

SAE-ARP1256

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AEROSPACE RECOMMENDED PRACTICE

SAE ARP1256

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Superseding ARP1256A

Submitted for recognition as an American National Standard

PROCEDURE FOR THE CONTINUOUS SAMPLING AND MEASUREMENT OF GASEOUS EMISSIONS FROM AIRCRAFT TURBINE ENGINES

1. SCOPE:

This Aerospace Recommended Practice (ARP) describes the continuous sampling and analysis of gaseous emissions from aircraft gas turbine engines and is intended to standardize the emission test procedures¹ and equipment for measuring carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, and total hydrocarbons. This ARP is not intended for in-flight testing, nor does it apply to engines operating in the afterburning mode.

2. SECTIONS:

This document is divided into the following sections:

3. Definitions and Terminology
4. Equipment
5. Analyzer Routines
6. Calibration Gases
7. System Layout
8. Test Procedure
9. Sampling
10. Information and Data to be Recorded
11. Calculation of Results

¹Excluding engine operating procedures and test modes.

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3. DEFINITIONS AND TERMINOLOGY:

- 3.1 ACCURACY: The closeness with which a measurement approaches the true value established independently.
- 3.2 AIRCRAFT GAS TURBINE ENGINE: Any gas turbine engine used for aircraft propulsion or power generation, including those commonly called turbojet, turbofan, turboprop, or turboshaft type engines.
- 3.3 CALIBRATION GAS: A mixture of gases of specified and known composition used as the basis for interpreting analyzer response in terms of the concentration of the gas to which the analyzer is responding.
- 3.4 CONCENTRATION: The volume fraction of the component of interest in the gas mixture - expressed as volume percentage or as parts per million.
- 3.5 CONTINUOUS SAMPLING: The presentation of a flowing sample to the analytical analyzer so as to obtain continuous measurement of concentrations of the components of interest.
- 3.6 FLAME IONIZATION DETECTOR: A hydrogen-air diffusion flame detector that produces a signal nominally proportional to the mass-flow rate of hydrocarbons entering the flame per unit of time - generally assumed responsive to the number of carbon atoms entering the flame.
- 3.7 FUEL/AIR RATIO: The mass rate of fuel flow to the engine divided by the mass rate of dry airflow through the engine.
- 3.8 GASEOUS EMISSIONS: Gases emitted downstream of the combustion chamber and limited to carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, and hydrocarbons.
- 3.9 INTERFERENCE: Analyzer response due to presence of components other than the gas (or vapor) that is to be measured.
- 3.10 NOISE: Random variation in analyzer output not associated with characteristics of the sample to which the analyzer is responding and which is distinguishable from analyzer drift characteristics.
- 3.11 NO_x: Oxides of nitrogen, specifically, the sum of nitric oxide (NO) and nitrogen dioxide (NO₂).
- 3.12 NONDISPERSIVE INFRARED ANALYZER: An analyzer that by absorption of infrared energy selectively measures specific components.
- 3.13 PARTS PER MILLION (ppm): The unit volume concentration of a gas per million unit volumes of the gas mixture of which it is a part. (Also applicable to weight measurements but only volume relationships are referred to in these procedures. Note also that in the context of the measurements of this procedure, "volume concentration (or volume fraction)" and "molar concentration (or mole fraction)" are synonymous).

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- 3.14 PARTS PER MILLION CARBON (ppm C): The mole fraction of hydrocarbon multiplied by 10^6 measured on a (C_1H_n) equivalence basis. Thus, 1 ppm of methane is indicated as 1 ppm C. To convert ppm concentration of any hydrocarbon to an equivalent ppm C value, multiply ppm concentration by the number of carbon atoms per molecule of the gas. For example, 1 ppm propane translates as 3 ppm C hydrocarbon; 1 ppm hexane as 6 ppm C hydrocarbon.
- 3.15 PRECISION: The closeness with which a measurement upon a given, invariant sample can be reproduced in short-term repetitions of the measurement with no intervening analyzer adjustment.
- 3.16 RESOLUTION: The smallest change in a measurement which can be detected.
- 3.17 RESPONSE: The change in analyzer output signal that occurs with change in sample concentration. Also, the output signal corresponding to a given sample concentration.
- 3.18 SPAN GAS: A calibration gas to be used for routine verification and adjustment of analyzer response.
- 3.19 SPAN DRIFT: The time related change in response of the analyzer in repetition of a span gas measurement under identical conditions of flow and concentration.
- 3.20 TEST SEQUENCE: A series of functionally related tests in which the test operation without interruption progresses systematically from one test mode to another.
- 3.21 TOTAL HYDROCARBONS: The total of hydrocarbon compounds of all classes and molecular weights.
- 3.22 ZERO DRIFT: Time related deviation of analyzer output from zero set point when it is operating on gas free of the component to be measured. This is not to be confused with "Interference".
- 3.23 ZERO GAS: A gas to be used in establishing the zero, or no-response, adjustment of an analyzer.

4. EQUIPMENT:

Precautions: The performance specifications indicated are typical of those analyzers offered by major manufacturers and are generally related to analyzer full scale reading. Error at part scale may be a significantly greater percentage of reading.

Typically:

$$\text{Error in measurement} = \frac{\text{Range}}{\text{measurement value}} \times \text{Specification error}$$

For example, for a measurement at 20% of full scale, the error in measurement may be 5 x specification error (quoted as percent of full scale).

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4. (Continued):

The relevance and importance of such increases must be considered when preparing to make measurements. If better performance is necessary, then appropriate precautions must be taken.

4.1 Carbon Monoxide and Carbon Dioxide Analyzers:

Nondispersive infrared (NDIR) analyzers shall be used for the continuous monitoring of carbon monoxide (CO), and carbon dioxide (CO₂) in the turbine exhaust.

NDIR analyzers operate on the principle of absorption, in the sample cell, of infrared radiation in a frequency band specific to the gaseous component of interest. The transmitted radiation is measured by a suitable detector and compared with that received when there is no specific gas component absorption. This differential absorption generates an electrical signal proportional to the concentration of absorbing gas in the sample cell. This signal is amplified, often linearized, and continuously displayed.

4.1.1 Analyzer Performance Specifications:

Zero Drift	-	Less than $\pm 1\%$ of full scale in 1 h.
Span Drift	-	Less than $\pm 1\%$ of full scale in 1 h.
Noise	-	Less than $\pm 1.0\%$ of full scale.
Resolution	-	Better than $\pm 0.5\%$ of full scale.
Precision	-	CO: Better than $\pm 1\%$ of full scale for ranges above 100 ppm full scale. Better than $\pm 2\%$ of full scale for ranges below 100 ppm full scale.
		CO ₂ : Better than $\pm 1\%$ of full scale for all ranges.
Linearity	-	For linearized analyzers, response shall be linear within $\pm 2\%$ of full scale.
Total Range	-	Typically CO 0-2500 ppm CO ₂ 0-10% in appropriate steps.

NOTE: Full scale applies to range selected for measurement.
Also in 4.2.1 and 4.3.1.

4.1.2 NDIR Cells: All NDIR analyzers shall be equipped with cells of suitable length to measure concentrations within the required range. Range changes may be accomplished by use of stacked sample cells and/or changes in the electronic circuitry.

If CO and CO₂ samples are analyzed "wet", the sample cells shall be maintained at a temperature of not less than 323 K (50°C, 122°F) with a stability of ± 2 K ($\pm 2^\circ\text{C}$, $\pm 3.6^\circ\text{F}$). An optional water removal device is allowed ahead of the CO and CO₂ analyzers (Figure 4) provided that it can be shown that CO and CO₂ are not adversely affected. If such a

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4.1.2 (Continued):

device is used, then the sample cells shall be maintained at least 10 K (10°C, 18°F) above the sample dew point, with a stability of ± 2 K ($\pm 2^\circ\text{C}$, $\pm 3.6^\circ\text{F}$). If the sample is dried, a "dry" to "wet" correction of the measured values must be made (see Section 11). Also, the dew point should be measured to ensure the following:

- a. The drier efficiency remains constant.
- b. The correct 'dry' to 'wet' correction is made.
- c. The correct interference correction is applied (see 4.1.3).

CO and CO₂ analyzers may be connected either in series or in parallel. If the "in series" option is used, care should be taken to ensure that there is no back pressurization of the first analyzer by the second.

4.1.3 Interferences: Interferences from ethylene, water vapor, and carbon dioxide will affect the reading of the CO analyzer. Response of the CO analyzer should not, in general, exceed the following limits:

- a. 500 ppm/percent ethylene concentration.
- b. 2 ppm/percent CO₂ concentration.
- c. 2 ppm/percent water vapor concentration.

Interference from oxygen will affect the reading of the CO₂ analyzer. Response of the CO₂ analyzer should not, in general, exceed the following limit:

0.1% of reading/percent of O₂ concentration.

Optical filters are the preferred method of discrimination. In some cases a water removal device may be used to reduce water content to a level below which its interference is acceptable. If the sample is dried, then a dry to wet correction of the measured values must be made (see Section 11).

If the interference limitations cannot be met, appropriate correction factor(s) shall be determined, reported, and applied. It is recommended however, as consistent with good practice, that such correction procedures should be adopted in all cases.

4.1.4 Analyzer Response Time: Analyzer response time should not exceed 10 s from introduction of a sample to the analyzer inlet to achievement of 90% of final reading.

4.2 Total Hydrocarbon Analyzer:

The measurement of total hydrocarbons is made by an analyzer using a flame ionization detector (FID). With this type of detector, an ionization current is produced which is approximately proportional to the mass rate of hydrocarbon entering the hydrogen flame. This small current is measured using an electrometer amplifier and is continuously indicated.

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4.2 (Continued):

The analyzer shall be fitted with a constant temperature oven housing the detector and sample-handling components. It shall maintain temperature within the range $433\text{ K} \pm 5$ ($160^\circ\text{C} \pm 5$, $320^\circ\text{F} \pm 9$) with a stability of $\pm 2\text{ K}$ ($\pm 2^\circ\text{C}$, $\pm 3.6^\circ\text{F}$).

4.2.1 Analyzer Performance Specifications:

- Zero Drift - Less than $\pm 1\%$ of full scale in 1 h.
 - Span Drift - Less than $\pm 1\%$ of full scale in 1 h.
 - Noise - Less than $\pm 1\%$ of full scale.
 - Resolution - Better than $\pm 0.5\%$ of full scale.
 - Precision - Better than $\pm 1\%$ of full scale for ranges above 100 ppm C full scale.
 - Better than $\pm 2\%$ of full scale for ranges from 10 to 100 ppm C full scale.
 - Better than $\pm 5\%$ of full scale for ranges below 10 ppm C full scale.
 - All determined using propane calibration gas.
 - Linearity - Response with propane in air shall be linear within $\pm 2\%$ of full scale for each range.
 - Oxygen Synergism - The response to propane in 21% O_2 shall not differ by more than 3% from the response to propane in 10% O_2 .
 - Relative Carbon Response - The responses to n-hexane, propylene or toluene in air shall not differ by more than 5% from the response to propane in air.
- Total Range - Typically 0 to 5000 ppm C in appropriate steps.

4.2.2 Analyzer Response Time: Analyzer response time should not exceed 10 s from introduction of a sample to the analyzer inlet to achievement of 90% of final reading.

4.3 Oxides of Nitrogen Analyzer:

A chemiluminescence analyzer with an NO_2 converter shall be used for measuring nitric oxide (NO) and total oxides of nitrogen (NO_x). The chemiluminescence method utilizes the principle that NO reacts with ozone (O_3) to give nitrogen dioxide (NO_2) and oxygen (O_2). Approximately 10% of the NO_2 is electronically excited. The transition of excited NO_2 to the ground state yields a light emission. This light emission is measured utilizing a photomultiplier tube and associated electronics.

The method also utilizes the principle that NO_2 decomposes to NO according to the catalyzed thermal reaction, ($2\text{NO}_2 \rightarrow 2\text{NO} + \text{O}_2$). A converter unit designed to provide essentially complete conversion of NO_2 to NO without affecting the NO originally present in the sample, is included as a part of the chemiluminescence analyzer package. If a sample is passed through the converter prior to entering the chemiluminescence analyzer, an NO_x reading ($\text{NO} + \text{NO}_2$) is obtained. If the converter is bypassed, only the NO portion is indicated.

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4.3 (Continued):

Water removal devices are not permitted in the sample line upstream of the oxides of nitrogen analyzer. The temperature of the sample passages in the analyzer should be maintained high enough to avoid condensation of water.

