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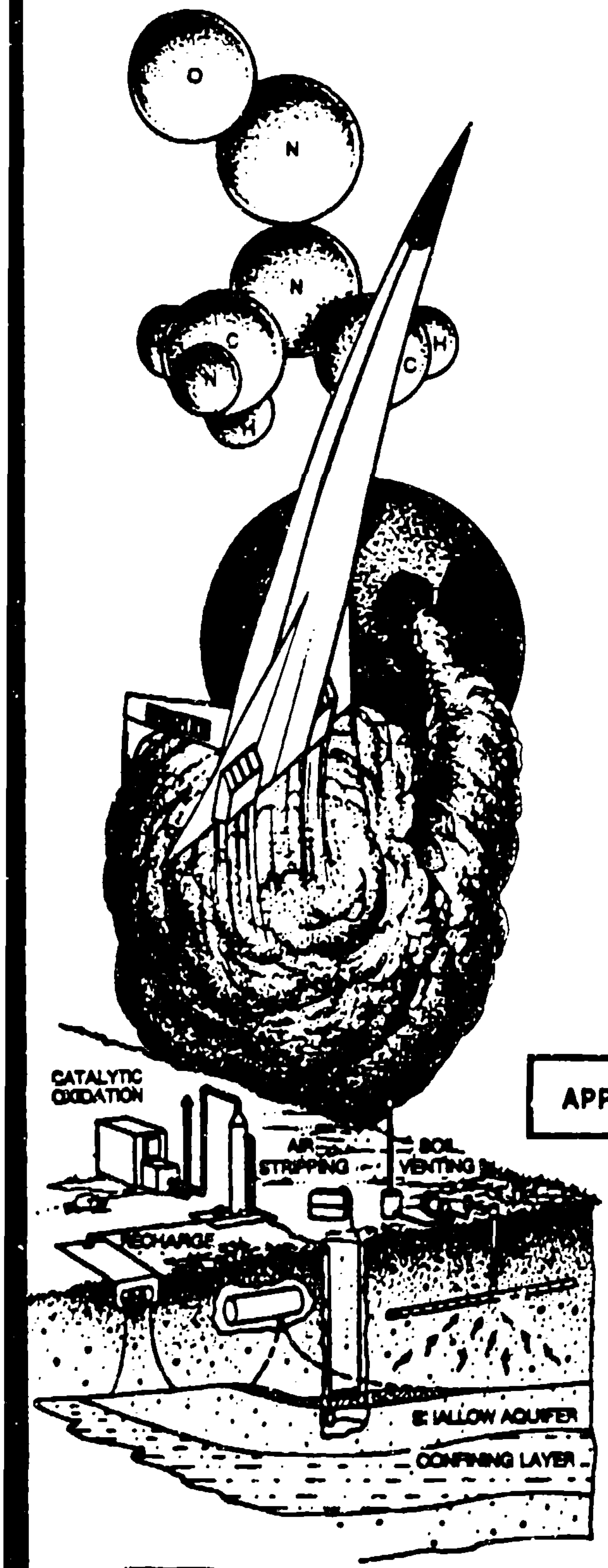

AIRCRAFT EMISSIONS CHARACTERIZATION: F101 AND F110 ENGINES

C.W. SPICER, M.W. HOLDREN, D.L. SMITH,
S.E. MILLER, R.N. SMITH, D.P. HUGHES

BATTELLE COLUMBUS DIVISION
505 KING AVENUE
COLUMBUS OH 43201-2693

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Assessment of the environmental impact of aircraft operations is required by Air Force regulations. This program was undertaken to quantify gaseous and particulate emissions associated with two Air Force turbine engines (F101 and F110). The emissions tests were carried out using a test cell at Tinker AFB, Oklahoma City, OK. All tests employed JP-4 as the fuel, and fuel samples were characterized by standard tests and analyzed for composition. Emissions were measured at five power settings for each engine. Detailed organic composition, CO, CO_2, NO, NO_x, smoke emissions, particle concentration, and particle size distribution were measured. A multiport sampling rake was used to sample the exhaust, and heated Teflon® tubing was used to transfer exhaust to the monitoring instrumentation. Measured and calculated fuel/air ratios were compared to assure representative sampling of the exhaust.

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MARK D. SMITH, Capt, USAF, BSC

22b. TELEPHONE *(Include Area Code)*
(904) 283-4234

22c. OFFICE SYMBOL
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The results have been used to calculate emission indices and emission rates for CO, CO_2, total hydrocarbons, NO, NO_2, and NO_x. The distribution of organic compounds in the exhaust from each engine and at various power settings has been compared, and the distribution by compound class and by carbon number are reported. Smoke numbers and particle size distributions have been derived from the test data. The report also contains a review of the emissions of selected toxic chemicals, and a comparison with other emission sources.

PREFACE

This report was prepared by Battelle Columbus Division, Columbus, OH 43201-2693 under Contract Number F08635-85-C-0122 for the Air Force Engineering and Services Center, Engineering and Services Laboratory (AFESC/RDV), Tyndall Air Force Base, FL 32403.

This final report describes the experimental methods and presents the results and interpretive analysis of the gas and particle composition of exhaust from two turbine engines. This work was performed between June, 1988 and March, 1989. The AFESC project officer was Capt. Mark Smith.

Principal research staff at Battelle included Messrs. M. W. Holdren, S. E. Miller, R. N. Smith, Ms. D. L. Smith, and Dr. C. W. Spicer. Assistance in conducting the program was provided by Dr. M. R. Kuhlman, Ms. J. C. Chuang, Dr. G. M. Sverdrup, Mr. M. K. Pence, Mr. G. D. Nichols, Mr. G. F. Ward, Mr. N. Russell, Ms. A. J. Osburn, and Ms. C. F. Dye. Engine testing at Tinker AFB was conducted with the cooperation and assistance of the Production Engine Test Section; we are especially grateful for the assistance provided by Mr. David Hughes. We are indebted to Mr. C. Martel of Wright Patterson AFB for the use of an automated Smoke Meter, and to the Naval Air Propulsion Center for the use of a sampling rake.

This report has been reviewed by the Public Affairs Officer (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

MARK D. SMITH, Capt, USAF, BSC
Project Officer

F. THOMAS LUBOZYNSKI, Maj, USAF, BSC
Chief, Environics Division

Wayne P. Chepren
WAYNE P. CHEPREN, Capt, USAF
Chief, Environmental Sciences Branch

Richard M Hanes
RICHARD M. HANES, Col, USAF
Director, Engineering and
Services Laboratory

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SECTION I

INTRODUCTION

A. OBJECTIVE

Assessment of the environmental impact of aircraft operations is required by Air Force regulations, and by federal, state, and local authorities. Information on the composition of exhaust emissions from aircraft engines is needed for such an assessment. The objective of this program is to quantify the gaseous and particulate emissions from two Air Force turbine engines.

B. BACKGROUND

During the 1970s, the Air Force conducted emission measurements to develop a data base of all known engine emission data. Emission data collected included smoke plume opacity and gaseous emission levels. An engine emission catalog was prepared and issued to environmental planners for use in determining environmental impacts of military aircraft operations. Since the catalog was last updated in 1978, the military has introduced new engines, and updated or modified existing ones to improve operating efficiency of their aircraft. Exhaust emission data are not available for all of these engines.

When the emission catalogs were compiled in the 1970s, federal, state, and local governments were mainly interested in the control of engine exhaust smoke and documentation of gaseous exhaust emission levels. Since then, these regulatory agencies have come to require much more information for environmental assessments. A joint Air Force/Navy program has been established to review all data currently available on military gas turbine engines still in the system, assess the validity of these data for current engine models, identify deficiencies in the data, and develop an updated engine emission data base. The purpose of this project is to conduct engine exhaust measurements to provide missing data and update the emissions catalogs. We have previously reported emissions measurements for the TF39 and CFM56 engines (Reference 1), the TF41-A2, TF30-P103, and TF30-P109 engines (Reference 2), and the TF33-P3, TF33-P7, and J79 (smokeless) engines (Reference 3).

C. SCOPE

This study was initiated to determine the gas and particle composition of exhaust from two turbine engines. These engines are F101 and F110. Tests were conducted using JP-4 fuel at five engine power settings. The nominal power settings used for the F101 engine were idle, 44 percent, 75 percent, intermediate (108 percent at high mach), and stage 1 augmentation. The F110 tests were run at nominal settings of idle, 30 percent, 63 percent, intermediate (105 percent at high mach), and Stage 1 augmentation. The exhaust sampling was carried out in an indoor engine test facility at Tinker AFB, Oklahoma City, OK. The sampling and analysis methods employed during this study were developed and validated previously (Reference 4), and used to determine the emissions from a TF39 and a CFM56 engine (Reference 1), TF41-42, TF30-P103, and TF30-P109 engines (Reference 2), and TF-P3, TF33-P7, and J79 engines (Reference 3).

SECTION II

EXPERIMENTAL METHODS

A. ENGINE TEST FACILITY

Engine emissions sampling was performed in two indoor test cells at Tinker Air Force Base, Oklahoma City, OK. The F110 engine was tested in Cell 11, while Cell 12 was used for the F101 tests. A diagram of a generic test cell is shown in Figure 1. The engine exhaust flows into a 15-foot 11-inch diameter cone and through an 84-foot long steel augmentor tube, the last 30 feet of which are perforated with numerous 1-1/4-inch holes. The perforated portion of the tube is contained in a separate "blast room" which is vented to the outside. The hot exhaust passes through the perforations and out of the blast room through fifty-six 3-foot diameter vent tubes in the ceiling of the blast room. The test cell is instrumented to record numerous engine performance parameters included in this report.

Figure 1 shows the position of the sampling probe at the inlet to the augmentor tube. This position was used for emission sampling at power settings from idle through intermediate. Measurements at the Stage 1 augmentation (afterburner) power level were done with a sampling probe mounted on one of the exhaust vents on the roof of the test cell, as shown in Figure 1.

B. EMISSIONS SAMPLING

For nonafterburner power modes, a 12-port sampling rake provided by the Naval Air Propulsion Center was used for exhaust emissions sampling. The rake is of cruciform design, with three 1/16-inch orifices spaced along each of the four 12.5-inch arms of the rake. The rake was bolted to adjustable steel arms clamped to the inlet cone of the augmentor tube. A schematic diagram of a test cell, including sampling apparatus, is shown in Figure 2. The rake mounting was adjustable, to allow the rake to be centered 1-2 feet behind the exhaust nozzle of each engine. The rake and associated sampling systems were moved from Cell 11 to Cell 12 between the F110 and F101 tests.

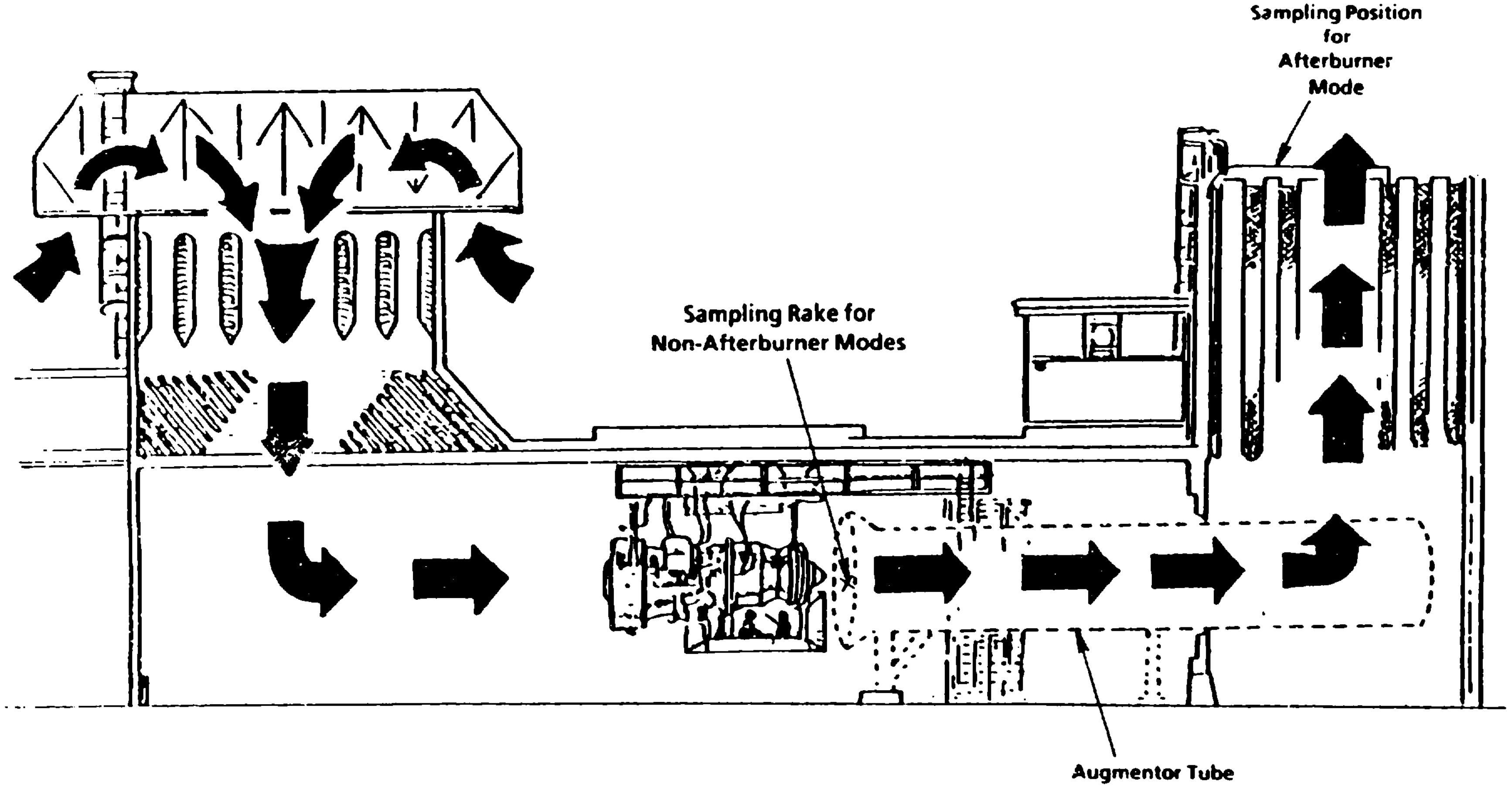

Figure 1. Test Cell Cross Section

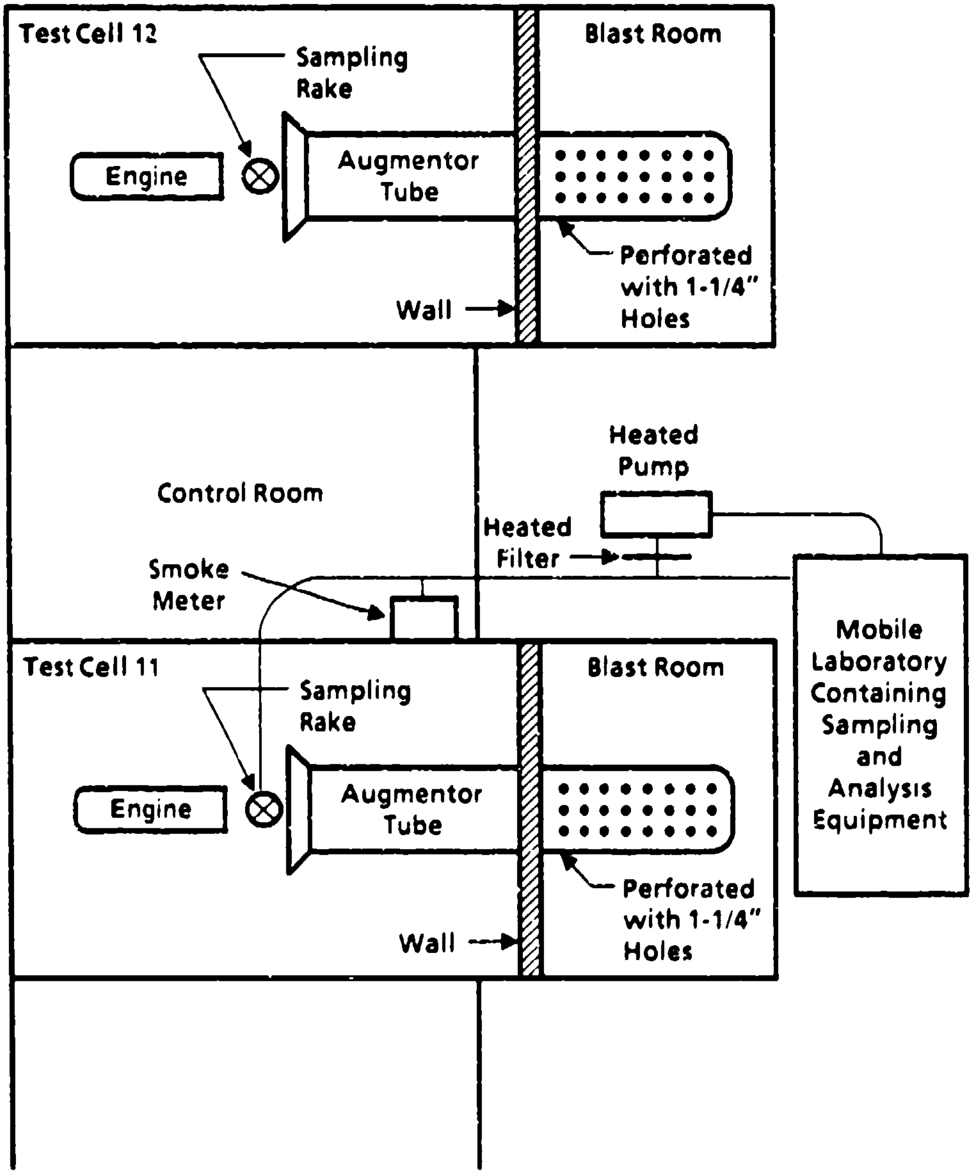

Figure 2. Schematic Diagram of Test Cells 11 and 12 (Top View), With Sampling Apparatus Connected to Cell 11

The sampling ports on the rake are internally connected to a common manifold. The sample lines in the rake head are stainless steel, and a common sample line passes down the support strut where it joins an electrically heated, flexible Teflon® line. At this point, the sample line was connected via a tee to a clean-air purge line and pumping station. A diagram of the sampling apparatus is included in Figure 3.

For augmented power (afterburner) measurements, exhaust samples were collected from one of the test cell exhaust vents located on the roof of the cell (see Figure 1). The sample probe used for afterburner measurements was a single stainless steel tube, facing into the exhaust vent and anchored to the test cell roof. This probe was connected to the heated pump and exhaust sampling system with 3/8-inch heated Teflon® tubing.

All afterburner emission measurements were made with Stage 1 augmented power. Higher afterburner power settings require augmentor tube cooling by water spray, and emission measurements were not practical under these conditions. A photograph showing the F110 engine operating under augmented power is shown in Figure 4. The exhaust plume is directed into the augmentor tube noted in Figure 1.

In addition to augmented power emission measurements, one rooftop sampling test was run with the F110 engine at intermediate power. This test was conducted to permit a comparison between data collected at the same power setting at the exhaust exit plane (by the rake) and the test cell vents (by the single probe).

The heated pumping station shown in Figure 3 contained a 6-inch diameter stainless steel filter holder coupled to a stainless steel metal bellows pump (Metal Bellows Corp. