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AEROSPACE RECOMMENDED PRACTICE

ARP 1256A

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

1. PURPOSE

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 procedures[1] and equipment for measuring carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, and total hydrocarbon. This ARP is not intended for in-flight testing, nor does it apply to afterburning engines.

2. SECTIONS

The procedure is divided into the following sections:

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

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, and afterburning engines in the nonafterburning mode of operation.

3.3 Calibration Gas: A mixture of gases of specified and known composition used as the basis for interpreting instrument response in terms of the concentration of the gas to which the instrument 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 instrument 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.

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[1]Excluding engine operating procedures and test modes.

3.7 Fuel/Air Ratio: The mass rate of fuel flow to the engine divided by the mass rate of dry air flow through the engine.

3.8 Gaseous Emissions: Substances emitted in the form of gas downstream of the combustion chamber and limited to carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, and hydrocarbons.

3.9 Interference: Instrument response due to presence of components other than the gas (or vapor) that is to be measured.

3.10 Noise: Random variation in instrument output not associated with characteristics of the sample to which the instrument is responding and which is distinguishable from instrument drift characteristics.

3.11 NO_x: Oxides of nitrogen, specifically, the sum of nitric oxide (NO) and nitrogen dioxide (NO_2).

3.12 Nondispersive Infrared Analyzer: An instrument 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).

3.14 Parts Per Million Carbon (ppmC): 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 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 translates as 3 ppmC hydrocarbon; 1 ppm hexane as 6 ppmC 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 instrument adjustment.

3.16 Response: The change in instrument output signal that occurs with change in sample concentration. Also, the output signal corresponding to a given sample concentration.

3.17 Span Gas: A calibration gas to be used for routine verification and adjustment of instrument response.

3.18 Span Drift: The time related change in response of the instrument in repetition of a span gas measurement under identical conditions of flow and concentration.

3.19 Test Sequence: A series of functionally related tests in which the test operation without interruption progresses systematically from one test mode to another.

3.20 Total Hydrocarbons: The total of hydrocarbon compounds of all classes and molecular weights.

3.21 Zero Drift: Time related deviation of instrument 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".

3.22 Zero Gas: A gas to be used in establishing the zero, or no-response, adjustment of an instrument.

4. EQUIPMENT

4.1 NDIR Instruments: Nondispersive infrared (NDIR) analyzers shall be used for the continuous monitoring of carbon monoxide (CO), and carbon dioxide (CO_2) in turbine exhaust.

The NDIR instruments operate on the principle of differential energy absorption from parallel beams of infrared energy. The energy is transmitted to a differental detector through parallel cells, one containing a reference gas, and the other, sample gas. The detector, charged with the component to be measured converts the optical signal to an electrical signal. The electrical signal thus generated is amplified and continuously indicated.

4.1.1 Instrument Performance Specification:

Zero Drift - Less than ±1% of full scale in 2 hrs.
Span Drift - Less than ±1% of full scale in 2 hrs.
Noise - Less than ±1.0% of full scale
Sample Cell Temperature - Minimum 50°C (122°F) for undried samples. Cell temp. maintained within ±2°C (3.6°F) of set point.

Range and Precision

	Range	Precision Excluding Interferences
CARBON MONOXIDE		
For ranges below 100 PPM Full Scale		±2% of full scale
For ranges above 100 PPM Full Scale		±1% of full scale
Total range	0 to 2500 ppm	
CARBON DIOXIDE	For all ranges	±1% of full scale
Total range	0 to 5%	

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

If CO and CO_2 samples are analyzed "wet", the sample cells should be maintained at a temperature of not less than 50°C (122°F) with a stability of ±2°C (3.6°F). An optional cold trap or membrane dryer is allowed ahead of the CO and CO_2 analyzers (Fig. 4), in which case the sample cells should be maintained at least 10°C (18°F) above the sample dew point with a stability of ±2°C. The CO and CO_2 analyzers may be connected either in series or in parallel.

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

(1) 500 ppm for 1% ethylene concentration.
(2) 2 ppm for 1% CO_2 concentration.
(3) 2 ppm for 1% water vapor concentration.

Optical filters are the preferred method of discrimination. In some cases a cold tray or membrane dryer may be used to reduce water content below the level at which its interference is acceptable. If the sample is dried, a dry to wet correction (See Sec. 11) must be made to the measured values.

