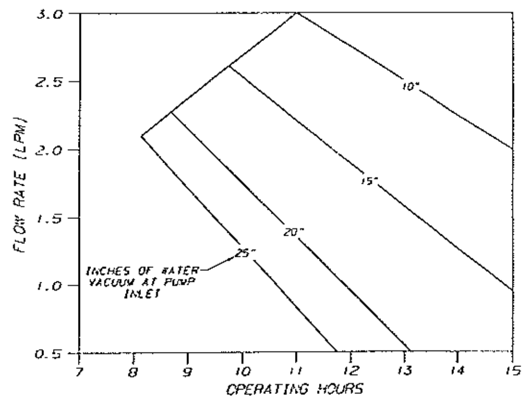


FIGURE 3. Typical Flow and Load Regime



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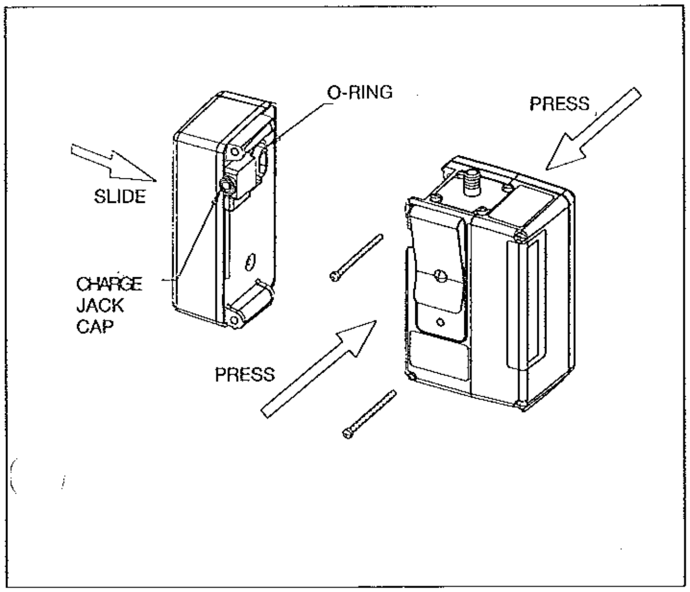
*Trademark of the DuPont Company

The port for the charging jack is located on the battery pack (see Figure 4) rather than the pump module, so that the battery can be recharged either while on the unit or when removed. Note that while the charge jack is sealed internally, a captive sampling plug is provided to prevent water entry and contact corrosion while the pump is in use.

FIGURE 4. Escort ELF Battery Pack



Operation

As shown in Figure 5, air flow from the pump outlet passes through the ELF sensor's laminar flow element, a hollow cylinder of porous stainless steel. Air flowing through the pores of the element produces an air pressure difference between the outer and inner walls of the cylinder, which is monitored by connections to the differential pressure sensor. The electrical signal from the sensor, which is linearly proportional to the air flow through the laminar element, is compared to the flow set-point in the electronic circuit. Any deviation in flow rate is sensed, and the motor power is adjusted to increase or decrease pump speed and maintain the preset flow rate.

Because of this method of flow detection, pressure changes due to atmospheric changes or sample load have minimal effect on flow rate. Figure 6 shows a typical test run where severe load changes were deliberately induced.

