Measurement of Emissions from Jet Engines in Altitude Test Cells

J. Lloyd Grissom*
ARO, Inc., Arnold Air Force Station, Tenn.

An instrumentation system for the measurement of selected exhaust emissions from jet engines operating under simulated flight conditions is described. The system is designed to function over a total pressure range of 2.5 to 40 psia at the exhaust exit plane, and at exhaust temperatures up to 3600°R. Species measured include CO, CO_2, Hydrocarbons, NO, NO_2, NO_x, SO_x, Water Vapor, and Particulate Matter. The system provides for redundant measurements of several species using different techniques, and a comparison of these measurements is included.

Introduction

ALTHOUGH jet engine operations constitute the source of only a small part of those emissions defined as "air pollution,"[1,2] the species, concentrations, and variations of these emissions with external variables such as altitude, Mach number and power setting is of considerable interest. Also, because jet engines operate a significant part of the time in a part of the atmosphere which is poorly understood in terms of chemistry,[3] considerable concern has been expressed over the possible detrimental effects of high altitude operations especially by supersonic aircraft and by other aircraft as well.

Since facilities for testing and operation of jet engines under realistically simulated flight conditions, and over a wide range of altitudes and Mach numbers already exist at Arnold Engineering Development Center (AEDC), it was quite logical that the AEDC should develop a capability for evaluation of engine emissions.

The system that will be discussed in this paper was developed to characterize the emitted concentrations of the pollutant components deemed most important to a study of the impact of an operating supersonic aircraft fleet upon the climate of the world. This evaluation program was conducted as a part of CIAP[4] (Climate Impact Assessment Program) for the Department of Transportation (DOT). Also, the Transportation System Center, DOT, participated in the development of the measurement systems, and furnished one of the particulate analysis systems. The system conceptual design was initiated in November 1971 and was first used in June 1972, in the Engine Test Facility's J-2 Test Cell at the AEDC.

Species Measured

Table 1 shows the constituents of the exhaust which the system was designed to measure. They comprised eight (8) unique species; CO, CO_2, Hydrocarbons, NO, NO_2, SO_x, H_2O and particulates. In addition, NO_x, which is actually the sum of NO + NO_2, was measured as a redundant species, permitting comparison with the sum of the NO and NO_2 measured values.

Both DOT and AEDC agreed that, as nearly as was practicable, the Society of Automotive Engineers Committee E-31 recommendations[5] would be followed, both as to analysis technique and gas sample conditioning. Table 1 lists the analysis techniques which were used. The SAE recommended techniques covered only CO (NDIR), CO_2 (NDIR), unburned hydrocarbons (FID), NO (NDIR or, provisionally, chemiluminescence) and NO_2 (NDUV). The remaining compounds of interest were measured using techniques which were judged to offer the most promise for our particular type of operation. These were NO_x (chemiluminescence) and SO_x (FPD), H_2O (capacitance membrane), and particulates by two methods—electrostatic grid for size distribution, and gravimetric filter for total weight per unit volume. Also, to permit comparisons with other analysis techniques which had been previously used in some ground level work at the AEDC two additional analyzers, NO_2 (electrochemical cell) and NO_x (electrochemical cell) were added.

In addition, since the gravimetric filter technique left much to be desired in terms of sample time, and requires much laborious hand work in evaluation of results, a particulates analyzer (piezoelectric mass change) which offered promise of continuous, instantaneous rate, particulate concentration was included in the system design.

Columns 2 and 4 of Table 1 list the specific manufacturers and model numbers of the equipment that was fi-

Table 1 AEDC engine emissions analyzer types and ranges.

