

Procedure for the Continuous Sampling and Measurement of
Gaseous Emissions from Aircraft Turbine Engines

RATIONALE

Define the set point temperature range of the hydrocarbon analyzer.

1. SCOPE

This SAE Aerospace Recommended Practice (ARP) describes the continuous sampling and analysis of gaseous emissions from aircraft gas turbine engines. The measured gas species include carbon monoxide (CO), carbon dioxide (CO₂), nitric oxide (NO), nitrogen dioxide (NO₂), hydrocarbons (HC) and water vapor (H₂O). This ARP excludes engine operating procedures and test modes, and is not intended for in-flight testing, nor does it apply to engines operating in the afterburning mode.

It is recognized that there will probably be major advances in the gas analysis measurement technology. It is not the intent of this ARP to exclude other analysis techniques, but to form the basis of the minimum amount of conventional instruments (those in common industry usage over the last fifteen years) required for the analysis of aircraft engine exhaust. It is the responsibility of the analyst to demonstrate the alternative measurement technology has comparable (or better) performance than the techniques described in this ARP.

The measurement of other exhaust gas species is beyond the scope of this ARP.

It should be noted the measurement of oxygen (O₂) is generally accepted as essential for assessing data quality, but is not covered by this ARP. Sulfur dioxide (SO₂) is normally not measured using conventional systems but is calculated from fuel sulfur content. Again this is not covered by this ARP.

2. REFERENCES

2.1 APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP1533 Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines

SAE Technical Standards Board Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be reaffirmed, revised, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2011 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE WEB ADDRESS: <http://www.sae.org>

**SAE values your input. To provide feedback
on this Technical Report, please visit
<http://www.sae.org/technical/standards/ARP1256D>**

3. SECTIONS

This document is divided into the following sections:

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

4. DEFINITIONS AND TERMINOLOGY

4.1 ACCURACY

The closeness of agreement between a measured value and a true value.

4.2 AIRCRAFT GAS TURBINE ENGINE

Any gas turbine engine used for aircraft propulsion or power generation, including those commonly called turbojet, turbofan, turboprop, or turbo-shaft type engines.

4.3 CALIBRATION GAS

A certified and traceable gas mixture of specified and known concentration used for adjustment of the analyzer gain to establish the basis for interpretation of the values of quantities indicated by the measuring instrument and those values realized by the calibration gas mixture(s).

4.4 CERTIFIED AND TRACEABLE

Documentary evidence awarded to an instrument, process or gas mixture that defines the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

4.5 CHEMILUMINESCENT DETECTOR (CLD)

An instrument specific to Nitric Oxide (NO) that operates by detecting the light emitted when NO is reacted with ozone (O₃). The same instrument in a different measurement mode, can be used to analyse Oxides of Nitrogen (NO_x) by catalytically converting the NO_x to NO. The difference between this NO_x and the original NO measurement is assumed to be Nitrogen Dioxide (NO₂).

4.6 CONCENTRATION

The volume fraction of the component of interest in the gas mixture expressed as volume percentage or as parts per million by volume (ppmv).

4.7 CONTINUOUS SAMPLING

The presentation of a flowing sample to a gas analyzer so as to obtain a continuous measurement of concentration of the components of interest.

4.8 FLAME IONIZATION DETECTOR (FID)

A hydrogen-air diffusion flame detector that produces a signal nominally proportional to the mass-flow rate of hydrocarbons entering the flame, and generally assumed responsive to the number of carbon ions dissociated from the hydrocarbons entering the flame.

4.9 FUEL/AIR RATIO

The mass rate of fuel flow to the engine divided by the mass rate of dry airflow through the engine.

4.10 GAS DIVIDER

A certified and traceable device that mixes a calibration gas with a diluent gas in precise fractions to produce a range of gas concentrations with which to demonstrate analyzer linearity. Gas dividers are commercially available and include gas mixing pumps, capillary and sonic nozzle type devices. Gas dividers are generally more accurate than a range of calibration gases to demonstrate analyzer linearity, and help reduce calibration gas cylinder inventory.

4.11 GASEOUS EMISSIONS

The gas phase components in the exhaust stream of an aircraft gas turbine engine that for the purposes of this ARP are restricted to the measured carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide and hydrocarbon gases.

4.12 INTERFERENCE

Analyzer response due to presence of components other than the gas (or vapor) that is to be measured.

4.13 LINEARITY

The response from an instrument described by the best mathematical straight-line between an instrument zero and full scale, for a given analyzer range.

4.14 NOISE

Analyzer noise has a frequency of 0.5 Hz or greater, and can be regular or irregular variations in instrument output not associated with characteristics of the sample to which the analyzer is responding. Instrument output variations with a frequency less than 0.5 Hz are not considered noise, but shall be accounted for in the analyzer drift and resolution characteristics.

4.15 NO_x

Oxides of nitrogen, calculated from the sum of the measured values of nitric oxide (NO) and nitrogen dioxide (NO₂).