4.1.3 (Continued)

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 should be adopted in all cases.

4.1.4 Instrument Response Time: Instrument repsonse time should not exceed 10 sec. 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 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.

The analyzer shall be fitted with a constant temperature oven housing the detector and sample-handling components. It shall maintain temperature within ±2°C (±3.6°F) of the set point, which shall be within the range 155 to 165°C (311 to 329°F).

4.2.1 Instrument Performance Specifications:

Zero Drift - Less than ±1% of full scale in 2 hrs.
Span Drift - Less than ±1% of full scale in 2 hrs.
Noise - Less than ±1.0% of full scale.
Linearity - Response with propane in air shall be linear within ±2% of full scale for each range.
Precision - For ranges below 10 ppmC full scale: ±5% of full scale with propane calibration gas.
- For ranges from 10 ppmC to 100 ppmC full scale: ±2% of full scale with propane calibration gas.
- For ranges above 100 ppmC: ±1% of full scale with propane calibration gas.

Total Range-0 to 5000 ppmC

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

4.3 Chemiluminescence Analyzer: A chemiluminescence analyzer with an NO_x 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 (0_3) to give nitrogen dioxide (NO_2) and oxygen (0_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, ($2NO_2 \rightarrow 2NO + O_2$). 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 ($NO + NO_2$) is obtained. If the converter is bypassed, only the NO portion is indicated.

Drying agents or cold traps are not permitted in the sample line upstream of the chemiluminescence analyzer. The temperature of the sample passages in the analyzer should be maintained high enough to avoid condensation of water.

4.3.1 Instrument Performance Specifications:

Zero Drift - Less than ±1% of full scale in 2 hrs.
Span Drift - Less than ±1% of full scale in 2 hrs.
Noise - Less than ±1% of full scale.
Linearity - Response shall be linear for each range within ±2% of full scale or ±2 ppm whichever is greater.
Precision - ±1% of full scale on all ranges.
Total Range - 0 to 1000 ppm.

4.3.2 Interferences: Interferences from water vapor and carbon dioxide will affect the reading of the chemiluminescence analyzer. Response of the NO instrument should not exceed the following limits:

(1) 0.05% of reading for 1% CO_2 concentration.
(2) 0.1% of reading for 1% water vapor concentration.

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 should be adopted in all cases.

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

5. INSTRUMENT ROUTINES

5.1 NDIR Instruments: Following the instrument manufacturer's instructions for start up of instruments, the following minimum requirements shall be adhered to:

5.1.1 Preparatory Routine: These checks are to be made prior to the testing program:

(1) Check instrument for leaks.
(2) Check detector tuning, following manufacturer's prescribed routine.
(3) Set instrument zero using dry nitrogen as the zero gas.
(4) Using previous gain setting, check calibration curves using calibration gas with nominal concentrations of 30, 60, and 90% of each range used. Use the same gas flow rate through instruments during calibration as when sampling exhaust. Any response value differing from the previous value by more than ±3% of the previous value at the same gain setting may reflect some problem in the instrument system, and a thorough instrument check should be made. Confirm or reestablish calibration curves for each range. Record gain setting and zero setting of the instrument.
(5) Check Response of interference gases as called out in 4.1.3. If unacceptable, determine cause and correct -- detector replacement may be indicated.

5.1.2 Daily Routine

(1) If analyzer power is not left on continuously, allow 2 hrs. for warmup. (If daily use is anticipated, it is recommended that analyzer be left on continuously).
(2) Clean or replace filters.
(3) Check instrument for leaks.
(4) Check detector tuning and record reading. If the reading changes by more than ±3% from the previous value, instrument readjustment is indicated. For the following tests the temperatures of zero gas, span gas and sample gas in the instrument cells shall be similar, and gas-flow rates through the instruments shall be the same for zero and span gas as for sample gas.
(5) Zero the instrument on dry nitrogen. If there is a significant change in setting of zero control from the previous value, determine the cause and correct.

5.1.2 (Continued)

(6) Using span gas to give 75 to 95% full-scale deflection, check the response of the instrument on each range using the gain setting from the previous use. If the reading differs from the previous value by more than 3%, an instrument problem may be indicated. Check and correct as necessary. If instrument reading is within ±3% of previous value, adjust gain control to produce proper instrument output.