FIGURE 5. Flow- Feedback Control System

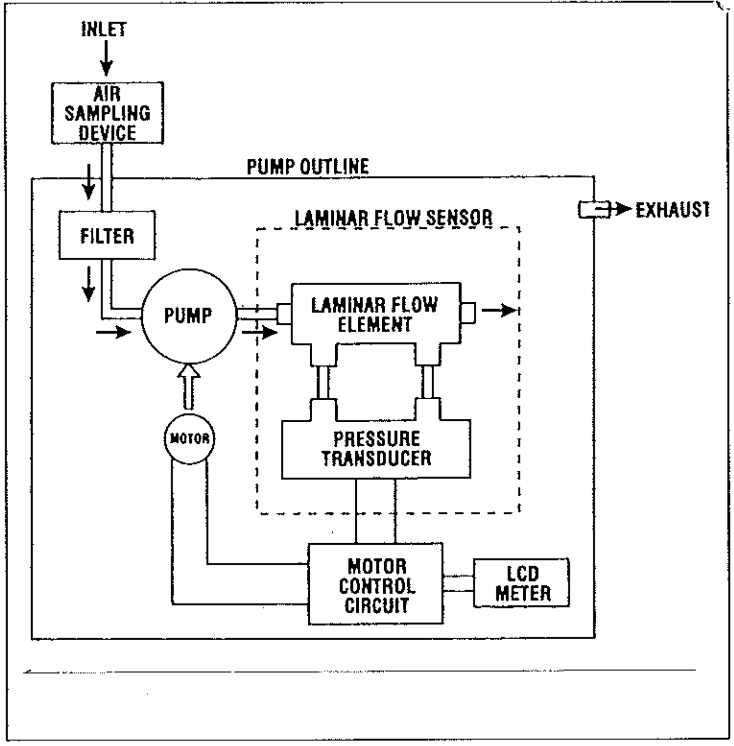
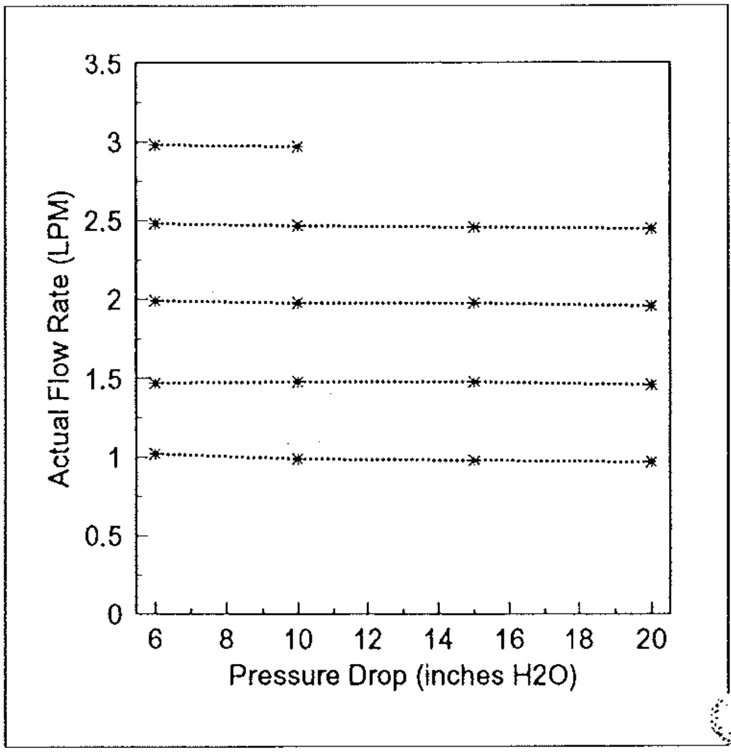


FIGURE 6. Actual Test Data Showing Typical Effect of Pressure Drop Changes on Flow Rate Control



The display automatically sets itself to zero when the pump is turned on. The timer accumulates and displays total elapsed running time in minutes. When the pump is turned off, the elapsed running time remains on the display so that it can be recorded by the user. Only when the pump is turned on again will the timer reset to zero and the display alternately indicate elapsed time and flow rate values.

In the event that a flow blockage occurs, the Flow-Fault Indicator circuitry illuminates an LED to alert the user. Within 90 seconds, the pump automatically shuts off, but the cumulative elapsed time remains on the display.

If the battery voltage drops to 4.3 volts, the LOW BATT LED blinks to caution the user that the pump will soon shut down. If the sampling is continued and the battery drops below 4.1 volts, a low-battery condition results. When this condition occurs, the LED illuminates continuously and the pump immediately shuts off. However, the accumulated elapsed time to that point is retained on the display for user reference. Further battery drain is limited to just a few milliamperes, which helps prevent damage to the battery pack through deep discharge.

The pump calibration is very stable over long periods and will not require recalibration more than monthly (or after 200 hours of operation for coal dust sampling) to insure accurate sampling. A special calibration mode is provided for this purpose. An independent NIST traceable flow measurement is made of pump flow. The flow display is then stepped up or down in 0.01 LPM increments to match the NIST Standard measurement. Turning off the pump completes the calibration.

Specifications

Electrical Characteristics:

Power Supply: 4.8-volt battery pack of four nickel cadmium cells.