4.16 NONDISPERSIVE INFRARED ANALYZER (NDIR)

An analyzer that selectively measures specific components by absorption of infrared energy.

4.17 PARTS PER MILLION (ppmv)

The unit volume concentration of a gas per million unit volumes of the gas mixture of which it is a part. 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.

4.18 PARTS PER MILLION CARBON (ppmC)

The mole fraction of hydrocarbon multiplied by 10^6 . Thus, 1 ppm of methane (CH_4) is indicated as 1 ppmC. To convert ppm concentration of any hydrocarbon to an equivalent ppmC value, multiply ppm concentration by the number of carbon atoms per molecule of the gas. For example, 1 ppm propane (C_3H_8) translates as 3 ppmC hydrocarbon 1 ppm hexane (C_6H_{14}) as 6 ppmC hydrocarbon.

4.19 PRECISION

The closeness of agreement between independent test results obtained under stipulated conditions. For the purposes of this ARP measurements are performed upon a given, invariant sample in short-term repetitions of the measurement, with no intervening analyzer adjustment, in the normal working environment of the analyzer.

4.20 RESOLUTION

The smallest possible change in output from an analytical instrument that can be produced and detected.

4.21 RESPONSE

The change in analyzer reading, digital or analog output that occurs with change in sample concentration. Also, the output signal corresponding to a given sample concentration.

4.22 SAMPLING PROBE

The device placed in the engine exhaust plume, used to extract a representative sample.

4.23 SPAN GAS

A certified and traceable gas mixture to be used for routine verification and adjustment of analyzer response.

4.24 SPAN DRIFT

The time related change in response of the analyzer in repetition of a span gas measurement determined over a stated period of unattended operation, performed in the normal operating environment of the instrument, under similar conditions of flow and pressure as that employed on test. The span drift of an analyzer between times 1 and 2, is calculated from $(\text{span } 2 - \text{zero } 2) - (\text{span } 1 - \text{zero } 1)$.

4.25 TEST SEQUENCE

A series of functionally related conditions in which the test operation without interruption progresses systematically from one mode to another.

4.26 HYDROCARBONS

The sum of all hydrocarbon compounds of all classes and molecular weights as measured by an instrument incorporating a flame ionization type detector (FID). Hydrocarbons are sometimes referred to as total hydrocarbons (THC) or unburned hydrocarbons (UHC). Hydrocarbons are referenced against a propane (C_3H_8) span gas, but reported as methane (CH_4) equivalent. The final hydrocarbon emission index result (see the latest revision of ARP1533) is expressed as CH_α where " α " is the hydrogen to carbon ratio of the fuel, reflecting the composition of the hydrocarbons in the exhaust.

4.27 UNCERTAINTY

An estimate attached to a test result which characterizes the range of values within which the true value is asserted to lie or a parameter associated with the result of a measurement that characterize the dispersion of the values that could reasonably be attributed to the quantity subjected to measurement. An estimate of uncertainty incorporates what is known about both random and systematic effects on the measurement process, and is probably the most appropriate way of expressing the accuracy of results.

4.28 ZERO DRIFT

Time-related deviation of analyzer output from the zero set point in repetition of a zero gas measurement determined over a stated period of unattended operation, performed in the normal operating environment of the instrument, under similar conditions of flow and pressure as that employed on test.

4.29 ZERO GAS

A certified and traceable gas used in establishing the zero or null response point of a calibration curve for a given analyzer range. The zero gas is typically high purity nitrogen or air, depending on the type of instrument.

5. 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:

$$\text{Error in measurement} = \frac{\text{Range}}{\text{measurement value}} \times \text{Specification error} \quad (\text{Eq. 1})$$

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).

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.

The calculation of the gaseous results from the measured concentration data is described in the latest version of ARP1533. This document describes how to apply interference coefficients to the measured data to determine the final results and how to calculate humidity from the measured dew/frost point temperatures.

5.1 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 of infrared radiation in a frequency band specific to the gaseous component of interest within the sample cell. 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.

5.1.1 Analyzer Performance Specifications

Zero Drift	- Less than ±1% of full scale in 1 hour.
Span Drift	- Less than ±1% of full scale in 1 hour.
Noise	- Less than ±1% of full scale.
Resolution	- Better than 0.5% of full scale.
Precision	- CO: Better than ±1% of full scale for all ranges - CO ₂ : Better than ±1% of full scale for all ranges.
Linearity	- Response shall be linear within ±1% of full scale, when instrument output is linearized.
Total Range	- Typically CO: 0 to 1000 ppm and CO ₂ : 0 to 10% in appropriate ranges.

NOTE: Full scale applies to the range selected for measurement.

5.1.2 NDIR Cells

All NDIR analyzers shall be equipped with cells of suitable length to measure concentrations within the required range.

5.1.3 If CO and CO₂ samples are analyzed “wet”, the sample cells shall be maintained at a constant temperature not less than 323 K (50 °C, 122 °F). An optional water removal device is permitted ahead of the CO and CO₂ analyzers. If such a device is used, then the sample cells shall be maintained at a constant temperature at least 10 K (10 °C, 18 °F) above the sample dew point. If the sample is dried, a “dry” to “wet” correction of the measured values must be made (see Section 11). The dew point temperature of the sample exiting the drier shall be measured to ensure the following:

- The sample dew point temperature exiting the drier is stable and meets the criteria above.
- The correct ‘dry’ to ‘wet’ correction is made.
- The correct interference correction is applied (see 5.1.4).

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.

5.1.4 Interferences

Interferences from (a) ethylene (C₂H₄), (b) carbon dioxide [interference coefficient = L], and (c) water vapor [interference coefficient = M] will affect the reading of the CO analyzer. A better estimate of the true value of CO in the exhaust gas sample is obtained by applying mathematical corrections to the measured concentration results using the interference coefficients L and M and employing methods described in the latest version of ARP1533. The response of the CO analyzer should not exceed the following limits:

- 500 ppm/percent ethylene concentration.
- 2 ppm/percent CO₂ concentration, expressed as interference coefficient $L = -0.0002 \text{ mole CO / mole CO}_2$.
- 2 ppm/percent water vapor concentration, expressed as interference coefficient $M = -0.0002 \text{ mole CO / mole H}_2\text{O}$.

Interference from oxygen [interference coefficient = J], 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, expressed as interference coefficient $J = 0.1 \% \text{ Reading / \% O}_2$.

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 12).

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 shall be adopted in all cases.

5.1.5 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.

5.2 Hydrocarbon Analyzer

An instrument incorporating a flame ionization detector (FID) performs the measurement of hydrocarbons. With this type of detector, an ionization current is produced which is approximately proportional to the mass rate of hydrocarbon entering the hydrogen-air flame. This small current is measured using an electrometer amplifier and is continuously indicated. The gain of the hydrocarbon analyzer is normally adjusted using suitable, certified and traceable propane calibration gases, and suitable zero grade gas mixtures. The results from the hydrocarbon analyzer are generally expressed as parts per million by volume methane equivalent ppmC.

Analyzer Performance Specifications

- Zero Drift - Less than $\pm 1\%$ of full scale in 1 hour.
- Span Drift - Less than $\pm 1\%$ of full scale in 1 hour.
- Noise - Less than $\pm 1\%$ of full scale.
- Resolution - Better than 0.5% of full scale.
- Precision - Better than $\pm 1\%$ of full scale for all ranges.
- Linearity - Response with propane in air shall be linear within $\pm 1\%$ of full scale.
- Total Range - Typically 0 to 1000 ppmC in appropriate steps.

NOTE: Full scale applies to the range selected for measurement.

To prevent sample condensation and maintain instrument stability the flame ionization detector and sample handling components of the hydrocarbon analyzer are normally housed in a temperature controlled oven maintained in the range 423 to 483K (150 to 210 °C, 302 to 410 °F).

Most hydrocarbon analyzer manufacturers recommend the use of 40% hydrogen 60% helium fuel gas for exhaust measurement applications. It is permissible to use 100% hydrogen fuel provided all analyzer performance specifications, oxygen synergism and relative response criteria are met in full.

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

Relative Carbon Response: The relative responses to n-hexane, propylene and toluene in air shall not differ by more than 5% from the relative response of propane in air.

5.2.2 Analyzer Response Time

Analyzer response time shall not exceed 10 s from introduction of a sample to the analyzer inlet to achievement of 90% of final reading.

5.3 Oxides of Nitrogen Analyzer

A chemiluminescence analyzer with a nitrogen dioxide (NO₂) converter shall be used for measuring nitric oxide (NO) and total oxides of nitrogen (NO_x). The chemiluminescence method is NO specific and utilizes the principle that NO reacts with ozone (O₃) to give nitrogen dioxide (NO₂) and oxygen (O₂). Approximately 10% of the NO₂ is electronically excited. The transition of excited NO₂ to the ground state yields a light emission. This light emission is measured utilizing a light detection device and associated electronics.

The method also utilizes the principle that NO₂ decomposes to NO according to the catalyzed thermal reaction, (2NO₂ → 2NO + O₂). A unit designed to convert NO₂ to NO without affecting the NO originally present in the sample, is included as an integral part of the chemiluminescence analyzer. If a sample is passed through the converter prior to entering the chemiluminescence analyzer, a NO_x reading (NO + NO₂) is obtained. If the converter is bypassed, only the NO portion is analyzed.

5.3.1 Analyzer Performance Specifications

- Zero Drift - Less than $\pm 1\%$ of full scale in 1 hour.
- Span Drift - Less than $\pm 1\%$ of full scale in 1 hour.
- Noise - Less than $\pm 1\%$ of full scale.

- Resolution - Better than 0.5% of full scale.
- Precision - Better than $\pm 1\%$ of full scale.
- Linearity - Response shall be linear within $\pm 1\%$ of full scale
- Total Range - Typically 0 to 1000 ppm in appropriate ranges.

NOTE: Full scale applies to the range selected for measurement.

Converter Efficiency - Greater than 90% (also expressed as a fractional efficiency (η) of greater than 0.90).

5.3.2 A heated analyzer inlet system is recommended to avoid potential losses of NO_2 through absorption in water.

If a water removal device is used to dry the sample upstream of the oxides of nitrogen analyzer, it must be proven that no oxides of nitrogen be lost. Water removal devices are occasionally incorporated within the chemiluminescence analyzer, and are located downstream of the converter because of the high solubility of NO_2 in water. In both cases appropriate corrections to the measured results shall be applied to correct for the water removal. If drying is not used, the temperature of the sample passages in the analyzer should be maintained high enough to avoid condensation of water.

5.3.3 Interferences

Interference from carbon dioxide [interference coefficient = L'] and water vapor [interference coefficient = M'] will affect the reading of the analyzer. Unlike the interference on infra-red analyzers the effects of water vapor and carbon dioxide will only be apparent during the NO reaction with ozone (O_3). Collisions with water vapor and carbon dioxide molecules within the instrument reaction chamber quench or lower the light emissions from the excited NO_2 to give an instrument reading lower than would have been the case had there been no water vapor or carbon dioxide present in the sample. A better estimate of the true value of NO in the exhaust gas sample, is obtained by applying mathematical corrections to the measured concentration results using the interference coefficients L' and M' and employing methods described in the latest version of ARP1533.

Response of the analyzer shall not, in general, exceed the following limits:

- 0.05% of reading/percent CO_2 concentration, expressed as interference coefficient $L' = 0.05 \text{ \% Reading} / \text{\% CO}_2$.
- 0.1% of reading/percent water vapor concentration, expressed as interference coefficient $M' = 0.1 \text{ \% Reading} / \text{\% H}_2\text{O}$.

If the interference limitation(s) for CO_2 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 shall be adopted in all cases.

5.3.4 Analyzer Response Time

Analyzer response time shall not exceed 10 s from introduction of a sample to the analyzer inlet to achievement of 90% of final reading.

5.4 Water Vapor Analyzer

An automatic condensation hygrometer is recommended for the measurement of dew/frost point temperatures (expressed as THYG). A dew/frost point measurement is used in the calculation of the water content of the engine inlet air (expressed as h). If sample drying to the relevant gas analyzers is employed, the water content of the semi-dry sample (expressed as h_{sd}), is used to correct measured concentrations from the relevant gas analyzers for both water removal and any interferences due to the remaining water vapor in the semi-dry sample.

Automatic condensation hygrometers commonly referred to as “chilled mirror” hygrometers, pass the gas sample over a thermoelectrically cooled condensate detection mirror. An optical device monitors the reflected light from the mirror surface, that by means of a feedback loop to the thermoelectric heat pump, maintains the mirror at the dew/frost point. A precision thermometer is embedded within the mirror that monitors the mirror temperature at the established dew/frost point.

A precision gas pressure measurement device, of suitable detection range, is recommended to monitor the sample gas pressure (expressed as PHYG) at the hygrometer.

5.4.1 Analyzer Performance Specification

Accuracy: -Better than $\pm 0.4K$ ($\pm 0.4^\circ C$, $\pm 0.7^\circ F$)

6. ANALYZER ROUTINES

6.1 General Analyzer Routines

Analyzer characteristics may vary with time and it is necessary to periodically check that they are still within tolerance, by means of a regular instrument performance audit. The time period between performance audits shall be based on documented historic information and manufacturers recommendations. In the absence of any evidence to the contrary, a time period of 30 days shall be used. Analyzers of the same type supplied by different manufacturers must be assessed independently.

Working ranges of analyzers shall be selected based on the engine under test. The selection of analyzer ranges and appropriate span gases are critical to the accuracy and precision of the final measurement. Prior knowledge of the expected concentration ranges for each exhaust gas constituent, over the entire engine test sequence, is essential for making the decision. The maximum exhaust gas concentration shall not exceed the selected instrument range for the engine test sequence, with the span gas concentration as close as possible to, but slightly in excess of, this maximum exhaust gas concentration. Ideally, the sample gas concentrations shall be in the 20 to 95% of scale range. Depending on the engine under test, it may be necessary to use more than one instrument range and span gas to obtain adequate precision.

The setting of zero and span gains of analyzers may be performed physically or electronically when operating under remote computer control. If it can be demonstrated that both measurement accuracy and precision have not been adversely affected, it is acceptable not to make such adjustments to the instrument gain controls. The analyzer outputs for zero and span modes are recorded and appropriate measurement conversion formulas applied.

6.2 Specific Analyzer Routines

The following specific routines are necessary for initial setting up or periodic performance audit checks of the various analyzers. All analyzers will be checked in a similar operating environment to that in which the analyzer is normally used, at the same sampling conditions of gas flow rate and/or pressure.

6.2.1 Linearity/Calibration Curve Check (all analyzers)

- a. Analyzers with a linear signal output characteristic shall be checked on all working ranges using certified and traceable gas mixtures or a certified and traceable gas divider. If gas mixtures are used in addition to the zero and span gas a minimum of three additional gas mixtures at nominal concentrations of 30, 60 and 90% of full scale shall be used.

A gas divider will typically generate a minimum of 11 points between 0 and 100% full scale, generally at nominal 10% increments for a capillary type device.

The maximum response deviation of any of the points between 10 and 100% full scale shall not exceed $\pm 1\%$ of full scale value from the mathematical best fit straight line from the zero to the full scale span gas reading. If this linearity requirement cannot be met, 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. It should be noted that if gas mixtures are used more mixes will be required to adequately define the curve shape.

6.2.2 Optimization of Detector Response (HC Analyzer)

- a. Follow manufacturer's instructions for analyzer start-up and basic operating adjustment. The fuel gas, normally 40% hydrogen 60% helium unless otherwise recommended by the manufacturer, shall contain less than 1 ppmC hydrocarbon. Air shall be "hydrocarbon-free" grade containing less than 1 ppmC hydrocarbon.
- b. Allow the hydrocarbon analyzer oven to reach the set-point temperature and follow the manufacturers' instructions to ignite the FID. Allow at least an additional 1/2 hour after oven reaches temperature and the FID has been ignited for the system to equilibrate.
- c. Introduce a mixture of propane in air at a propane concentration of about 500 ppmC. 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 adjustments. Figure 1 shows a typical curve for response versus fuel flow.
- d. To determine optimum air flow, use the fuel flow setting determined above and varies air flow. Figure 2 shows a typical curve for response versus air flow.

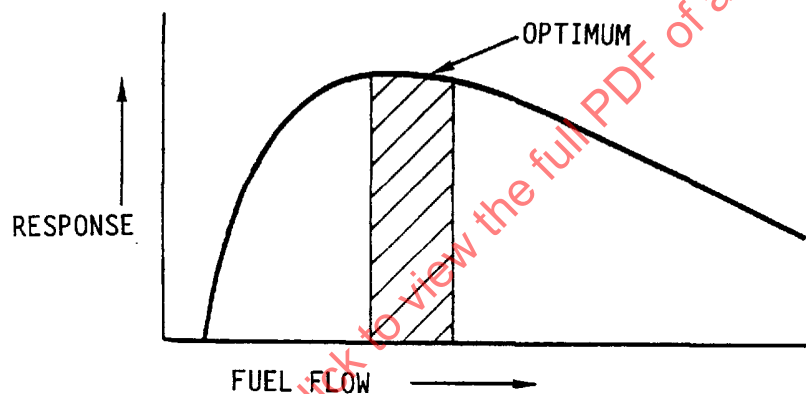


FIGURE 1 - FUEL FLOW RESPONSE CURVE

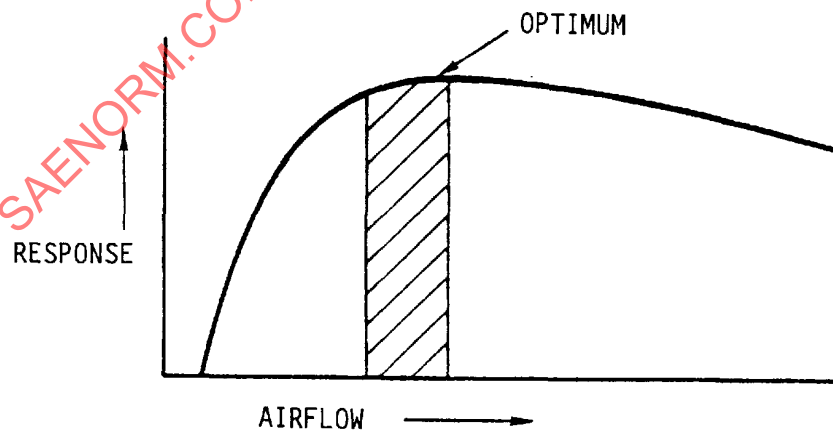


FIGURE 2 - AIRFLOW RESPONSE CURVE

- e. If no optimum fuel or air flow can be determined by the previous procedures, the analyzer manufacturer's recommended settings shall be used.

After the optimum flow settings have been determined, record the values for future reference.

6.2.3 Oxygen Synergism Effect (HC 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 6.2.2.

- a. Introduce zero grade air and zero the analyzer. Span the analyzer with suitable certified and traceable propane in air gas mixture. Recheck zero using nitrogen (N_2) zero gas. The difference between the two zero gases shall be less than 1% of full scale or ± 1 ppmC whichever is greater.
- b. The following blends of propane shall be used to determine the effect of oxygen (O_2) in the sample:

Propane in 10% $O_2 \pm 1\%$, balance N_2 .

Propane in 21% $O_2 \pm 1\%$, balance N_2 .

The volume concentration of propane in each mixture shall be about 500 ppmC, and the concentration of both the O_2 and propane shall be certified and traceable to within $\pm 1\%$ 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% O_2 shall not differ by more than 3% from the normalized response to propane in 10% O_2 .

- c. If this specification cannot be met by changing the sample flow rate or detector parameters, such as air and/or fuel flow rate, the detector shall be replaced.

6.2.4 Relative Carbon Response (HC 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 ppmC concentration in zero air. The concentration of each gas shall be known within $\pm 1\%$ of the absolute value. If the difference in normalized 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.

6.2.5 Converter Efficiency Check (NO_x Analyzer)

In the absence of any specific manufacturer's instructions, the NO_2 to NO converter efficiency may be determined by the following procedure, using the apparatus described and illustrated in Figure 3.

- a. Attach the NO balance N_2 gas mixture supply (150 to 500 ppm NO) at position (C2), the O_2 supply at position (C1), and the analyzer inlet connection to the efficiency detector at position (C3). If lower concentrations of NO are used, air may be used in place of O_2 to facilitate better control of the NO_2 generated during step [d].
- b. With the efficiency detector autotransformer off, place the NO_2 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 O_2) and adjust valve MV1 (O_2 supply metering valve) to blend enough O_2 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]. NO_2 is now being formed from the $NO + O_3$ reaction. A minimum of 10% unreacted NO shall remain at this point. Record this concentration.
- e. When a stable reading has been obtained from [d], place the NO_2 converter in the convert mode. The analyzer will now indicate the total NO_x concentration. Record this concentration.
- f. Turn off the ozonator and allow the analyzer reading to stabilize. The mixture $NO + O_2$ 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 NO_2 . If the reading is less than that at [c], a loss of NO in the converter is indicated, which shall be investigated and rectified.

- g. Close valve V3. The NO concentration shall 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 shall be investigated and rectified.

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

$$\% \text{ Efficiency} = \frac{e - d}{f - d} \times 100\% \quad (\text{Eq. 2})$$

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

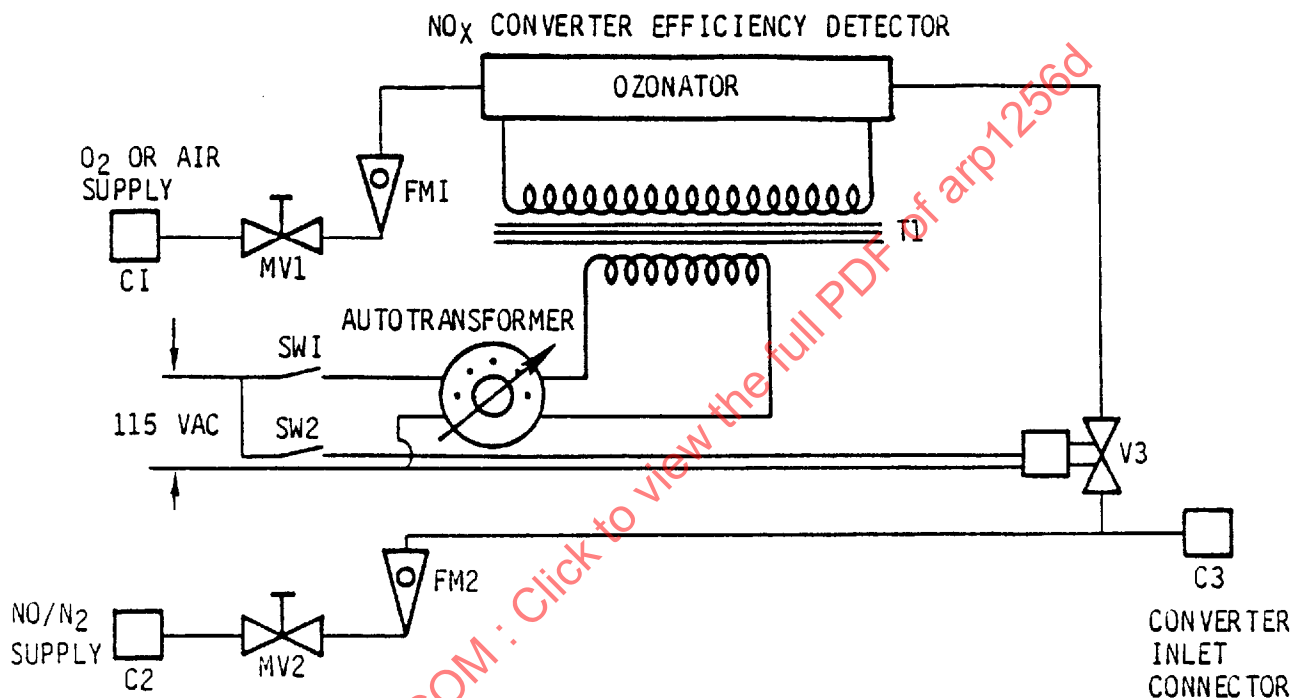


FIGURE 3 - TYPICAL SYSTEM FOR DETERMINATION OF NO₂ CONVERTER EFFICIENCY

- 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. The measured NO_x value shall be adjusted (see Section 12) to take into account the converter efficiency.

6.3 Periodic Checks

The following checks are to be made prior to the testing program and/or at intervals as determined in 6.1:

- a. Check Zero Drift, Span Drift, and Noise (all analyzers): Zero drift, span drift and noise are three distinct properties and care should be taken to ensure that each is measured and quantified individually. Zero and span working range of analyzer as detailed in 6.4. Over a period of 1 hour, monitor the instrument output with zero gas flowing. Noise is defined as variations in instrument output of 0.5 Hz or greater. Instrument noise should be averaged out when observing both zero and span drift. Zero drift in terms of $\pm$ concentration per hour is calculated from the difference between the observed maximum and minimum zero concentration mean readings divided by 2. The zero drift is then reported as $\pm$ % full scale for the analyzer range selected. Span drift is calculated in a similar manner after observing span gas passing through the instrument for an hour. The analyzer is then re-zeroed at the end of the span drift hour period, such that any zero drift can be compensated for. Maximum noise is often (but not always) observed during the span drift check. Noise of 0.5 Hz or greater is calculated in a similar manner, as the difference between the maximum and minimum concentration deflections divided by 2. The noise is then reported as $\pm$ % full scale for that selected analyzer range.

- b. Check linearity/calibration curve (all analyzers) as outlined in 6.2.1.
- c. Check repeatability and analyzer response time to 90% of full scale (all analyzers).
- d. Check O₂ effect (HC analyzer) as outlined in 6.2.3.
- e. Check responses of propylene, toluene and n-hexane (HC analyzer) as outlined in 6.2.4.
- f. Check converter efficiency (NO_x analyzer) as outlined in 6.2.5.
- g. Check response to interference gases as specified in 5.1.3 (CO, CO₂ analyzers) and 5.3.3 (NO_x analyzer).
- h. Record all results from [a] to [g].

Any response differing significantly from historic records of previous checks may reflect some problem in the analyzer system. A thorough check of the analyzer and system should be made, the problem rectified and the tests repeated..

6.4 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 shall be left on continuously.)
- b. Clean or replace filters, as necessary.
- c. Check temperatures of analyzers and flow distribution system.
- d. Check all sample forwarding pumps and the resulting sample flows and/or pressures.
- e. Select suitable working ranges and appropriate span gases for each analyzers based on the engine under test (see 6.1). Ensure each working range has been performance audited.
- f. Zero working ranges of analyzers using zero gas as specified in 7.3.
- g. Span working ranges of analyzers for the selected analyzer measuring ranges.
- h. Check zero. Repeat [f] and [g] if necessary.
- i. Zero and span shall be checked within 1 hour before and after each test and at least once per hour during the test (see Section 9 (h)).

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

7. CALIBRATION GASES

7.1 Mixture Composition

The preferred diluent for carbon monoxide, carbon dioxide and nitric oxide calibration gases is nitrogen. Hydrocarbon calibration gas shall be propane in zero air. The use of multi component mixes and different diluent gases are permitted if the analyst can demonstrate the accuracy of the mixture has not been compromised by cross interference effects of the components in the mixture and the stability of the mixture is assured. If air is chosen as the diluent for the carbon monoxide and carbon dioxide span gases the correction for the effect of oxygen in the span gas shall be determined and applied (as described in the latest version of ARP1533).

7.2 Calibration Gases and Span Gases

Recommended calibration gases and span gases shall be certified and traceable by the vendor to the stated accuracy specified in Table 1. In addition, the test gases in Table 2 are required to measure the effects of oxygen pressure broadening on the carbon dioxide analyzers (5.1.3), both oxygen synergism (6.2.3b) and relative hydrocarbon response (6.2.4) on hydrocarbon analyzers, and linearity checks.

TABLE 1 – SPAN GASES

Analyzer	Gas	Accuracy ¹
CO	CO in zero nitrogen	±1%
CO ₂	CO ₂ in zero nitrogen	±1%
HC	Propane in zero air	±1%
NO _x	NO _x in zero nitrogen	±1%

¹ Taken over the 95% confidence interval.

TABLE 2 – TEST GASES

Analyzer	Gas	Accuracy ¹
HC	Propane in 10% ± 1% oxygen, balance zero nitrogen	±1%
HC	Propane in 21% ± 1% oxygen balance zero nitrogen	±1%
HC	Propylene in zero air	±1%
HC	Toluene in zero air	±1%
HC	n-hexane in zero air	±1%
HC	Propane in zero air	±1%
CO ₂	CO ₂ in zero air	±1%
CO ₂	CO ₂ in zero nitrogen	±1%
CO	CO in zero nitrogen	±1%
NO _x	NO _x in zero nitrogen	±1%

¹ Taken over the 95% confidence interval.

Changes in gas mixture composition can occur over extended periods of time. Gas vendors supply certified and traceable gas mixtures with a “valid until” date that shall not be exceeded.

7.3 Zero Gases

Zero gases shall be certified and traceable by the gas vendor. Zero nitrogen shall be high purity nitrogen (at least 99.99% nitrogen) containing less than 1 ppmC 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.

8. SYSTEM LAYOUT

A typical system layout is presented in Figure 4. The system shall be designed such that low spots, cold spots and dead flow legs within the sample transfer lines are avoided. Maximum flow volume shall be extracted with excess flow spilled through flow by-pass legs.

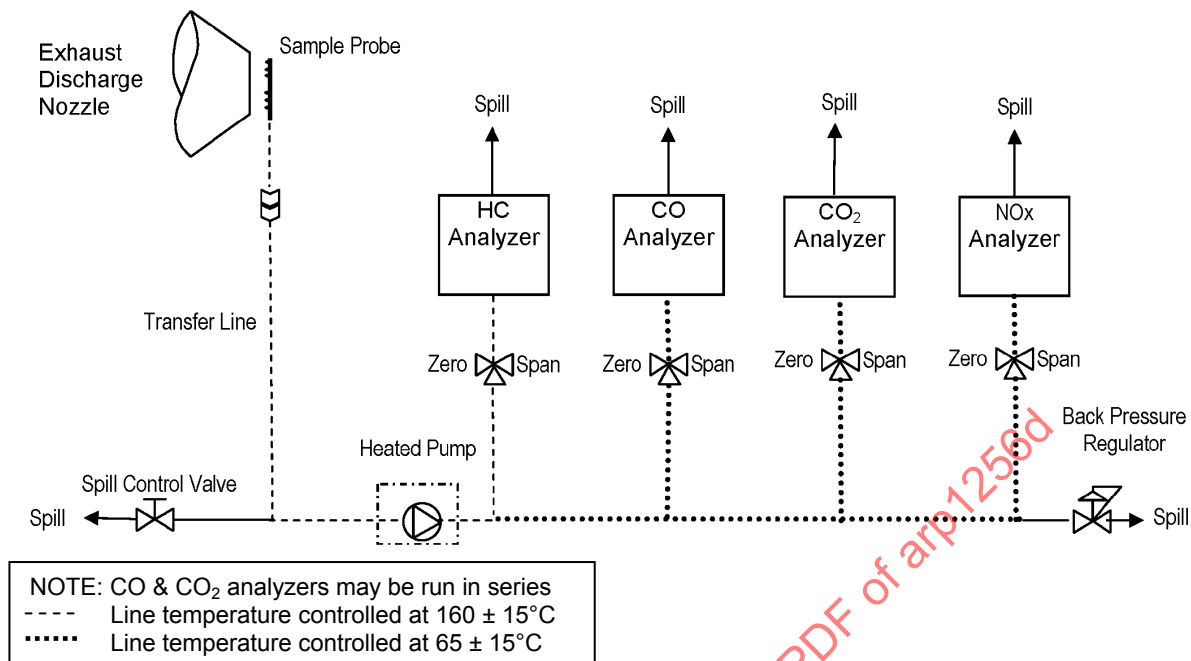


FIGURE 4 - SAMPLING SYSTEM AND ANALYZER ARRANGEMENT

9. TEST PROCEDURE

- The probe and sample transport system will be checked for leaks by isolating the analyzers and temporarily blocking the probe orifices. Allow the sample transport system to equilibrate at the operating temperature, close the spill control valve and operate 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.
- The probe and sample transfer system shall be cleanliness checked. Zero grade air is introduced into the sample probe with the sample transport system maintained at the operating temperature. The system may be considered free from contamination if the hydrocarbon analyzer indicates less than 1.0% of the hydrocarbon sample value at the engine idle condition or 3 ppmC whichever the lesser.
- The leak and cleanliness checks are to be performed as a final check prior to engine test. If any of the sample transport or spill control connections are broken and re-made before commencing testing, the leak and cleanliness checks of steps (a) and (b) will be repeated.

Under extreme circumstances (for example when the probe is inaccessible in the final engine build) it is permitted to perform the probe and sample transport system leak and cleanliness checks independently. The combined totals for both leak and cleanliness checks shall not exceed the limits in (a) and (b), and the number of final connections from the probe to the sample transport system kept to a minimum.

- Check the sample transfer time from the probe to the analyzers by calculation or measurement (see 10.3).
- Calibrate analyzers following the daily routine (see 6.4). Recheck and record as measured zero and span of each analyzer immediately prior to the start of test, and no greater than 1 hour before commencing testing.
- Start sample flow to analyzers.
- Measurements can now be made following any desired engine mode schedule. Characteristic engine stabilization patterns shall be determined and appropriate precautions taken to allow adequate time for stabilization. Test procedures shall be prescribed for each class of engine to be tested.

PRECAUTIONARY NOTE: Raw fuel discharged during the engine start can contaminate the sampling system. Back-purging the sample transport system with a clean, high pressure gas is good practice.