CONSTITUENT	ANALYZER MFR. AND MODEL	ANALYSIS TECHNIQUE	FULL SCALE RANGES
CO	Beckman 315B	Non-Dispersive Infrared ▲	0-1500 PPM, 0-3000 PPM, 0-7500 PPM
	Beckman 315BL	Non-Dispersive Infrared ▲	0-50 PPM, 0-100 PPM, 0-500 PPM
CO_2	Beckman 315B	Non-Dispersive Infrared ▲	0-5%, 0-10%, 0-20%
Hydrocarbons	Beckman 402	Flame Ionization ▲	0-5, 0-25, 0-50, 0-250, 0-500, 0-2500, 0-5K, 0-25K ●
NO	TECO 10A	Chemiluminescence △	0-2.5, 10, 25, 100, 250, 1000, 2.5K, 10K
	Beckman 315BL	Non-Dispersive Infrared ▲	0-50, 0-150, 0-500
NO_2	Beckman 255BL ■■	Non-Dispersive Ultraviolet ▲	0-50, 0-150, 0-500
	Dynasciences NR-210	Electrochemical Cell	0-25, 0-75, 0-250
NO_x	TECO 10A	Chemiluminescence with Converter	0-2.5, 10, 25, 100, 250, 1K, 2.5K, 10K
	Dynasciences NX-130	Electrochemical Cell	0-100, 0-300, 0-1000
SO_x	Meloy SA-160R	Flame Photometric	0-10 PPMV
H_2O	Panametrics 1000	Variable Capacitance	-110°C to +60°C (6 Overlapping Ranges) Dew/Frost Point Temperature
Particulates	Thermosystems 3210B	Piezoelectric Mass Change	0-0.003, 0-0.03, 0-0.3, 0-3, 0-30, 0-300 milligrams/m^3
	Gelman & Millipore	Grav. Filters	
	DOT/TSD	Electrostatic Capture Grid	

● Each range can be further desensitized by a factor of up to 10, yielding a minimum sensitivity of 0-250K.

■■ A "borrowed" 255A was used for the early part of the program.

▲ Techniques specified by SAE ARP-1256.

Presented as Paper 72-1068 at the AIAA/SAE 8th Joint Propulsion Specialist Conference, New Orleans, La., November 29-December 1, 1972; submitted February 5, 1973; revision received May 16, 1973. The research reported in this paper was sponsored by Arnold Engineering Development Center (AEDC), Air Force Systems Command, Arnold Air Force Systems Command, Arnold Air Force Station, Tennessee. The results were obtained by ARO, Inc., contract operator of AEDC.

Index categories: Airbreathing Engine Testing; Thermochemistry and Chemical Kinetics; Atmospheric, Space, and Oceanographic Sciences.

*Group Supervisor.

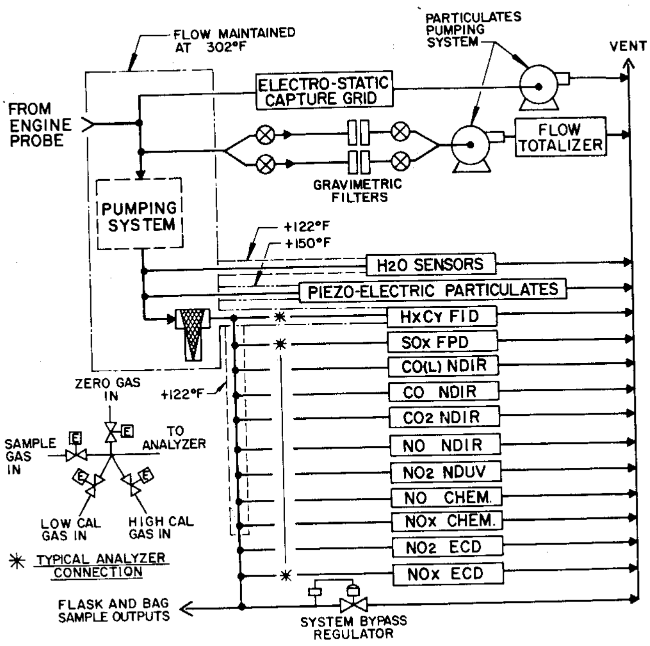

Fig. 1 System flow and thermal configuration.

nally chosen to implement the measurement concepts previously outlined. As may be seen from the table, considerable redundancy was employed. For CO, the wide variations expected in concentration over various flight conditions required the use of two instruments, having widely different sensitivities. The units are basically very similar, differing in optical path length of the sample and reference cells. The various full scale ranges of each of the analyzers is shown in column 4. In general, the CO, CO_2, and THC data were the most widely dispersed.