Battery Pack Capacity: 1.8 amp-hours.

Battery Pack Recharge Time: 14-16 hours (overnight) with Omega™ Charger.

Typical Battery Pack Life: 300 or more charging cycles.

Operating Characteristics:

Calibration Interval:
To meet OSHA Technical Manual[12] requirements, the ELF flowmeter itself could be considered as the cited secondary calibration device. As such, it must be calibrated at least once a month with a bubble meter. (Recommended every 200 hours of operation per CFR Part 74.3 Title 30 for coal dust sampling).

Flow Control:
Volumetric flow rate held within ±2.5% of set-point over the 1.0 to 3.0 LPM operating range (±5% to 0.5 LPM) over any eight hour day, with automatic compensation for battery voltage, altitude, temperature and sample load changes.

Flow Rate:
Flow rate adjustable between 0.5 and 3.0 LPM in 0.1 LPM intervals.

Flow Indication:
Liquid Crystal Display provides 0.01 LPM resolution and ±2.5% accuracy of actual flow.

Operating Range:
30 inches of water load up to 2.0 LPM; 20 inches up to 2.5 LPM and 10 inches up to 3.0 LPM.

Flow Blockage Detection:
Flow-Fault LED comes on immediately when block is detected. Pump shuts down within 90 seconds if block is not cleared.

Elapsed Time Readout:
To 999 minutes in increments of 1 minute. Holds the last reading after either flow blockage or low-battery shutdown and when pump is off or in hold mode.

Operating Time:
Varies with flow rate and sampling device loading (see Figure 3).

Operating Temperature Limits: 32°F-113°F (0°C-45°C).

Physical Characteristics:

Weight: 19 oz. (550 gm), with battery pack.

Dimensions:
2" deep x 4" high x 3⅞" wide (5.1 cm x 10.3 cm x 9.8 cm), with battery pack.

Serial Number Identification:
Located on side of pump under battery pack.

Approvals:

UL: Intrinsic safety certification (File E 106436) for use in hazardous locations - Class I, Groups A, B, C, and D; Class II, Groups E, F, and G and Class III, Division I locations.

NIOSH: Certified for coal mine dust sampling (TC-74-030).

MSHA: Certified as intrinsically safe for underground use (Approval No. 2G-3924-1).

FLOW STABILITY TESTS

Several early production Escort ELF pumps have been drawn from stock at random and subjected to in-house testing to evaluate long term flow stability. These results are reported here.

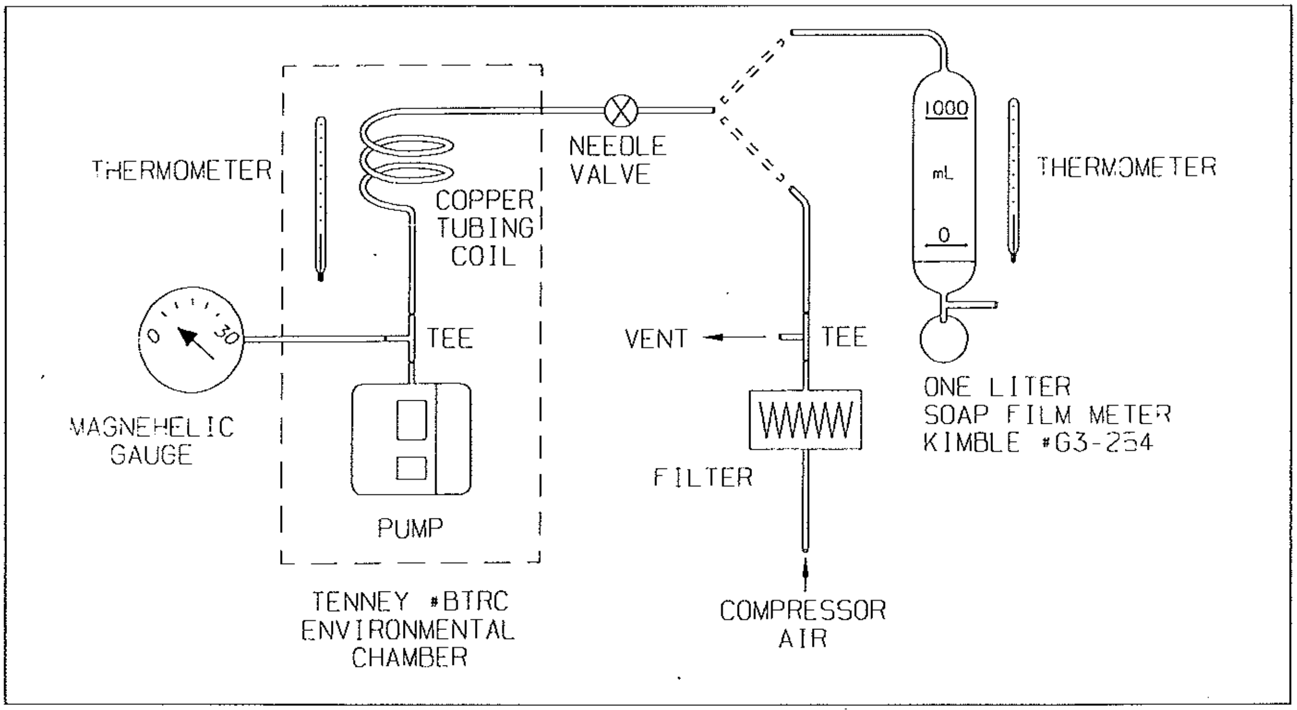
A long term calibration accuracy test was devised to verify compliance of the original calibration to within ±5% after 200 hours of operation as required by MSHA.[1]