(7) Check zero with dry nitrogen and repeat step 6 if necessary. Log gain setting and zero setting after final adjustment

(8) Zero and span shall be checked before and after each test.

5.2 Total Hydrocarbon Analyzer:

5.2.1 Initial Alignment:

5.2.1.1 Optimization of Detector Response:

(1) Follow manufacturer's instructions for instrument startup and basic operating adjustment. Unless otherwise recommended by the manufacturer, fuel shall be 60% helium, 40% hydrogen containing less than 1 ppmC hydrocarbon. Air shall be "hydrocarbon-free" grade containing less than 1 ppmC hydrocarbon.

(2) Set oven temperature at 160 ± 5°C (320 ± 9°F) and allow at least 1/2 hr. after oven reaches temperature for the system to equilibrate. The temperature is to be maintained at set point ±2°C (±3.6°F).

(3) Introduce a mixture of propane in air at a propane concentration of about 500 ppmC. Vary the fuel flow to burner and determine the peak response. A change in zero may result from a change in fuel flow; therefore, the instrument 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.

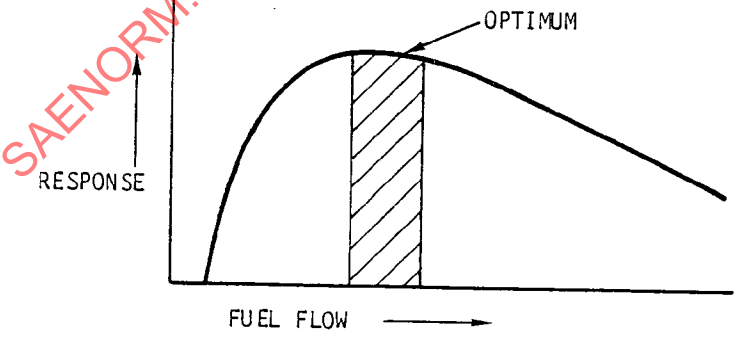

Figure 1 Fuel Flow Response Curve

(4) To determine the optium air flow, use fuel flow setting determined above and vary air flow. A typical curve for response versus air flow is shown below:

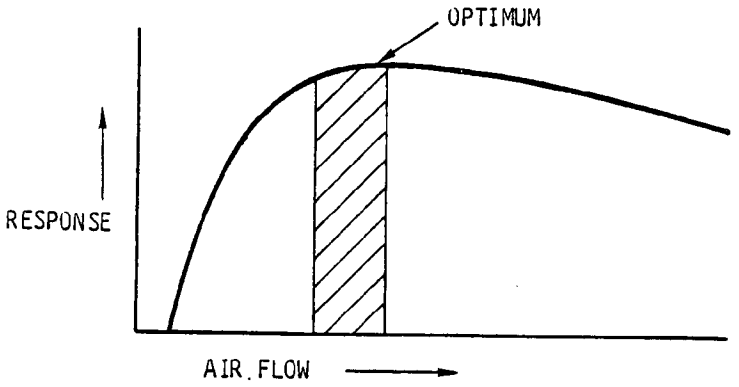

Figure 2 Air Flow Response Curve

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

5.2.1.2 Oxygen Synergism Effect: 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 5.2.1.1.

(1) Introduce nitrogen (N_2) zero gas and zero the analyzer. Check zero using hydrocarbon-free air. The zero should be the same.

(2) The following blends of propane shall be used to determine the effect of oxygen (O_2) in the sample:

Propane in 10 ± 1% O_2, balance N_2.

Propane in 21 ± 1% O_2, balance N_2.

The volume concentration of propane in each mixture should be about 500 ppmC, and the concentration of both the O_2 and propane should be known within ±1% of the absolute value. The zero should 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 response to propane in 10% O_2.

If this specification cannot be met by changing the sample flow rate or burner parameters, such as air and/or fuel flow rate, it is recommended that the detector be replaced.

5.2.1.3 Linearity and Relative Response:

(1) With analyzer optimized per 5.2.1.1, the linearity of each analyzer range shall be checked by applying propane in air samples at concentrations of approximately 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 ±2% of the full scale value. If it does a calibration curve shall be prepared for operational use.

(2) 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 ±1% of the absolute value. If the difference in response to any of these with respect to propane is greater than 5%, check instrument operating parameters. Reducing sample flow rate improves uniformity of response.