4.3.1 Analyzer Performance Specifications:

Zero Drift - Less than $\pm 1\%$ of full scale in 1 h.
Span Drift - Less than $\pm 1\%$ of full scale in 1 h.
Noise - Less than $\pm 1\%$ of full scale.
Resolution - Better than $\pm 0.5\%$ of full scale.
Linearity - Response shall be linear within $\pm 2\%$ of full scale.
Precision - Better than $\pm 1\%$ of full scale.
Converter Efficiency - Greater than 90%.

Total Range - Typically 0 to 2500 ppm in appropriate steps.

4.3.2 Interferences: Interferences from water vapor and carbon dioxide will affect the reading of the analyzer. Response of the analyzer should not, in general, exceed the following limits:

- a. 0.05% of reading/percent CO₂ concentration.
- b. 0.1% of reading/percent water vapor concentration.

If the interference limitation(s) for CO₂ and/or water vapor above cannot be met, appropriate correction factor(s) shall be determined, reported and applied. It is recommended however, as consistent with good practice, that such correction procedures should be adopted in all cases.

4.3.3 Analyzer Response Time: Analyzer response time should not exceed 10 s from introduction of a sample to the analyzer inlet to achievement of 90% of final reading.

5. ANALYZER ROUTINES:

5.1 General:

Analyzer characteristics may vary with time and it is necessary periodically to check that they are still within tolerance. The validity of the periodic checks in the following sections has usually been accepted as 30 days. However, many analyzer specifications remain within limits for much longer periods. Provided that there is adequate documented evidence to justify extensions beyond 30 days, users may assign alternative intervals for specification checks of analyzers in operational use. Such extensions cannot be assumed to hold for all analyzers, or for analyzers of the same type supplied by different manufacturers - each must be assessed independently.

In this and subsequent subsections reference to setting of zero and span of analyzers assumes physical adjustment of controls. Some practitioners prefer not to make such adjustments but to measure the zero and span mode

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5.1 (Continued):

indicated analyzer outputs and to determine appropriate measurement conversion formulas. This practice can be particularly appropriate and efficient when analyzer systems are operated under computer control.

Such procedures are acceptable and references throughout the following to the physical adjustment, etc., of zero and/or span controls may be replaced by appropriate amendments incorporating zero/span calibration.

5.2 Specific:

The following specific routines are necessary for initial setting up or periodic checks of the various analyzers.

- 5.2.1 Linearity/Calibration Curve Check (all analyzers): Use the same gas flow rate through the analyzers during these checks as when sampling exhaust.
- a. Analyzers with a linear signal output characteristic shall be checked on all working ranges using calibration gases at known concentrations of approximately 0, 30, 60, and 90% of full scale. The maximum response deviation of any of these points from a least squares straight line (fitted to the points and the zero reading) shall not exceed $\pm 2\%$ of full scale value. If it does, a calibration curve shall be prepared for operational use.
 - b. Analyzers with a nonlinear signal output characteristic (or those which do not meet the requirement of linearity given above) shall have calibration curves prepared for all working ranges using calibration gases at known concentrations of approximately 0, 30, 60, and 90% of full scale. Additional mixes should be used, if necessary, to define properly the curve shape.
- 5.2.2 Optimization of Detector Response (THC Analyzer):
- a. Follow manufacturer's instructions for analyzer start-up and basic operating adjustment. Unless otherwise recommended by the manufacturer, fuel shall be 60% helium, 40% hydrogen containing less than 1 ppm C hydrocarbon. Air shall be "hydrocarbon-free" grade containing less than 1 ppm C hydrocarbon.
 - b. Set oven temperature at $433\text{ K} \pm 5$ ($160^\circ\text{C} \pm 5$, $320^\circ\text{F} \pm 9$) and allow at least 1/2 h after oven reaches temperature for the system to equilibrate. The temperature is to be maintained at set point $\pm 2\text{ K}$ ($\pm 2^\circ\text{C}$, $\pm 3.6^\circ\text{F}$).
 - c. Introduce a mixture of propane in air at a propane concentration of about 500 ppm C. Vary the fuel flow to the detector and determine the peak response. A change in zero may result from a change in fuel flow; therefore, the analyzer zero should be checked at each fuel flow rate. Select an operating flow rate that will give near maximum response and least variation in response with minor fuel flow variations. Figure 1 shows a typical curve for response versus fuel flow.

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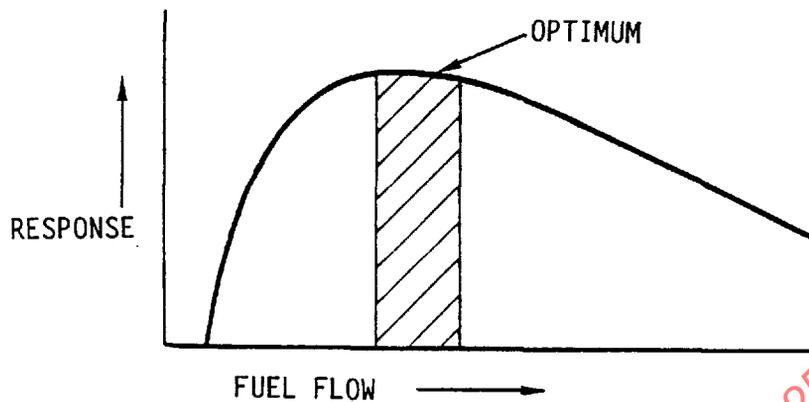


FIGURE 1 - Fuel Flow Response Curve

5.2.2 (Continued):

- d. To determine the optimum airflow, use fuel flow setting determined above and vary airflow. Figure 2 shows a typical curve for response versus airflow:

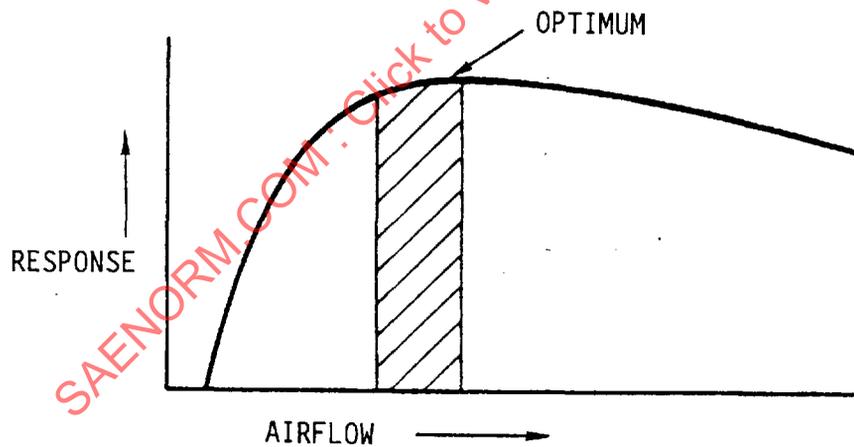


FIGURE 2 - Airflow Response Curve

After the optimum flow settings have been determined these flows are to be recorded for future reference.

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5.2.3 Oxygen Synergism Effect (THC Analyzer): Check the response of the detector with varied concentrations of oxygen in the sample following the steps outlined below. This test shall be made with oven temperature at the set point and with gas flow to the detector at optimum conditions, as determined in 5.2.2.

- a. Introduce nitrogen (N₂) zero gas and zero the analyzer. Check zero using hydrocarbon-free air. The zero should be the same.
- b. The following blends of propane shall be used to determine the effect of oxygen (O₂) in the sample:

Propane in 10% O₂ ± 1, balance N₂.

Propane in 21% O₂ ± 1, balance N₂.

The volume concentration of propane in each mixture should be about 500 ppm C, and the concentration of both the O₂ and propane shall be known within ±1% of the absolute value. The zero shall be checked after each mixture is measured. If the zero has changed, then the test shall be repeated.

The response to propane in 21% O₂ shall not differ by more than 3% from the response to propane in 10% O₂.