Experimental Materials and Methods

Three production pumps were used in the following test protocol. The pumps were initially calibrated at room temperature (20°C) at a flow setting of 2.5 LPM. Actual flow data points were then taken at 0.1 LPM intervals from 1.0 to 3.0 LPM using a 1.0 liter soap film volumeter. The original pump calibration setting was not changed during the 100 calendar days of the test program. Each working day (60 days total) thereafter each pump was operated for an 8 hour shift, usually for a 5 day week.

The flow rate each day was set at either 1.6, 2.0, 2.5, or 3.0 LPM in a random, but specified pattern, so that each flow rate was tested for an equal number of days.

FIGURE 7. Performance Test Apparatus



Depending on the flow rate, the vacuum load was also changed in a similar matrix to either 4, 10, 17, 20, or 30 inches w.c. in order to provide a wide-ranging test protocol.

The first hour's operation was at room temperature and the next seven hours at either 0°C or 45°C (on alternate working days) in a Tenney* environmental test chamber. Flow calibration data was taken at the specified flow setting both at room temperature and at the test temperature for that day. In all, the test program encompassed 60 working days. Weekends, holidays and vacation time account for the 40 days of non-operating time. The test apparatus system is shown in Figure 7. It should be noted that the bubble meter and humidifier were connected to the pump only during flow measurements to preclude excessive condensation at low test temperatures. All bubble meter values were corrected to actual Tenney chamber temperatures.

