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Formaldehyde Sampling From Automobile Exhaust: A Hardware Approach

William M. Pidgeon

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Test and Evaluation Branch
Emission Control Technology Division
Office of Mobile Sources
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1. Introduction

Formaldehyde emissions sampling system hardware became an issue with the Environmental Protection Agency's (EPA) release of a Notice of Proposed Rulemaking (NPRM) for Methanol-Fueled Vehicles and Engines[1]. This report discusses a formaldehyde sampling system that EPA's Emission Control Technology Division, Test and Evaluation Branch (TEB) will use for tests of light duty vehicles and light duty trucks. It also discusses the considerations involved in selecting the specific hardware used to meet TEB's needs.

The purpose of this report is to provide information on one approach for sampling formaldehyde emissions and to explain why this approach was taken.

2. Summary

TEB found that using a thermal mass flow controller in a system to sample vehicle formaldehyde emissions has three major advantages over a critical flow venturi. The thermal mass flow controller:

1. allows proportional sampling with a heated or unheated probe;
2. allows the flow rate to be easily varied; and,
3. is less restrictive to flow

Additionally, the flexibility needed to allow using larger low restriction formaldehyde collectors is enhanced by using a twin diaphragm sample pump installed downstream of the controller.

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[1] "Proposed Emission Standards and Test Procedures for Methanol-Fueled Vehicles and Engines, Draft Regulations," U.S. Environmental Protection Agency, Office of Mobile Sources, Emission Control Technology Division, Summer 1986.

3. The NPRM Required Sampling System

To comply with the NPRM, a formaldehyde sampling system must meet the following basic requirements:

1. It must be used with a constant volume sampler (CVS) which mixes ambient air with the vehicle exhaust and measures the total volume of the resulting dilute exhaust.

2. The formaldehyde sample flow must be taken from the dilute exhaust flow (CVS flow) and the sample flow rate must be proportional to the CVS flow rate.

3. The total formaldehyde sample volume must be measured.

4. The formaldehyde sample probe and sample lines must be heated and maintained at 235°F ±15°F. (The final regulation may not require the sample probe to be heated.)

4. Formaldehyde Sampling System Design Considerations

Section 4 presents three issues that arose in designing a formaldehyde sampling system to be used with a critical flow venturi (CFV) type CVS while meeting the requirements of the NPRM.

4.1 A Basic System for Formaldehyde Sampling

The system in Figure 1 illustrates a formaldehyde sampling system that can be added to a CFV-CVS. The sample probe in Figure 1 holds a small CFV that is located just upstream of the dilute exhaust CFV (not shown). The sample probe's CFV is used to meet the NPRM's requirement that the sample mass flow be proportional to the dilute exhaust mass flow. The rest of the components in Figure 1 should be self-explanatory.

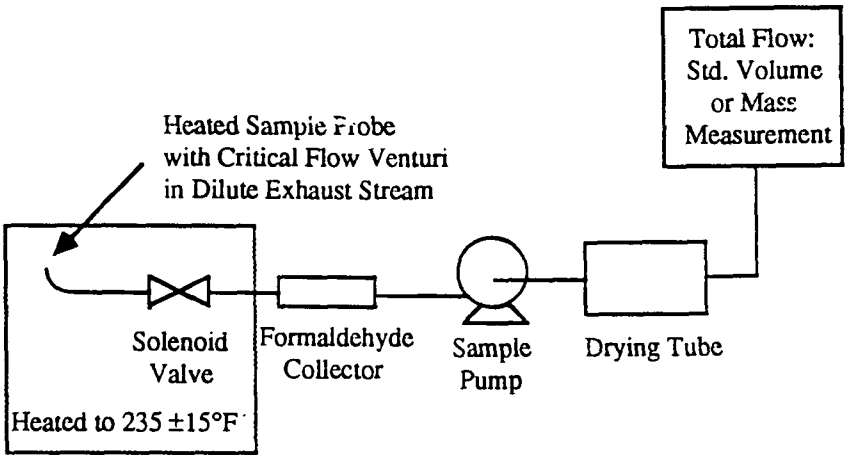

Figure 1

This CFV system did not meet TEB's needs for three reasons that will be discussed in Sections 4.2 through 4.4. Section 5 will discuss the thermal mass flow controller system that was used to overcome the problems discussed below.