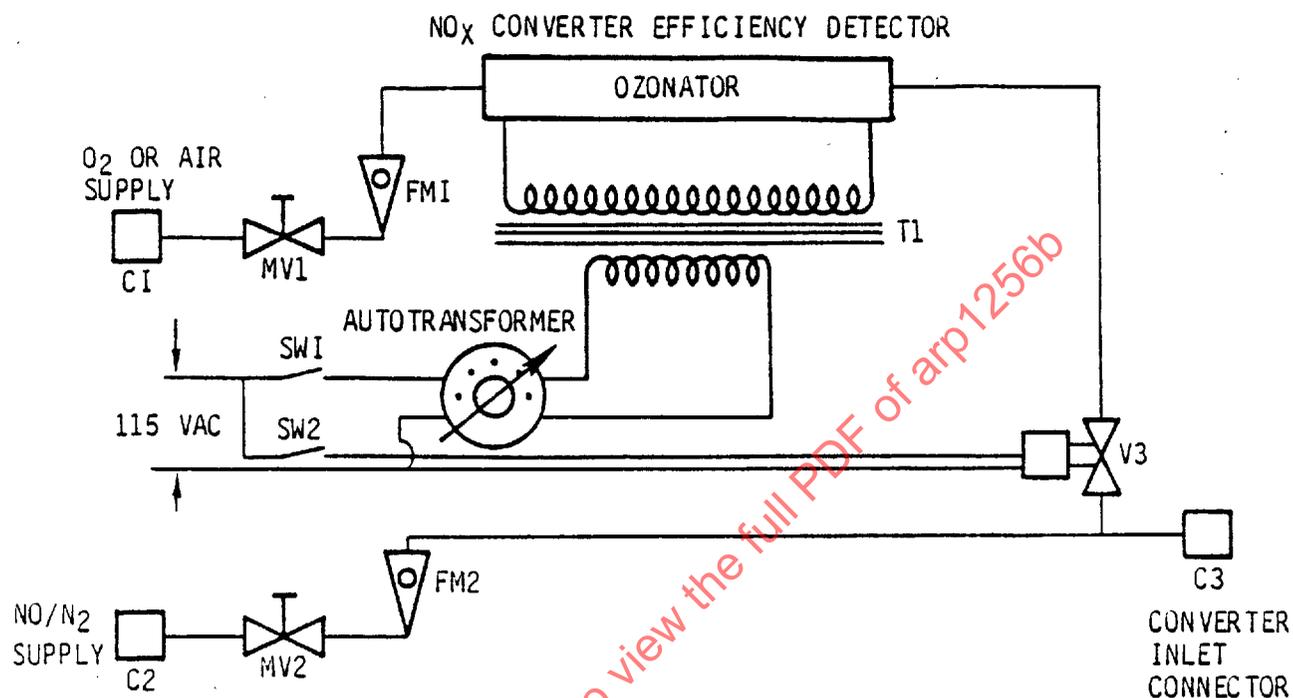
- c. If this specification cannot be met by changing the sample flow rate or detector parameters, such as air and/or fuel flow rate, it is recommended that the detector be replaced.
- d. Alternatively, appropriate corrections should be determined, reported and applied. It is recommended, however, as consistent with good practice, that such correction procedures should be adopted in all cases.

5.2.4 Relative Carbon Response (THC Analyzer): A comparison of response to the different classes of compounds shall be made using (individually) propane, propylene, toluene, and n-hexane, each at approximately 500 ppm C concentration in zero air. The concentration of each gas shall be known within ±1% of the absolute value. If the difference in response to any of these with respect to propane is greater than 5%, check analyzer operating parameters. Reducing sample flow rate improves uniformity of response.

5.2.5 Converter Efficiency Check (NO_x Analyzer): In the absence of any specific manufacturer's instructions, the NO₂ to NO converter efficiency may be determined by the following procedure, using the apparatus described and illustrated in Figure 3.

- a. Attach the NO/N₂ supply (150 to 500 ppm NO) at C₂, the O₂ supply at C₁, and the analyzer inlet connection to the efficiency detector at C₃. If lower concentrations of NO are used, air may be used in place of O₂ to facilitate better control of the NO₂ generated during d.

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FIGURE 3 - Typical System for Determination of NO₂ Converter Efficiency

5.2.5 (Continued):

- b. With the efficiency detector autotransformer off, place the NO₂ converter in bypass mode and close valve V3. Open valve MV2 until sufficient flow and stable readings are obtained at the analyzer. Zero and span the analyzer output to indicate the value of the NO concentration being used. Record this concentration.
- c. Open valve V3 (on/off flow control solenoid valve for O₂) and adjust valve MV1 (O₂ supply metering valve) to blend enough O₂ to lower the NO concentration b about 10%. Record this concentration.
- d. Turn on the ozonator and increase its supply voltage until the NO concentration of c is reduced to about 20% of b. NO₂ is now being formed from the NO + O₃ reaction. There must always be at least 10% unreacted NO at this point. Record this concentration.
- e. When a stable reading has been obtained from d, place the NO₂ converter in the convert mode. The analyzer will now indicate the total NO_x concentration. Record this concentration.

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5.2.5 (Continued):

- f. Turn off the ozonator and allow the analyzer reading to stabilize. The mixture NO + O₂ is still passing through the converter. This reading is the total NO_x concentration of the dilute NO span gas used at c. Record this concentration. It should be greater than or equal to the reading at c indicating whether or not the NO contains any NO₂. If the reading is less than that at c, a loss of NO in the converter is indicated, which should be investigated and rectified.
- g. Close valve V3. The NO concentration should be equal to or greater than reading of b indicating whether the NO contains any NO₂. If the NO concentration is less than the reading at b, this is an indication of a loss of NO in the converter, which should be investigated and rectified.

Calculate the efficiency of the NO_x converter by substituting the concentrations obtained during the test into the following equation.

$$\% \text{ Efficiency} = \frac{e - d}{f - d} \times 100\%$$

The efficiency of the converter should be greater than 90%. Adjustment of the converter temperature may be needed to maximize the efficiency.

- h. If the converter efficiency is not greater than 90%, the cause of the inefficiency shall be determined and corrected before the analyzer is used.
- i. It is recommended, as consistent with good practice, that the measured NO_x value be adjusted (see Section 11) to take into account the converter efficiency.

5.3 Periodic Checks:

The following checks are to be made prior to the testing program and/or at intervals as determined in 5.1:

- a. Check linearity/calibration curve (all analyzers) as outlined in 5.2.1.
- b. Check O₂ effect (THC analyzer) as outlined in 5.2.3.
- c. Check responses of propylene, toluene and n-hexane (THC analyzer) as outlined in 5.2.4.
- d. Check converter efficiency (NO_x analyzer) as outlined in 5.2.5.
- e. Check response to interference gases as specified in 4.1.3 (CO, CO₂ analyzers) and 4.3.2 (NO_x analyzer).
- f. Record all results from a through e.

Any response differing significantly from the previous check may reflect some problem in the analyzer system and a thorough check should be made.

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5.4 Daily Routine:

The following checks are to be made at time of test.

- a. If analyzer power is not left on continuously, follow the manufacturer's instructions for start up. (If frequent/daily use is anticipated, it is recommended that the analyzers are left on continuously.)
- b. Clean or replace filters, as necessary.
- c. Check temperatures of analyzers and flow distribution system.
- d. Check all flows.
- e. Zero working ranges of analyzers using zero gas as specified in 6.3.
- f. Span working ranges of analyzers using span gases giving 75 to 95% of full scale deflection.
- g. Check zero and repeat f if necessary.
- h. Zero and span shall be checked within 1 h before and after each test and at least once per hour during the test (see Section 8 (h)).

Any response value differing by more than $\pm 2\%$ from the previous value may indicate an analyzer problem. Check and correct as necessary.

6. CALIBRATION GASES:

6.1 Mixture Composition:

Calibration gases for carbon monoxide and carbon dioxide shall be prepared using zero air as the diluent. They may be blended singly or as dual component mixtures. Hydrocarbon calibration gas shall be propane in zero air. Three component mixtures of CO, CO₂, and propane in zero air may be used provided the stability of the mixture is assured. Nitric oxide calibration gas shall be blended in zero nitrogen.

6.2 Calibration Gases and Span Gases:

Calibration gases and span gases shall be certified by the vendor to a stated accuracy within $\pm 2\%$. Note, that the gases referred to in 5.2.3(b) and 5.2.4 have a required accuracy of $\pm 1\%$. Since changes in the gas mixture may occur over a period of time after mixing, final analysis, and certification should be performed after a suitable aging period.

6.3 Zero Gases:

Zero nitrogen shall be high purity nitrogen (at least 99.99% nitrogen) containing less than 1 ppm C hydrocarbon, 1 ppm CO, 100 ppm CO₂, and 1 ppm NO_x. Zero air shall be high purity air, but may be "artificial" air consisting of 20 to 22% oxygen blended with nitrogen. It shall contain less than 1 ppm C hydrocarbon, 1 ppm CO, 100 ppm CO₂, and 1 ppm NO_x.

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7. SYSTEM LAYOUT:

The system layout shall be as shown in Figure 4, with the exception that optional arrangements or devices as described in the text, are permitted.

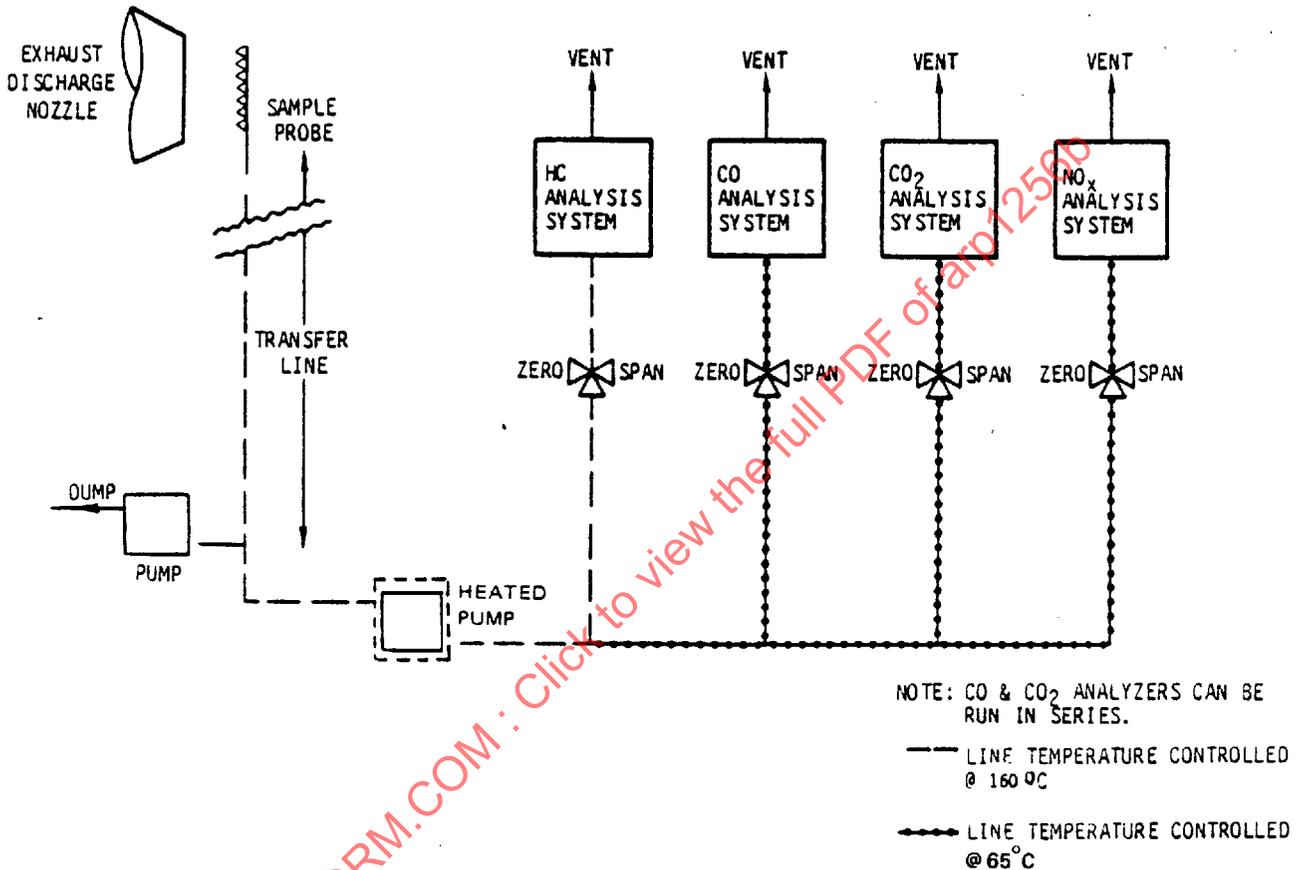


FIGURE 4 - Sampling System and Analyzer Arrangement

8. TEST PROCEDURE:

- Check the system for leaks by isolating the probe and analyzers and operating the sample flow pump. The system shall be satisfactory if no more than 2.0 standard liters (0.07 standard ft³) pass in a 5 min period.
- Check the sampling lines to ensure that they are free from contamination.
- Check the sample transfer time from the probe to the analyzers by calculation or measurement. (See 9.2.)