System Flow and Thermal Configuration

The essentials of the gas and particulate sample handling system, showing locations and general configuration of the entire emissions analyzer, is shown in Fig. 1. The sample system was divided into two parts upstream of the pumps, and one part was routed through the two particulates analyzers (gravimetric filter and electrostatic grid). A flow totalizer consisting of a positive displacement gas flow meter (Wet Test Meter) was used to total the flow that corresponded to the loading of the gravimetric filter. Two identical filter legs were used, one at a time, to expedite testing. The electrostatic grid was operated for a short period of time, just long enough to collect an adequate sample, at each test condition.

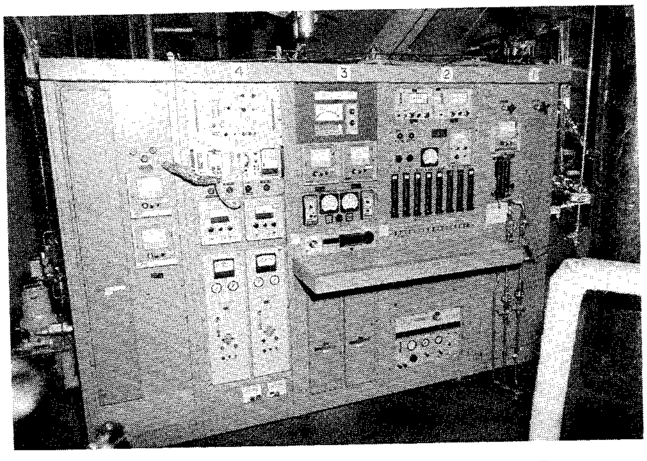

Fig. 2 Front view, emissions analysis console.

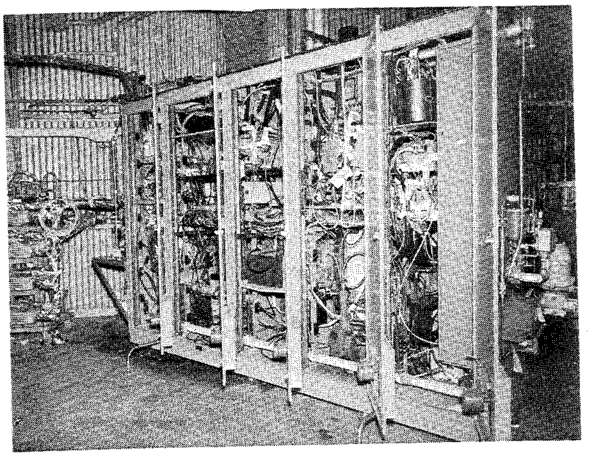

Fig. 3 Rear view, emissions analysis console.

The remaining part of the sample stream was pumped to a pressure of 1 psig by means of an external pumping system described in another paper[6] and a small portion (1 l/m) was passed through the piezoelectric microbalance particulates analyzer. Also, at this point in the flow system, the water vapor analyzer sensors were installed.

The remainder of the sample was filtered to remove all particulates, and passed through the various analyzers for determination of the level of the various gas species.

An automatic pressure controller was used to bypass and dump excess sample, holding the analyzer inlet manifold pressure constant within very close limits. Under all except the lowest engine exit plane total pressure conditions, the bypass flow was several times larger than was required for all of the analyzers, including particulates. The length and volume of the flow path from the analyzer inlet manifold to the analyzer inlet was kept to the minimum possible in order to further minimize lag time in the system.

The sample temperature was regulated in three zones. The entire sample was conditioned to 302°F from the engine probe to the hydrocarbon analyzer to prevent condensation of heavier hydrocarbon compounds. In addition, the sample stream leading to the piezoelectric particulates analyzer was conditioned to 150°F, and the water vapor sensor sample was conditioned to 122°F. The 302°F, the 150°F, and the 122°F systems consisted of hot water traced lines, with insulation and electrical heaters strategically applied over the tracing.

The system, of course, required the use of many valves, flowmeters, pressure and temperature monitoring devices, and related items which have not been mentioned here, and which are omitted from the figure for clarity.

One aspect of this system which is rather unique is the valving arrangement which allows a zero or either of two span gases to be applied to each analyzer, or to a single analyzer, by means of electrically operated valves. The arrangement for a typical analyzer is shown in Fig. 1.