4.2 The Proportional Flow Problem When Using a Heated Probe

The NPRM required the formaldehyde sample CFV to be heated to 235 ±15°F. However, to maintain a sample flow rate that is proportional to the CVS flow rate, the temperature and pressure at the inlets of the dilute exhaust CFV and the sample CFV have to be the same or change by the same magnitude. Heating the sample CFV to 235°F and controlling it there isolates the sample CFV from temperature changes at the dilute exhaust CFV. The sample flow rate consequently does not respond to exhaust temperature excursions as the CVS venturi does, and proportional flow is not maintained. Testing performed after the NPRM was published confirmed that proportional flow could not be maintained when the sample CFV was heated.[2] If the final regulation drops the requirement for a heated probe, this problem will not be relevant.

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[2] Adams, Walter A. "Use of Heated Crtitical Flow Venturi Sample Probes To Maintain Proportional Flow," U.S. EPA, Report No. EPA-AA-TEB-87-01, Office of Mobile Sources, Emission Control Technology Division, Test and Evaluation Branch, February 1987.

In summary, TEB's need to comply with the NPRM requirements for proportional sample flow through a heated probe was the first problem encountered in using a CFV for formaldehyde sampling.

4.3 The High Pressure Drop Problem

One of TEB's design objectives was to use 2,4 dinitrophenylhydrazine (DNPH) coated Sep-Pak silica cartridges[3] rather than impingers for formaldehyde collection. The cartridges are easier to handle and much smaller (1 cm outside diameter by 2 cm long) than impingers.

The pressure drop across two cartridges in series is 8.7 pounds per square inch (psi) when flowing 1 standard liter per minute (slpm). Gabrysiak[4] found that the pressure drop across a CFV used with the Sep-Pak silica cartridges made it impractical to use a CFV. Gabrysiak's calculations showed that using one Sep-Pak cartridge with a CFV requires a CFV outlet pressure of 1.9 pounds per square inch absolute (psia) with the inlet pressure at 14.7 psia. His calculation assumed that the CFV required an outlet to inlet pressure ratio (P_{out}/P_{in}) of 0.60 or less to achieve critical flow conditions. This pressure ratio assumption was based on an unpublished study by Carl Ryan and Bill Harbowy on the sample CFVs used at EPA's Motor Vehicle Emission Laboratory for bag samples that was cited by Paulina [5]. The study showed that P_{out}/P_{in} had to be 0.60 or less to maintain critical flow.

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[3] Tejada, Silvestre B. "Evaluation of Silica Gel Cartridges Coated *In Situ* with Acidified 2,4-Dinitrophenylhydrazine for Sampling Aldehydes and Ketones in Air," U.S. EPA, International Journal of Environmental Analytical Chemistry, Vol. 26, pp. 167-185, 1986.

[4] Gabrysiak, John. "Heavy Duty Methanol Engine Test Development Project Overview: Briefing for the Branch Chief," U.S. EPA, Standards Development and Support Branch, January 21, 1988.

[5] Paulina, Carl. "Non-Propotional Sample Rates in a Critical Flow Venturi Constant Volume Sampler: Effects on Federal Emission Test Fuel Economy," Engineering Operations Division, U.S. EPA, Report No. EPA-AA-EOD-84/2, January 1982.

Better performing CFVs allow a P_{out}/P_{in} as high as 0.80 in the 1 slpm range. Figure 2 shows the calculated pressure drops across a system using two cartridges in series with a CFV permitting a P_{out}/P_{in} of 0.80, and using Ann Arbor's average atmospheric pressure of 14.3 psia. These conditions reduce the vacuum pump's inlet pressure to only 2.7 psia at 1 slpm, without considering the pressure drops through the control valves and other components. This shows that even with the more efficient of the CFVs, the pressure drop is still prohibitively high.