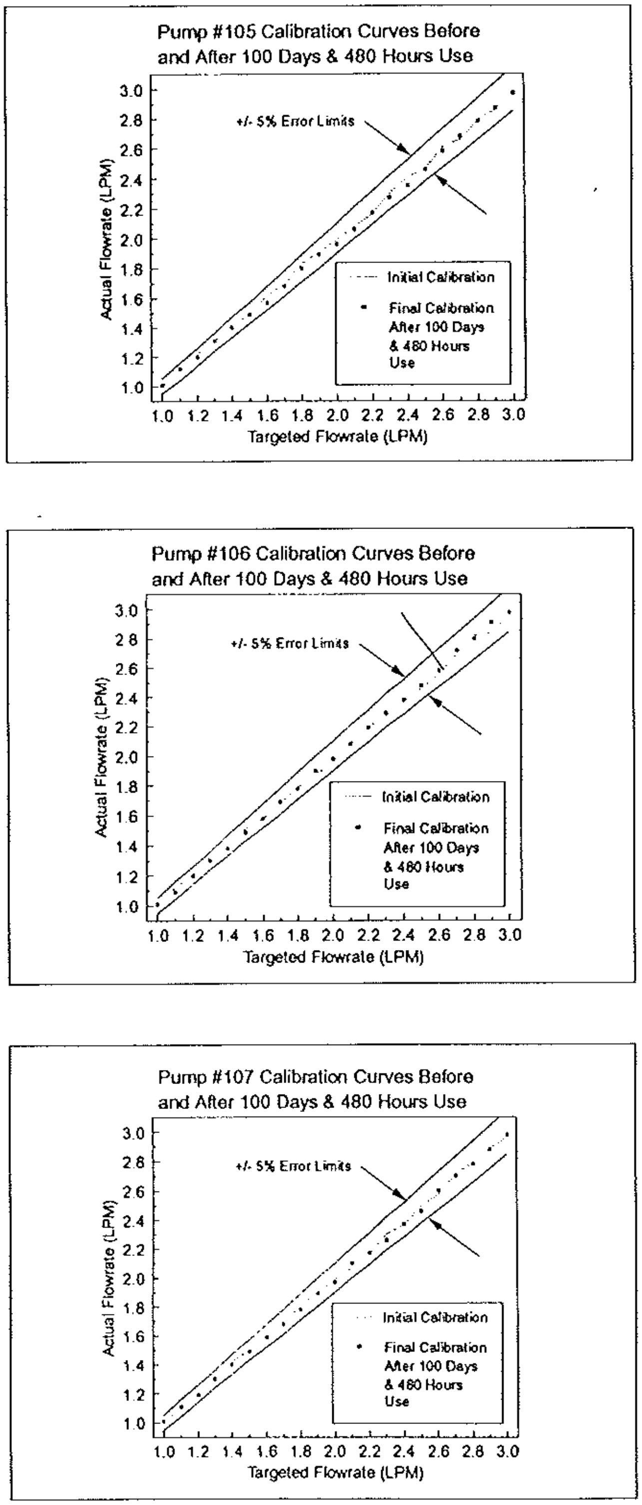
Results and Discussion

At the end of the 100 day period, (480 hours operating time for each pump), the original pump calibration data were verified by rechecking the data points at 0.1 LPM intervals. Figure 8 shows these comparison data. All three pumps showed similar performance, i.e., all held their original calibration to within ±2.5% or better. In addition, all the flow data points from the room temperature, 0°C and the 45°C tests (over a 1000 data points) were accumulated and subjected to a Student's t-distribution analysis, where it was found that over the 1440 total hours of operation, the original calibration held within the required ±5% window for coal mine dust sampling (1.6 to 2.0 LPM) at all test conditions. The histograms in Figure 9 on the following pages show the actual frequency distribution of the raw flow data at 1.6, 2.0, 2.5, and 3.0 LPM, respectively. The data clearly illustrate that the 95% Confidence level criteria for flow calibration are met.

SUMMARY

Both these in-house tests and the many favorable customer comments have verified the efficacy of the laminar flowmeter approach to measurement and control of personal sampling pumps. The data indicate that calibration of the pump's internal secondary standard is required only every 200 or more hours of operation. It is expected that this technique will be considered as "state-of-the-art" in sample pump design for many years to come.