5.2.2 Preparatory Routine: These checks are to be made prior to the testing program:

(1) Check instruments for leaks.

(2) Check and optimize burner flows (air and fuel) as required by criteria of 5.2.1.1.

(3) Check O_2 effect as outlined in 5.2.1.2.

(4) Check responses of propylene, toluene, and n-hexane as outlined in 5.2.1.3.

(5) Check linearity as outlined in 5.2.1.3.

5.2.3 Daily Routine:

(1) Clean or replace filters.

(2) Check instrument for leaks.

(3) Check instrument temperatures.

(4) Ascertain that all flows to detector are correct.

(5) Check zero with zero air as defined in 6.3.

(6) Using span gas blends of propane in air to give 75 to 95% full-scale deflection, check the response of the instrument on each range using the gain setting from the previous use. If the reading differs from the previous value by more than ±3%, an instrument problem may be indicated. Check and correct as necessary. If instrument reading is within ±3% of previous value, adjust gain control to produce proper instrument output.

(7) Check zero with zero air and repeat step 6 if necessary. Record gain setting and zero setting after final adjustment.

(8) Zero and span shall be checked before and after each test.

5.3 Chemiluminescence Analyzer: Follow the instrument manufacturer's instructions for startup of instrument.

5.3.1 NO_x Converter Efficiency Check: Check the NO_x to NO converter efficiency by the following procedure. Use the apparatus described and illustrated below:

(a) Attach the NO/N_2 supply (150-500 ppm NO) at C_2, the O_2 supply at C_1, and the analyzer inlet connection to the efficiency detector at C_3. 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_x 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. 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 NO_x 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 step (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 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 NO_2. 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:

$$\% \text{ Eff.} = \frac{(e) - (d)}{(f) - (d)} \times 100\%$$

The efficiency of the converter should be greater than 90%. Adjusting 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 instrument is used.

(i) It is recommended, as consistent with good practice, that the measured NO_x value be adjusted as shown in 11.4 to take into account the converter efficiency.

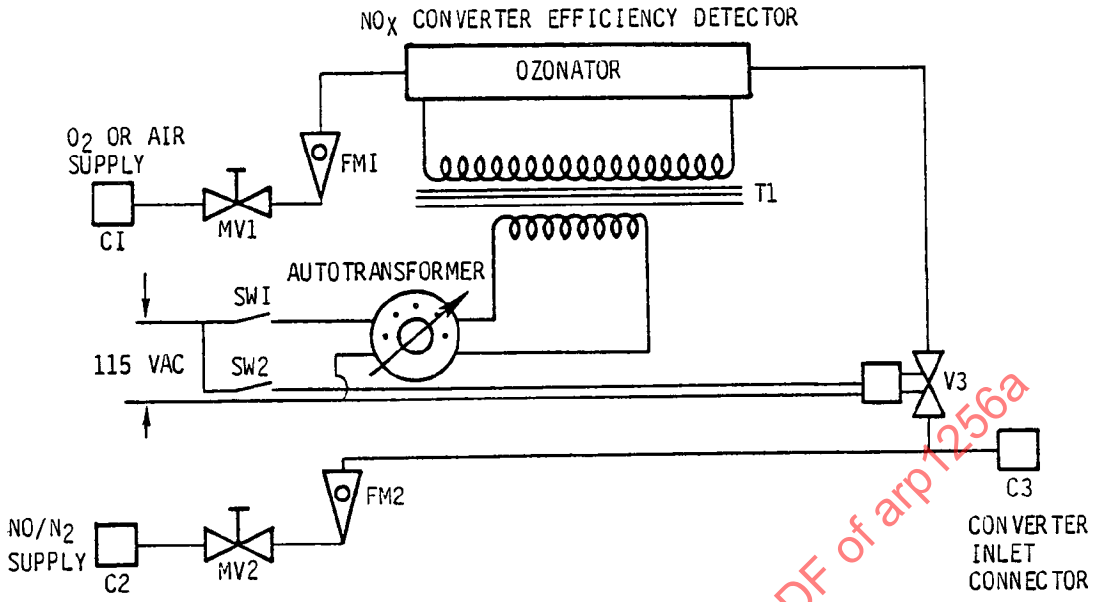

Figure 3 Typical NO_x Converter Efficiency Detector

5.3.2 Linearity: The instrument linearity shall be checked on all working ranges using calibration gases at concentrations of approximately 0, 30, 60, and 90% of full scale. The maximum response deviation of any of these points from at least squares straight line (fitted to the points and the zero reading) shall not exceed ±2% of the full scale value. If it does a calibration curve shall be prepared for operational use.

5.3.3 Preparatory Routine: These checks are to be made prior to the testing program:

(1) Check instrument for leaks.

(2) Adjust analyzer to optimize performance.

(3) Conduct NO_x converter efficiency check as outlined in 5.3.1.

(4) Check linearity as outlined in 5.3.2.

5.3.4 Daily Routine:

(1) Clean or replace filters.

(2) Check instrument for leaks.

(3) Check temperatures of instrument and NO_x converter if applicable.

(4) Ascertain that all flows to detector are correct.

(5) Check zero with zero gas as defined in 6.3.

5.3.4 (Continued)

(6) Using span gas blends to give 75 to 95% of full-scale deflection, check the response of the instrument on each range using the gain setting from the previous use. If the reading differs from the previous value by more than ±3%, an instrument problem may be indicated. Check and correct as necessary. If instrument reading is within ±3% of previous value, adjust gain control to produce proper instrument output.

(7) Recheck zero and repeat step 6 if necessary. Record gain setting and zero setting after final adjustment.

(8) Zero and span shall be checked before and after each test.

6. CALIBRATION CASES

6.1 Mixture Composition: Calibration gases for carbon monoxide and carbon dioxide shall be prepared using zero nitrogen as the diluent. They may be blended singly or as dual component mixtures. Three component mixtures of CO, CO_2 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. Hydrocarbon calibration gas shall be propane in zero air.

6.2 Calibration Gases and Span Gases: Calibration gases and span gases shall be certified by the vendor to a stated accuracy within ±2%. Note, that the gases referred to in 5.2.1.2(2) and 5.2.1.3(2) have a required accuracy of ±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 CO, 100 ppm CO_2 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 ppmC hydrocarbon, 1 ppm CO, 100 ppm CO_2 and 1.0 ppm NO_x.

7. INSTRUMENT LAYOUT

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

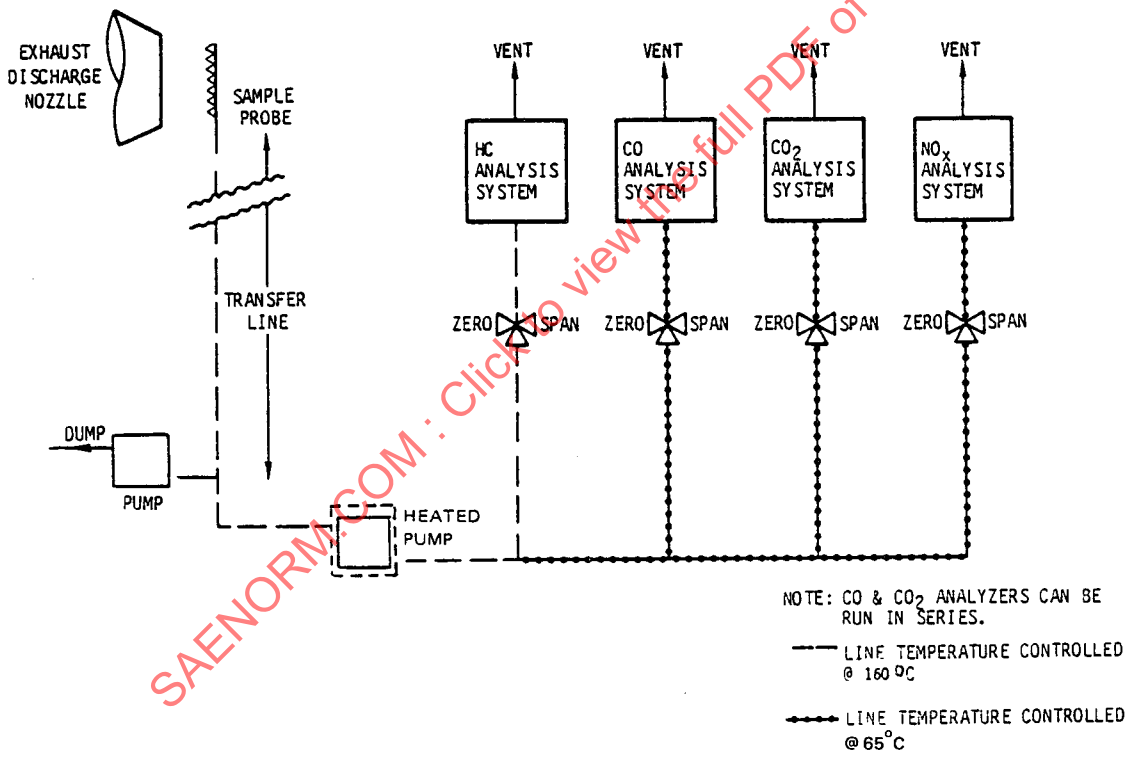

Figure 4 Sampling System and Instrument Arrangement

8. TEST PROCEDURE

(1) Check the sampling system for any leaks that could dilute the exhaust gas.

(2) Check the sampling lines to ensure that they are free from contamination.

(3) Check the sample transfer time from the probe to the analyzers. (See Sec. 9.2.)

(4) Calibrate instruments following the daily procedures.

(5) Start sample flow to analytical instruments.

(6) Measurements can now be made following any desired engine mode schedule. Characteristic engine stabilization patterns should 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 load up the sampling system. Back-purging the sampling lines when emissions are not being measured is good practice.)

(7) Readings should be taken using the appropriate range after the engine and instrumentation system have stabilized.

(8) During the testing sequence, recheck the zero and span of each instrument at intervals not greater than one hour. If either has changed by more than ±2% of full scale, from previous check, that portion of the test must be rerun.

9. SAMPLING

9.1 Sampling Probe:

9.1.1 Probe Design Concept: The probe shall be made of stainless steel. If a mixing probe is used, all sampling holes shall be of equal diameter and total probe orifice area shall be such that at least 80% of the pressure drop through the probe assembly (from free stream to probe outlet) shall be taken at the orifices.

9.1.2 Probe Orientation and Sampling Location:

9.1.2.1 A minimum of twelve sampling points shall be used. Either mixing or individual probes are acceptable.

9.1.2.2 The axial location of the sampling plane shall be as close to the plane of the exit nozzle as engine performance parameters permit but in any case shall be held within 0.5 exit nozzle diameter of the exit plane.

9.1.2.3 The sampling points shall be arranged over the exhaust nozzle exit area for straight turbojet, turboprop, turboshaft, and mixed flow (or confluent flow) fan engines, and over the core nozzle exit area for nonmixed fan engines.

9.1.2.4 In order to promote uniformity of emission measurements, a specific probe design should be standardized for use with a given type or series of engines. It must be shown, by means of detailed traverse measurements in the exhaust plane, that this probe design provides a representative emission sample.

9.1.2.5 As a test of representative sample collection, the average fuel air ratio shall be calculated from the emissions measurements by a carbon balance method as described in Sec. 11. This fuel air ratio shall be compared with the value obtained from fuel flow and air flow data. The two values must agree within 15% at idle and 10% at higher power settings. Fuel flow and emissions measurements should be taken at the same time. Air flow data preferably are from direct measurement but if such measurement is impractical, the data may be taken from air consumption curves generated for the particular engine model under test, corrected to actual temperature and pressure conditions. Total air flow shall be used for straight turbojet, turboprop, turboshaft, and mixed flow fan engines. Core air flow shall be used for nonmixed flow fan engines. This test for representative sample shall be conducted at each power setting specified in the test sequence.

9.2 Sample Transfer: The sample shall be transferred from the probe to the analytical instruments through a heated sample line of either stainless steel or PTFE (Polytetrafluoroethylene). Sample line inside diameter shall be 4.0 to 8.5 mm (0.16 to 0.33 in.). The line temperature for the sampling probe entrance to the instrument system connection shall be maintained at 160 ± 15°C (320 ± 27°F) except for the distance required to cool the gas from the engine exhaust temperature to the line temperature. The line temperature shall be maintained with a stability of ±10°C (±18°F) during the period of measurement.

Line temperature from the instrument system connection to the various analyzers shall be as follows:

(1) To hydrocarbon analyzer	160 ± 15°C (320 ± 27°F)
(2) To CO and CO_2 analyzers or to optional drying device	65 ± 15°C (149 ± 27°F)
(3) To NO_x analyzer	65 ± 15°C (149 ± 27°F)

Line temperature from optional drying device to CO and CO_2 analyzers shall be maintained at least 10°C (18°F) above the sample dew point.

The sample flow rate and the line length shall be such that the measured or calculated sample transport time from probe to instruments is less than 10 sec. If desired, a dump pump (Fig. 4) may be used to reduce the transport time.

10. INFORMATION AND DATA TO BE RECORDED

10.1 Information

10.1.1 General:

(a) Facility performing test
(b) Date of test
(c) Description of test equipment
(d) Probe location as determined in 9.1.

10.1.2 Aircraft Description (if applicable):

(a) Manufacturer
(b) Model Number
(c) Serial Number
(d) User or Operator
(e) Engine Installation Position

10.1.3 Engine Description:

(a) Manufacturer
(b) Model Number
(c) Engine configuration/special configuration identification
(d) Time since overhaul and other pertinent maintenance information

10.2 Test Data: At least the following shall be recorded:

(a) Engine power setting and rotor speed(s)
(b) Date, time of day and data point number
(c) Ambient conditions (barometric pressure, temperature, humidity) at beginning and end of test
(d) Fuel flow rate
(e) Fuel type, fuel additives (if used), fuel hydrogen/carbon ratio
(f) Engine air flow and method of determination
(g) Exhaust gas pressure and EPR
(h) Sample line temperatures and flow rate
(i) For each analytical instrument:
    (1) Full scale range (of ranges used)
    (2) Zero pot setting
    (3) Span pot setting
    (4) Span gases used and instrument response

(j) In addition for the hydrocarbon analyzer:
    (1) Detector air flow
    (2) Detector fuel flow
    (3) Oven temperature
    (4) Sample flow and/or sample inlet pressure

(k) Description of sample dryer (if used)

11. CALCULATION OF RESULTS

11.1 Results to be Reported: If single point probes are used, the number to be reported (for each component) shall be the arithmetic average of the values obtained at each sampling point.

If multipoint probes are used, the number to be reported shall be the average of the values of the several probes, giving each probe a weighting factor equal to the number of sample points in that particular probe.

Results shall be reported:

(1) In terms of the volume concentrations as measured of CO, CO_2, NO and NO_x, and of hydrocarbon (HC) expressed as (C_1H_n) equivalent.

(2) In terms of the Fuel-air Ratio (F/A), namely, the ratio of the fuel flow to the relevent air flow (see 9.1.2.5) (a) calculated from the gas analytical measurements and (b) calculated from engine air and fuel flow measurements or estimates.

(3) In terms of Emission Index (EI), namely, the mass of each emission produced in grams per kilogram of fuel (lb per 1000 lb. of fuel).

11.2 Symbols and Suggested Values:

[CO] = mole fraction concentration of CO in exhaust

[CO_2] = mole fraction concentration of CO_2 in exhaust

11.2 (Continued)

[HC] = mole fraction concentration of hydrocarbon in exhaust, expressed as (C_1H_n) equivalent = ppmC/10^6

[H_2O] = mole fraction concentration of H_2O in exhaust

[NO] = mole fraction concentration NO in exhaust

[NO_2] = mole fraction concentration of NO_2 in exhaust

[NO_x] = mole fraction concentration of NO_x in exhaust

[z] = mole fraction concentration of constituent z in exhaust

EI_z = Emission Index of constituent z, g/kg fuel (lb/1000 lb. fuel)

F = mass rate of fuel usage, kg/h (lb/hr)

F/A = fuel-air ratio

h = humidity of inlet air, moles of water vapor per mole of dry inlet air

h_{sd} = humidity of exhaust sample leaving optional CO/CO_2 dryer, moles of water vapor per mole of dry sample gas

K = ratio of wet concentration to completely dry concentration

K_{sd} = ratio of completely dry concentration to semi-dry concentration (after optional CO/CO_2 dryer)

L = interference coefficient for effect of CO_2 on CO

L' = interference coefficient for effect of CO_2 on NO/NO_x

M = interference coefficient for effect of H_2O on CO

M' = interference coefficient for effect of H_2O on NO/NO_x

m,n = molecular constants for fuel, C_mH_n (see 11.5)

M_{AIR} = molecular weight of dry air = 28.965

M_C = atomic weight of carbon = 12.011

M_H = atomic weight of hydrogen = 1.008

M_N = atomic weight of nitrogen = 14.0067

M_O = atomic weight of oxygen = 15.9994

M_z = molecular weight of constituent z

N_2' = sum of nitrogen (N_2) and argon (A) in inlet air

P_T = total moles of exhaust products (Equations 5 and 16)

P_z = moles of exhaust constituent z per mole of fuel (Equation 5)

11.2 (Continued)

R = mole fraction of O_2 in dry inlet air = 0.20948

S = mole fraction of nitrogen plus argon in dry inlet air = 0.79020

T = mole fraction of carbon dioxide in dry inlet air = 0.00032

w_z = mass emission rate of constituent z, kg/h (1b/hr)

x, y = molecular constants for exhaust hydrocarbons, $C_x H_y$

X = moles of dry air/mole of fuel

Z = parameter defined in Equation 27

α = (atomic) hydrogen-carbon ratio of fuel = n/m

η = NO_x converter efficiency

Subscripts:

c = corrected value

d = completely dry basis

ms = measured value

sd = semi-dry basis

w = wet basis

z = constituent z

11.3 Interference Corrections: CO_2 and water vapor in the exhaust product may cause interference effects on the CO and NO_x readings.

For CO:

$$\left[CO\right]_c = \left[CO\right]_{ms} + L\left[CO_2\right] + M\left[H_2O\right] \quad (1)$$

For NO or NO_x:

$$\left[NO_x\right]_c = \left[NO_x\right]_{ms}\left(1 + L'\left[CO_2\right] + M'\left[H_2O\right]\right) \quad (2)$$

where L, L', M and M' are interference factors to be determined by experiment or from the vendor.

For normal NDIR instruments, the values of L and M will be negative.

If the CO sample is dried before analysis, the interference from water vapor usually becomes negligible.

11.4 Converter Efficiency Correction: The NO_x value should be corrected for the NO_x converter efficiency, η, according to the equation:

$$\left[NO_x\right]_c = \left[NO\right]_{ms} + \frac{1}{\eta}\left[NO_2\right]_{ms} \quad (3)$$

where

$$\left[NO_2\right]_{ms} = \left[NO_x\right]_{ms} - \left[NO\right]_{ms} \quad (4)$$

11.5 Combustion Equation: The chemical equation for the combustion of hydrocarbon fuel and air is:

$$C_mH_n + X\left[R(0_2) + S(N_2') + T(CO_2) + h(H_2O)\right]$$

$$= P_1(CO_2) + P_2(N_2') + P_3(O_2) + P_4(H_2O) + P_5(CO)$$

$$+ P_6(C_xH_y) + P_7(NO_2) + P_8(NO) \quad (5)$$

In this equation it is assumed that dry air consists of O_2, N_2, Ar and CO_2, and

$$R + S + T = 1 \quad (6)$$

Suggested values for R, S and T are:

R = .20948
S = .79020
T = .00032

The value for S includes the sum of nitrogen and argon. This may be broken down into .78084 moles of nitrogen plus .00936 moles of argon. During the chemical reaction, the number of moles of argon remains unchanged.

The suggested value for the molecular weight of dry air, M_{AIR}, is 28.965.

Since the composition of the hydrocarbons in the exhaust (C_xH_y) is not usually known, it should be assumed that x = m and y = n for the final calculations. However, most of the equations in Sec. 11.7 are the result of the generalized solution. Whenever the above assumption is made, it is so indicated.

Suggested values for the carbon number of the fuel, m, are as follows:

Jet B and JP-4	9.5
Jet A and JP-8	12.5
JP-5	13

It should be assumed that x = m. The calculations indicated in Sec. 11.7 are very insensitive to the value of x so that the use of an approximate value is justified.

The characteristic hydrogen-carbon ratio of the exhaust hydrocarbon, y/x, also appears in the calculations and does have a significant effect on the results. It should be assumed that (y/x) = (n/m) = α. The hydrogen-carbon ratio of the fuel, α, should be determined by actual analysis.

The humidity of the inlet air, h, is expressed as moles of water vapor per mole of dry air. It is equal to the specific humidity (mass of water vapor per mass of dry inlet air) multiplied by (28.965/18.016).