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(R) CONSTANT VOLUME SAMPLER SYSTEM FOR EXHAUST EMISSIONS MEASUREMENT

Foreword**—**This Document has also changed to comply with the new SAE Technical Standards Board format.

Development of CVS System—Constant volume sampler (CVS) systems have been used since the late 1950s. The engine exhaust to be sampled is diluted with ambient air so that the total combined flow rate of exhaust and dilution air mix is nearly constant for all engine operating conditions. The CVS system is sometimes called a variable dilution sampler. Recently constant volume sampler systems have been abbreviated PDP-CVS or CFV-CVS. The PDP-CVS system is the older system that uses a positive displacement pump to maintain a constant total flow. The CFV-CVS system uses a critical flow venturi to maintain a nearly constant total flow. Some of the newer CFV systems no longer use a heat exchanger to bring the mix of engine exhaust and dilution air to a constant temperature, but instead monitor the mix temperature continuously in order to calculate the total flow accurately. These CFV systems are not constant volume samplers, but since they are used to measure emissions, the units are discussed here.

Hydrocarbons in the dilution air were recognized from the first as a problem in the CVS procedure. Studies were initiated on the feasibility of removing the unwanted hydrocarbons. As a result, the installation of charcoal filters in the dilution air system was chosen as the most practical solution. On a long-term basis, charcoal does not remove the hydrocarbon materials but it does stabilize their concentration level during a given test and thereby permit the collection of an accurate background sample.

1. Scope**—**This SAE Information Report describes uniform laboratory techniques for employing the constant volume sampler (CVS) system in measuring various constituents in the exhaust gas of gasoline engines installed on passenger cars and light trucks. The techniques described relate particularly to CVS systems employing positive displacement pumps. This is essentially an almost obsolete system relative to usage in industry and government. Current practice favors the use of a critical flow venturi to measure the diluted exhaust flow. In some areas of CVS practice, alternative procedures are given as a guide toward development of uniform laboratory techniques.

The report includes the following sections:

Introduction

1. Scope
2. References
2.1 Applicable Publications
3. Definitions
4. Test Equipment

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2. *References*

2.1 Applicable Publications—The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated the lastest revision of SAE publications shall apply.

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

SAE J1506—Emission Test Driving Schedules

2.1.2 FEDERAL PUBLICATIONS—Available from the Superintendent of Documents, U. S. Government Printing Office, Washington, DC 20402.

1975 Federal Test Procedure: 40 CFR 86 Subpart B
The Federal Register

3. ***Definitions*****—**The following definitions apply to the term indicated as the term is used in this document.

3.1 Analytical Train—A general term to define the entire system required to sample and analyze a particular constituent in exhaust gas. Typically, this train will include items such as tubing, condenser, particulate filter, sample pump, analytical instrument, and flow meter.

3.2 Calibration Curve—Normally, the dependent variable y, the concentration of the calibration gas, is plotted as a function of the independent variable x, the instrumental voltage. For nonlinear analyzers, a polynomial of degree no greater than the fourth power is used. Sufficient data points should be used to adequately define the analyzer response. The calibration curve should agree to within 1% of the measured data point.

3.3 Calibration Frequency—Analyzers should be checked at least monthly to determine if significant change has occurred in the calibration. In addition, the calibration should be verified when a problem is suspected and when large gain shifts are observed.

3.4 **Calibrating Gas—**A gas mixture of accurately known concentration which is used periodically to calibrate the analytical instruments. Usually, calibration requires a number of mixtures of different concentrations. Calibrating gases are usually divided into groups such as National Institute of Standards and Technology (NIST) standard reference gases, golden standards, primary standards, and working gases. The naming of the working gases should be traceable to the NIST standard reference gases. A standard gas divider is normally used to blend a gas with a zero (or near zero) gas to generate a calibration curve. It provides a significant reduction in calibration gas cylinders.

3.5 **Chassis Dynamometer—**A laboratory power absorption unit capable of simulating to a limited degree the road operation of a vehicle. The dynamometer should possess the capability to simulate the inertia and road load power developed by a vehicle.

3.6 **Chemiluminescent (CL) Analyzer—**An instrument which measures nitric oxide by measuring the intensity of chemiluminescent radiation from the reaction of nitric oxide with ozone. The addition of a converter will permit the measurement of the oxides of nitrogen.

3.7 **Chock—**A block or wedge that prevents movement of the wheels of a vehicle.

3.8 **Coastdown—**The procedure used to determine the total horsepower absorbed by a dynamometer at 80 km/h (50 mph). The time required for the rolls to coast down from 88 to 72 km/h (55 to 45 mph) is observed.

3.9 **Constant Volume Sampler (CVS)—**A device for collecting samples of diluted exhaust gas. The exhaust gas is diluted with air in a manner that keeps the total flow rate of exhaust gas and dilution air constant throughout the test. The device permits measuring mass emissions on a continuous basis and also, through use of a second pump, allows a proportional mass sample to be collected.

3.10 **Converter—**A thermal or catalytic reaction device which usually precedes the chemiluminescent analyzer and converts oxides of nitrogen to nitric oxide. The converter may also convert ammonia and other nitrogen containing compounds to nitric oxide.

3.11 **Counter—**A mechanical and/or electrical device that totalizes the number of revolutions of the CVS for each test phase.

3.12 **Curve Fitting—**See calibration curve, Lagrangian fit, polynomial fit.

3.13 **Detector—**That Component in an analytical instrument which is sensitive to a particular gas.

3.14 **Dilution Air—**Ambient air which is passed through filters to stabilize the background hydrocarbon concentration and which is used to dilute the vehicle exhaust.

3.15 **Dilution Factor—**Based on stoichiometric equation for fuel with composition $CH_{1.85}$, the dilution factor is defined as:

$$\frac{13.4}{CO_2 + (HC + CO) \times 10^{-4}} \qquad \text{(Eq. 1)}$$

where:

CO_2 is equal to the concentration in dilute exhaust sample in mole percent, HC in ppm carbon equivalent, and CO in ppm corrected for water vapor and CO_2 extraction.

3.16 **Dilution Ratio—**The ratio of CVS volume to exhaust volume, usually found by dividing the undiluted exhaust CO_2 concentration by the dilute CO_2 concentration.

3.17 Driver Aid—An instrument used to guide the vehicle driver in operating the vehicle in accordance with the specified acceleration, deceleration, and cruise operating modes of a specific driving procedure.

3.18 Exhaust Emissions—Substances emitted to the atmosphere from any opening downstream from the exhaust port of a motor vehicle engine.

3.19 Fifth Wheel—A calibrated wheel, axle, and tachometer generator assembly that can be used to determine the true speed of the vehicle (by towing the wheel assembly), or true speed of the dynamometer rolls (by permitting the rolls to drive the fifth wheel assembly).

3.20 Filter Cell—That portion of the NDIR instrument which is filled with a particular gas in order to reduce interference signals.

3.21 Flame Ionization Detector (FID)—A device containing a hydrogen-in-air diffusion flame that produces an electrical current approximately proportional to the mass of the carbon component of the hydrocarbons entering the flame per unit time.

3.22 Hang-up—The absorption-desorption of sample (mainly higher molecular weight hydrocarbons) from the surfaces of the sample system that can cause instrument response delay and lower concentration at the analyzer, followed by higher readings in subsequent tests.

3.23 Heat Exchanger—An air-to-air or air-to-water heat exchanger, which is used to control the temperature of the dilution air-exhaust gas mixture.

3.24 Horsepower

3.24.1 ABSORBED HORSEPOWER—Total power absorbed by the absorption unit of the dynamometer and by the frictional components of the dynamometer.

3.24.2 ABSORBED HORSEPOWER AT 80.5 KM/H (50 MPH) ROAD LOAD—The dynamometer setting values for various inertia weight vehicles published in the Federal Register.

3.24.3 FRICTIONAL HORSEPOWER—Power absorbed by the frictional components of the dynamometer.

3.24.4 INDICATED HORSEPOWER—Power values indicated by the power meter of the dynamometer.

3.24.5 INDICATED HORSEPOWER AT 80.5 KM/H (50 MPH) ROAD LOAD—The dynamometer setting values, determined by calibration, that correspond to the dynamometer setting values published in the Federal Register.

3.25 Inertia Weights—A series of rotating disks used on a chassis dynamometer to simulate to the nearest 57, 113, or 227 kg (125, 250, or 500 lb) increments of the test weight of a vehicle during accelerations and decelerations. The inertia weights have no effect during steady states.

3.26 Lagrangian Fit—A computer technique used to interpolate polynomial curves generated from a set of data points (calibration points): N data points are required to generate a curve to N—1 degree. A feature of this technique is that the interpolated curve goes through each data point exactly.

3.27 Laminar Flow Element (LFE)—A flow rate measuring device that has a linear relationship between flow rate and pressure drop.

3.28 **Light-Duty Truck—**Any motor vehicle rated at 8,500 pounds GVWR or less which has a vehicle curb weight of 6,000 pounds or less and which has a basic vehicle frontal area of 45 square feet or less, which is:

a. Designed primarily for purposes of transportation of property or is a derivation of such a vehicle, or
b. Designed primarily for transportation of persons and has a capacity of more than 12 persons, or
c. Available with special features enabling off-street or off-highway operation and use.

3.29 **Light-Duty Vehicle—**A passenger car or passenger car derivative capable of seating 12 passengers or less.

3.30 **Loaded Vehicle Weight—**The curb weight of a light-duty vehicle plus 136 kg (300 lb).

3.31 **Mixing Device—**A device that is used in the main flow stream of a CVS to promote mixing of the exhaust gas with the dilution air.

3.32 **Mode—**A particular operating condition (for example, acceleration, cruise, deceleration, or idle) of a test cycle.

3.33 **Nondispersive Infrared (NDIR) Analyzer—**An instrument to determine carbon monoxide, carbon dioxide, nitric oxide, and hydrocarbons in exhaust gas. Now primarily being used for carbon monoxide and carbon dioxide determinations.

3.34 **Normalizing Gas (Span Gas)—**A single calibrating gas blend routinely used in calibration of each analytical instrument.

3.35 **Optical Filter—**That portion of the NDIR instrument which eliminates wavelength regions where interference signals are obtained.

3.36 **Oxides of Nitrogen—**The sum total of the nitric oxide and nitrogen dioxide in a sample expressed as equivalent mass of nitrogen dioxide.

3.37 **Ozonator—**An electrical device that generates ozone from oxygen or air.

3.38 **Parts Per Million Carbon—**The mole fraction of hydrocarbon measured on a methane equivalence basis.

3.39 **Polynomial Fit—**A technique of generating a calibration curve from a set of points.

3.40 **Positive Displacement Pump—**A CVS blower, gas pump, or constant displacement pump that delivers a metered amount of air per revolution measured at inlet conditions.

3.41 **Probe—**A sample line inserted into the exhaust stream of a vehicle or engine in such a manner as to obtain a homogeneous or well-mixed exhaust sample.

3.42 **Reference Cell—**That portion of the NDIR instrument that is usually filled with air (sometimes nitrogen) and provides the reference signal to the detector.

3.43 **Remote Filter Box—**Particular CVS design that has the dilution air filters and mixing chamber housed in a separate cabinet which can be located close to the tailpipe of the test vehicle.

3.44 **Sample Cell—**That portion of the NDIR instrument which contains the flowing sample gas.

3.45 **Stratification—**Variation in concentration of a sample stream when samples are taken at different points on a cross section of the mixed CVS stream just ahead of the CVS positive displacement pump.

3.46 **Tailpipe Pressure—**The static pressure measured at the tailpipe when a CVS is connected to a test vehicle.

4. Test Facilities and Equipment

4.1 Sampler—CVS systems can exist in a variety of physical configurations but all of them permit measuring emissions of vehicles:

4.1.1 BASIC EQUIPMENT—The principal component of a CVS is either the positive displacement pump (PDP) of the older models or the critical flow venturi (CFV) of more recent designs. The positive displacement pump consists of a pair of symmetrical rotating, two-lobe impellers driven in opposite directions and encased by a housing. A critical flow venturi CVS has a CVS compressor unit that is used in conjunction with the critical flow venturi. Figure 1 shows a sketch of a CFV-CVS.

4.1.1.1 A dilution air filter system consisting of a particle (dust) filter, a charcoal filter to stabilize hydrocarbons, and a second particle filter to remove airborne particles and trap charcoal particles.

4.1.1.2 A flexible coupling to the tailpipe of the test car brings in undiluted exhaust gas to the mixing chamber.

4.1.1.3 A mixing chamber combines the automotive exhaust from the test car and the dilution air into a homogeneous (nonstratified) mixture.

4.1.1.4 A heat exchanger is used to control the temperature of the exhaust gas dilution air mixture. The heat exchanger should be capable of controlling the temperature of the dilute exhaust gas ±5.6 °C (±10 °F) during testing. In some models of CVS, a temperature controller regulates both the flow of cooling water or hot water (from a hot water heater) through the heat exchanger to control mixture temperature. In other models of CVS, the dilution air is preheated so that the temperature controller regulates the flow of cooling water through the heat exchanger in order to control the mixture temperature.

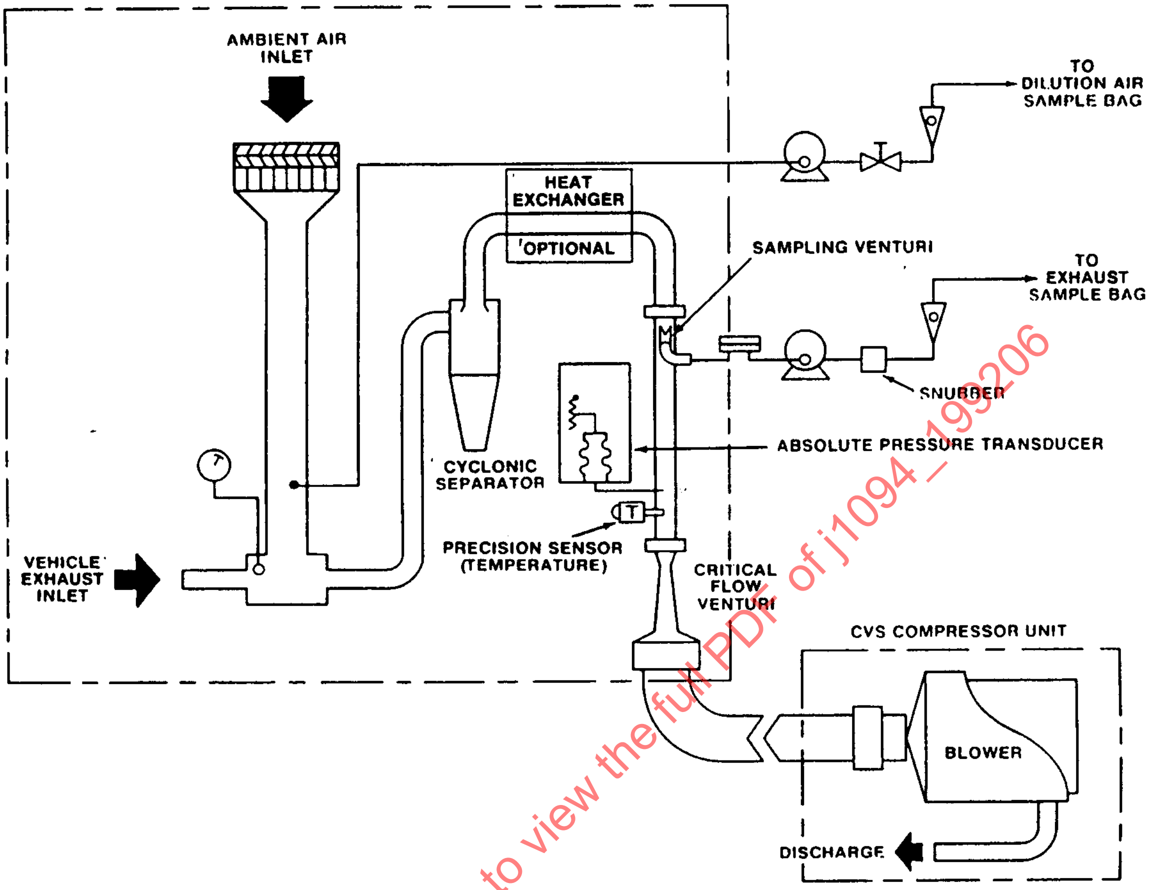

FIGURE 1—CFV—CVS SAMPLER UNIT

4.1.1.5 A secondary heater system maintains the heat exchanger at a temperature to prevent water condensation.

4.1.1.6 A sampling system transfers the exhaust-air mixture from the CVS to the bag at a constant flow rate. The minimum sample flow rate should be 0.28 m^3/h (10 ft^3/h). Each sampling system consists of fiberglass filter, a diaphragm type pump, a flow control valve, and a flow meter or other gas measuring device. All of the surfaces in contact with the sample air or air-gas mixture are stainless steel or other nonreactive material.

4.1.1.7 A similar sampling system collects dilution air from a point just downstream of the air filter and transfers it to a separate bag.

4.1.1.8 An evacuation and purge pump to remove the excess sample from the bags and purge the bags with clean air.

4.1.1.9 A set of bags (sample and background) and appropriate controls is needed for each of the test phases.

4.1.2 SUPPLEMENTARY EQUIPMENT—In addition to the above basic equipment, the following items can be added for operating convenience:

4.1.2.1 A muffler located after the CVS pump to reduce the noise.

4.1.2.2 A four-speed motor, transmission, or other suitable means for driving the positive displacement pump will permit a choice of different dilution ratios.

4.1.2.3 An optional remote control operating station containing the counter, the operations logic module, and the various control function switches and indicator lights that permit convenient operator control at a distance from the CVS console.

4.1.2.4 Optional modal analysis at the analytical bench during the filling of the bag is made possible through the use of a separate sampling probe(s). One probe is used if continuous modal analysis is conducted using diluted exhaust.[1] The second probe in this case is used to monitor diluted CO_2 which is used as a tracer gas to determine engine flow. Tail pipe sample should either be returned to the CVS bulk stream if the amount withdrawn is a significant fraction of total exhaust flow (greater than 1%), or the loss in tail pipe sample should be corrected mathematically.

4.2 Analysis Instrumentation—Bag Analysis

4.2.1 SCHEMATIC—Figure 2 is a sketch of the sampling and analysis train that is a typical flow schematic for the bag analysis of engine exhaust using the CVS.

4.2.2 COMPONENT DESCRIPTION—The following components are suggested for the CVS bag sampling and analytical systems for the analysis of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), carbon dioxide (CO_2), and oxygen (O_2):

4.2.2.1 NDIR analyzers for measurement of CO and CO_2 with cells of appropriate length for concentration ranges being measured. Typical ranges are shown in Table 1.

4.2.2.2 Chemiluminescent (CL) NO analyzer is equipped with a bypass and NO_2 to NO converter for the measurement of NO_x with concentration range selection as shown in Table 1.

4.2.2.3 FID for measurement of HC. The instrument employed should be capable of measuring HC for ranges shown in Table 1.

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[1] Two probes are required if continuous modal analysis is conducted using undiluted exhaust.

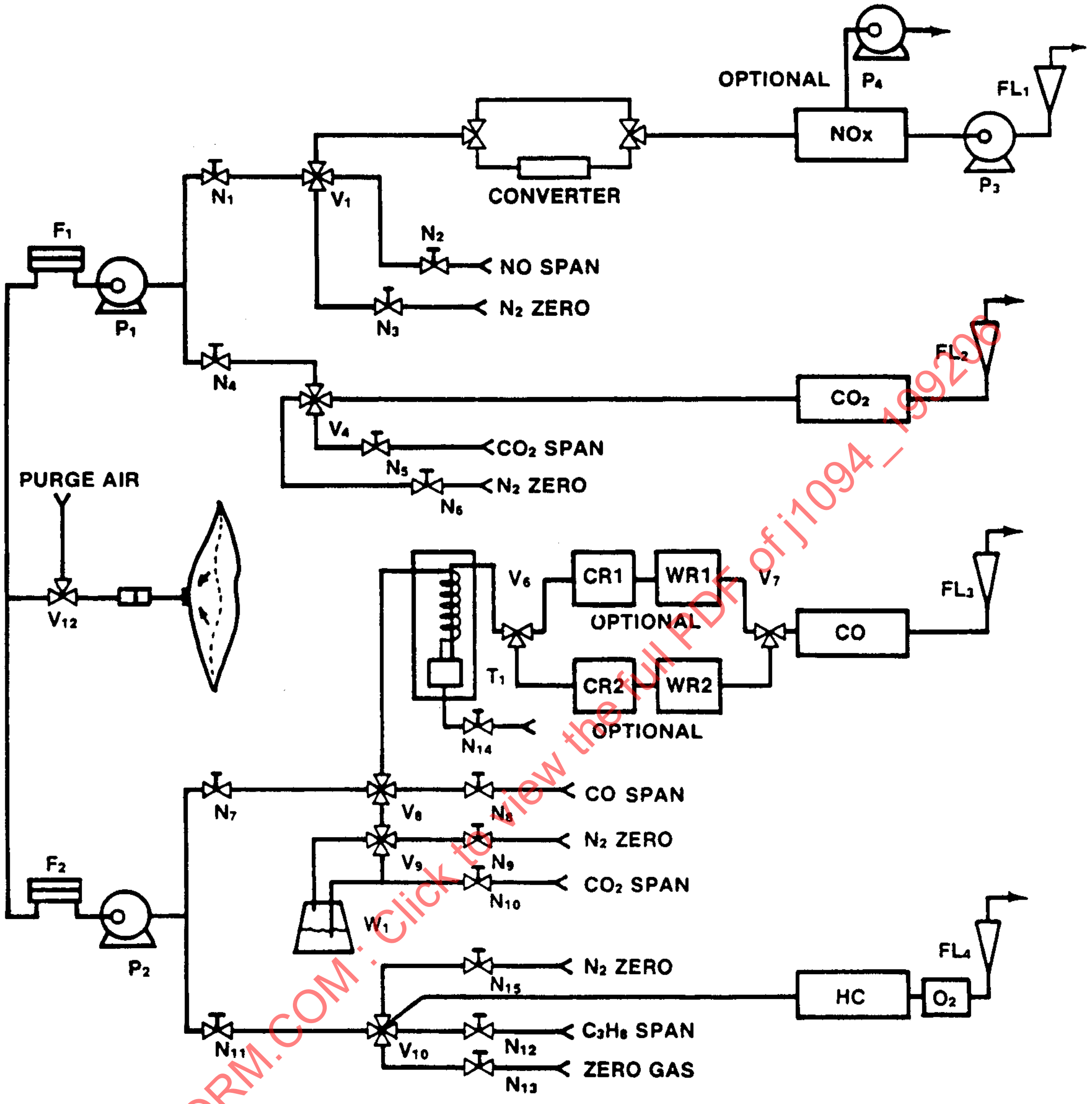

FIGURE 2—BAG SAMPLING AND ANALYSIS TRAIN

4.2.2.4 Oxygen analyzer for measurement of O_2 with range of measurement as shown in Table 1.

4.2.2.5 Valves V_{12} used to direct the sample or purge air to the analyzers.

4.2.2.6 Valves V_1, V_4, V_8 (optional), V_9, and V_{10} used to direct the sample, zero gas, or span gas streams to the analyzers.

4.2.2.7 Filters F_1 and F_2 for removing particulate materials from the sample prior to analysis. A glass fiber filter of at least 7 cm diameter is suitable.

4.2.2.8 Pumps P_1 and P_2 to move the sample through the system. Pumps should have stainless steel or aluminum chambers with diaphragms and valves made from or covered with an inert material, such as Teflon. Free air capacity should be approximately 1.1 m^3/h (40 ft^3/h). Pumps P_3 for bypass flow of chemiluminescent analyzer and vacuum pump P_4 (optional depending upon the design of the chemiluminescent analyzer) for evacuation of the chemiluminescent reactor chamber.

4.2.2.9 Needle valves N_1, N_4, N_7, and N_{11} to regulate sample gas flow to the analyzers.

4.2.2.10 Needle valves N_2, N_5, N_8, and N_{12} to regulate span gas flow to the analyzers.

4.2.2.11 Optional valve V_9 used to direct CO_2 span gas through the water bubbler for checking the performance of drier and absorber system or to check the H_2O and CO_2 interference rejection characteristics of the CO analyzer. Needle valve N_2 is used to regulate CO_2 flow.

4.2.2.12 Needle valves N_3, N_6, N_9, N_{13}, and N_{15} to regulate zero gas flow to the analyzers.

4.2.2.13 Flow meters FL_1, FL_2, FL_3, and FL_4 to indicate span gas, zero gas, and sample flow to the analyzers.

4.2.2.14 Water trap T_1, if necessary, to partially remove water and a valve N_{14} to allow the trap to be drained.

TABLE 1—TYPICAL LOW RANGES FOR ANALYSIS OF HC, CO, CO_2, NO_X, AND O_2 IN SPARK IGNITION ENGINE EXHAUST

Component	Ranges CVS Bag Sample	Ranges Undiluted Exhaust Gas
HC	0–300 ppmC	0–500 ppmC
CO	0–100 ppm	0–0.3%
NO_x		
1975	0–250 ppm	0–2500 ppm
1976	0–10 ppm	0–250 ppm
CO_2	0–2.0%	0–15%
Dilute CO_2	—	0–5%
O_2	0–21%	0–10%

4.2.2.15 Optional[2] sample conditioning columns CR_1 and CR_2 containing Ascarite to remove CO_2 from the CO analysis stream, and WR_1 and WR_2 containing indicating $CaSO_4$ or indicating silica gel to remove the remainder of the water. Equivalent drying techniques such as diffusion driers may be used. These optional sample conditioning techniques must be used if the CO instrument is subject to CO_2 or water interference. However, several CO analyzers are commercially available that have negligible CO_2 and water interference and their use is strongly recommended.

4.2.2.16 Optional valves V_6 and V_7 to permit switching from exhausted absorbing columns to fresh columns.

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[2] The criteria for CO interference by CO_2 and water is given in the Code of Federal Regulations (40 CFR 86.122): A CO instrument will be considered to be essentially free of CO_2 and water vapor interference if its response to a mixture of 3% CO_2 in N_2, which has been bubbled through water at room temperature (68 to 86 °F), produces an equivalent CO response, as measured on the most sensitive CO range, which is less than 1% of full scale CO concentration on instrument ranges above 300 ppm CO or less than 3 ppm on instrument ranges below 300 ppm CO.

4.2.2.17 Optional water bubbler W_1 to allow saturation of CO_2 span gas to check the efficiency of the absorbing columns in the CO system.

4.2.2.18 Optional methane analyzer with a range of 0 to 50 ppmC.

4.3 Analysis Instrumentation—Modal Analysis (Undiluted Exhaust Gas)

4.3.1 GENERAL—Figure 3 is a schematic drawing of the sampling and analysis train that is recommended for the modal analysis of spark ignition engine exhaust using the CVS. The system is very similar to that required for bag analysis, with the exception that water traps are required on all instrument sampling steams and an additional CO_2 analyzer is required. In addition, instruments of only approximately 1/10 the sensitivity of those used for bag analysis are needed. This system is based upon measuring continuously undiluted exhaust gas concentrations of HC, CO, NO_x, and CO_2 and the diluted exhaust CO_2 concentration.

The undiluted and diluted exhaust CO_2 concentrations are used to calculate a dilution factor which, in conjunction with the total diluted volume, can be used to calculate the vehicle exhaust volume. With the calculated exhaust volume and the undiluted exhaust concentrations, the modal mass emissions of each pollutant can be calculated as described in 6.2.2.