FIGURE 8. Calibration Accuracy of Escort ELF Pumps



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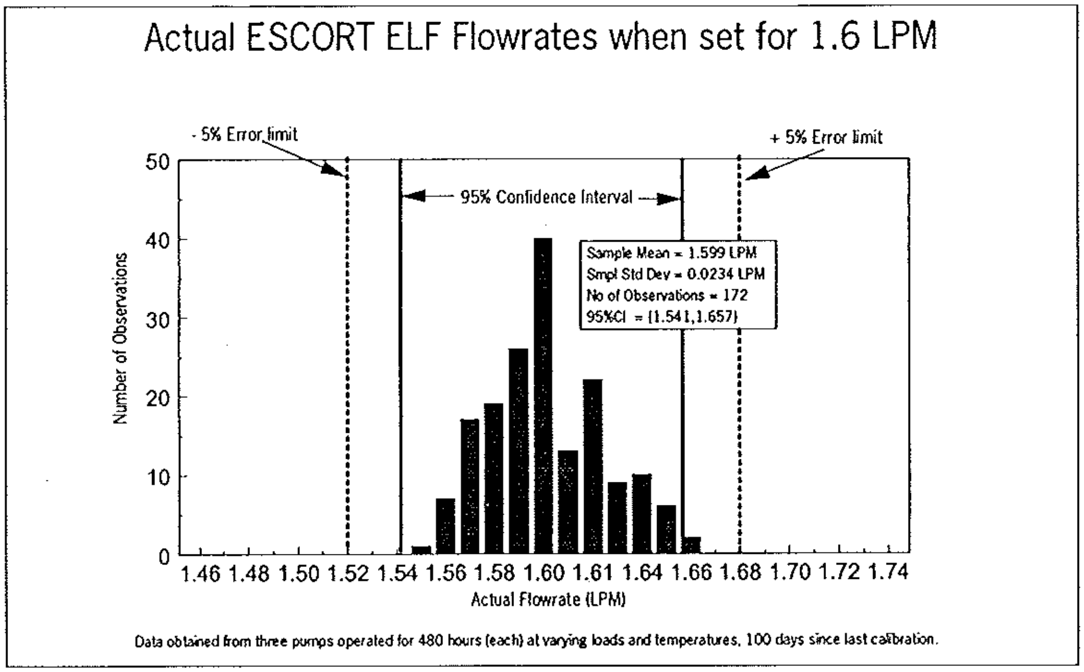
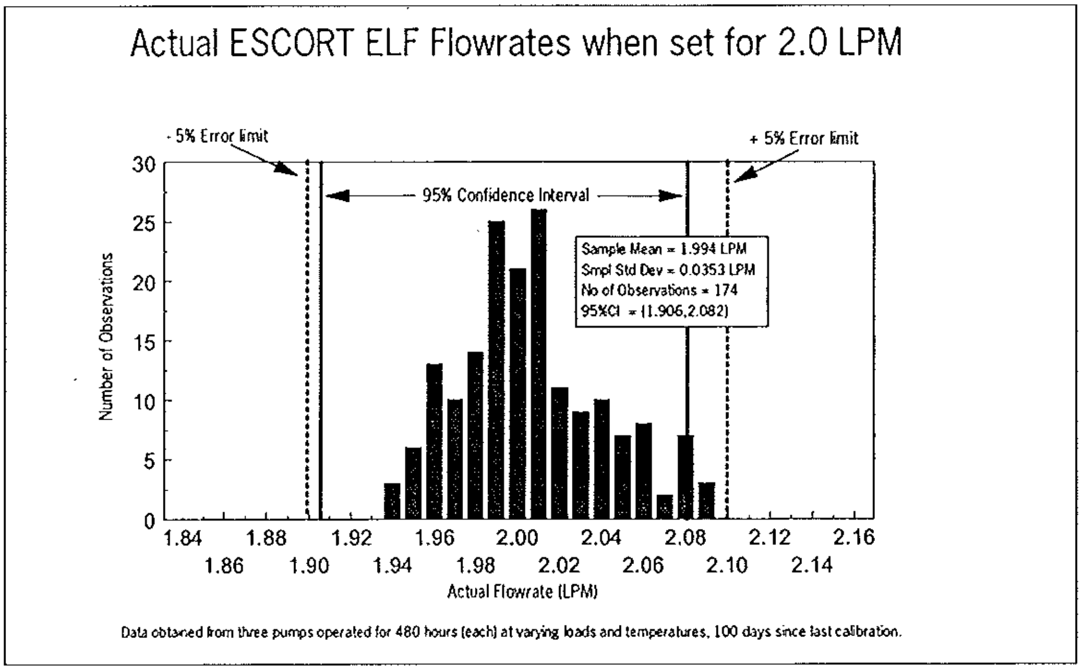
*Tenney is a trademark of the Tenney Company

FIGURE 9. Frequency Distribution of Data Used to Calculate Students t-95% Confidence Intervals at Various Flow Rates

