

## Determination of Sulfur Compounds in Automotive Exhaust

**Foreword**—Automotive engines, depending upon the amount of sulfur in the fuel burned, emit varying quantities of sulfur compounds in the exhaust. Catalytic converters, which oxidize carbon monoxide and hydrocarbons also may alter the proportion of the various forms of sulfur emitted. This SAE Information Report describes equipment, procedures, and the measurement of normal sulfur compounds in automotive exhausts, and presents analytical methods related to this activity along with some comments on their suitability. The information contained in this document does not represent current testing techniques and equipment. It is being retained because of its historical value.

**1. Scope**—This SAE Information Report deals exclusively with the determination of sulfur compounds in automotive exhaust. Engine operating cycles and interpretation of results are not covered. Methods described in detail are those that have been or are being used by various laboratories. None are specifically recommended as superior to others. Since intensive measurement of automotive sulfur compounds is a relatively new activity, methods and practices have changed rapidly. Some methods are more experimental than others and are so noted in the test.

**1.1 Environmental Protection Agency Action**—EPA has issued a detailed recommended practice on the determination of sulfates in automotive exhaust. Copies can be obtained by writing the Director, Emissions Control Tech., Environmental Protection Agency, 2565 Plymouth Rd., Ann Arbor, MI 48105.

## 2. References

**2.1 Applicable Publications**—The following publications form a part of this specification to the extent specified herein. The latest issue of SAE publications shall apply.

**2.1.1 SAE PUBLICATION**—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE Paper 770166 "Automotive Sulfate Emissions—A Baseline Study," Somers, Garbe, Lawrence, and Baines.

**2.1.2 FEDERAL AND MILITARY STANDARDS**—Available from U. S. Government, DOD SSP, Subscription Service Division, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094

Federal Test Procedure—Federal Register 40 CFR 86

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**2.2 Related Publications**—The following publications are provided for information purposes only and are not a required part of this document.

2.2.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

- G. J. Barnes and J. C. Summers, "Hydrogen Sulfide Formation Over Automotive Oxidation Catalysts." SAE Paper 750093. February 1975.
- C. R. Begeman, et al., "Sulfate Emissions from Catalyst-Equipped Automobiles." SAE Paper 741060. October 1974.
- M. Beltzer, et al., "Measurements of Automotive Exhaust Particulate Emissions." SAE Paper 740286. February 1974.
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- R. L. Bradow, et al., "Sulfate Emissions from Catalyst and Non-Catalyst Equipped Automobiles." SAE Paper 740528. October 1974.
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- J. Braddock and R. L. Bradow, "Emission Patterns of Diesel-Powered Passenger Cars." SAE Paper 750682. June 1975.
- B. J. Cooper, et al., "Sulfate Emissions from Monolithic Catalysts During Mileage Accumulation." SAE Paper 760035, February 1975.
- F. A. Crestwick, et al., "Sulfuric Acid Emissions from an Oxidation-Catalyst Equipped Vehicle," SAE Paper 750411, February 1975.
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- K. Habibi, "Automotive Particulate Emissions and Their Control." SAE Paper 710638, October 24, 1970. Midland, MI.
- R. H. Hammerle and M. Mikkor, "Some Phenomena Which Control Sulfuric Acid Emissions from Oxidation Catalysts." SAE Paper 750097, February 1975.
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- D. A. Trayser, et al., "Effect of Catalyst Operating History on Sulfate Emissions." SAE Paper 760036, February 1976.

2.2.2 CRC PUBLICATIONS—Available from the Coordinating Research Council, 219 Perimeter Center Parkway, Atlanta, GA 30346.

- J. F. Foster, et al., "Fifth Annual Summary Report on Chemical and Physical Characterization of Automotive Exhaust Particulate Matter in the Atmosphere." CRC Project CAPE-19-70. March 1976.
- D. A. Trayser, et al., "Sixth and Final Annual Summary Report on Chemical and Physical Characterization of Automotive Exhaust Particulate Matter in the Atmosphere," CRC Project CAPE-19-70, September 1976.

## 2.2.3 MISCELLANEOUS PUBLICATIONS

- M. Beltzer, "Particulate Emissions from Prototype Catalyst Cars." EPA-650/2-75-054. May 1975.
- J. B. Burkart, et al., "Catalytic Converter Exhaust Emissions." Paper No. 74-129, APCA 67th Annual Meeting, Denver, CO. June 1974.
- J. W. Butler and D. N. Locke, "Photometric End-Point Detection of the Ba-Thorin Titration of Sulfates." J. Environmental Science Health—Environmental Science Eng., A11(2), 79–92 (1976).
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- H. N. S. Schafer, "An Improved Spectrophotometric Method for the Determination of Sulfate with Barium Chloranilate as Applied to Coal Ash and Related Materials." Anal. Chem. 39, 1719 (1967).
- M. J. Van Der Zijden, et al., "SO<sub>2</sub> and SO<sub>3</sub> in Exhaust Gases of Internal-Combustion Engines," J. Inst. Pet., 36, 561 (1950).
- P. W. West and G. C. Gaeke, "Analytical Chemistry," Vol. 28, P. 1816 (1956).
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## 3. Definitions

- 3.1 Aerosol**—A finely divided, noncondensable liquid and/or solid dispersed in a gas.
- 3.2 Dilution Tube (Or Tunnel)**—One of several types of ducts used to dynamically mix engine exhaust with dilution air in a stationary test set-up. Conditioned air, supplied by a blower, is mixed with engine exhaust at a mixing orifice in the upstream end of the tube while sampling takes place at a downstream location.
- 3.3 Goksoyr-Ross**—A controlled condensation coil named for its co-inventors. Fluid with condensable material is passed through a coil surrounded by a flowing, controlled-temperature liquid. Condensate trapped within the coil is recovered for analysis.
- 3.4 Impinger (Bubbler)**—A type of trap in which the sample stream impinges against a cool wall and then must flow through a liquid which retains the species of interest.
- 3.5 Isokinetic Sampling**—Withdrawing a sample stream at the same velocity as the parent stream. This method is used to obtain a representative sample when particulate matter is of interest.
- 3.6 Mass Median Equivalent Diameter**—The calculated diameter of a sphere of unit density which represents the midpoint particle obtained when the total particulate mass is divided into two equal parts.
- 3.7 Mixing Orifice**—An orifice, usually sharp-edge, located near the upstream end of a dilution tube. Engine exhaust discharges near the center while dilution air flows through the remaining area. Turbulence downstream from the orifice merges the two into well-mixed, air-diluted, exhaust gas stream.

**3.8 Particulate Matter**—Any dispersed solid or liquid in which the individual aggregates are larger than 0.001  $\mu\text{m}$  in diameter, excluding uncombined water.

**3.9 Probe**—The section of a sample line which is farthest upstream and thus is the first to encounter the material to be sampled. Typically, it is the part of the sample line physically located within the stream being examined.

**3.10 Sulfates**—Sulfuric acid or one of its salts.

#### **4. Brief Introduction to Sampling Systems in Use**

**4.1 Undiluted Exhaust System**—This technique involves extracting a small portion of the raw (undiluted) exhaust stream and passing it through collection equipment where sulfur-related components are trapped and held for analysis.

**4.1.1 CONTROLLED-CONDENSATION COLLECTION (GOKSOYR-ROSS)**—The probe and sample line are maintained above 200 °C followed by the G-R condensation coil maintained at about 60 °C. Sulfuric acid is condensed and held in the coil whereas sulfur dioxide passes through. After collection, the sulfuric acid is washed from the coil and analyzed by one of several methods. Sulfur dioxide is also commonly determined simultaneously by connecting the exit of the G-R coil to a bubbler containing 3%  $\text{H}_2\text{O}_2$ .  $\text{SO}_2$  is oxidized in the bubbler to  $\text{H}_2\text{SO}_4$ , which is subsequently analyzed by the same method. Sample volume is measured by a gas meter.

**4.1.2 BUBBLER/IMPINGER COLLECTION (MODIFIED METHOD 8)**—The method was developed to determine  $\text{H}_2\text{SO}_4$  in stationary stack gas (Method 8). One type is made up of a probe and heated sample line followed by two bubblers in an ice bath. The first bubbler contains an isopropyl alcohol (IPA)/water solution to trap  $\text{H}_2\text{SO}_4$  but not  $\text{SO}_2$ , whereas the second bubbler contains a hydrogen peroxide/water solution to trap  $\text{SO}_2$  by oxidation to  $\text{H}_2\text{SO}_4$ . Following the bubblers is a dry ice trap, sample pump, and gas meter. At the end of the sampling period, the material from each bubbler is analyzed for sulfate.

A second type consists of a probe followed by a series of several midjet impingers, in an ice bath, each containing a solution of isopropyl alcohol (IPA) and water. Sample gas is pulled through the train by a pump with the flow rate measured by a suitable flow meter. Sulfur compounds trapped in the impingers are assumed to be sulfur trioxide or sulfate. Analysis of the impinger solution is by any method specific for sulfate.

**4.2 Dynamic Dilution System (Dilution Tube)**—In this technique the total exhaust gas stream is constantly emptied into a duct that also has a continuous supply of fresh, treated air. Flow is maintained by a constant-volume blower at one end of the duct. Exhaust and fresh air are mixed near the upstream end of the duct and the mixture sampled downstream. The purpose of air dilution is to cool the exhaust to condense sulfuric acid to form an aerosol but to prevent condensation of water. In cyclic operation, the dilution tube provides a mixture which when sampled at a uniform rate will yield a sample proportional to tailpipe output.

**4.2.1 FILTER COLLECTION**—Used for sample collection from diluted exhaust streams. The system employs a probe followed by one or more disc-type filters. Flow is maintained by a sample pump. Sulfur compounds deposited on the filter element are analyzed by one of several methods.

**4.2.2 CONTROLLED CONDENSATION COLLECTION (GOKSOYR-ROSS)**—Equipment and techniques are generally similar to those used for collection of undiluted exhaust samples (4.1.1). The probe is inserted at a downstream location in the duct. The entire sample probe and line to the inlet of the G-R coil must be maintained above 200 °C.

**4.3 Static Dilution System (Dilution Chamber)**—Partially diluted engine exhaust is directed into a large plastic chamber. Air in the chamber serves to dilute the exhaust further, cool it, and prevent condensation of sulfur-related compounds. Samples are withdrawn through special ports in the chamber wall.

4.3.1 **FILTER COLLECTION**—Filter collection systems used with static dilution chambers are similar to those employed with dynamic dilution. A measured volume of diluted sample is drawn through a disc-type filter element where the sulfate is trapped. Material held on the filter element is extracted and usually analyzed for sulfate by a barium iodate, spectrophotometric method. Other methods of analysis could be used.

4.3.2 **BUBBLER/IMPINGER COLLECTION (MODIFIED METHOD 8)**—This system is essentially the same as that described in 4.1.1 for undiluted exhaust sampling.

## 5. Detailed Description of Systems in Use

5.1 **Exhaust Handling Methods**—There are three general methods of handling vehicle exhaust gas and preparing it for sample collection. Each is described in detail in the following paragraphs.

5.1.1 **UNDILUTED EXHAUST**—The simplest method that has been used. A probe leading to the collection system is inserted into the vehicle exhaust pipe where it picks up a sample of raw undiluted gas. Quartz and stainless steel have been used as probe materials. A typical stainless steel design uses 6.35 mm OD tubing closed at one end with several 3.2 mm holes drilled around the circumference (Figure 1). Probes are inserted into the exhaust pipe at a location where the gas temperature is high enough to preclude condensation. Sample lines leading from the probe usually are heated to about 200 °C to prevent condensation ahead of the collection apparatus.