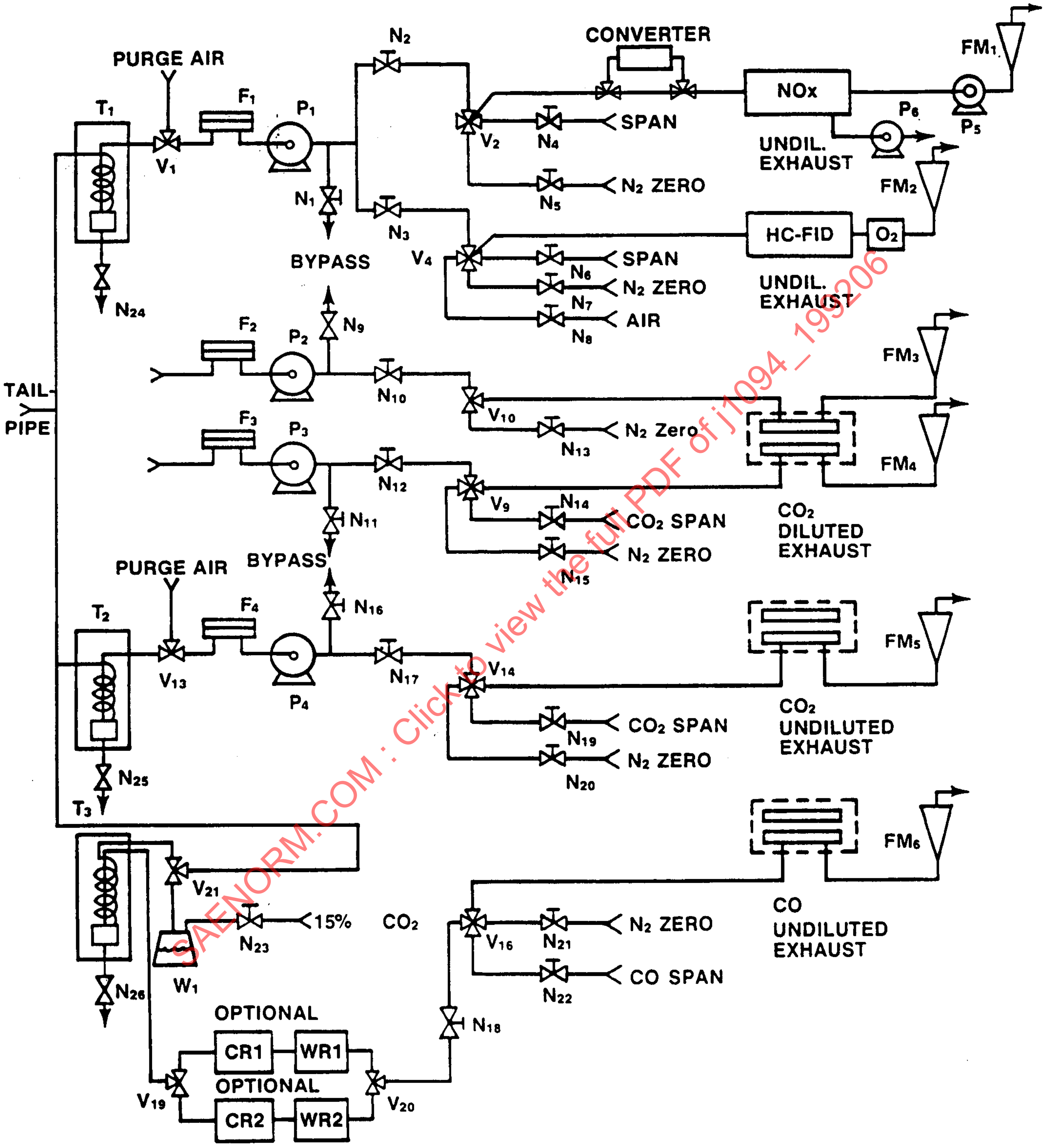

FIGURE 3—MODAL SAMPLING AND ANALYSIS TRAIN

4.3.2 COMPONENT DESCRIPTION—The following components are recommended for the analytical systems for the modal analysis of CO, HC, NO_x, CO_2, and O_2.

4.3.2.1 NDIR analyzers for measurement of CO and CO_2 with cells of appropriate length for the concentration ranges being measured. Typical ranges are shown in Table 1.

4.3.2.2 The CO_2 analyzer for the measurement of CO_2 in the diluted exhaust stream can be modified to the extent that the reference cell is replaced with a second sampling cell through which dilution air is passed during sampling. This feature will automatically correct the measured CO_2 in the diluted exhaust for the amount of CO_2 in the dilution air.

4.3.2.3 Chemiluminescent (CL) NO analyzer equipped with a bypass and a NO_2 to NO converter for the measurement of NO_x with the concentration range selection as shown in Table 1.

4.3.2.4 FID for measurement of HC. The instrument should be capable of measuring HC for the ranges shown in Table 1.

4.3.2.5 Oxygen analyzer for measurement of O_2 with range of measurement shown in Table 1.

4.3.2.6 Valves V_1 and V_{13} used to direct the sample of purge air to the analyzers or to purge air to the blowout traps.

4.3.2.7 Valves V_2, V_4, V_9, V_{10}, V_{14}, and V_{16}, used to direct the sample, zero gas, or span gas streams to the analyzers. Valve V_4, is used to direct the span gas to the O_2, sensor.

4.3.2.8 Filters F_1, F_2, F_3, and F_4, for removing the particulate from the sample prior to analysis. A glass fiber type of at least 7 cm in diameter is suitable.

4.3.2.9 Pumps P_1, P_2, P_3, and P_4, to move the sample through the system. Pump P_5, for bypass flow of the chemiluminescent analyzer and vacuum pump P_6 (optional dependent on design of chemiluminescent analyzer) for evacuation of the chemiluminescent reactor chamber. Pumps should have stainless steel or aluminum chambers with diaphragms and valves made from or covered with an inert material, such as Teflon. Free air capacity should be approximately 1.1 m^3/h (40 ft^3/h).

4.3.2.10 Needle valves N_2, N_3, N_{10}, N_{12}, N_{17}, and N_{18}, to regulate sample gas flow to the analyzers.

4.3.2.11 Needle valves N_4, N_6, N_{14}, N_{19}, and N_{22}, to regulate span gas flow to the analyzers.

4.3.2.12 Optional valve V_{21}, used to direct CO_2, span gas through the water bubbler for checking the performance of the absorbers in the CO analyzer stream. Needle valve N_{23}, (optional) is used to regulate CO_2, flow.

4.3.2.13 Needle Valves N_5, N_7, N_{13}, N_{15}, N_{20}, and N_{21}, to regulate zero gas flow to the analyzers.

4.3.2.14 Flow meters FM_1, FM_2, FM_3, FM_4, FM_5, and FM_6, to indicate span gas, zero gas, and sample flow to the analyzers.

4.3.2.15 Water traps T_1, T_2, and T_3, to partially remove water and valves N_{24}, N_{25}, and N_{26}, to allow the traps to be drained.

4.3.2.16 Optional sample conditioning columns CR_1, and CR_2, containing Ascarite to remove CO_2, from the CO analysis stream, and WR_1 and WR_2, containing indicating $CaSO_4$ or indicating silica gel to remove the remainder of the water. Ascarite produces water when it removes CO_2 from the stream. Equivalent drying techniques such as diffusion driers may be used. The volume of the conditioning columns must be sufficient to be effective for the duration of the test. Some operational ranges for continuous analysis may not require water and CO_2, removal. Some new CO instruments do not have water or CO_2 response.

4.3.2.17 Optional valves V_{19} and V_{20} to permit switching from the exhausted absorbing columns to fresh columns.

4.3.2.18 Optional water bubbler W_1 to allow saturation of CO_2 span gas to check the efficiency of the absorbing columns in the CO system.

4.3.2.19 Need valves N_1, N_9, N_{11}, and N_{16} to regulate the bypass sample flow.

4.4 Instrument Operating Procedures—Follow the instrument manufacturer's start-up and operating procedure for the particular type instrument being used. In addition, the following minimum calibration and instrument checks should be included.

4.4.1 INITIAL—The following instrument checks should be accomplished prior to making emission measurements with the instruments:

4.4.1.1 Optimize FID Response

a. Set sample flow rate to the minimum required for satisfactory sensitivity. (Suggested flow rate is 5cm^3/min.)
b. Present burner fuel composition now recommended is 40% H_2 60% He. However, hydrogen concentrations from 38% to 55% can be used, but the use of other than the recommended fuel could produce a correlation problem. The fuel mixture should contain less than 0.5 ppmC HC. Suggested hydrogen flow rate is 40 cm^3/min (e.g., 100 cm^3/min of 40% H_2/60% He fuel).
c. Suggested air flow rate is 10 times the hydrogen flow.
d. The suggested flows have been found, with many different FID's to reconcile the sometimes conflicting requirements of adequate hydrocarbon sensitivity, insensitivity to slight flow variation, reasonably uniform relative response to different hydrocarbons on a carbon atom basis, insensitivity to oxygen concentration in the sample, and good correlation between instruments. However with some FID's, it may be necessary to deviate somewhat from these suggested flows.

4.4.1.2 Determine Oxygen Response of FID Analyzer—Variations in the oxygen content of the sample can affect the FID response. This effect must be determined and minimized.

a. CVS bag analysis

1. Set flows as determined in 4.4.1.1 and ignite the burner. Wait for stabilization. Normally, the burner is operated continuously to avoid the stabilization problem.
2. Zero the analyzer on HC free air.
3. Determine the oxygen response by introducing propane gas at a concentration of approximately 30 ppmC in the following diluents: 100% N_2, 95% N_2/5% O_2, 90% N_2/10% O_2, 85% N_2/15% O_2, and 100% air.
4. Using the propane in the air gas as the baseline for no O_2 correction, plot a curve of the oxygen correction factor versus the percent O_2 in the sample:

$$O_2 \text{ correction factor} = 1.0 - \frac{(A - B)}{B} \qquad \text{(Eq. 2)}$$

where:

A = HC response in N_2/O_2 blends
B = HC response in air

5. Check the effect of O_2 using a propane concentration of 50 ppmC. If it is significantly different from the 30 ppmC correction data, establish a curve and apply the O_2 correction on a prorated basis as a function of HC concentration.
6. If the O_2 correction factor is less than 0.96 over the normal O_2 range encountered in CVS sampling, see 4.5.2.
7. It is recommended that a different detector be obtained if the oxygen correction factor is less than 0.90 for the O_2 range found in CVS samples.

b. Modal Analysis—Undiluted Exhaust Gas

1. Set flows as determined in 4.4.1.1 and ignite the burner. Wait for stabilization. Normally, the burner is operated continuously to avoid the stabilization problem.
2. Zero the analyzer with N_2.
3. Determine the oxygen response by introducing propane gas at a concentration of approximately 300 ppmC in the following diluents: 100% N_2,/ 95% N_2/10% O_2, 85% N_2/15% O_2, and 100% air.
4. Using the propane in N_2 (0% O_2) as the baseline for no O_2 correction, plot a curve of the oxygen correction factor versus the percent O_2 in the sample, where:

$$O_2 \text{ correction factor} = \frac{\text{HC response with propane in 100\% } N_2}{\text{HC response with propane in } O_2 \text{blends}} \quad \text{(Eq. 3)}$$

5. If the O_2 correction factor is greater than 1.05 over the range of 0 to 10% O_2, see 4.5.2.
6. It is recommended that a different detector be obtained if the oxygen correction factor is greater than 1.10 for the O_2 range found in the undiluted exhaust gas samples.

4.4.1.3 Determine Linearity of FID Response

a. Set up the FID as determined in 4.4.1.1 and 4.4.1.2. Set the sample flow rate at a low value (approximately 5 mL/min) consistent with good signal to noise ratio.
b. Using propane in air, or N_2, vary the concentration of HC over the expected HC range. If the response is linear, a simple linear calibration factor can be used. If the response is not linear, prepare a calibration curve.

4.4.1.4 *Optimize Performance of NDIR*—After adjusting the analyzers for optimum performance using the manufacturer's recommended procedures, a calibration curve must be generated for the ranges of the instrument that will be used. All emission measuring instruments are comparative devices. The generation of the calibration curves using standard gases (see 4.5.1) should be as accurate as possible. Since many analyzers are connected to computers, a variety of curve-fitting techniques are being used. No specific technique will be recommended here. Polynomial and Lagrangian curve fitting techniques are widely used. It is recommended to examine carefully an accurate plot of the calibration curve to verify that a smooth curve was generated, rather than a curve that has only high correlation at the data points.

4.4.1.5 *Optimize Performance of Chemiluminescence NO Analyzer*—Using the manufacturer's recommended procedures, adjust the analyzer for optimum performance. In addition, determine the efficiency of the NO_2 to NO converter, at the converter temperature recommended by the manufacturer, using the flow system shown schematically in Figure 4. A suggested procedure is given in Appendix A.

If the converter efficiency is below 90%, the converter temperature should be increased and the efficiency rechecked. Converter temperature should be set at a minimum required for near 100% conversion efficiency.

Care must be used to prevent condensation due to pressure buildup in the NO_x sample train between the sample pump and the analyzer. This has been found to be a critical area of the NO_x sample train, since condensation causes a lowering of the measured NO_x concentration and, therefore, an incorrect NO_x emission measurement.

4.4.2 MONTHLY—The following checks are to be made monthly or more frequently if there is any doubt regarding the accuracy of the analyses.

4.4.2.1 Calibrate the NDIR analyzers using the same gas flow rates as when sampling exhaust.

a. Allow 2 h warmup of analyzers.
b. Tune analyzer.
c. Set zero and span using prepurified N_2 and the 100% range calibration gas.
d. Recheck zero and repeat step 4.4.21(c), if necessary.
e. Calibrate each analyzer with calibrating gases that are approximately 15, 30, 45, 60, 75, and 90% of each range used. The concentration of the standard gases should be known with at least ±2% accuracy. If the analyzer proves to be nonlinear, use an eight point calibration with a set of calibration gases spread approximately uniformly over the analyzer range in question.
f. Compare values with previous curves. Any significant change reflects some problem in the system. Locate and correct the problem and recalibrate.

4.4.2.2 Check FID analyzer O_2 response and HC response.

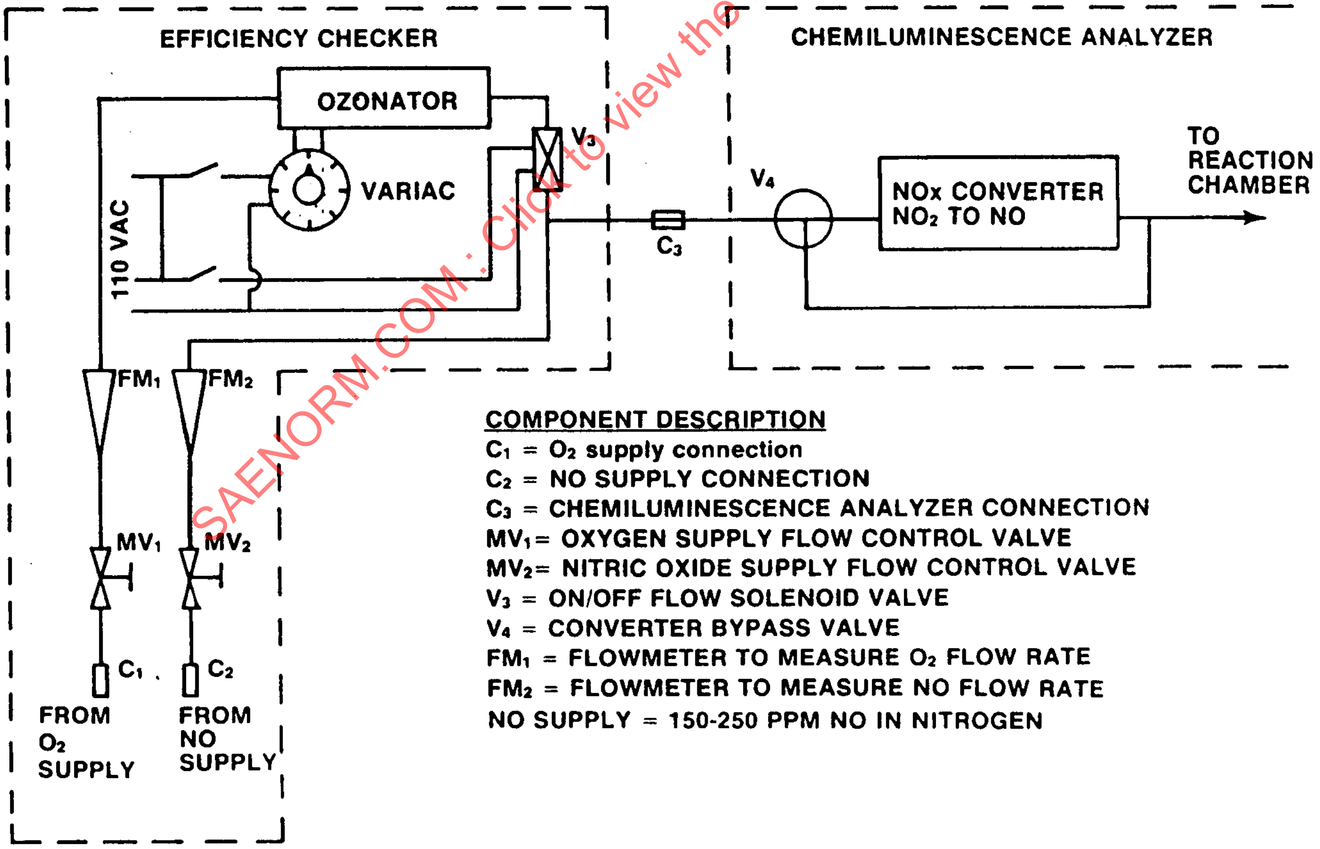

FIGURE 4—FLOW SCHEMATIC OF CONVERTER EFFICIENCY ANALYSIS SYSTEM

a. Ignite the burner and then set the fuel, air, and sample flow rates as determined in 4.4.1.1 and 4.4.1.2.
b. Introduce HC free air zero gas (CVS bag analysis) or N_2 (Modal-undiluted exhaust gas analysis) and zero analyzer.
c. Check O_2 effect on the response by introducing the calibration gases of propane in air, propane in N_2, and propane in 90% N_2/10% O_2.
d. Compare the O_2 response values with the previous curves. Any significant change (±10%) indicates a change in the burner operating characteristics. Check the burner system and measure the flows. If the change in the response cannot be resolved, establish a new O_2 response curve as per 4.4.1.2.
e. Check the calibration curve or response data as per 4.4.1.3.

4.4.2.3 Calibrate chemiluminescent analyzer using same flow rates as when sampling exhaust.

a. Set the sample flow and oxygen flow to the recommended settings.
b. Turn the ozone generator on and allow a 10 min warmup period.
c. Using nitrogen, zero the meter on the most sensitive range or the range to be used by means of the dark current suppression adjustment.
d. Set the span, using 100% range calibration gas on the range to be used.
e. Calibrate the analyzer with gases blended in N_2 that are approximately 25, 50, 75, and 100% of the range being used.
f. Check the values with the previous curves. Any significant change reflects some problem in the system. Locate and correct the problem and recalibrate.
g. Caution. The correct standby position for the NO_x converter is dependent on the converter type. See manufacturer's instructions.
h. Caution. Some NO_2 to NO converters can be rendered useless for many hours if they are allowed to sample rich exhaust gas (even momentarily) where high levels of CO, low levels of O_2, and free H_2 are present.

4.4.3 WEEKLY—Check the converter of the chemiluminescent analyzer using the procedure outlined in 4.4.1.5.

4.4.4 DAILY—Prior to daily testing carry out the following:

4.4.4.1 NDIR Analyzers—Normally, power is left on the NDIR analyzers continuously. Only the chopper motors are turned off. In some cases, more dependable performance has been achieved by leaving the chopper motors on.

a. Zero on prepurified N_2.
b. Introduce span gas and set the gain to match the calibration curves. Use the same flow rate for calibration, span gas, and exhaust gas to avoid correction for the sample cell pressure change. Use span gas having a concentration of the constituent being measured that will result in 75 to 95% of full-scale deflection. If the gain has shifted significantly, check the tuning: if necessary, check the calibration.
c. Check nitrogen zero and repeat steps 4.4.4.1(a) and 4.4.4.1(b), if necessary.
d. Repeat steps 4.4.4.1(a) through 4.4.4.1(c) prior to each exhaust gas analysis.
e. Span and zero should be rechecked after bag measurements.

4.4.4.2 FID Analyzer

a. Ignite the burner and then set the fuel, air, and sample flow rates as determined in 4.4.1.1 and 4.4.1.2.
b. Introduce zero gas (HC-free air for CVS analyzers, N_2 for undiluted exhaust gas analyzers) and zero analyzer.

c. Introduce HC span gas (propane in HC-free air for CVS analyzers, propane in N_2 for undiluted exhaust gas analyzers) of appropriate concentration to result in a response of at least 50% of full-scale on the range anticipated for use. If the calibration curve and span value disagree adjust the span potentiometer of the FID. Sample flow for zero and span must be the same as that used for analyzing exhaust sample.
d. Repeat steps 4.4.4.2(a) through 4.4.4.3(c) prior to each exhaust gas analysis.
e. Span and zero should be rechecked after bag measurements.

4.4.4.3 Chemiluminescent Analyzer—Normally power is left on continuously. Operate converter in standby mode as recommended by the manufacturer. Vacuum pumps are normally kept on continuously on those model analyzers using vacuum pumps. The ozonator should not be left on continuously for safety reasons. Vacuum pump and ozone problems can be minimized by replacing the pump oil with perfluorinated polyether fluid.

a. Turn on the sample pumps.
b. Set O_2 (in some models air is used) and sample flows using nitrogen.
c. Turn on ozone generator and allow a 10 min warmup.
d. With the converter in the NO mode, adjust the dark current suppression to zero the meter on the most sensitive range or the range to be used, using prepurified N_2.
e. Introduce span gas and set gain to match the calibration curves. Use a span gas having an NO concentration that will result in 75 to 95% of full-scale deflection.
f. Check dark current suppression and repeat steps 4.4.4.3(d) and 4.4.4.3(e) if necessary.
g. Span and zero should be rechecked after bag measurements.

4.4.4.4 Oxygen Analyzer

a. Introduce oxygen-free nitrogen and set zero.
b. Introduce air and set O_2 span. This is usually done concurrently when setting the zero on the FID analyzer.
c. Sample flow for zero and span must be the same as that used when analyzing exhaust gas samples.

4.5 Supplementary Discussion

4.5.1 CALIBRATION GASES—There are several suppliers of calibration gases in the ranges used in this procedure. These can be obtained with an analysis accuracy of ±2% or better. Stated gas analysis accuracies should be explicitly defined in terms of traceability to NIST standard reference gases or applicable gravimetric standards. It is recommended that all working gases be renamed using NIST standard reference gases or in-house primary reference gases. If a reference gas cylinder value does not fall on a smooth calibration curve, then that cylinder must not be used.

The CO and CO_2 gas can be purchased as a mixture in nitrogen. NO calibrating gas should be diluted with oxygen-free nitrogen and must not be mixed either with CO or CO_2. Propane calibrating gases are purchased with HC-free air as the diluent for use in CVS bag analysis and with N_2 as the diluent for use in undiluted exhaust gas analysis.

Zero gas impurity should not exceed 0.5 ppmC for HC, 1 ppm for CO, 0.1 ppm for NO, 400 ppm (0.04%) for CO_2, and 3 ppm for H_2O.

4.5.2 REDUCING THE OXYGEN EFFECT ON RESPONSE—The oxygen correction for FID should be reduced to attain the limits described in 4.4.1.2. The oxygen effect on response for a particular FID burner design may depend upon:

a. The type of burner fuel used, for example, 40% H_2/60% N_2, or 40% H_2/60% He
b. On the sample flow rate into the burner and
c. The air and fuel rate to the burner.

4.6 Tailpipe Connections—To obtain a good constant volume sample of exhaust gas it is imperative that no leakage, either into or out of the sampling system, occur at the tailpipe connection between the vehicle and the CVS sampler. The CVS sampler must be provided with dual inlets to accommodate vehicles with dual exhaust systems. When a vehicle with a single exhaust is being tested, the second sampler inlet must be tightly capped to prevent leakage.

Piping between the sampler and the vehicle should be kept to a minimum length and be of adequate diameter. (See Section 5 for more detail on this subject.) The actual connection between the vehicle tailpipe and the flexible tubing of the CVS can be made in one of two ways:

a. A flanged fitting such as a Marmon coupling. One end of this coupling is welded to the flexible piping from the CVS and a mating section is welded to the exhaust pipe(s) of each vehicle to be tested.
b. A silicone rubber boot clamped to the exhaust pipe and inlet plumbing to the CVS.

The first method, a flanged fitting, should be used whenever possible. However, when fittings cannot be welded to each vehicle to be tested, the silicon boot alternative has to be used. The main drawback of the silicone boot is that the hot exhaust gas causes rapid deterioration of the silicone. When vehicles with advanced control devices are tested, the very hot exhaust gases produced by these systems may cause the boot to crack internally after a single test.

4.7 Chassis Dynamometer

4.7.1 PROCEDURE FOR DYNAMOMETER ABSORBED POWER CALIBRATION—The following procedure describes one method for determining the absorbed power of a chassis dynamometer. The measured absorbed power includes dynamometer frictional power as well as the power absorbed by the power absorption unit. The dynamometer is driven above the test speed range to 96 km/h (60 mph). The device used to drive the dynamometer (in most cases a vehicle) is then disengaged from the dynamometer and the roll(s) allowed to coast down. The kinetic energy of the system is dissipated by the dynamometer friction and absorption unit. This method neglects the variations in roll bearing friction due to the drive axle weight of the vehicle and also neglects the variations in friction due to different inertia weights. The difference in coastdown time of the free (rear) roll relative to the drive (front) roll may be neglected in the case of dynamometers with paired rolls.

4.7.1.1 Equipment

a. Fifth wheel, tachometer generator, or other device to measure the speed of the front roll.
b. Hydraulic jack or other equipment to lift vehicle's drive wheels from the rolls.
c. Timing device to measure the time it takes the rolls speed to decrease from 88.5 to 72.4 km/h (55 to 45 mph) with 0.01 s accuracy.
d. Pair of chocks, vehicle tie-downs, and other safety devices used to assure safe operation of a vehicle on the rolls.

4.7.1.2 Preparation

a. Place the vehicle on the dynamometer rolls and set chocks against the front wheels. Tie-downs should be slack enough to allow the vehicle to be lifted from the rolls.
b. Verify the calibration of the fifth wheel, tach generator, or other speed monitoring equipment.

c. Position the lifting device at the rear of vehicle.
d. Place the lift pads under the rear bumper, adjacent to the bumper brackets.
e. Practice lift technique in disengaging the rear wheels to develop a familiarity with the lifting device's response.
f. When satisfied, raise the lift pads until they are in contact with the bumpers so that there is sufficient tension to keep the lift pads in place until ready to use.
g. Set dynamometer inertia to 1816 kg (4000 lb) or to the more common weight class to be tested.

4.7.1.3 Test Procedure

a. Drive the dynamometer with the test vehicle to 80.5 km/h (50 mph).
b. Adjust the dynamometer power absorption unit to an indicated 1.9 kW (2.5 hp).
c. Accelerate the dynamometer test vehicle to 96 km/h (60 mph). At this point, disengage the drive wheels from the rolls by means of the lifting device.
d. Record the time for the dynamometer to coast down from 88.5 to 72.4 km/h (55 to 45 mph).
e. Repeat steps 4.7.1.3(c) and 4.7.1.3(d) two more times.
f. Calculate an average from the three coastdown times.
g. Repeat steps 4.7.1.3(a) through 4.7.1.3(f) for 3.7, 5.6, and 7.4kW (5.0, 7.5, and 10.0 indicated hp) and calculate the average coastdown times for each.

4.7.1.4 Calculations—Calculate actual absorbed road horsepower from:

$$HP_{act} = \frac{1}{2}\,\frac{W_1}{32.2}\,\frac{(V_1^2 - V_2^2)}{550t} = \frac{0.06073\ W_1}{t} \qquad \text{(Eq. 4)}$$

Where:

W_i = equivalent inertia, lb
V_1 = initial velocity, ft/s (55 mph — 80.67 ft/s)
V_2 = final velocity, ft/s (45 mph — 66.00 ft/s)
t = elapsed time for rolls to coast down from 55 to 45 mph (88 to 72 km/h)

4.7.1.5 Belt Drive Dynamometers—The procedure outlined previously has been applied extensively to belt drive dynamometers. The next step is to plot the indicated road load power at 80 km/h (50 mph) versus the actual road power at 80 km/h (50 mph). See Figure 5..