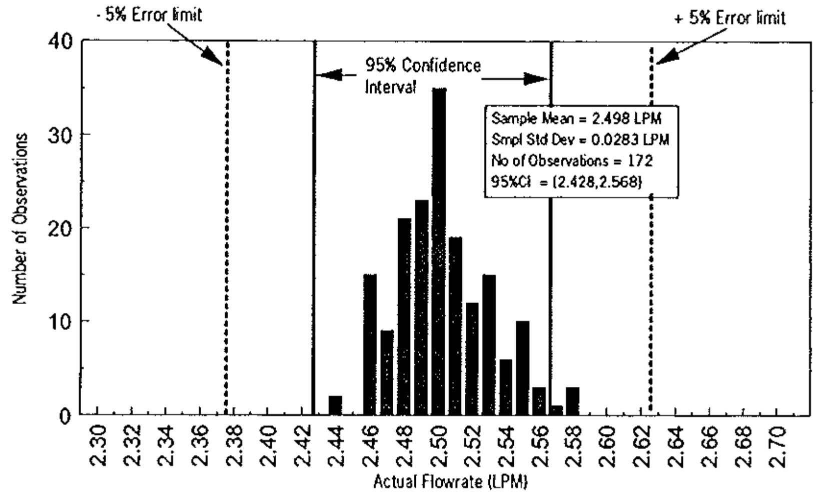


Data obtained from three pumps operated for 480 hours (each) at varying loads and temperatures, 100 days since last calibration.



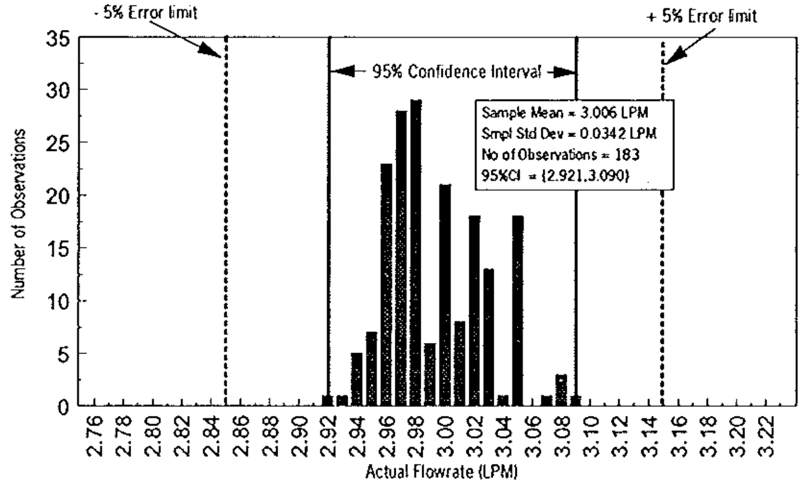
Data obtained from three pumps operated for 480 hours (each) at varying loads and temperatures, 100 days since last calibration.

Actual ESCORT ELF Flowrates when set for 2.5 LPM



Data obtained from three pumps operated for 480 hours (each) at varying loads and temperatures, 100 days since last calibration.

Actual ESCORT ELF Flowrates when set for 3.0 LPM



Data obtained from three pumps operated for 480 hours (each) at varying loads and temperatures, 100 days since last calibration.

ABOUT THE AUTHORS

CLAYTON J. BOSSART currently consults to Mine Safety Appliances Company after a distinguished career of 36 years in the development of portable instruments and sensors at MSA. Mr. Bossart's achievements include development of the first commercial programmed temperature process gas chromatograph as well as the first commercial dual temperature zone process gas chromatograph; pioneer work in the development of chemically bonded liquid phases; and development of the catalytic PELEMENT™ sensor, the industry benchmark standard for a poison resistant combustible gas detector. He holds twelve patents in gas chromatography and fluid analysis technology.

A Chemical Engineering graduate of the University of Wisconsin, Mr. Bossart won the Instrument Society of America Award for "Excellence in Documentation" and in 1982 was elected to the grade of Fellow of the Instrument Society of America for his technical contributions to gas analysis instrumentation.

BRUCE P. APEL has been with Mine Safety Appliances Company since 1985. As Quality Assurance Engineer at MSA's Instrument Division, Mr. Apel is responsible for product quality of all portable instruments. He develops new product qualification test plans, reviews manufacturing test procedures, and recommends test and design revisions to assure continued quality throughout a product's life cycle.

An Electronic Engineering Technology graduate of the University of Dayton, Mr. Apel is an ASQC Certified Quality Engineer and Certified Reliability Engineer.

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Note: This bulletin contains only a general description of the Escort ELF Sampling Pump and accessories. Wile users and performance capabilities are described, under no circumstances should the products be used except by qualifed, trained personnel and then not until the instructions, lables or other literature accompanying them have been carefully read and understood and the precautions therein set forth followed. Only they contain the complete and detailed information concerning these products.

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