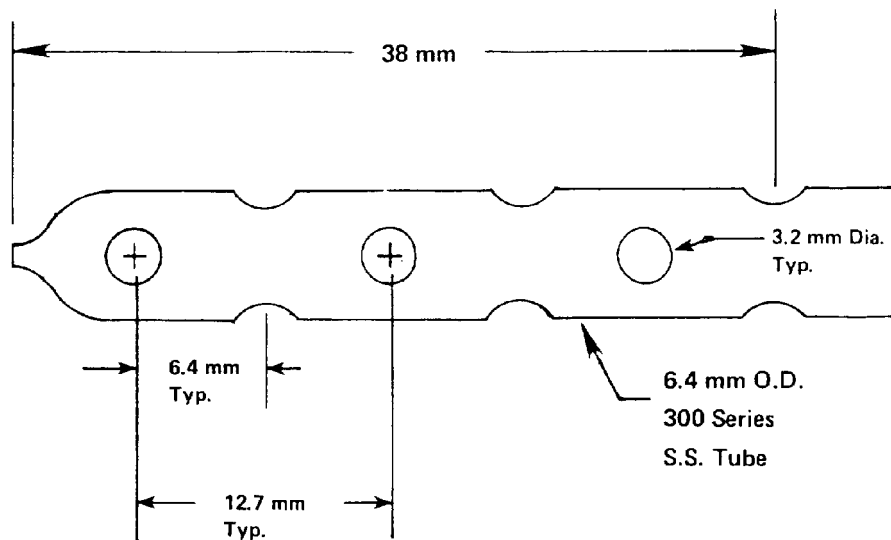


FIGURE 1—SAMPLE PROBE, UNDILUTED EXHAUST

## 5.1.2 DILUTED EXHAUST

- 5.1.2.1 *Dynamically Diluted Exhaust*—A common method of handling the exhaust of a vehicle operated in any cycle (for example, the S-7 Sulfate Cycle) in such a manner as to provide for the taking of a representative sample for analysis, is often designated the Constant Volume Sampling (CVS) system. In the CVS system all of the vehicle exhaust is mixed with an excess of relatively cooler air in the dynamic flow system, and the total flow of diluted exhaust pumped at a constant rate. A sample withdrawn at a uniform rate for the entire test cycle will be representative of the total emission from the vehicle in the cycle. Such a CVS system is utilized in the Federal Test Procedure (Ref. Federal Register). The method is also applicable to the determination of fine particulate matter, including sulfuric acid mist, in vehicle exhaust. However, with sulfuric acid mist, the diluted exhaust must be cool enough to avoid loss of acid as vapor and dry enough to avoid loss of acid by condensation of a water phase.

Exhaust from the car is conducted, via an extension of the tailpipe, into the dynamic dilution tube. The tailpipe extension is preferably short and of low mass so as to heat quickly and thus not act as a condenser for sulfuric acid once the vehicle exhaust system is hot. The diameter of the dilution tube appears not to be critical. Tubes of 95 mm to 584 mm diameter are in use. Mixing of exhaust with dilution air should be accomplished without directing the exhaust against any surface. The length of the dilution tube should be sufficient to provide complete mixing of exhaust and air. It is common for the distance from exhaust injection to sampling point to be a minimum of eight times the diameter of the dilution tube. In any case, the completeness of mixing should be verified by experiment.

- 5.1.2.1.1 System A—(Figure 2) This dynamic dilution system is designed to collect sulfates and other particulate material at essentially constant temperature during driving cycles such as the 1975 Federal Test Procedure, and during moderate speed conditions. It is capable of frequent operation and is compatible with CVS of auto exhaust. Compatibility is obtained because the collection system requires only a small portion of the diluted exhaust: the major portion of the sample is available to the CVS system for measurement of gaseous emissions.

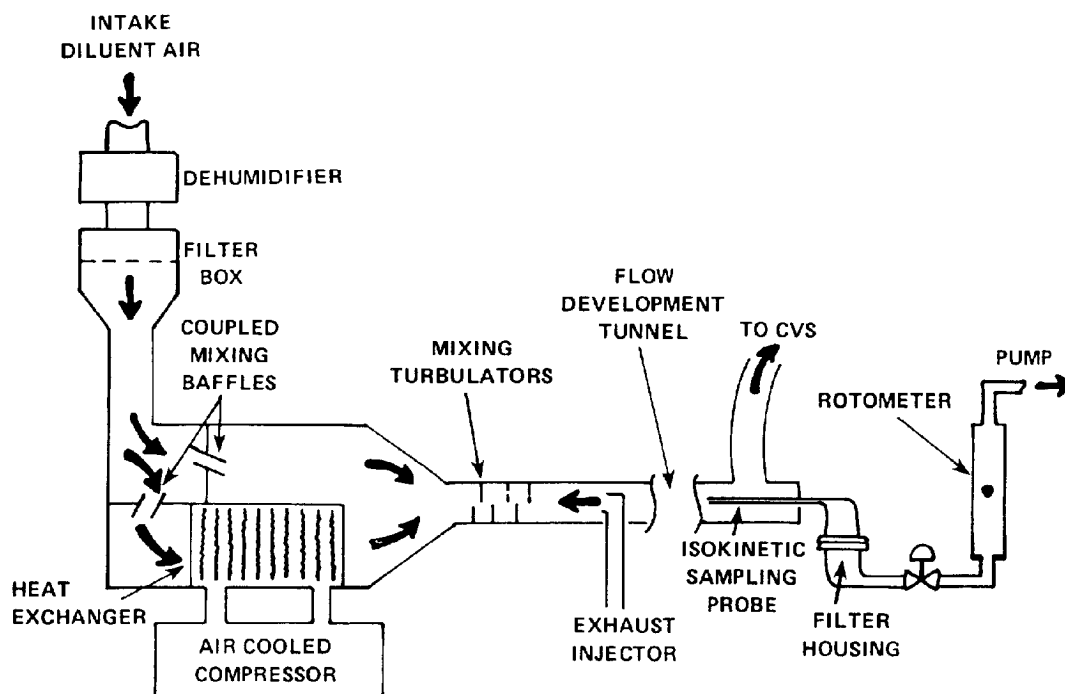


FIGURE 2—DYNAMIC DILUTION SYSTEM A

The system uses a relatively small tunnel which means that low dilution ratios are used, allowing gaseous emission such as CO, hydrocarbons, NO<sub>x</sub>, and SO<sub>2</sub> to be measured accurately. While low dilution ratios are desirable from the standpoint of CVS gaseous emission measurements, the collection of the proportional sample of particulate matter at constant temperature near 32 °C from a sample stream having a high dew point without causing condensation of water, requires a humidity and temperature control system.

Linear velocities are higher in smaller tunnels. An analysis of turbulent diffusion losses in both small and large tunnels has shown the following:

- For 10 μm particles, the turbulent diffusion loss would be about 20%, whereas, larger tunnels could handle particles up to 300 μm without internal turbulent diffusion losses.
- The longer residence times in the larger tunnels result in much greater settling losses of dense large particles.
- In practice, these two effects compensate each other so that ignoring entry losses, small and large dilution tunnels have an effective cut-off particle diameter of about 10 μm.

Since the H<sub>2</sub>SO<sub>4</sub> aerosol size is well below 1 μm, acid aerosol losses in both tunnel types should be equivalent and negligible. This has been substantiated by experiment in which it was shown that sulfate aerosol losses in either tunnel system were about 1%. Therefore, both size tunnels are effective aerosol samplers.

#### 5.1.2.1.1.1

**Diluent Air Preparation**—This subsystem consists of a dehumidifier filter, coupled mixing baffles, a cooling system, and mixing turbulators.

The dehumidifier shown schematically in Figure 3 minimizes the possibility of condensation occurring in the system during a run, and is an integral part of the temperature control system. Diluent air is dried by passage through a filter and a slowly rotating desiccant wheel containing laminated flat and corrugated asbestos, impregnated with a regenerable desiccant, LiCl. Dehumidification of diluent air and desiccant reactivation are concurrent processes, so that dehumidification can be carried out on a continuous basis.

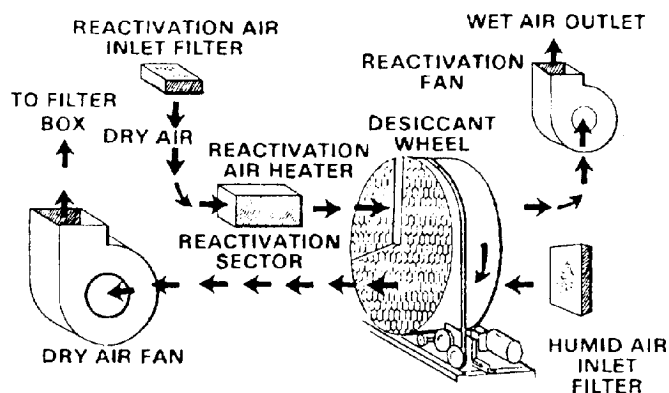


FIGURE 3—DEHUMIDIFIER, SYSTEM A

Dehumidified inlet air passes from the dehumidifier to a filter box containing a paper filter, a bed of activated charcoal, and a second paper filter. This assembly can be the standard filter box assembly for a CVS unit. The filter assembly removes the particulate matter present in the diluent air and reduces and stabilizes the background hydrocarbon content of the diluent air. Because regeneration of the desiccant is accomplished by heating, the dehumidified air emerging from the drum is above ambient temperature. A precooling coil situated between the dehumidifier and the CVS filter cools the dehumidified airstream down to ambient temperature to remove the additional cooling load imposed by the dehumidification step from the final cooling system. The precooling coil consists of several rows of coils through which chilled city water is passed.

The coupled mixing baffles continuously divide the dehumidified, filtered air into two portions, one of which passes through the cooling system, and the second of which bypasses the cooling system. The position of the mixing baffles is controlled by a rapid response, deviation-type controller operating on an input signal from a thermocouple in the filter housing.

The controller operates by comparing an input signal from a thermocouple in the filter housing with a set point signal, and takes corrective action to either raise or lower the output signal until the set point and thermocouple input are equal. The output signal from the controller is fed to an electropneumatic transducer which in turn activates a pneumatic controller which operates the coupled baffles. The cooling system is an air cooled condensing evaporator. Maximum flow through the diluent air preparation system is determined by the cooling capacity of the chiller, and the desired sampling temperature. The mixing turbulators insure that chilled air is thoroughly mixed with the portion of air bypassing the cooling system before the stream is used to dilute the vehicle exhaust. The turbulators consist of six semicircular perforated plates attached to a 12.7 mm diameter thickwall tube at their centers, arranged in a helical series sequence along the tunnel axis. This arrangement allows both longitudinal and latitudinal mixing.

5.1.2.1.1.2 Dilution Tube—Exhaust and diluent air are mixed and a uniform velocity profile is developed in the flow development tunnel. The flow development tunnel is a 2.29 m (7.5 ft) long section of a nominal 102 mm (4 in) diameter Schedule 5 stainless steel pipe (109 mm actual diameter). Neither the length nor the diameter of the flow development tunnel have been optimized, but a dilution tunnel of these dimensions is satisfactory. The probe is located at the end of the tunnel, ahead of the connection leading to the CVS unit.

An important factor in choosing the diameter of the flow development tunnel is its effect on the length of the tunnel and the diameter of the probes. As a general rule, eight to ten pipe diameters are usually sufficient to develop a fully turbulent velocity profile. The larger the diameter, the longer the tunnel required and the longer the residence time in the flow development section.

Longer residence time may lead to higher particulate settling which may cause errors in the measurements. Therefore, the tunnel diameter should be minimized. However, as tunnel diameter decreases, the pressure drop through the tunnel increases and the size of the probes needed for isokinetic sampling decreases. The problems caused by high pressure drop are obvious. Smaller diameter probes should be avoided since they provide higher surface to volume ratios and result in more loss of particulate by impaction. The 109 mm diameter pipe in use offers a reasonable compromise between these various factors.

5.1.2.1.1.3 Exhaust Injection System—Raw exhaust is mixed with the diluent air normally used in the CVS in such a way as to completely mix the two in as short a time interval as possible. This is accomplished by injecting the exhaust in a direction countercurrent to the diluent airstream. Experiments have shown this to be the most efficient way of obtaining a rapidly mixed, uniformly distributed diluted exhaust sample stream. Figure 4 shows a schematic of the exhaust injector in the countercurrent position.

5.1.2.1.1.4 Dilution Tube Losses—Particulate deposition in the flow development section is measured by introducing an artificially produced monodisperse (3.5  $\mu\text{m}$  diameter) methylene blue aerosol into the exhaust injector in the same manner as for auto exhaust. The system is disassembled after the run, the tube surface washed with methanol, and the washing analyzed spectrophotometrically. The sensitivity of the method for methylene blue is in ppb range. Analysis has shown that tube losses are small, amounting to less than 1% of the total aerosol introduced. No dye was detected in the tube section housing the exhaust injector. About 0.1% of the aerosol was deposited in the tube midsection, and about 0.3% was deposited in the tube section housing the probes. Tests with a tube of similar dimensions have confirmed the results regarding sampling losses.

5.1.2.1.1.5 Temperature Capabilities and Effects—A typical installation of System A had a 9.8 kW cooling capacity and a total flow rate of 12.8  $\text{m}^3/\text{min}$ . Under these conditions a temperature between 32 and 38 °C usually was maintained at the sample collection point throughout a 1975 FTP cycle with a catalyst-equipped car. If temperature at the collection point is not to exceed 32 °C, it may be necessary to add a finned-tube cooler (Figure 5) between the exhaust pipe and the exhaust ejector. This cooler also is useful in controlling temperature during high-speed cruise tests. Sulfates and other exhaust particulate matter can also be collected at set temperatures above 32 °C. In these cases the finned-tube cooler may not be needed.