The Federal Register advises running coastdowns at the inertia weight most frequently used. Common practice is to run coastdowns at either all inertia weight settings of a dynamometer or at least all inertia weights that are used for testing.

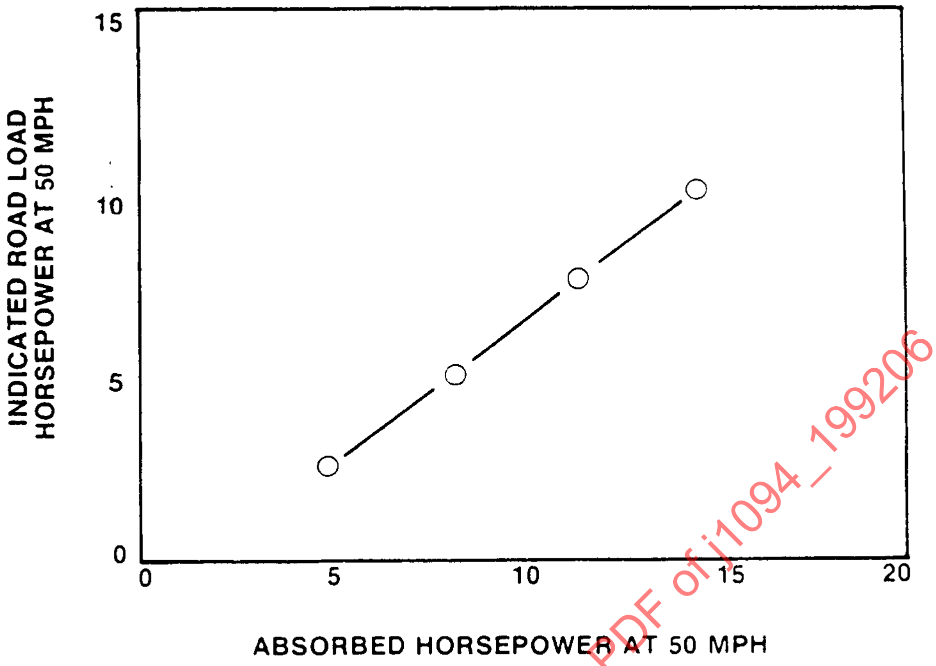

FIGURE 5—DYNAMOMETER CALIBRATION CURVE

4.7.1.6 *Direct-Drive Dynamometers*—The same procedure can be used for direct-drive dynamometers as for belt drive dynamometers and should be used for manual loading calibration of these units. However, automatic loading features of the new direct-drive dynamometers can improve the coastdown procedure.

The direct-drive dynamometer procedure sets up the dynamometer for operation at the desired operating points rather than finding a linear range for each inertia weight. This procedure is rapid and reproducible in both running coastdowns and in operation. It is recommended that a plot of frictional horsepower versus inertia weight be made for each set of coastdown data. These plots can aid in determination that the coastdown data is valid.

In Figure 6, the frictional power is plotted as a function of inertia weight for nine automatic loading direct-drive dynamometers. The data show that the frictional powers are confined to an approximate 745 kW (1 hp) band. On these plots, the "over 5500" values are plotted at 6000 for convenience.

An example of the effect of recalibration is shown in the frictional power versus inertia weight plot in Figure 7. A dynamometer recalibration indicated a shift of over 0.3 kW (0.5 hp) friction. A recalibration showed that a speed calibration error had been made. After correction, a typical shift of less than 0.3 kW (0.5 hp) was observed.

4.7.2 DYNAMOMETER PROCEDURE

4.7.2.1 The vehicle shall be tested from a cold start. Engine startup and operation over the driving schedule make a complete test run. Exhaust emissions are diluted with air to a constant volume and a portion is sampled continuously during each of the three test phases. The composite samples, collected in three bags, are analyzed for HC, CO, NO_x, and CO_2. Three parallel samples of dilution air are similarly analyzed. CO_2 is measured because it is needed in determining the carbon balance fuel economy.

4.7.2.2 A fixed-speed cooling fan with a nominal capacity not to exceed 150 m^3/min (5300 ft^3/min) is positioned during dynamometer operation so as to direct cooling air to the vehicle in an appropriate manner with the engine compartment cover open. In the case of vehicles with front engine compartments, the fan is squarely positioned between 200 and 300 mm (8 and 12 in) in front of the cooling air inlets (grill). In the case of vehicles with rear engine compartments or if special designs, the cooling fan or fans should be placed such that engine/vehicle temperatures normally encountered during road operation are approximated. The vehicle should be nearly level when tested in order to prevent abnormal fuel distribution.

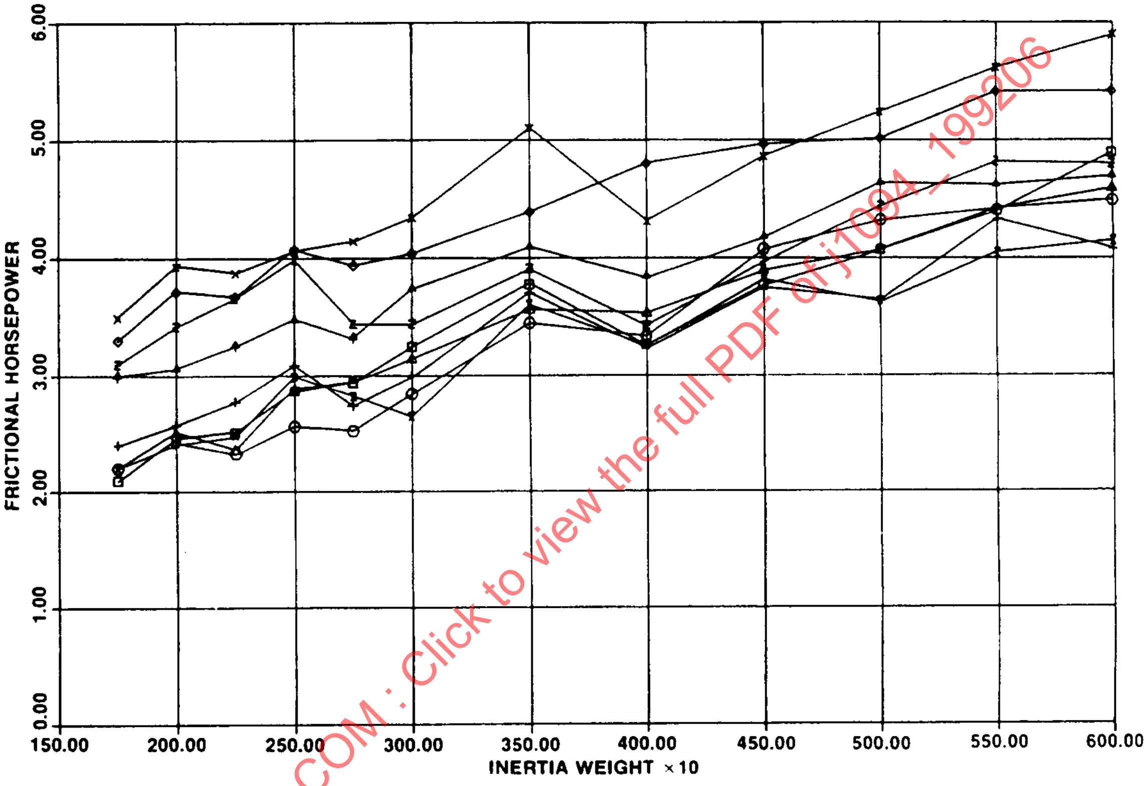

FIGURE 6—TYPICAL FRICTIONAL HORSEPOWERS

4.7.2.3 Flywheels, electrical, or other means of simulating inertia as shown in Table 2 should be used. If the equivalent inertia specified is not available on the dynamometer being used, the next higher equivalent inertia available, not exceeding 113 kg (250 lb), should be used.

4.7.2.4 *Power Absorption Unit Adjustment*

a. The power absorption unit is adjusted to reproduce absorbed horsepower at 80 km/h (50 mph) road load. The relationship between absorbed power and indicated power for a particular dynamometer should be determined by the procedure previously outlined.
b. The absorbed power listed in Table 2 is used or the vehicle manufacturer may determine the absorbed power by the following procedure and request its use:

    1. Measure the absolute manifold vacuum of a representative vehicle of the same equivalent inertia weight, when operated on a level road under balanced wind conditions at a true speed of 80 km/h (50 mph).

2. Note the dynamometer indicated power setting required to reproduce the manifold vacuum, when the same vehicle is operated on the dynamometer at a true speed of 80 km/h (50 mph). The tests on the road and on the dynamometer should be performed with the same vehicle ambient absolute pressure (usually barometric), that is, within ±5 mm of Hg.
3. The absorbed power values are listed in Table 2.

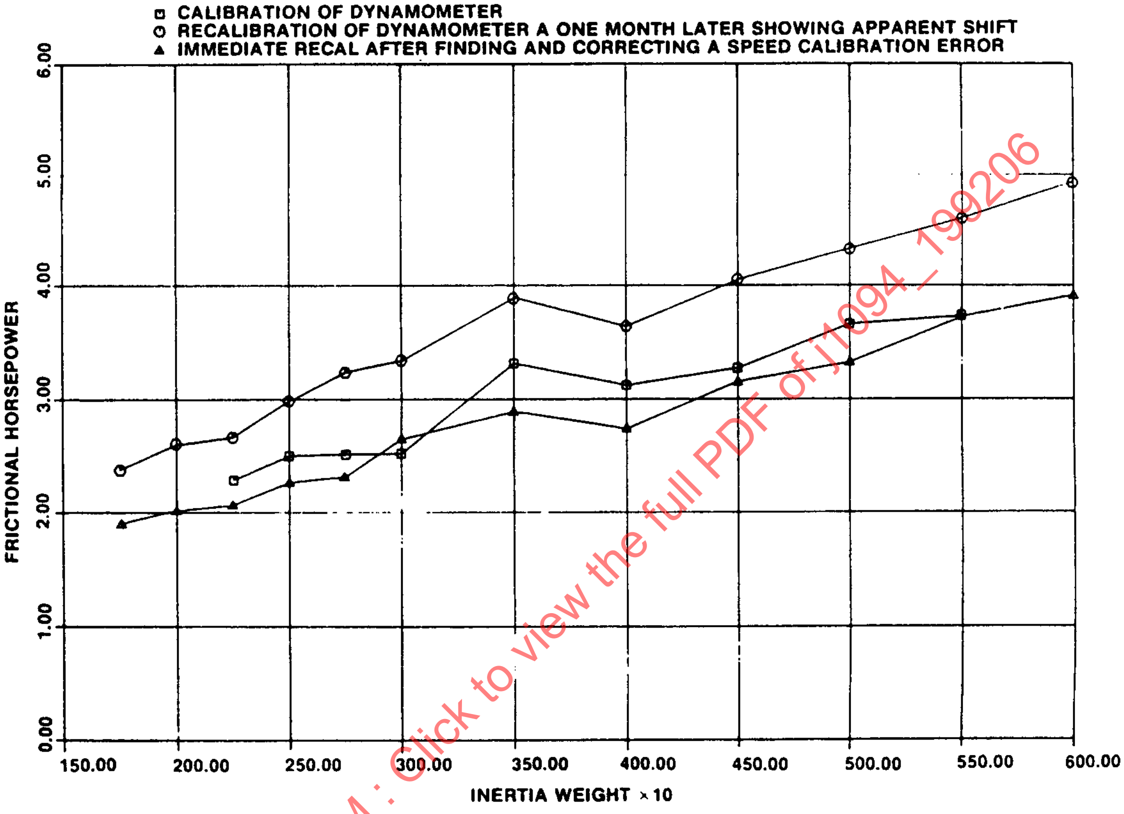

FIGURE 7—EFFECT OF RECALIBRATION

TABLE 2—EQUIVALENT INERTIA WEIGHT AND ABSORBED POWER

Loaded Vehicle Weight kg	Loaded Vehicle Weight lb	Equivalent Inertia Weight kg	Equivalent Inertia Weight lb	Absorbed Power at 80 km/h (50 mph) Without and With Air-Conditioning Load Simulation Without kW	Absorbed Power at 80 km/h (50 mph) Without and With Air-Conditioning Load Simulation Without hp	Absorbed Power at 80 km/h (50 mph) Without and With Air-Conditioning Load Simulation With kW	Absorbed Power at 80 km/h (50 mph) Without and With Air-Conditioning Load Simulation With hp
Up to 511	Up to 1125	454	1000	4.4	5.9	4.8	6.5
512 to 624	1126 to 1375	568	1250	4.8	6.5	5.4	7.2
625 to 738	1376 to 1625	681	1500	5.3	7.1	5.8	7.8
739 to 851	1626 to 1875	895	1750	5.7	7.7	6.3	8.5
852 to 975	1876 to 2125	908	2000	6.2	8.3	6.8	9.1
976 to 1085	2126 to 2375	1022	2250	6.6	8.8	7.2	9.7
1086 to 1195	2376 to 2625	1135	2500	7.0	9.4	7.7	10.3
1196 to 1306	2626 to 2875	1250	2750	7.4	9.9	8.1	10.9
1307 to 1475	2876 to 3250	1362	3000	7.7	10.3	8.4	11.3
1476 to 1700	3251 to 3750	1590	3500	8.4	11.2	9.2	12.3
1701 to 1930	3751 to 4250	1816	4000	8.9	12.0	9.8	13.2
1931 to 2150	4251 to 4750	2045	4500	9.5	12.7	10.4	14.0
2151 to 2380	4751 to 5250	2270	5000	10.0	13.4	11.0	14.7
2381 to 2610	5251 to 5750	2500	5500	10.4	13.9	11.4	15.3
2611 or more	5751 or more	2500	5500	10.7	14.4	11.8	15.8

4.7.2.5 The vehicle speed must be measured by a tachometer generator installed on the rear (or idler) roll. A tachometer generator installed on the front (or drive) roll is used to measure coastdown speed. Even though most conducted integrating front and rear tachometer generator speeds over the test cycle have shown only small differences in total distance, the rear (or idler) roll must be used to measure vehicle speed because of tire distortions that occur on accelerations which change the rolling radius.

4.7.2.6 The Federal Register recommends that minimum throttle action should be used to maintain the proper speed-time relationship. When using a two-roll dynamometer, a truer speed-time trace may be obtained by minimizing the rocking of the vehicle in the rolls. The rocking of the vehicle changes the tire rolling radius on each roll. The rocking may be minimized by restraining the vehicle horizontally (or nearly so) by using a cable and winch. Care must be used to prevent tightening this cable too much as this could cause vehicle to be pulled off rolls.

4.7.2.7 Drive wheel tires must be inflated to a cold gage pressure of 310 kPa (45 psi). This document acknowledges that all is not fully understood regarding the rolls-tire interaction.

4.7.2.8 *Warmup of Dynamometer*—If the dynamometer has not been operated during the 2 h period immediately preceding the test, it should be warmed up for 15 min by operating it at 48 km/h (30 mph) using a nontest vehicle.

5. Calibrating and Operating Procedure

5.1 Calibration Procedure—The purpose of this procedure is to provide a reliable method for calibrating CVS systems.

A detailed discussion of the major requirements for conducting an accurate CVS calibration follows. The individual sections are arranged in proper sequential order and provide detailed instructions for conducting the necessary checks that must be performed for satisfactory results.

5.1.1 PREPARATION OF CVS SYSTEM FOR CALIBRATION

5.1.1.1 Installation of Sampling Taps and Lines—For measurement of the pressure differential across the CVS pump, install static pressure taps of the type shown in Figure 8 at the top and bottom of the CVS pump drive head plate, centering on the inlet and outlet pump cavities. The same static pressure taps used for CVS calibration should be used for vehicle emission testing. The location should provide at least one diameter of straight pipe up and downstream from the tap to minimize flow disturbances. If a straight length of pipe is not available, a piezometer ring from which a single gage connection is led may be used.

5.1.1.2 If the straight section of pipe is vertical, the static tap can be installed anywhere around the periphery. If the pipe is horizontal, the tap should be located in the periphery of the upper half (above the pipe centerline). The pump inlet pressure tap should be located downstream from the gas sample probes.

The diameter and hole edge rounding of the pressure tap should conform with the recommendations shown in Table 3.

NOTE—It is realized that it will seldom be practical and, generally, it will be impossible actually to measure the radius of the hole-edge rounding. However, if any dulling or rounding is done, the values in Table 3 offer a guide for estimating the maximum desirable degree of edge rounding.[3]

All burrs and irregularities should be removed from the inner wall surface near the static tap.

5.1.1.3 The sample probes should be made of stainless steel and be the design haown in Figure 8. They should be faced upstream directly into the flow. All sample lines leading from the probes should be routed upward. This will allow any water which may condense to drain out of the line and thereby prevent hydraulic blockage. (Similar precautions should be taken when installing static pressure lines).

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[3] Static Pressure Cups and Fluid Meters—Theory and Application, Fifth Chapter, Section A3, pp. 18–19. American Society of Mechanical Engineers, 345 East 47th Street, New York, New York 10017.

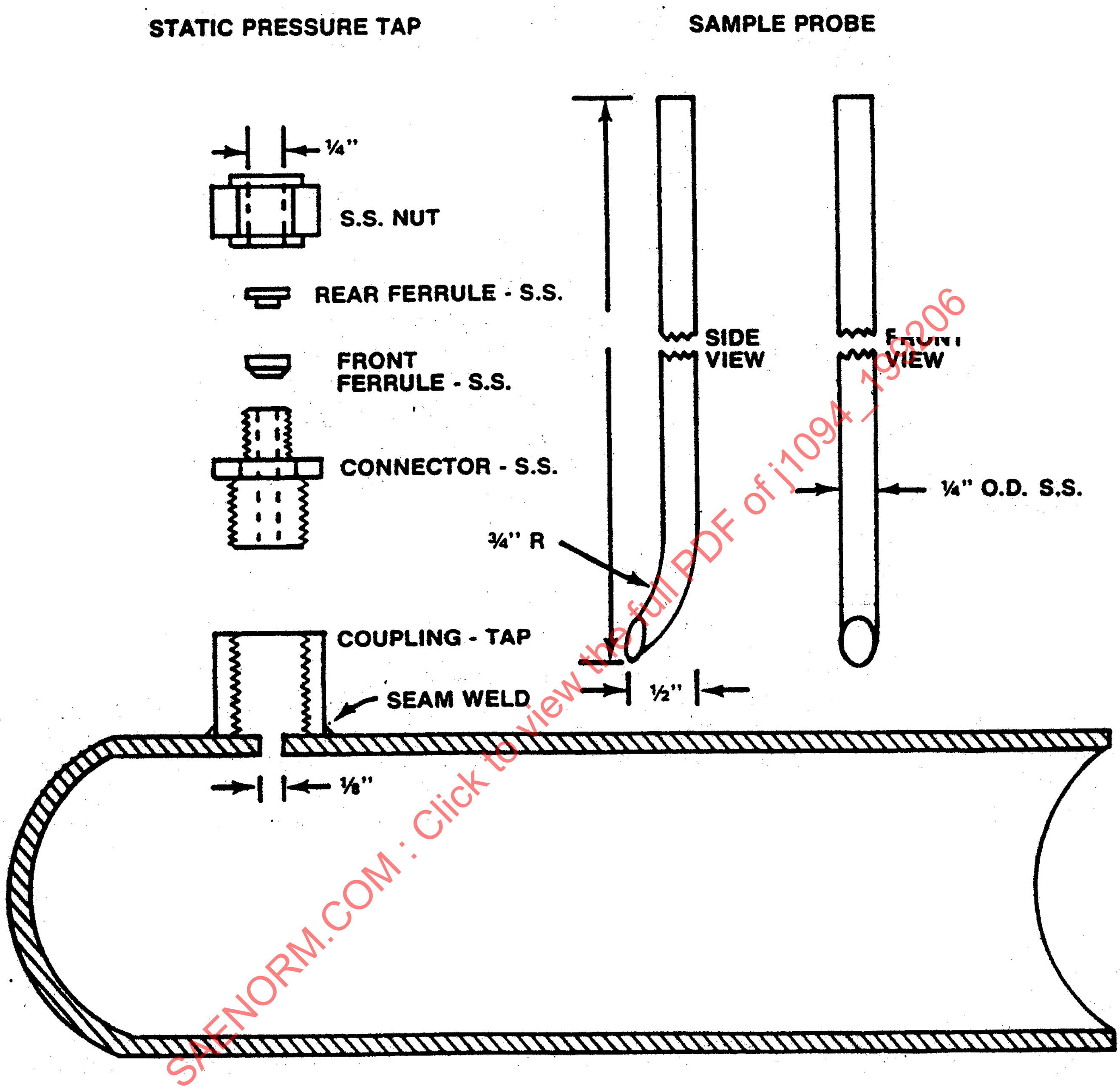

FIGURE 8—STATIC PRESSURE TAP FITTINGS AND PROBE DESIGN

TABLE 3—PRESSURE TAP HOURS

Nominal Inside Pipe Diameter cm	Nominal Inside Pipe Diameter in	Pressure Hole Diameter mm	Pressure Hole Diameter in	Hole-Edge Radius mm	Hole-Edge Radius in
Under 5	Under 2	6.4 ± 3.2	1/4 ± 1/8	About 0.4	About 1/64
5 to 7.5	2 to 3	9.5 ± 3.2	3/8 ± 1/8	Less 0.8	Less 1/32
10 to 20	4 to 8	12.7 – 3.2 + 6.4	1/2 – 1/8 + 1/4	Less 0.8	Less 1/32
25 +	10 +	19.0 + 6.4	3/4 + 1/4	Less 1.6	Less 1/16

5.1.2 FLANGE GASKETS—When installing the plumbing on the inlet side of the pump, compression of the gasket may cause a decrease in its inside diameter. If this occurs, it will affect the restriction on the pump and may affect the accuracy of the static pressure reading if the gasket protrusion is upstream of the static tap. Therefore, when assembling the plumbing insure that the gasket ID as installed is not smaller than the pipe ID.

The placement of modal analysis probes relative to the bag sample probe can also disrupt sampling. It has been shown that the backflushing of a modal analysis cart through a probe can significantly affect the bag sampling probe sample during a CVS calibration verification with propane injection.

5.1.3 PRIMARY CVS CALIBRATION WITH LAMINAR FLOW ELEMENT

5.1.3.1 This procedure utilizes a laminar flow element and a variable restriction device to generate a pump performance curve (flow rate as a function of pressure differential). Figure 9 is a schematic of the test layout and instruments required to perform this calibration. The volumetric flow is determined by a laminar flow element (LFE) placed upstream of the CVS pump (as shown in Figure 9) to avoid introducing flow disturbances in the LFE. A straightener section of 10 times the exit diameter is added to the outlet of the LFE. This is followed by an adjustable restriction valve. Since the LFE and the pump are in series, it is necessary that all connections between these two items be free of leakage. It is advisable to plug all openings and pressure test the system to insure that the system is free of leaks.

Some LFE have straightener sections built into the device. This obviates the use of a straightener section. However, these LFEs are subject to calibration shifts if they are disassembled for cleaning. If these units are cleaned, they should be recalibrated.

When conducting calibration, the restriction device should be used to generate data points above and below the normal CVS system operating pressure. Data should be obtained beginning with the pump inlet depression corresponding to LFE as the only restriction. Pump inlet depression should be increased by increments of 500 to 1250 Pa (2 to 5 in H_2O) until 6 to 8 data points are determined. Usually, it is difficult to get points below the normal CVS system operating pressure unless the heat exchanger is removed from the system. Most calibrations are done with the heat exchanger in the system.

The following listing of the data to be recorded, unit conversions, and calculations will be followed by a sample calculation and a computer print-out.

5.1.3.2 Data Recorded

a. LFE inlet depression, = Pa (in H_2O)
b. Delta P LFE, Pa (in H_2O)
c. LFE inlet temperature, °C (°F)
d. Pump inlet depression, Pa (in H_2O)
e. Pump inlet temperature, °C (°F)
f. Delta P pump, Pa (in H_2O)
g. Barometric pressure, Pa (in Hg)
h. Pump rpm. A pump revolutions counter should be used and elapsed test time should be measured.

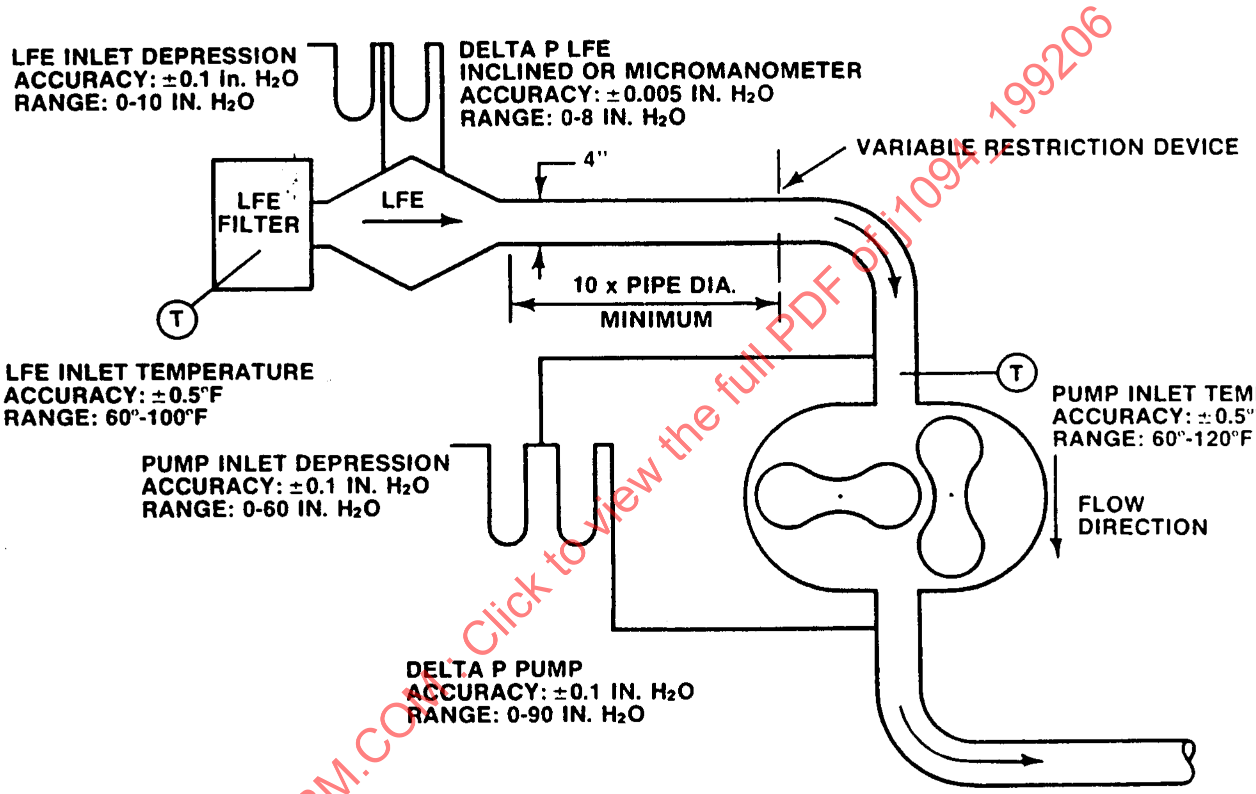

FIGURE 9—CVS CALIBRATION WITH LAMINAR FLOW ELEMENT—SCHEMATIC

5.1.3.3 Conversion of Units

a. Convert in H_2O to in Hg pressure:

$$\text{LFE inlet depression (in Hg)} = \text{LFE inlet depression (in } H_2O) \times 0.07355 \text{ in Hg/in } H_2O \qquad \text{(Eq. 5)}$$
$$\text{Pump inlet depression (in Hg)} = \text{Pump inlet depression (in Hg)} \times 0.07355 \text{ in Hg/in } H_2O$$

b. Convert from degrees Fahrenheit to degrees Rankine:

$$\text{LFE inlet temperature (R)} = \text{LFE inlet temperature } (°F) + 460 \qquad \text{(Eq. 6)}$$
$$\text{Pump inlet temperature (R)} = \text{pump inlet temperature } (°F) + 460$$

c. Conversion to absolute pressure:

$$\text{Absolute pressue (in Hg) at LFE inlet} = \text{barometric pressure (in Hg)—LFE inlet depression (in Hg)} \qquad \text{(Eq. 7)}$$
$$\text{Absolute pressure (in Hg) at pump inlet} = \text{barometric pressure (in Hg)—pump inlet depression (in Hg)}$$

5.1.3.4 Calculations

a. Determine air viscosity correction factor for LFE inlet air temperature from LFE correction curve obtained from LFE manufacturer.
b. Determine pressure correction factor for LFE inlet pressure from LFE correction table obtained from LFE manufacturer.
c. Determine uncorrected volume flow rate from curve supplied by LFE manufacturer and pressure drop. Then determine corrected volume flow rate by multiplying uncorrected volume flow rate × air viscosity correction factor × pressure correction factor.
d. Using Ideal Gas Law, convert the volume flow rate at LFE standard conditions (530 R, 29.92 in Hg) to the volume flow rate at the pump inlet temperature and pressure:

$$\text{pump ft}^3/\text{min} = \text{LFE ft}^3/\text{min} \times \frac{29.92}{\text{pump abs inlet pressure (in Hg)}} \times \frac{\text{Pump inlet temperature (R)}}{530} \qquad \text{(Eq. 8)}$$

e. Determine pump ft^3/rev by dividing ft^3/min by the pump rpm.
f. Plot pump ft^3/rev versus the square root of pump delta P. Determine the first degree equation of the line by the least squares method.

5.1.3.5 Example of Calculations for LFE CVS calibration, using typical data from a 400 ft^3/min LFE.

5.1.3.5.1 Data Recorded

a. LFE inlet depression = 1.00 in H_2O
b. Delta P of LFE = 6.520 in H_2O
c. LFE inlet temperature = 75.5 °F
d. Pump inlet depression = 37.8 in H_2O
e. Pump inlet temperature = 78.0 °F
f. Delta P pump = 60.0 in H_2O
g. Barometric pressure = 29.34 in Hg
h. Pump rpm = 1421

5.1.3.5.2 Conversion of Units

a. LFE inlet depression = 0.07355 in Hg
b. Pump inlet depression = 2.78 in Hg
c. LFE inlet temperature = 535.5 R
d. Pump inlet temperature = 538 R
e. LFE inlet, absolute pressure = 29.27 in Hg
f. Pump inlet, absolute pressure = 26.56 in Hg

5.1.3.5.3 Calculations

a. Air viscosity correction factor at 75.5 °F (from LFE manufacturer's curve) = 1.006.

b.

$$\text{Pressure correction factor} = \frac{29.27}{29.92} = 0.9783 \quad \text{(Eq. 9)}$$

c. Uncorrected flow rate (from LFE manufacturer's curve) = 342.8 ft^3/min.

d. Corrected volume flow rate = 342.8 × 1.006 × 0.9783 = 337.4.

e.

$$\text{Pump ft}^3/\text{min} = 337.4 \times \frac{29.92}{26.56} \times \frac{538}{530} = 385.8 \quad \text{(Eq. 10)}$$

f.

$$\text{Pump ft}^3/\text{rev} = \frac{385.8}{1421} = 0.2715 \quad \text{(Eq. 11)}$$

5.1.4 GAS STRATIFICATION CHECK

5.1.4.1 With the CVS operating in its testing configuration, introduce a tracer gas, such as 100% propane, into the vehicle exhaust inlet of the CVS system as shown in Figure 10. The tracer gas should be introduced at a rate that will give a bag sample which produces at least a 3/4 full-scale deflection on the HC range normally used for reading bags. The use of a continuous HC analyzer on the dilute continuous sampling probe makes this rate determination simple. The continuous analyzer is needed for the profile determination of 5.1.4.2.

5.1.4.2 Starting with the sample probe inlet opening at one side of the dilute stream, run a cross-sectional profile of the pipe, sampling at 13 mm (0.5 in) intervals (wall to wall). Record the concentration at each sampling point location. Conduct a second cross-sectional profile at 90 degrees to the first profile. If concentrations from wall to wall vary more than 1%, there is incomplete mixing.

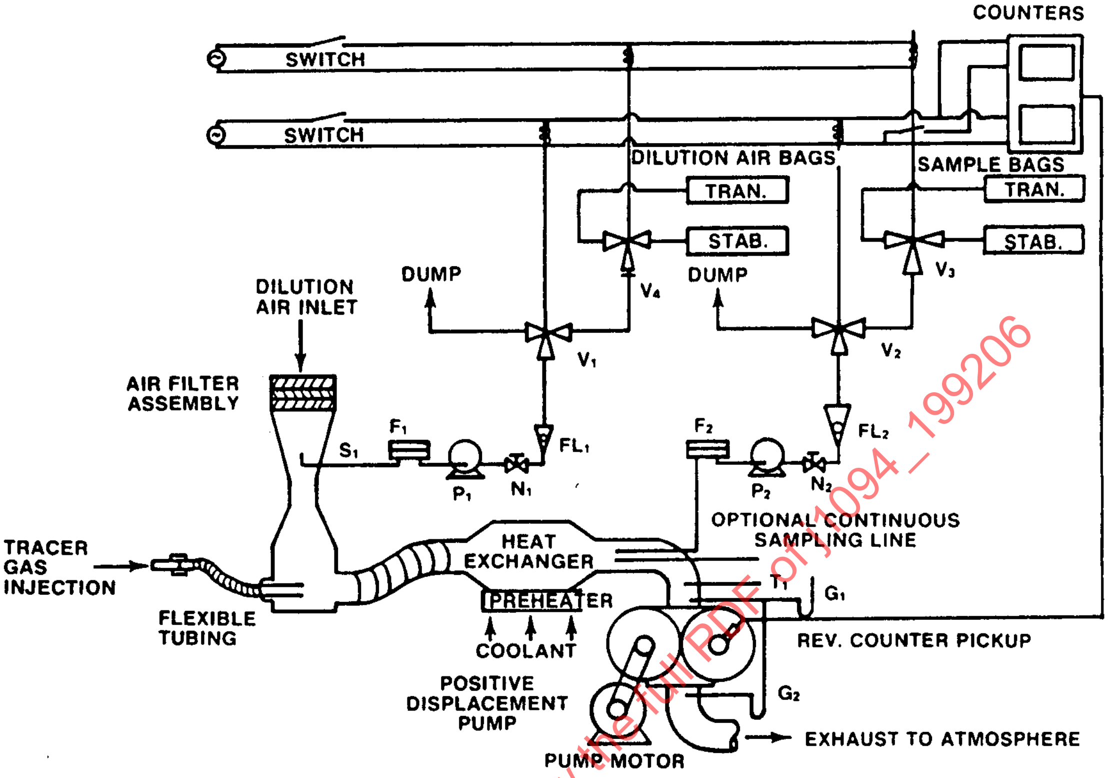

FIGURE 10—EXHAUST GAS SAMPLING SYSTEM

5.1.5 INDEPENDENT CVS SYSTEM VERIFICATION

5.1.5.1 *Introduction*—The system verification technique involves the introduction of a measured quantity of a tracer such as propane (or CO) at the tailpipe sampling location. If all components of the system are functioning properly, the quantity of tracer calculated from that collected in the sample bag should agree closely with the quantity which was injected. A measured amount of tracer gas partially diluted with air from a small auxiliary blower (Figure 11) is then mixed with dilution air in the main stream of the CVS. To avoid possible leakage, the tracer gas should be introduced downstream of the auxiliary blower. The auxiliary blower is needed to aid mixing of the 0.56 L (0.02 ft^3) of propane that is used in a test. When propane is used as the tracer gas, it may be necessary to remove the charcoal filter from the CVS. This will equalize the HC background in the two dilution air streams.

5.1.5.2 *Equipment*

a. CVS system to be checked.
b. A container of instrument grade tracer gas.
c. Analytical balance with a capacity to weigh the charged gas container and flow regulator with a resolution of 0.01 g.
   Instead of the weighing technique, flow measurement techniques can be used to determine the amount of tracer gas injected into the CVS. These include: wet test meter, rotameter, and critical flow orifice.
d. A tracer gas flow regulator which is capable of adjustment to yield bag concentrations which are normally encountered during testing.
e. An auxiliary blower of 0.005 to 0.014 m^3/s (10 to 30 ft^3/min) capacity.

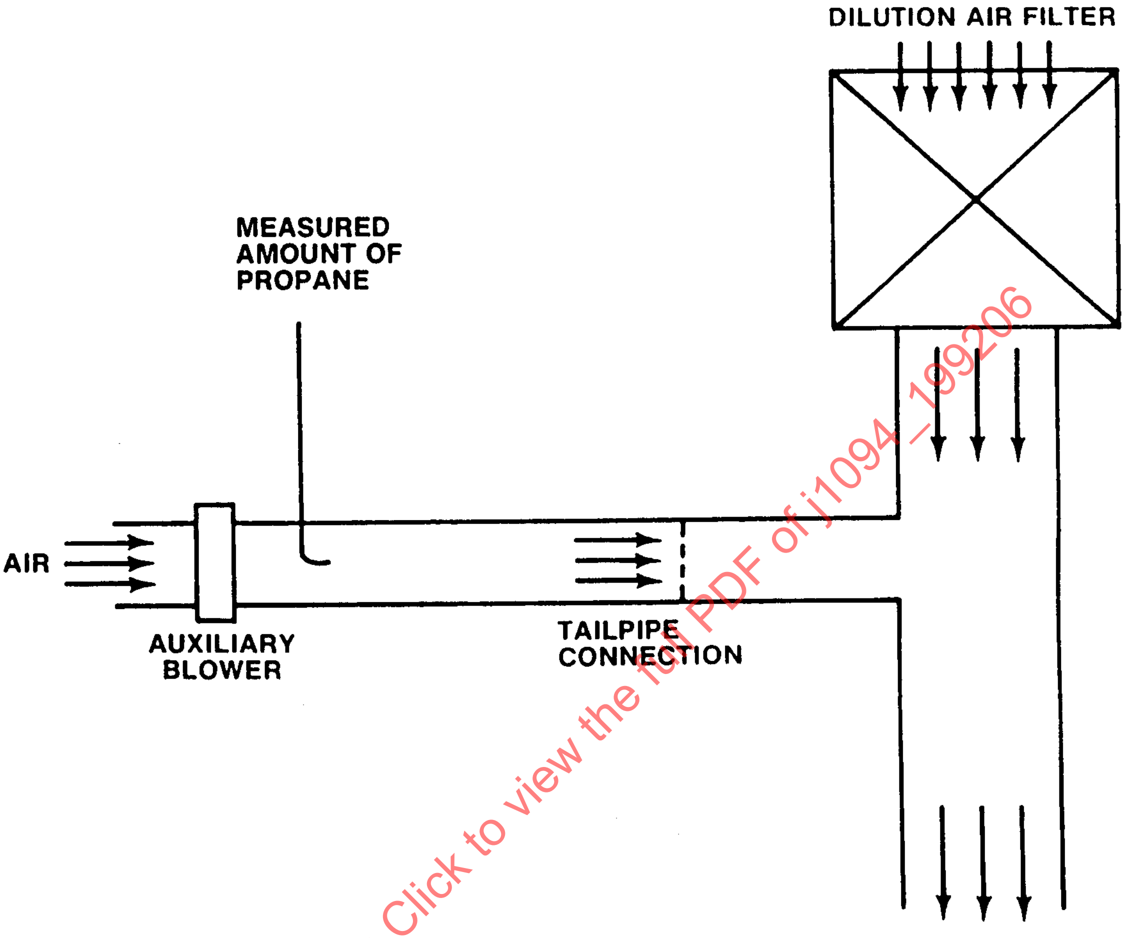

FIGURE 11—CVS SYSTEM VERIFICATION

f. Analyzers to measure tracer gas.

5.1.5.3 *Procedure*

a. Turn on CVS and allow stream pressure and temperature to stabilize.
b. Weigh gas container with the flow regulator connected and record weight.
c. Purge the gas sample bags with dilution air.
d. Simultaneously, activate CVS mixture and dilution air bag sampling and the positive displacement pump revolution counter.
e. After 30 s, begin injecting tracer gas into the CVS. Set tracer gas flow rate to yield sample stream concentrations approximating those encountered during vehicle testing.
f. Record CVS data during tracer gas injection:
    1. Average pump inlet temperature, °C (°F)
    2. Average pump inlet pressure, Pa (in H_2O)
    3. Average pump differential pressure, Pa (in H_2O)

g. After 14 min 30 s total elapsed time, stop the tracer gas injection.
h. After 15 min total elapsed time, stop the CVS mixture and dilution air bag samples and the pump revolution counter simultaneously. Record total CVS pump revolutions.
i. Analyze gases in the CVS mixture and dilution air sample bags. Record concentrations.
j. Weigh tracer gas container and record weight.
k. Determine the injected weight of tracer gas by subtracting weight measured in step 5.1.5.3(j) from weight measured in step 5.1.5.3(b). Record difference.

5.1.5.4 *Calculations*

a. Determine the mass of injected tracer gas indicated by the CVS using the following formula:

$$\text{Calculated mass} = V_{mix} \times \text{density} \times \text{conc} \qquad \text{(Eq. 12)}$$

where:

$$V_{mix} = K_1 \times V_0 \times N \times \frac{P_p}{T_p}$$

$$K_1 = \frac{528R}{29.92 \text{ in Hg}}$$

V_o = volume of gas pumped by the positive displacement pump, ft^3/rev at ambient conditions. This volume is dependent on the pressure differential across the positive displacement pump.
N = number of revolutions of the positive displacement pump during the test while samples are being collected
P_p = absolute pressure of the dilute exhaust entering the positive displacement pump, that is, barometric pressure minus the pressure depression below atmospheric of the mixture entering the positive displacement pump
T_p = average temperature of dilute exhaust entering positive displacement pump during test while samples are being collected, R
Density = Ideal Gas Law density of tracer gas, g/ft^3 at 68 °F and 29.92 in Hg pressure.
Example—Propane = 51.91 g/ft^3
CO = 32.97 g/ft^3
Conc = concentration of gas in sample bag minus concentration of gas in background bag.

b. Compare the measured tracer gas weight to the calculated tracer gas weight and determine the percent difference, based upon the measured weight and determine the percent difference, based upon the measured weight.
c. If the difference is greater than ±2% investigate possible sources of error and repeat the verification.