Materials compatibility is, of course, a major consideration in such a system, since many of the species of interest are very easily destroyed. All materials in contact with the gases prior to analysis were either 316 stainless steel or Teflon.

Physical Arrangement

The entire emissions analysis system is contained within a 5-bay console. The console is mounted on casters and is approximately 120 in. W × 80 in. H × 24 in. D. Figure 2 is a front view of the console, and shows the location of individual analyzers within the console. Bay 1 contains the long path NDIR-CO analyzer, and the gravimetric filters. Bay 2 contains the ECD-NO_2, ECD-NO_x, and H_xC_y-FID

SPAN GAS	NOMINAL CONCENTRATION	ANALYZERS USED WITH
NO	40 PPMV	NO Chemiluminescence, NO-NDIR, NO_x-ECD
NO	100 PPMV	
NO_2	40 PPMV	NO_x Chemiluminescence, NO_2-NDUV, NO_2-ECD
NO_2	200 PPMV	
CO	40 PPMV	CO-NDIR (Low Range)
CO	400 PPMV	CO-NDIR (Low Range) CO-NDIR (High Range)
CO	3000 PPMV	CO-NDIR (High Range)
CO_2	2% V	CO_2 NDIR
CO_2	20% V	
* H_xC_y	50 PPMV	H_xC_y - FID
H_xC_y	500 PPMV	
SO_2	1 PPMV	SO_x -FPD
SO_2	10 PPMV	
Zero Gas	-	All Analyzers

*Methane

Fig. 4 Calibration gases and concentrations.

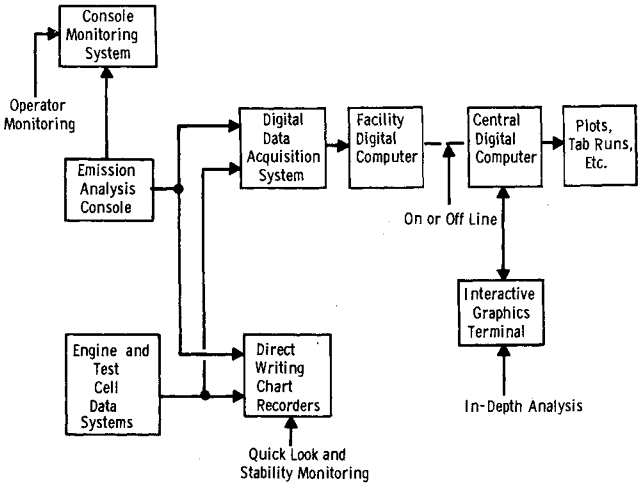

Fig. 5 Data recording and processing system.

analyzer. Bay 3 contains the H_2O analyzer, the high range NDIR-CO, and the NDIR-CO_2 analyzer. Bay 4 contains the FPD-SO_x analyzer, the piezoelectric particulates analyzer and the chemiluminescence NO and NO_x analyzers. Bay 5 contains the NDUV-NO_2 and the NDIR-NO analyzers.

Additionally the calibration and valve control systems are located in Bay 2, along with most of the individual analyzer flowmeters. The analyzer inlet manifold pressure control system controls are located in Bay 3, as is the analyzer output signal and temperature control system monitor station. The electrostatic grid particulates unit is located to the extreme right outside the enclosure.

A rear view of the console is shown in Fig. 3, which shows the amount of insulated tubing, control wiring, valves, and pumps that are required by the system. The bypass control valve is also visible in Fig. 3 at the extreme right (exterior of Bay 5).

Equipment not shown, but very necessary, is approximately 20 bottles of service and calibration gases which must be located nearby. These include the hydrogen-helium mixtures and hydrocarbon free air for the FID (H_xC_y) analyzer, oxygen for the chemiluminescence analyzers, and hydrogen for the FPD (SO_x) analyzer, as well as the zero and calibration gases.

Calibration System

Gas analyzers require frequent recalibration if accuracy is to be maintained. The AEDC emissions analysis system has provisions for a three-step calibration for each analyzer, except for the water vapor and particulates analyzers.

The calibration gases chosen, and the analyzer(s) with which they are used, are shown in Fig. 4.