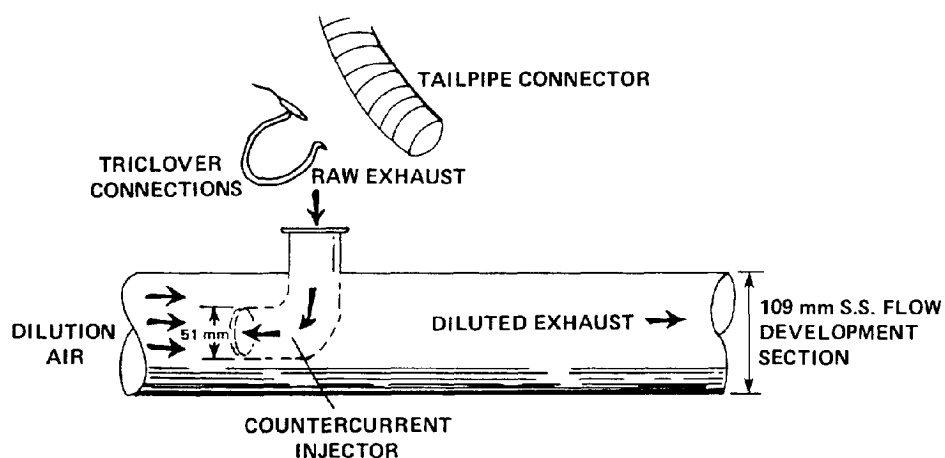


FIGURE 4—EXHAUST INJECTOR SYSTEM A

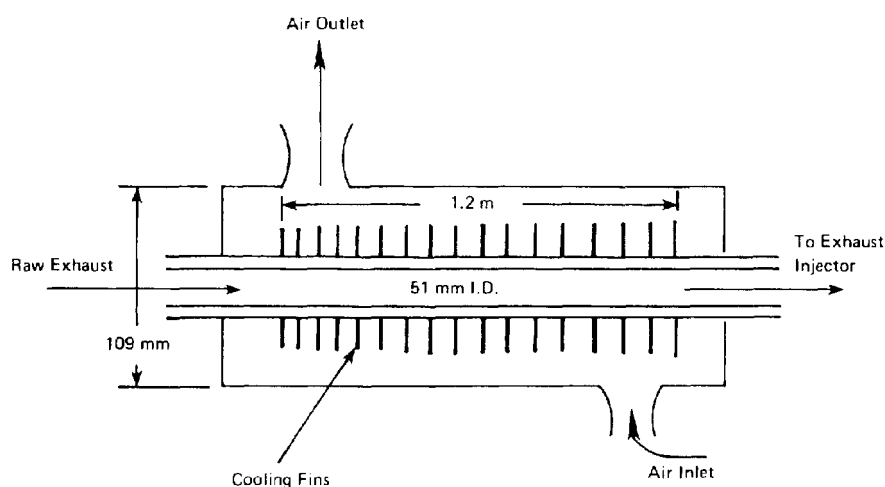


FIGURE 5—FINNED-TUBE COOLER

The set-point temperature is essentially determined by the fraction of the dehumidified air that is cooled. If collection at a higher temperature is desired, the fraction of dehumidified air that goes through the heat exchanger is decreased. This fraction is determined by the set-point temperature and the actual instantaneous temperature of the exhaust-dilution air mixture in the filter housing. Thus a range of particulate collection temperatures is possible, the lower limit being the dew point of the air exhaust mixture at the lowest dilution ratios, and the upper limit the minimum amount of cooled-dehumidified air required to prevent temperature increases at low dilution ratios.

The dehumidifier is a key component of the temperature control system, particularly since the exhaust handling system is one in which the air/exhaust dilution ratios are low. This means that the relative humidity of the diluent air is a key parameter. For example, during the rapid acceleration portion of the FTP, the exhaust volume flow rate from a vehicle equipped with a 5.7 L V-8 engine may be as high as 3.4 m<sup>3</sup>/min. Thus, with a 12.8 m<sup>3</sup>/min flow limit, the dilution ratio would drop below 3 in the sampling tunnel. If the relative humidity of the diluent air were high, attempts to control the collection temperature to a level of 32 °C would result in condensation of water vapor, with the associated loss of particulate matter.

If the relative humidity of the diluent air is low, for example, below 50%, it should be possible to maintain a 32 °C collection temperature without condensation occurring. In the absence of the dehumidifier, on humid days, the dew point of the mixture would exceed 32 °C at dilution ratios as high as four, so that condensation would invariably occur during the acceleration portions on FTP driving cycle.

Attempts to control collection temperatures by omitting the dehumidification step and chilling the diluent air would be difficult to accomplish since water condensing on the coils would feed back latent heat, decreasing the efficiency of the cooler. Continued running would probably result in the condensed water freezing on the heat-exchangers, rendering them inoperative. The collection of sulfuric acid aerosol should be independent of temperature as long as the collection temperature is below sulfuric acid dew point. Thus, if the collection temperature does not exceed about 90 °C, all of the acid exists as aerosol. Although the dilution tube residence time is small (0.1 s), the formation of aerosol droplets is virtually instantaneous.

5.1.2.1.2 System B—(Figure 6) This system uses a relatively large dilution tube and also can be used to examine particulates other than sulfates. The exhaust handling system includes a dilution air filter, a clear polyacrylate dilution tube, and a blower to induce flow. Exhaust gas is introduced into the tube upstream near the dilution air filter and diluted samples are collected downstream near the blower.

5.1.2.1.2.1 Dilution Air Preparation—Before mixing with automobile exhaust, the dilution air is filtered through a 610 x 610 x 292 mm pleated filter of approximately 23 m<sup>2</sup>, rated 95% efficient for 0.3 µm particles by a DOP test and 99% efficient by a NBS color test. A pressure drop less than 12 mm (118 Pa) water, at the flow of dilution air used, is desirable.

5.1.2.1.2.2 Dilution Tube—The dilution tube portion of the system is built in sections and has two different diameters. The first group of sections, near the entrance, is 2.3 m long and 216 mm in diameter. The second group is 3.6 m long and 333 mm in diameter. The sections are joined with O-ring seals and, except for the short entrance and transition sections, is fabricated of clear polyacrylate having 6.4 mm wall thickness. The overall length of the exhaust handling system is approximately 12 m including dilution air filter and blower. The distance between the exhaust inlet and sample probes is 5.7 m. It is in this 5.7 m section that mixing of exhaust with dilution air and the development of a relatively flatfront velocity profile take place. The relatively large nonairborne particles settle from the main stream during the approximately 2 s required for the exhaust to travel this distance.

The dilution tube is located parallel with the vehicle and as close as feasible (about 1 m clearance).