5.1.5.5 *Critical Flow Orifice*—A simpler alternative to the gravimetric procedure described in 5.1.5.3 for CVS system verification is the use of a critical flow orifice (CFO). The advantage of a calibrated CFO is that the weighting steps are replaced by a single determination of a high pressure level reading. The CVS measurement is compared to the CFO measurement using the CFO as the measurement as the standard. Again, if the percent difference is greater than ±2%, investigate possible sources of error and repeat the verification.

5.2 Operating Procedure—A wide variety of CVS configurations are currently available. The detailed operating procedure for each configuration will be unique, and will depend upon the nature of the test being performed. Requirements for hot and cold weighting and inclusion of multiple background bags all necessitate changes in the detailed operating procedure. Furthermore, the required degree of operator attention to the CVS console during performance of an emission test varies from installation to installation. Fully automated systems require almost no attention to detail. Once the test is initiated, all functions including the diverting of exhaust gas into the appropriate sample bags at the correct times and even changing of the paper filters are all accomplished automatically. Other units may require the operator to perform each of these operations manually. As a result of these many factors (configuration of equipment, interfacing equipment for automatic control, and test procedure), no attempt will be made here to provide a detailed step-by-step procedure. Any such procedure would be specific for a particular unit and test objective, rather than of universal value. Each operator should, of course, follow the instructions of the CVS manufacturer and/or systems designer as well as the test procedure outlined in the appropriate governmental regulations. The remainder of this section will be devoted to items which may be best described as "good operating practice" and are more universally applicable.

First, it should be pointed out that the concept of CVS sampling is still evolving. Areas of uncertainty still exist. Such an area is that of defining the acceptable "tailpipe depression" at idle or positive pressure during modes such as acceleration and cruise, which the CVS may exert upon the vehicle during the performance of an emissions test. The objective of the operator should be to employ his given CVS unit in a way which will minimize its effect upon vehicle operation. Actual CVS design has a large impact on tailpipe depression or pressurization. Above and beyond this the operator can minimize effects by insuring that connections between the vehicle and the CVS are relatively short (1.5 to 1.8 m [5 to 6 ft]), of large enough diameter (100 mm [4 in]) or larger.

A second area which deserves attention is that of preventing moisture condensation in the CVS or sampling lines. Condensation may remove soluble gas species from the sample stream and interfere with the accuracy of NO_x measurements. The dew point of concentrated exhaust gas is typically 49 to 54 °C (120 to 130 °F). Therefore, it is essential that the exhaust temperature not approach this range before dilution in the CVS mainstream. The use of a short (1.5 to 1.8 m [5 to 6 ft]) connection between the vehicle tailpipe and the CVS inlet will help prevent condensation in the connecting line. If the CVS configuration is such that the exhaust gas is cooled prior to mixing with the dilution air, it will be necessary to insure that condensation does not occur before dilution. Dilution of the exhaust gas should be sufficient to preclude condensation of moisture in the main flow stream.

Condensation of the dilute exhaust sample may occur in sample lines, pumps, filters, and meters, particularly when the relative humidity of the dilution air exceeds 50%. Unless bubbles appear in the flow meters, this condensation may be difficult to detect. Dampness in the paper filters in the sample streams is an indication that condensation is occurring. If condensation is a problem, it may be necessary to install drain lines to divert the condensation back into the main flow path of the CVS upstream of the positive displacement pump. Better approaches to avoid the condensation problem are to match the sample pump capacity more closely to the sampling system and to use back-pressure regulated sample pumps to reduce the maximum pressure to which the sample is exposed and thus reduce the tendency for condensation to occur.

Deposits will slowly build up in the CVS. These are most likely to occur in the heat exchanger. Good operating practice dictates regularly scheduled cleaning. Increase of depression at the pump inlet is a good indicator of deposit buildup. Even though the CVS flow conditions are corrected for the changing operating conditions, the deposit buildup is not uniform and consequently can cause stratification at the sample probe. Deposit buildup will be a function of the number and type of tests. For a very active testing program, monthly cleaning would be recommended.

CVS pumps have been known to seize. Usually, this is due to deposits and moisture that remain in a CVS after a series of intermittent tests. This problem can be avoided by connecting the CVS outlet to a laboratory exhaust system that has sufficient capacity to rotate the blower slowly when the CVS is off. The laboratory exhaust is effective in removing the moisture.

Foreign objects can enter the CVS inlet and effectively destroy mixing or cause severe stratification. Large mesh screens have been used effectively to prevent foreign objects from reaching the mixing area and the heat exchanger.

The dilution air filter is not intended to remove all hydrocarbons from the inlet air, but rather to stabilize their level. Precautions should be taken to insure that the dilution air is not contaminated with excessive HC vapor from spilled gasoline, etc. The dilution air filter package is normally a set of three 600 × 600 mm (24 × 24 in) filters. The first is a dust filter, the second a charcoal filter, and the third filter is to remove charcoal particles from the dilution air stream. These filters can become loaded with dirt. An acceptable method for determining the useful life of these filters is to monitor the pressure drop across the filter when the CVS blower is operating at high speed. When the pressure drop across the three filters reaches 125 Pa (0.5 in H_2O), the filter set should be changed. If desired the charcoal could be reactivated and reused.

A detailed calibrating procedure appears in another section. It should be noted that, while this procedure is intended to uncover mechanical and flow problems which may exist, it is not a cure-all. Actual operating conditions are somewhat different from calibrating conditions. For example, the temperature and flow rate entering the CVS during calibration is different than the temperature and flow rate of exhaust entering during vehicle emission testing. The degree of stratification under actual test conditions could differ from that observed during calibration. Mixing difficulties at other than calibrating conditions will lead to a situation where, even though a CVS checks out during the calibration, during actual operation the mass obtained by integrating the continuous diluted exhaust stream concentration does not agree with that collected in the bags. When a situation like this is observed, it will be necessary to repeat the stratification check outlined in the calibrating procedure with exhaust gas supplied by a vehicle operating at 80.5, 64, and 48 km/h (50, 40, and 30 mph) steady-states. If mixing is not complete it may be necessary to experiment with unique mixing devices to aid or replace those supplied with the CVS unit. Considerations such as those outlined here emphasize the importance of paying careful attention to each step of CVS operation even when the unit is completely automated. Each configuration has its unique advantages and problems. Furthermore, changes in a given unit may occur from time to time, so that what is not a problem at one moment may become one later.

6. ***Data Analysis***—Two types of data analysis are possible, bag and modal. Bag analysis will yield emission values which are the composite for a complete test. This kind of analysis is simpler to perform, and is satisfactory for determining whether a vehicle will pass a given test. Therefore, bag analysis is used for surveillance or compliance testing. For development of emission control systems, modal analysis is necessary to determine the relationships between emissions and driving mode.

6.1 **Bag Analysis—**The HC, CO, NO_x (NO + NO_2), and CO_2 concentrations are measured in the diluted exhaust and the background bags. Depending upon the specific cycle used, more than one exhaust and one background bag may be needed. For the 1975 Federal Test Procedure, separate exhaust bags are needed for the cold transient, cold stabilized, and hot transient phases of the driving cycle, thus allowing weighting factors to be applied to the cold and hot transient phases of the test. It is good practice to use a separate background bag for each sample bag used, in case the background concentrations change during a test.

6.1.1 EXHAUST EMISSION CALCULATIONS—One diluted exhaust sample bag and one background bag are required for each test phase. The concentrations of HC, CO, NO_x, and CO_2 in the bags are determined by passing the gases through the analyzers described in 4.2.

6.1.1.1 The final reported test results are computed as follows:

$$Y_{wm} = 0.43\frac{Y_1 + Y_2}{D_1 + D_2} + 0.57\frac{Y_3 + Y_2}{D_3 + D_2} \qquad \text{(Eq. 13)}$$

where:

Y_{wm} = weighted mass emissions of each pollutant, that is HC, CO, and NO_x, g/vehicle mile

Y_1, Y_2, Y_3 = mass emissions for each phase, g/phase

1=cold transient test phase
2=cold stabilized test phase
3=hot transient test phase

D_1, D_2, D_3, = actual distance driven for each test phase, as measured by the rear roll revolutions

6.1.1.2 The mass of each pollutant for each phase of the test is determined from the following:

a. HC_{mass}:

$$HC_{mass} = V_{mix} \times density_{HC} \times \frac{HC_{conc}}{1\,000\,000} \quad \textit{(Eq. 14)}$$

b. CO_{mass}:

$$CO_{mass} = V_{mix} \times density_{CO} \times \frac{HC_{conc}}{1\,000\,000} \quad \textit{(Eq. 15)}$$

c. NO_{xmass}:

$$NO_{x_{mass}} = V_{mix} \times density_{NO_2} \times \frac{NO_{x_{conc}}}{1\,000\,000} \times Kh \quad \textit{(Eq. 16)}$$

d. CO_{2mass}:

$$CO_{2_{mass}} = V_{mix} \times density_{CO_2} \times \frac{CO_{2_{conc}}}{100} \quad \textit{(Eq. 17)}$$

6.1.1.3 *Meaning of Symbols*

HC_{mass} = hydrocarbon emission, g/test phase

$Density_{HC}$ = density of hydrocarbons in the exhaust gas, assuming an average carbon-to-hydrogen ratio of 1:1.85, g/ft^3 at 20 °C (68 °F) and 101 kPa (29.92 in Hg) pressure (16.33 g/ft^3)[4]

HC_{conc} = hydrocarbon concentration of the dilute exhaust sample corrected for background, ppm carbon equivalent, that is equivalent propane × 3

$HC_{conc} = HC_e\text{-}HC_d(1\text{-}1/DF)$

HC_e = hydrocarbon concentration of the dilute exhaust sample as measured, ppm carbon equivalent

HC_d = hydrocarbon concentration of the background as measured, ppm carbon equivalent

CO_{mass} = carbon monoxide emissions, g/test phase

$Density_{CO}$ = density of carbon monoxide, g/ft^3 at 20 °C (68 °F) and 101 kPa (29.92 in Hg) pressure (32.97 g/ft^3)

CO_{conc} = carbon monoxide concentration of the dilute exhaust sample corrected for background, water vapor, and CO_2 extraction, ppm

$CO_{conc} = CO_e - CO_d(1-1/DF)$

CO_e = carbon monoxide concentration of the dilute exhaust sample corrected for water vapor and carbon dioxide extraction, ppm. The calculation assumes the hydrogen-carbon ratio of the fuel is 1.85:1

$CO_e = (1-0.01925\ CO_{2e}-0.000323\ R)\ COe_m$

($CO_e = COe_m$, if instrument has no CO_2 or H_2O response)

CO_{em} = carbon monoxide concentration of the dilute exhaust sample as measured, ppm

CO_{2e} = carbon dioxide concentration of the dilute exhaust sample, mol %

R = relative humidity of the dilution air, %

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[4] Density of emissions are based on Ideal Gas Law. Density is equal to 1.17714 times the molecular weight.

CO_d = carbon monoxide concentration of the background air corrected for water vapor extraction, ppm

$CO_d = (1–0.000323\ R)COd_m$

($CO_d = COe_m$, if instrument has no H_2O response)

COd_m = carbon monoxide concentration of the background air sample as measured, ppm

NOx_{mass} = oxides of nitrogen emissions, g/test phase

$DensityNO_2$ = density of oxides of nitrogen in the exhaust gas, assuming they are in the form of nitrogen dioxide, g/ft^3 at 20 °C (68 °F) and 101 kPa (29.92 in Hg) pressure (54.16 g/ft^3)

NOx_{conc} = oxides of nitrogen concentration of the dilute exhaust sample corrected for background, ppm

$NOx_{conc} = NOx_e – NOx_d(1-1/DF)$

NOx_e = oxides of nitrogen concentration of the dilute exhaust sample as measured, ppm

NOx_d = oxides of nitrogen concentration of the background as measured, ppm

$CO2_{mass}$ = carbon dioxide emissions, g/test phase

$Density_{CO}$ = density of carbon dioxide, g/ft^3 at 68 °F (20 °C) and 29.92 in Hg (101 kPa) pressure (51.81 g/ft^3)

$CO2_{conc}$ = carbon dioxide concentration of the dilute exhaust sample corrected for background, %

$CO2_{conc} = CO_2e - CO_{2d}(1-1/DF)$

$CO2_e$ = carbon dioxide concentration of the dilute exhaust sample as measured, %

$CO2_d$ = carbon dioxide concentration of the background as measured %

$$DF = \frac{13.4}{CO_{2e} + (HC_e + CP_e)\ 10^{-4}} \qquad \text{(Eq. 18)}$$

V_{mix} = total dilute exhaust volume, ft^3/test phase corrected to standard conditions (528 R, 101 kPa) (68 °F, 29.92 in Hg)

$V_{mix} = V_o \times N \times (P_p/29.92)(528/T_n)$

V_o = volume of gas pumped by the positive displacement pump, ft^3/rev. This volume is dependent upon the pressure differential across the positive displacement pump

N = number of revolutions of the positive displacement pump during the test phase while samples are being collected

P_p = absolute pressure of the dilute exhaust entering the positive displacement pump, in Hg, that is, barometric pressure minus the pressure depression below atmospheric of the mixture entering the positive displacement pump

T_p = average temperature of dilute exhaust entering the positive displacement pump during test while samples are being collected

P_b = barometric pressure, in Hg

T_w = wet bulb temperature, °F

T_d = dry bulb temperature, °F

P_w = saturation water vapor pressure, in Hg at wet bulb temperature

$$P_w = -4.14438\ 10^{-3} + 5.76645\ 10^{-3} T_w - 6.32788\ 10^{-5} T_w{}^2 + 2.12294\ 10^{-6} T_w{}^3 - 7.85415\ 10^{-9} T_w{}^4 + 6.55263\ 10^{-11} T_w{}^5 \qquad \text{(Eq. 19)}$$