Since test time is the most important (and expensive) part of altitude testing, it was deemed necessary to automate the calibration of the analysis system. This was accomplished by designing a control system which individually, by means of a single console control, or simultaneously for all analyzers, applied either the zero, or the proper span gas (low or high span) to each analyzer. The individual mode was used for setup, adjustment, or checkout to conserve gas, and the simultaneous mode was used to conduct system calibrations.

Data Recording, Display, and Processing

The output of the analysis system consists of electrical signals, in addition to indicators located on the console itself. To permit assessment of the stability of the instruments (and the engine under test) graphic multichannel chart recorders located in the analysis area were used to monitor and record the console outputs. Additionally, a digital data acquisition system was used to record a short record (480 samples of each channel, over a 90-sec interval) at each condition where data were desired. Calibrations were similarly recorded using the calibration gases and system previously described. In general, the digitally recorded data were used for all processing and reduction, while the charts were used for stability determinations, system checks and tests, and for "quick look" purposes.

The facility computer complex, consisting of an SEL-810A, a Raytheon R-520, and an IBM 370/155, was used for processing of all data. The system permits off-line correction for zero shifts, removal of interference related errors, and graphic plotting of the data in many selectable formats, such as concentration vs probe position, fuel flow, altitude, or combinations of these. A block diagram of the system, illustrating the salient features is shown in Fig. 5.

Systems Test and Results

Both prior to the engine phase of the test program, and after completion, validation tests were conducted to identify and confirm various real and possible problems.

The tests which involved the behavior of the sample handling system (i.e., probe sample lines, pumps, and materials compatibility) are described in another paper.[6] In

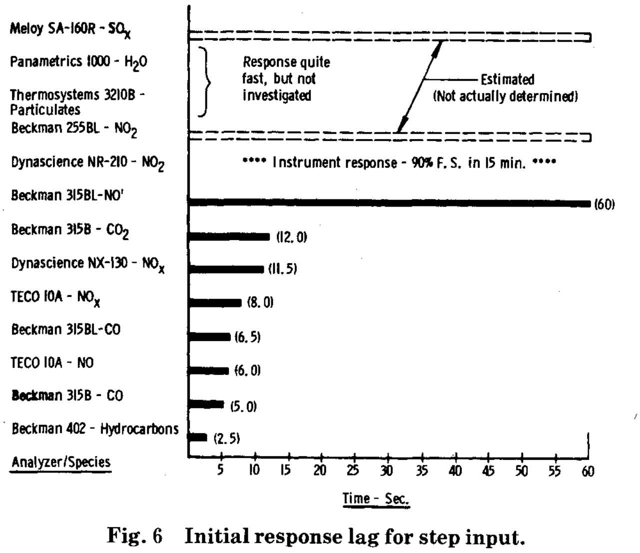

Fig. 6 Initial response lag for step input.

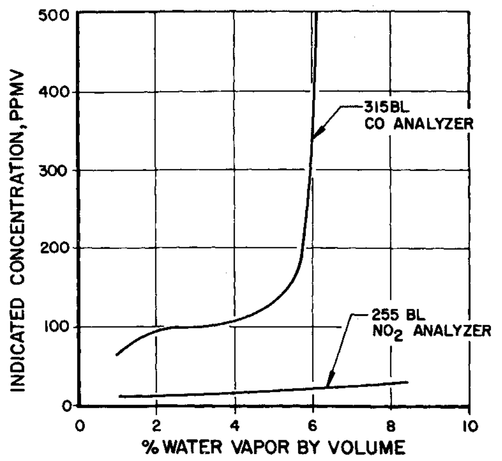

Fig. 7 H_2O-interference, NO_2-NDUV and CO, NDIR (high sensitivity) analyzers.