The blower for pumping diluted exhaust through the dilution tube is equipped with a variable sheave pulley drive for adjusting the fan speed between approximately 700 and 1400 rpm, corresponding to flow rates of between about 17 and 33 m<sup>3</sup>/min.

Velocity profiles and volumetric flow rates are measured in the exhaust dilution tube at the 333 mm diameter sampling section with a Pitot tube, and the volumetric flow is determined by the tube.

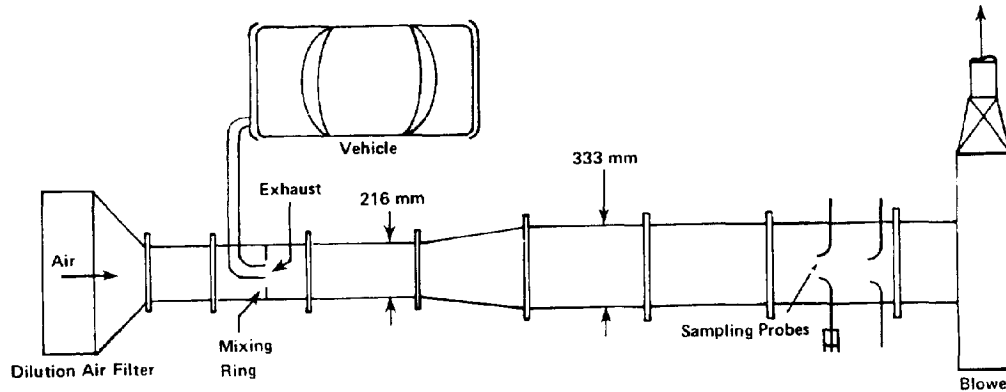


FIGURE 6—DYNAMIC DILUTION SYSTEM B

The Pitot tube is inserted through glands in the flange at the downstream edge of the sampling section. The tip of the Pitot tube projects forward about 254 mm so that the velocity is measured near the cross section of the particle sampling probes (the probes are removed for the velocity measurement).

Velocity profiles are illustrated in Figure 7 for maximum and minimum fan speeds. For the practical purpose of integration, velocity at the tube wall is assumed to be one-half the centerline velocity, as recommended. Velocity is symmetrical with respect to the tube centerline and reasonably uniform over the central 216 mm diameter section.

Volumetric flow rates are calculated from the velocity profiles integrated using 12.7 mm annular radius segments and velocities are read from Figure 7. Typical volumetric flow rates are shown in Table 1:

TABLE 1—VOLUMETRIC FLOW

| Blower rpm | Total Flow, m <sup>3</sup> /min | Total Flow, m <sup>3</sup> /min |
|------------|---------------------------------|---------------------------------|
|            | Exh. In. Closed                 | Exh. In. Open                   |
| 730 Min    | 16.22                           | 17.24                           |
| 1385 Max   | 31.57                           | 34.00                           |

Because the exhaust inlet is downstream of the dilution air filter, air admitted at the exhaust inlet reduces the pressure drop of the system slightly, with a resulting slight increased flow. To the degree that the capacity of the blower depends on the  $\Delta P$  across the blower, the exhaust dilution system is not a true Constant Volume Sampling system. The sampling probes are located on a circle of approximately 102 mm diameter with respect to the tube axis and are, therefore, in the area of nearly maximum and uniform velocity.

A standard size vehicle, operating through the 1972 FTP driving cycle, produces an average of approximately 1.22 m<sup>3</sup>/min exhaust gas (at 21 °C), including water vapor. At low fan speed, the addition of 1.13 m<sup>3</sup>/min gas at the exhaust inlet is equivalent to the measured flow with the exhaust inlet open. Therefore, for operation on the 1972 FTP driving cycle with the fan at 730 rpm, the average total flow is taken as 17.27 m<sup>3</sup>/min. For operation on the FTP at high fan rpm, the average flow is taken as 32.84 m<sup>3</sup>/min.

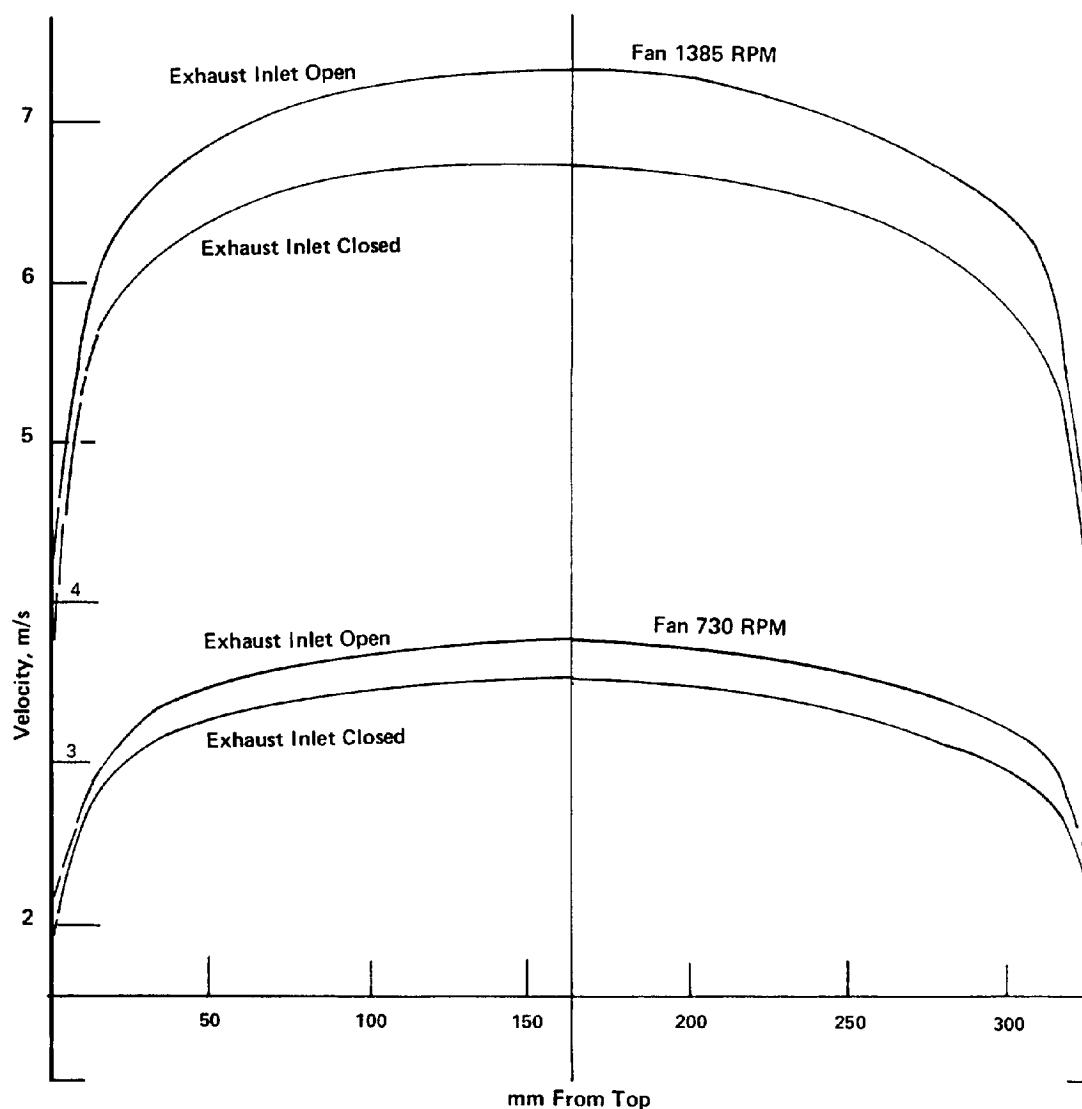


FIGURE 7—VELOCITY PROFILES AT SAMPLING SECTION

Reynolds numbers at the sampling section are shown in Table 2.

TABLE 2—REYNOLDS NUMBER

|                           | Re      |
|---------------------------|---------|
| 32.84 m <sup>3</sup> /min | 130 000 |
| 17.27 m <sup>3</sup> /min | 70 000  |

Thus, the flow is turbulent.

Temperature at the sampling section during the 1972 FTP driving cycle, at 17.27 m<sup>3</sup>/min total flow, ranges from 27 to 54 °C.

5.1.2.1.2.3 Exhaust Injection System—All of the exhaust from a vehicle operated on a chassis dynamometer is fed via a 51 mm diameter tailpipe extension to the dilution tube, and is directed into the dilution tube on the centerline of the second 216 mm diameter section. The exhaust pipe discharges downstream. An annular ring, 216 mm OD x 165 mm ID is located coplanar with the discharge end of the exhaust pipe extension. This annular orifice produces relatively greater local turbulence at the area of exhaust introduction, resulting in rapid mixing of exhaust and dilution air.

5.1.2.1.2.4 Mixing of Auto Exhaust and Dilution Air—It is important for representative sampling that the exhaust be uniformly mixed with dilution air. Because inertial and gravitational effects are greater for discrete particles (depending on size and density) than for gases, uniform mixing of particles with dilution air may be more difficult. Nevertheless, a minimum requirement of the exhaust dilution system would be for exhaust gas to be uniformly mixed with dilution air. Should this requirement not be met, then uniform distribution of sulfates would certainly not occur.

The system is tested for mixing effectiveness by introducing propane at the exhaust inlet port and monitoring the propane concentration at the sampling section with a flame-ionization hydrocarbon analyzer. Propane flow is adjusted to give a calculated of  $-50$  ppm at  $32.84 \text{ m}^3/\text{min}$ . The results obtained in such a test are illustrated in Figure 8.

Mixing of propane was found to be very uniform at a fan speed of 1385 rpm. At a fan speed of 730 rpm, propane concentration was found to be very uniform horizontally, and nearly uniform vertically except for a slightly low concentration at the bottom of the tube. Overall, uniformity of mixing was considered very good and satisfactory.

Uniformity of mixing of a gas does not necessarily guarantee uniformity of mixing of particulate matter. However, the mean particle size of freshly generated sulfate particulate matter derived from combustion is so small (less than  $0.1 \text{ }\mu\text{m}$ ) that the particles behave very much like a gas. Therefore, the mixing effectiveness determined with propane will also apply to these particles.

5.1.2.1.2.5 Loss of Sulfate in the Dilution Tube—The transparent 6.4 mm wall clear polyacrylate dilution tube allows visual inspection of the mixing of the exhaust and dilution air. The blowing-in of liquid water with every cold start as well as the gradual deposition of film and sediment on the walls can be seen. The film-type deposit, distributed throughout the length of the tube, indicates the loss of some small particles, and a few much larger particles accumulate along the bottom of the tube. Characteristically, a portion of the sediment is rust-like material and accumulates in the first 216 mm diameter section near the exhaust inlet, where it is streaked along the bottom of the tube. This is the area in which the blow-in water first accumulates and then evaporates to leave a rusty residue.

The sulfate losses in the tube have been measured by disassembling it after several emission tests, wiping the inside with a damp cellulose filter, and analyzing the filter for sulfate. The large particles were brushed out beforehand. This procedure maximizes the calculated loss because the wipings include some material blown in with the condensed water. The sulfate losses in the tube ranged from 1 to 5% of the measured sulfate emissions.