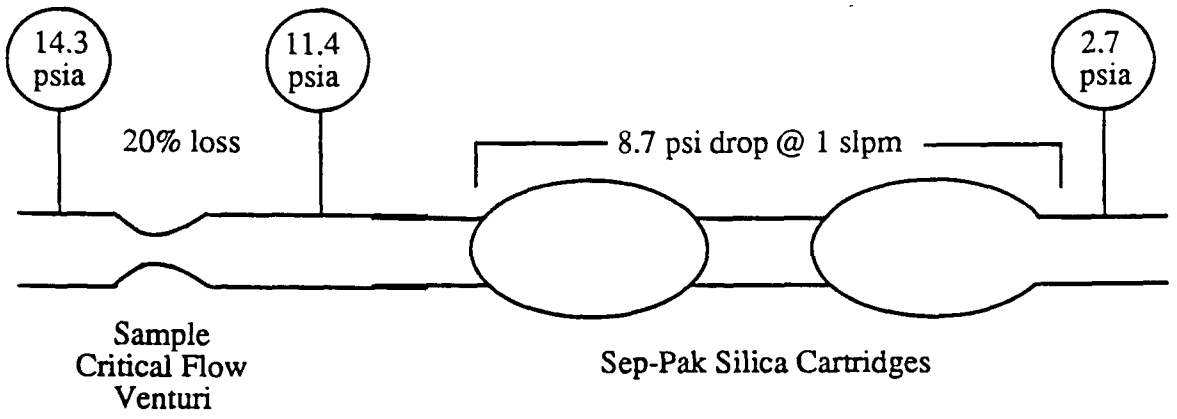


Figure 2

Additionally, the diameter of a 1 slpm CFV for this application is only .015 inches, which makes particulate contamination and maintenance an issue. And, since the maximum P_{out}/P_{in} to achieve critical flow conditions is 0.80, a safety factor is needed to ensure that critical flow is maintained. In actual use with vehicle exhaust, a maximum P_{out}/P_{in} of 0.75 is needed to provide an adequate safety factor, but this increases the restriction.

In summary, TEB's decision to use the highly restrictive Sep-Pak cartridges added a second problem to using a CFV for metering formaldehyde sample flow.

4.4 Variable Sample Flow Rate

TEB often tests prototype vehicles, catalyst and non-catalyst equipped vehicles, and also tests over wide temperature ranges (20-95°F). These factors cause formaldehyde emissions to vary over a wider range than is expected for certification vehicles tested under Federal Test Procedure (FTP) conditions. The quantity of formaldehyde in the formaldehyde collector will also vary widely if the sample flow rate is held at a constant proportion of the dilute exhaust sample flow rate.

Liquid chromatographs (LC), used to measure the formaldehyde gathered by the formaldehyde collector, are limited to a finite range over which measurements can be conveniently made. Naturally, as the LC's measurement range increases, its resolution decreases. The range in the amount of formaldehyde in the collector can be narrowed by making the formaldehyde sample flow rate adjustable. For example, if a very low emitting vehicle is tested, it may be desirable to increase the nominal flow rate from the commonly used rate of 1 slpm to 1.2 slpm. This 20% increase in flow increases the quantity of formaldehyde collected. An analogous situation exists for high emitting vehicles. Using the variable flow rate capability allows the LC to operate over a smaller range with greater resolution. CFVs do not allow the flow rate to be varied, except by replacement, which is not a viable alternative since they cost at least $700 each, and changing CFVs between tests would cause delays.

In summary, TEB's potential need for variable sample flow rates added a third problem to using a CFV for formaldehyde sampling.

5. The TEB Formaldehyde Sample System

TEB decided to use a thermal mass flow controller system to overcome the three problems discussed in Sections 4.2 through 4.4. First, proportional sampling can be achieved with the mass flow controller, even with a heated probe. Second, the thermal mass flow controller system is less restrictive, and third, the nominal flow rate can be changed by simply dialing in a new setting. TEB's formaldehyde sampling system is shown in Figure 3 (page 20).

The standard thermal mass flow controller system has two components, an interface module and a mass flow controller unit. Note the terminology; the mass flow controller unit is one component of the mass flow controller system. The system refers to both

components which are electrically connected with a cable. The controller unit is a plumbing component in the sampling system, where it performs two functions. As a sensor it measures the flow rate, and as an actuator it mechanically controls the flow rate. The interface module contains the control circuitry of the system and includes the flow rate set-point controls and a digital display used for monitoring the flow rate and displaying the set-point.

Proportional sampling is achieved by connecting the CVS's nominal 0-10 volt direct current (vdc) flow rate signal to a modified thermal mass flow controller system. The standard controller system (without the CVS connected) uses a potentiometer on the interface module to adjust the set-point, which is sent as a 0-5 vdc input signal to the controller unit. The actual flow rate, through the controller unit, is represented by a 0-5 vdc output signal from the controller unit which is sent to the interface module where it is displayed. The difference between the set-point input signal and the actual flow rate output signal "calls" for appropriate flow control to achieve agreement between the two signals. The CVS's 0-10 vdc signal must be substituted for the interface module's 0-5 vdc set-point signal to keep the formaldehyde sample flow rate proportional to the CVS flow rate.

A voltage divider circuit (see Figure 4) is used to lower the CVS signal from 0-10 vdc to make it compatible with the flow controller unit's need for a 0-5 vdc set-point signal. The interface module's set-point potentiometer is disabled and a separate potentiometer, which is an element of the voltage divider circuit shown in Figure 4, is substituted for the original set-point control.

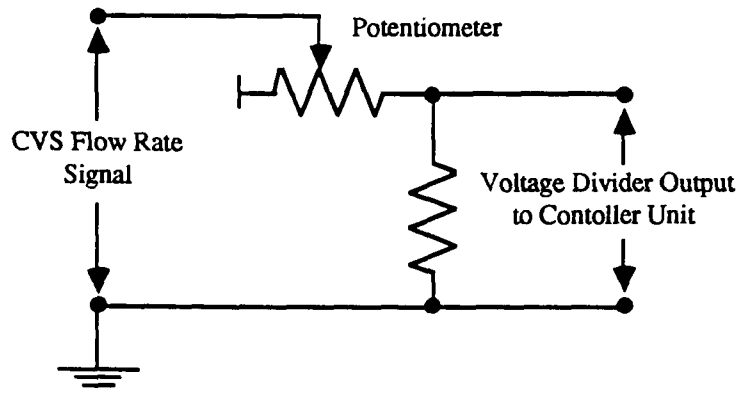


Figure 4

A change in function of the mass flow controller system also occurs as a result of using the voltage divider. The interface module's digital display normally indicated the controller unit's flow rate, and depressing the Flow/Set-Point switch caused the set-point to be displayed. The set-point was an absolute setting. Adding the voltage divider deactivates the ability to display a set-point, so the display normally indicates the actual flow rate and gives an irrevalent reading when the Flow/Set-Point switch is depressed. Adjusting the voltage divider's potentiometer changes the actual flow rate, thereby replacing the set-point control, but unlike the original set-point adjustment, the actual flow rate setting is no longer an absolute setting. Remember that the signal source for controlling the "set-point" is the CVS's 0-10 vdc flow rate signal which varies with changes in the CVS mass flow rate. The voltage divider's potentiometer can tailor this signal in a relative sense, but unlike the original set-point adjustment, the voltage divider's potentiometer setting will not maintain a fixed flow rate. The sample flow rate will now change with CVS flow rate changes. So, TEB normally uses the voltage divider's potentiometer to initially set the nominal sample flow rate, but the flow rate will then vary proportionally with CVS flow rate changes. These modifications were relatively simple and only involved the cable between the interface module and the flow controller unit; neither component was internally modified.

During a test with the new system, an increase in the dilute exhaust mass flow rate will cause the sample mass flow rate to increase proportionally from the nominal formaldehyde sample flow rate setting (typically 1 slpm for formaldehyde sampling). Analogous sample mass flow rate reductions are made for the more typical case where the dilute exhaust mass flow rate decreases with the increasing dilute exhaust temperatures that accompany warm-up during the test. In the CFV type of CVS, the mass flow rate is inversely proportional to the square root of the CFV's inlet absolute temperature and directly proportional to its inlet pressure, under critical flow conditions.

The TEB system uses an electronic totalizer to measure the total sample flow. The mass flow controller unit's 0-5 vdc output signal, which is proportional to the formaldehyde sample flow rate, is sent to a linear frequency converter (see Figure 3) that changes the analog signal to a frequency signal. The resulting frequency signal is sent to a liquid crystal display totalizer that displays the total flow, and is referred to as "counts." The counts were calibrated to units of standard volume (EPA uses standard conditions of 68°F and 29.92 inches of Hg) with a wet test gas meter. The wet test gas meter's accuracy specification is ±1/2% of true volume, making it suitable for use as a calibration standard.

5.1 Thermal Mass Flow Controller System Performance

The critical requirement for the thermal mass flow controller system is for it to maintain a sample flow rate that is proportional to the CVS flow rate. But the measurements ultimately needed to calculate emissions in mass/distance units are the total sample flow and the total CVS flow, rather than the respective flow rates. These totals are read from their respective digital totalizers.

The results from a test to evaluate whether the total formaldehyde flow remains proportional to the total CVS flow as the CVS flow rate changes are listed in Table 1. Using counts, rather than a more direct measure such as the output voltages, allows the performance of the entire formaldehyde sampling system to be evaluated. Included are the frequency converter, totalizer, and thermal mass flow controller system.

Table 1
Proportionality of Sample Flow Counts to CVS Counts

- Calibrator Settings - Pressure (mm Hg)	Temp. (°F)	Time (secs.)	CVS Total Flow (counts)	Formaldehyde Controller Total Flow (counts)	Ratio of Formaldehyde Controller to CVS Flow (counts)	CVS Flow Rate (scfm)	Form. Controller Flow Rate (slpm)
760	70	900	5396	10472	**1.941**	359.7	1.0
760	70	900	5401	10471	**1.939**	360.1	1.0
500	32	240	941	1863	**1.980**	235.3	0.7
500	130	240	860	1708	**1.986**	215.0	0.6
650	70	240	1219	2377	**1.950**	304.8	0.9

Average Ratio	**1.959**
Standard Deviation	0.022
Coefficient of Variation	1.14%

Ideally, the ratio of the total formaldehyde sample flow to the total CVS flow should remain constant. The results show that the ratio of formaldehyde counts to CVS counts remained very constant, with a coefficient of variation of less than 2%, over a 40

percent change in the CVS flow rate, which is a much larger change in CVS flow rate than would occur in normal testing. These data show that the mass flow controller precisely maintains a sample flow rate that is proportional to the CVS flow rate.

A CVS calibrator, rather than a vehicle, was used for the test. The calibrator allows a wider range in CVS flow rates than can be easily achieved with a vehicle, and thereby increases the stringency of the test. The CVS's CFV inlet pressure and temperature sensor connectors were removed from their sensors and connected to the calibrator. The calibrator sends simulated pressure and temperature signals to the CVS computer, so the CVS counts do not represent the true total flow through the CVS. This is a valid method since the computer in the CVS uses the simulated sensor signals just as it would use the normal signals to calculate flow through the CFV. And also as in normal operation, sends the result to the CVS totalizer and to the mass flow controller, as previously discussed. The calibrator settings for each test point are listed in columns 1 and 2 of Table 1.

The mass flow controller's response time to changes in CVS flow rate was also checked with a qualitative test. One channel of a chart recorder was connected to the CVS's 0-10 vdc flow signal output and a second channel was connected to the sample flow controller's flow signal output. The recorder was started with a vehicle at zero speed, then the vehicle was accelerated to 50 mph. As the CVS flow decreased with increasing dilute exhaust temperature, the sample flow tracked the CVS flow very precisely. This was true even for some rapid flow rate transients of small amplitude.

In summary, the mass flow controller system was checked to determine if it can maintain proportional sample flow as the CVS flow rate changes and the data indicated that it does.

5.2 Flow Controller and Sample Pump Selection Interactions

This section discusses three issues regarding flow controllers and sample pumps. They include: 1) the operating pressure of the flow controller, 2) whether the pump should be located upstream or downstream of the flow controller, and 3) the pump selection.

The mass flow controller unit is calibrated at the factory for the intended operating pressure, so the operating pressure should be specified when ordering the controller. Determining the operating pressure was difficult because the pressure is determined by

both the sample pump's characteristics and the pressure drop across the formaldehyde sampling system's components.

Simply selecting the pump before specifying the controller pressure appears to be the solution, but as discussed below, other factors had to be considered. The sample pump and the flow controller interact. As the mass flow controller operating pressure is dependent on the sample pump, so too is the pump selection dependent upon the pressure drops in the mass flow controller and the other sample system components.

An orifice in the flow controller unit causes a significant pressure drop, thus reducing the sample flow rate for a given pump. Since the controller manufacturer uses different sized orifices, depending on the specified operating conditions. This interaction between the pump and the controller must be considered when selecting a pump and specifying the calibration pressure of the controller.

Another issue is whether the pump should be located upstream or downstream of the controller. Some manufacturer's controllers will not operate under vacuum conditions (pump downstream). Porter Instrument Company recommended using their controller with an upstream pump, even though the controller can operate under vacuum conditions. One reason is that the controller is calibrated at a specific pressure, hence a measurement error will occur at any other operating pressure.

Measurement errors can be avoided by placing the pump upstream of the controller with a pressure regulator installed at the controller's inlet. The pressure regulator maintains a constant pressure at the controller's inlet despite varying flow rates, thus meeting the need to maintain the calibration pressure.

Measurement errors can not be avoided with the pump downstream of the controller. As the controller changes the pressure drop across itself to regulate the flow rate, the pressure at the inlet of the controller also changes. Nothing analogous to a pressure regulator was found that can keep the pressure at the inlet of the controller constant while allowing the flow rate to change. So a measurement error will occur at any pressure other than the calibration pressure, if the pump is downstream of the controller.

Initially the controller manufacturer's recommendations were followed with the pump located upstream of an on-hand controller. With an upstream pump, leaks can not be tolerated because the flow controller system is used to measure the total flow through

the cartridges. Carbon vane pumps and piston pumps typically have small leaks and metal bellows type pumps are expensive, leaving diaphragm pumps as the best alternative. Using an on-hand single diaphragm pump, the maximum flow rate was limited to 0.75 slpm. As stated earlier, our objective was to attain a nominal sampling rate of at least 1 slpm with the capability to use higher sampling rates if necessary. The upper limit was 5 slpm since thermal mass flow controllers are commonly available as 0-5 or 0-10 slpm units, and there was not a need for anything more than 5 slpm..

In looking for a suitable pump, the pump manufacturers recommended locating the pump downstream of the flow controller, directly contrary to the controller manufacturers' preference for placing the pump upstream of the controller. The decision became a matter of choosing the configuration which had the fewest drawbacks.

The following discusses the problems that arise with the pump located upstream of the controller. Diaphragm vacuum pumps are not designed to operate with pressures above atmospheric at their outlets. If an oversized pump is used, the mass flow controller is forced to restrict the pump outlet, thus creating a positive pressure at the outlet. Too much restriction will overload the pump and motor, causing damage, while an undersized pump will fail to deliver the required flow rate. In effect, any pump will be oversized when prevented from delivering full flow by restricting the outlet. These considerations severely restrict the range in flow rates than can be achieved without causing damage.

A second pump durability problem arises with the pump located upstream of the controller. An upstream pump must simultaneously pull a vacuum across the cartridges and deliver a pressure at the inlet of the controller to overcome the pressure drop caused by the orifice and the flow regulating valve in the controller. But diaphragm pumps are designed as either vacuum or pressure pumps exclusively. The pump manufacturers said that pulling a vacuum at the inlet of the pump while simultaneously pushing a positive pressure at the pump's outlet adversely affects the diaphragm's durability, so is not recommended. The problem occurs during the transitions between positive pressure and negative pressure acting on the top surface of the diaphragm while atmospheric pressure is constantly acting on the diaphragm's underside. During the transitions, the diaphragm is snapped up when exposed to vacuum and snapped down when exposed to pressure.

For these reasons, the pump manufacturers do not publish flow rate specifications for conditions where the pump is simultaneously exposed to less than atmospheric pressure at the inlet and greater than atmospheric pressure at the outlet. Choosing a pump for an upstream location is practically impossible.

In addition to the durability issues, another disadvantage of installing the pump upstream of the controller is that the pump is the component most likely to develop a leak. A leak in an upstream pump would cause inaccuracies in the total flow volume measurement. A leak in a downstream pump would not cause measurement inaccuracies.

Another advantage of a downstream pump is that it enhances the flexibility of the sampling system. As discussed in Section 4.3, the Sep-Pak silica sampling cartridges are very restrictive to flow. TEB is looking into less restrictive cartridges and if successful, they will require the controller unit to further restrict the sample flow to maintain a constant flow rate. With the controller on the inlet side, the pump would not "see" a difference in restriction since the sum of the cartridge restriction plus the controller restriction will not change while maintaining a constant flow rate.

With the controller on the outlet side of the pump, the outlet pressure will increase in proportion to the lowered cartridge restriction. The increased pump loading resulting from a downstream controller restricting the pump outlet could cause the motor and/or pump to overheat. So less restrictive cartridges might require changing to a smaller pump on systems with upstream pumps. A downstream pump does away with these problems and makes the system more accommodating of component changes such as less restrictive cartridges.

Although there are significant advantages associated with a downstream pump, there are also two disadvantages. First, some manufacturers' controllers will not work under vacuum conditions thus reducing the number of suppliers, and second, flow rate measurement errors accompany operation at pressures other than the controller unit's calibration pressure.

The controller unit's calibration pressure turned out to be a minor issue. The Porter Model 201 0-5 slpm controller unit's pressure coefficient specification is 0.1%/atmosphere, so the maximum error would only be 0.1% if the controller is calibrated at atmospheric pressure even if a perfect vacuum were attained at the inlet. The error is even less if the controller is calibrated near the middle of its expected operating pressure range. It is also a simple matter to calculate a corrected flow rate although it requires measuring the difference between the calibration pressure and the operating pressure. The anticipated error is so insignificant that it would be difficult to justify even such a minor effort.

5.3 Flow Controller and Sample Pump Selection Decisions

The advantages of placing the pump downstream of the controller outweighed the disadvantages. A downstream pump lowers the probability of leaks, favorably affects system flexibility, and enhances pump durability.

A Gast 1/4 hp, 1575 rpm twin diaphragm pump model number DAA-155-EB was selected. This pump, and similar pumps manufactured by others, are available in series and parallel diaphragm configurations and they are easily changed from one configuration to the other, in the field. This can be an important consideration if lower restriction cartridges become available. At the high vacuums required with the present cartridges the series diaphragm configuration allows higher flow rates. If lower restriction cartridges become available, they may also be larger. In order to maintain equivalent sample concentrations with larger cartridges, higher flow rates will be necessary. The parallel diaphragm configuration delivers higher flow rates than the series diaphragm when the system restrictions are lessened.

Table 2 lists the pressures at the inlet of the controller using the Gast pump with a mass flow controller and two Sep-Pak silica cartridges in series.

Table 2
Flow Controller Inlet Pressures at Various Flow Rates
With Two Sep-Pak Cartridges in Series Upstream of Controller

Flow Rate (slpm)	Controller Inlet Pressure (psia)	Barometric Pressure (psia)
1.21	2.01	14.29
1.00	5.55	14.29
0.88	7.20	14.29
0.75	8.57	14.29
0.70	9.09	14.29

5.4 Additional Details of the TEB System

This section provides information on the other components in Figure 3 that complete the sampling system.

The first component considered are the three way heated solenoid valves just downstream of the sample probe. TEB's formaldehyde sampling system will share the sample probe with a methanol emission sampling system. The design of the methanol sampling system has not been finalized and is therefore not covered in this document. However, some of the components depicted in Figure 3 were selected to accommodate the methanol sampling system. The three way solenoid valves, for instance, would have been a two-way valve were it not for the methanol system.

The water used in the mode 1 methanol impingers can be sucked out when the test driver switches from mode 1 to mode 2 of the FTP. The high vacuum on the formaldehyde side of the combined formaldehyde/methanol system creates a vacuum reservoir that pulls water out of the impingers just after the mode change. With three-way solenoid valves, the downstream port opens to atmosphere when sampling stops at the mode change and prevents the formaldehyde circuit from pulling water out of the impingers.

The two valves just downstream of each of the heated solenoid valves allow the methanol sampling branch to be closed when only formaldehyde sampling is desired or vice versa. These are manually set by the technician prior to the test.

The three downstream mode valves allow one pump and controller to be used for the three modes of the FTP. Only one of these valves is open during each mode of the test, thus isolating the rest of the system from the pump.

The ambient solenoid valve and the needle valve were added to aid the accuracy of the total flow volume measurement and enhance pump durability. The following operating sequence explains why. The pump and flow controller system are turned on before a test begins to set the nominal flow rate and to allow a ten minute warm-up, as recommended by the controller manufacturer. The ambient solenoid valve is normally open and allows air to pass through the controller and pump. The downstream solenoid valves are normally closed and remain closed until the driver selects one of the test modes. The ambient solenoid valve thus prevents the pump from dead-heading which aids durability and permits air flow through the controller for setting the flow rate.

The needle valve improves the accuracy of the total flow measurement. When the driver selects mode 1, simultaneously the ambient solenoid valve closes, the mode 1 downstream solenoid valve opens, the mode 1 heated solenoid valve is energized to open the sample probe to the cartridges and close the ambient port, and the totalizer is energized and begins counting.

The sampling system pressure now begins decreasing from atmospheric pressure. The lines between the cartridges and the pump are evacuated to approximately 6 psia. Attaining this low pressure causes more air to flow through the controller unit than flows through the cartridges. Since only the flow through the cartridges is pertinent, this additional flow is being counted and becomes an error source. The counter is only actuated when one of the downstream solenoid valves is energized.

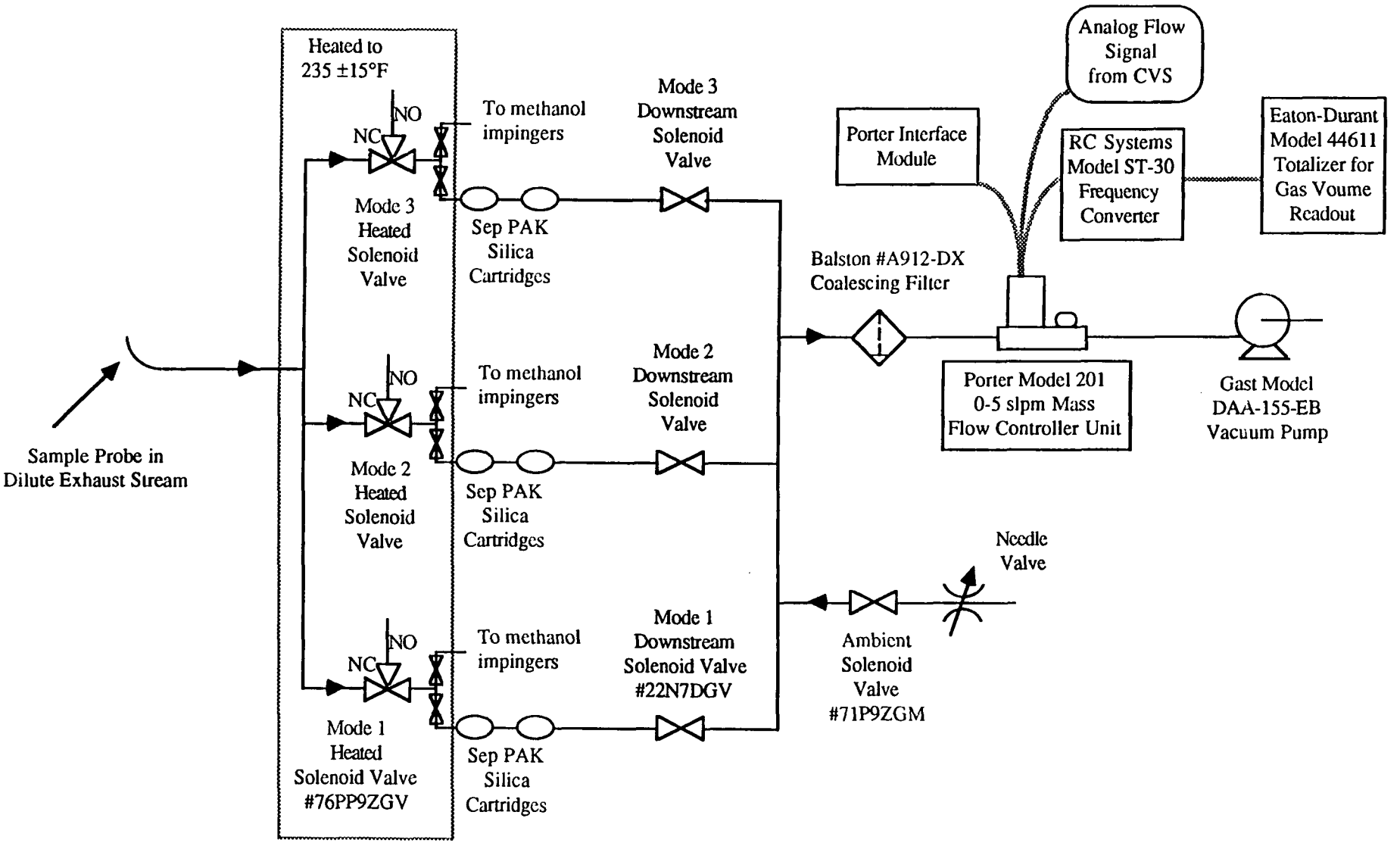
This error is minimized with the needle valve. By adjusting the needle valve to create the same pressure drop as the cartridges, the entire sampling system between the pump and the downstream solenoid valves can be evacuated to the sampling pressure, so the counters measure the flow through the cartridges without the additional flow required to evacuate the system. The distance between the cartridges and the downstream solenoid valves must be minimized to reduce the error associated with evacuating this volume.

The filter shown in Figure 3 is needed to protect the capillary tube in the flow controller unit from condensed water and solids. A problem with condensed water is unlikely under normal operating conditions since the pressure is so low at the inlet of the controller, but solids are still a potential problem. For example, a leak in the downstream solenoid valves of a prototype system was caused by silica from the cartridges. The silica, held by fine mesh filters, can escape unless care is taken to prevent breaking the seal between the cartridge's body and filters during installation. Also, during non-routine procedures such as repairs, the operating conditions could be amenable to water condensation or solids contamination, which further justifies the filter.

6. List of Suppliers

Thermal Mass Flow Controller Model 201 0-5 slpm	Porter Instrument Co. P.O. Box 326 Hatfield, PA 19440 215-723-4000
Sample Pump Model DAA-155-EB	Gast Manufacturing Corp. P.O. Box 97 Benton Harbor, MI 49022 616-926-6171
Solenoid Valves	Peter Paul Electronics Co. P.O. Box 1180 New Britain, CT 06050-1180 203-229-4884
Totalizer Model 44611	Eaton Corporation 901 South 12th Street Watertown, WI 53094 414-261-4070
Frequency Converter Model ST-30	RC Systems P.O. Box 57338 Webster, TX 77598 409-925-7808
Filter Model A912-DX with manual drain valve	Balston, Inc P.O. Box C Lexington, MA 02173 800-343-4048
Sep-Pak Silica Cartridges	Waters Chromatography Division Millipore Corporation 34 Maple Street Milford, MA 01757

Figure 3: Formaldehyde Sampling System



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