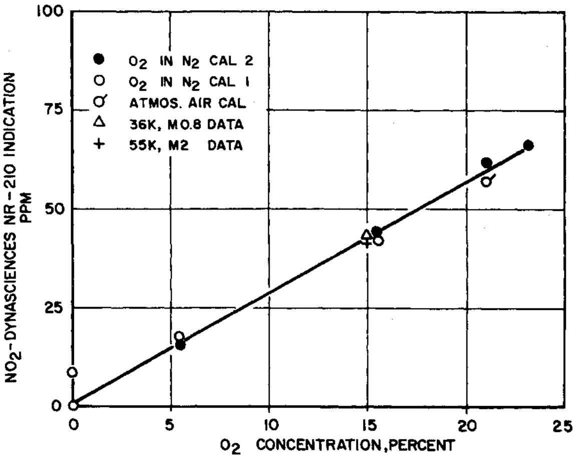

Fig. 8 O_2 interference-NO_2 analyzer.

addition, several tests were made to determine pertinent characteristics of the instrumentation system. These included time response, thermal stability (effects of sample temperature, as well as console ambient temperature), effect of sample pressure and flowrate variations, and the response of various analyzers to various interfering gases.

Time Response Characteristics

As expected, wide variation in analyzer lag time was noted, and is shown in Fig. 6. In general, these results were very close to manufacturer's quoted times, with allowances for the particular sample handling system configuration employed. As is evident, some of the analyzer lag times are not wholly compatible with altitude test cell time allowances and slowed the testing rate considerably.

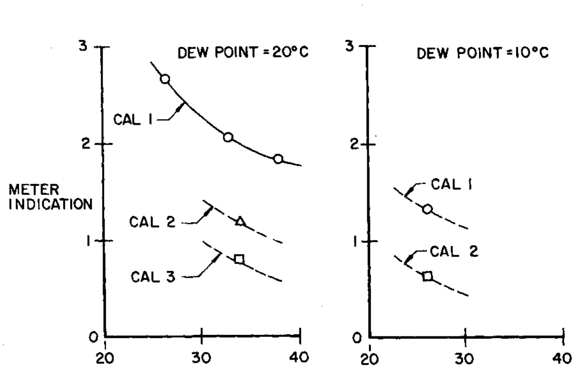

Fig. 9 H_2O analyzer calibration.

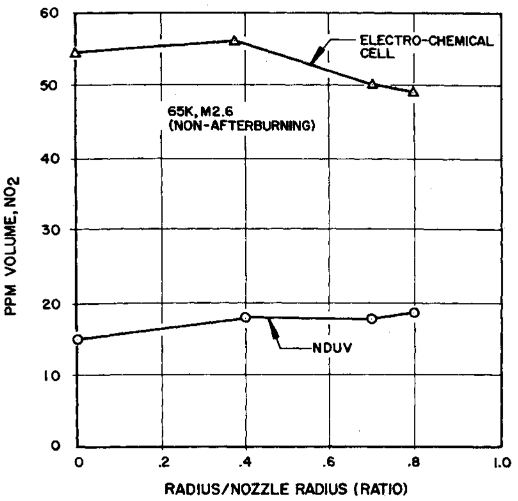

Fig. 10 Nitrogen dioxide concentration data.

Thermal Environmental Tests

The thermal environmental tests produced the rather pleasant result that, within reasonable limits of sample conditioning system performance (±10°F) and for reasonable ambient temperatures (80 + 10°F), no temperature effects exceeding 1% of expected range were found.

Sample Pressure and Flowrate Variation Tests

Variations in the sample manifold pressure and flowrates likewise had little effect on system performance. It was necessary to maintain proper sample flow into those instruments which are flow sensitive; however, the indicators that are supplied as part of the instruments were deemed adequate and sufficiently precise to permit the correct flows to be determined and set.

Interference Tests

One of the most prevalent sources of error in gas analysis, especially in the use of optical instruments, is interferences from other gases which alter the readings produced by a constant concentration of the species of interest. To characterize these interferences, a series of tests

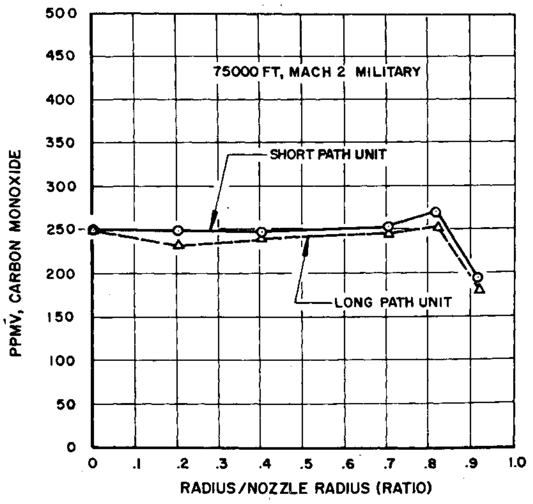

Fig. 11 Carbon monoxide concentration data.

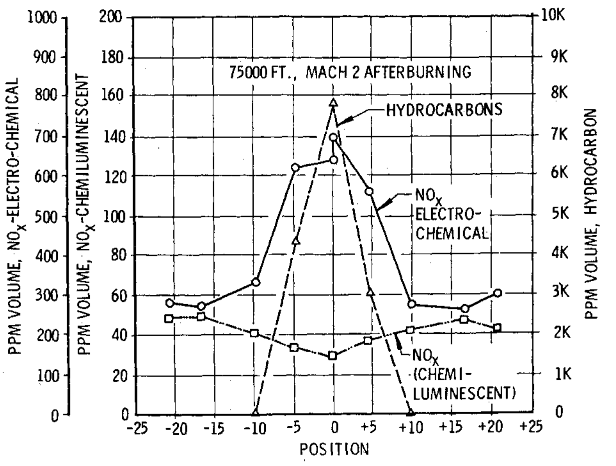

Fig. 12 Mixed oxides of nitrogen concentration data.

were made. The tests included the introduction of NO and NO_2 calibration gases to CO analyzers, and vice versa. All other combinations of gases and analyzers were also tested, and responses noted. Additionally, some indications were noted during the engine test phase which indicated a need for still other interference tests, involving species which were not of interest, such as O_2.

The results of these tests are summarized in Figs. 7 and 8.

As can be seen, water vapor interferences were found to be present for both the NO_2-NDUV and the CO-NDIR instruments. Water vapor concentrations are determinable by calculation, however, and corrections can be applied to the data once the amount of interference is determined.

Oxygen was found to be an interferent in the NO_2-Electrochemical analyzer. Since oxygen concentration varies quite markedly in jet engine exhaust, this interference was quite noticeable. Figure 8 shows the indication of the analyzer to zero ppm of NO_2 in varying concentrations of oxygen. Also shown in the figure is the indication obtained from two data points where oxygen concentration has been calculated from fuel-air ratio and engine data. These conditions were expected to produce very little NO_2, and this expectation is apparently realized, since the data falls almost directly upon the zero ppm line at the calculated oxygen concentration.

Another interference not illustrated was found in connection with the NO_x-Electrochemical analyzer. The introduction of acetylene from an unlighted torch was found to produce a severe overscale indication, from which the instrument did not recover for more than an hour. Data disagreements were also noted with this instrument, which suggest some hydrocarbon as an interferent. The species was not, however, identified.

The water vapor analyzer was subject to contamination, although this was not an interference in the strict sense of the word. The instrument did not hold calibration after exposure to exhaust products for any length of time as is shown in Fig. 9. Dry bulb temperatures were also very much a factor in this analyzer. The combination of contamination and dry bulb temperature sensitivity was such as to render the water vapor data unusable.

Data Comparisons

To illustrate the results produced by the differing techniques, Figs. 10–14 are presented. As may be seen, agreement obtained varies markedly with engine conditions and other species of gases. Hydrocarbon interferences are obvious in the data obtained from the Electrochemical cell (NO_x unit) at 75K, Mach 2 afterburning. Oxygen response is evident in the Electrochemical cell (NO_2 analyzer) at 65K, Mach 2.6. Some response to water vapor may also be indicated in the NDIR NO analyzer (Fig. 13). The NO + NO_2 sum as determined by the NDIR and NDUV analyzers correlated quite well with the NO_x data obtained from the Chemiluminescence analyzer. Figure 14 shows these values from the 65K, Mach 2.6 nonafterburning condition. Agreement at afterburning was somewhat poorer due to larger amounts of water vapor, but either technique will apparently yield acceptable results.

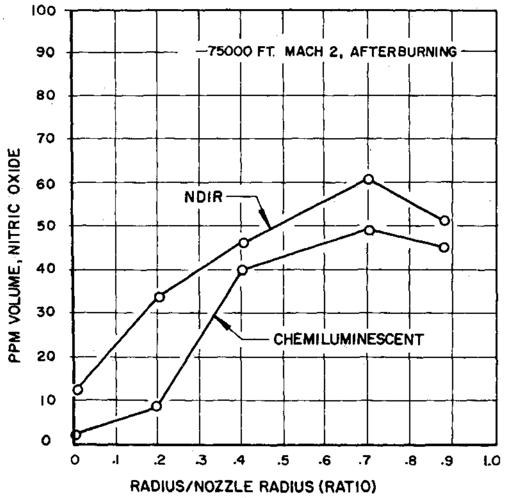

Fig. 13 Nitric oxide concentration data.

Conclusions

The acquisition of emissions data from jet engine operating at simulated flight conditions really is a science, not an art. Several problems are evident, however, and improvements in analyzer design and performance are needed. Recent discussions with manufacturers indicate their belief that some of the problems encountered in the use of the system described in this paper have been, or are in the process of being, overcome. Further testing and evaluation will be needed to verify this.

More study of the chemical processes associated with engine exhaust products is also needed. The sulfur oxide analyzer in this system seemed to perform well, but no oxides of sulfur were measured in the exhaust. Sulfuric acid was found in the gravimetric filter in small quantities, suggesting that perhaps the reaction $SO_x + H_2O \rightarrow$

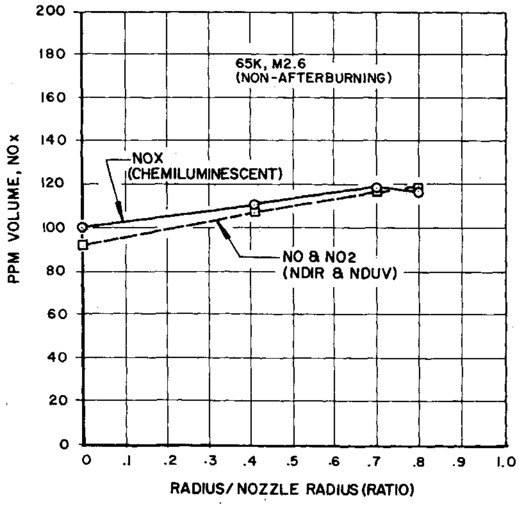

Fig. 14 Total oxides of nitrogen data.

H_2SO_4 is more rapid than had been expected for the sample handling system used.

Some of the analyzer types that were incorporated into the system described in this paper, although perhaps suited to ambient air monitoring, are not really suited to jet engine exhaust emissions work where varying and high levels of moisture, considerable particulates, and varying oxygen levels are encountered.

The instrument list specified by the SAE E-31 committee in ARP-1256 appears to have been a good selection at this particular time. However, it is hoped (and, indeed, expected) that significantly improved techniques and equipment will appear within the next few years.

Considerable work in the particulate analysis area is needed. The gravimetric and microscope techniques for particulate analysis are not very efficient and require large investments in time, equipment and skill; however, no suitable continuous analyzer for particulates is presently available.

References

[1]Northern Research and Engineering Corp., "Nature and Control of Aircraft Engine Exhaust Emissions," Rept. 1134-1, prepared for NAPCA, Dept. of HEW, Contract PH22-68-27, Nov. 1968.

[2]Secretary of HEW, "National Control of Aircraft Engine Exhaust Emissions," report of the Secretary of the United States Congress pursuant to PL 90-148, The Air Quality Act of 1967, Dec. 1968.

[3]"Chairman's Address: The DOT Climatic Impact Assessment Program," *Proceedings of the Survey Conference,* DOT-TSC-OST-72-13, Feb. 1972, Cambridge, Mass.

[4]"Preface," *Proceedings of the Survey Conference,* DOT-TSC-OST-72-13, Feb. 1972, Cambridge, Mass.

[5]"Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines," SAE Committee E-31, Aircraft Exhaust Emission Measurements, 1971, Society of Automotive Engineers.

[6]Neely, J. E., "Exhaust Emissions from a Supersonic Aircraft Gas Turbine Engine," AIAA Paper 72-1067, New Orleans, La., 1972.