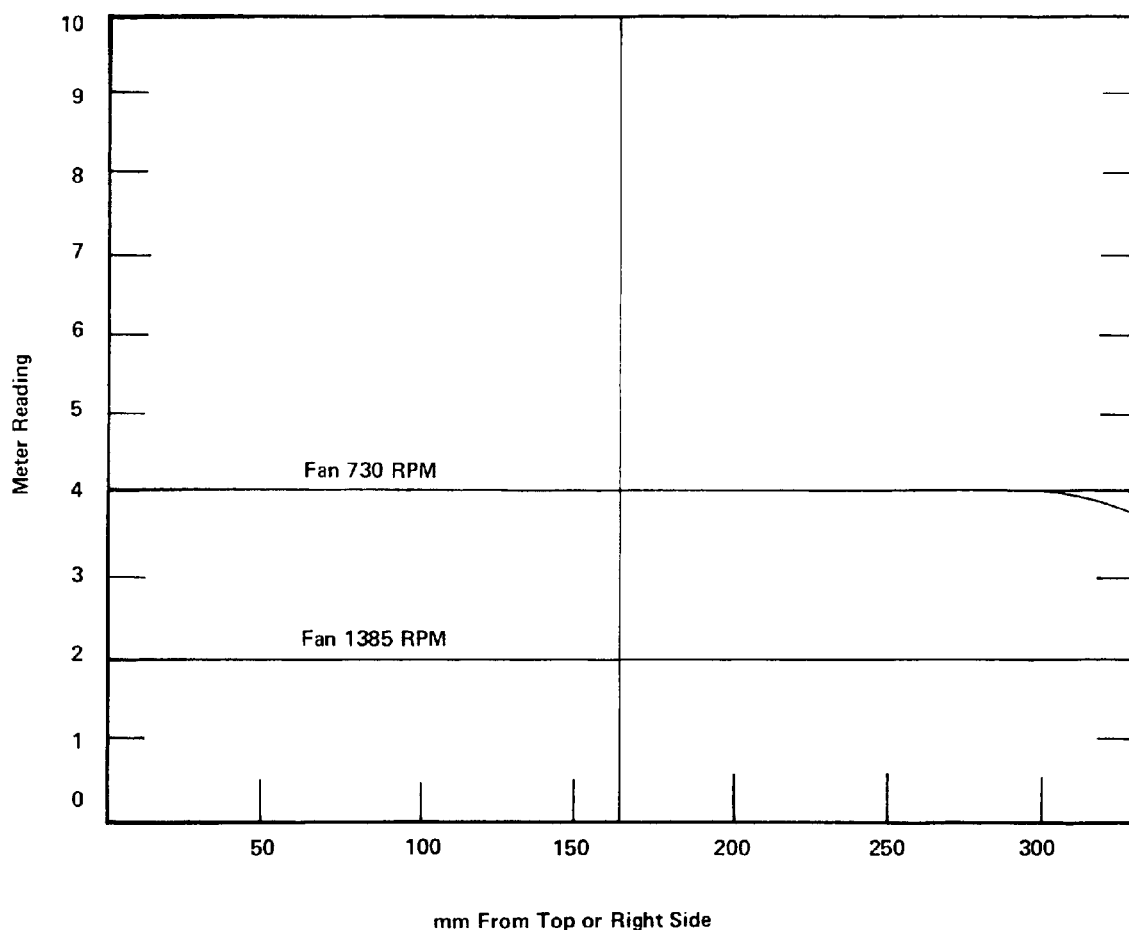


FIGURE 8—PROPANE CONCENTRATION PROFILES AT SAMPLING SECTION

5.1.2.1.3 System C—(Figure 9) This dynamic dilution system is a relatively large exhaust handling system designed to permit general particulate sampling as well as sulfate measurements. In this system the blower is upstream from the filter element and produces a positive pressure at the downstream sampling section.

5.1.2.1.3.1 Dilution Air Preparation—Dilution air is passed through two 0.1 m<sup>3</sup> High Efficiency Particulate Air (HEPA) filters contained in a 0.4 m<sup>3</sup> box fore it combines with engine exhaust at the mixing orifice. Typical filter material has an efficiency of 95% at 0.3 μm particle size and serves to minimize the contribution of background particulate matter to the test sample.

The blower used has sufficient capacity to supply up to 34 m<sup>3</sup>/min of dilution air flow at 25 mm H<sub>2</sub>O positive pressure; however, normal delivery is in the range of 25 to 28 m<sup>3</sup>/min for use with driving patterns similar to that of the Federal Test Procedure.

- 5.1.2.1.3.2 Dilution Tube—The dilution tube is 11 m long x 584 mm diameter. Each 1.8 m section is formed from a 1.8 x 1.8 m sheet of 16-gage stainless steel by rolling it into a cylinder and welding the longitudinal seam. Mild steel flanges 32 mm wide are welded to each end of the tunnel sections for bolting them together. Dilution air and exhaust gases are mixed by means of turbulence created by a 203 mm diameter orifice at the dilution tube entrance. Dilution air flow rate through the tube is controlled by adjustment of three dampers, one at the blower inlet, one at the blower outlet, and one at a spill port between the blower and the filter box. Nominal dilution ratios between 10:1 and 30:1 are typical for this system. The sample point is about 10 m downstream from the exhaust gas-dilution air mixing orifice.

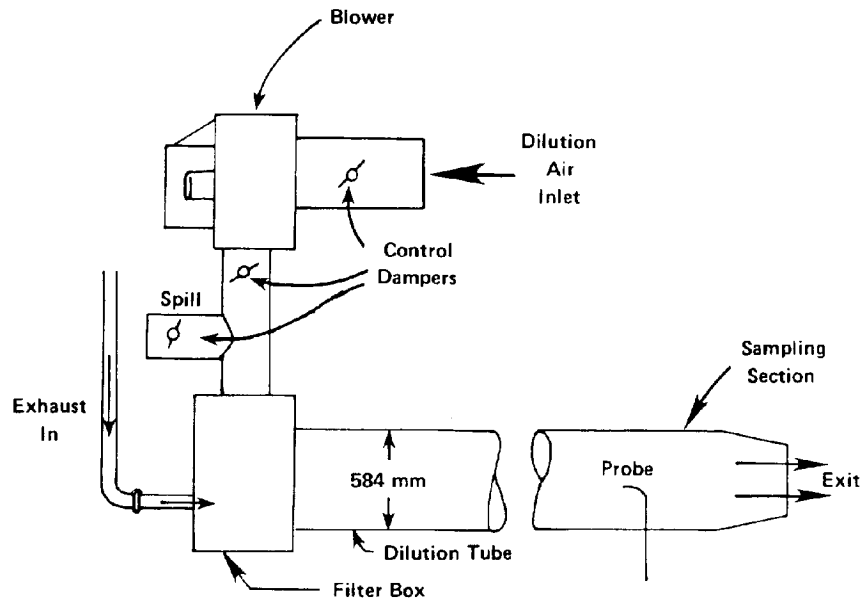


FIGURE 9—DYNAMIC DILUTION SYSTEM C

- 5.1.2.1.3.3 Exhaust Injection System—The vehicle exhaust enters the system downstream from the dilution air filter box and at the entrance to the dilution tube as described in 5.1.2.1.3.2.
- 5.1.2.1.3.4 Velocity and Gas Mixing—Velocity profiles in the dilution tube are measured at various sampling stations at two total flow rates and two exhaust-gas flow rates, using shop air to simulate exhaust gas flow. Velocity measurements are made with an anemometer using a hot-film sensor projecting into the airstream. Mixing profiles are determined at 176.8 m/min using CO as a tracer gas added to the simulated exhaust gases and an NDIR CO analyzer to measure the CO concentrations in the tube.

Both velocity and mixing profiles are measured by traverses of probes in vertical and horizontal planes. In each traverse, 14 positions are measured for the velocity profiles and 15 positions for the mixing profiles. Tests are run separately for horizontal and vertical velocity traverses, without attempting to adjust flow to exactly the same value in each test. Velocity and mixing profiles show whether mixing of exhaust gases and dilution are good and whether velocity profiles are satisfactorily flat in the cross section up to 203 mm from the centerline of the tube. The velocity and mixing profiles are not affected by changes of exhaust-gas flow rate.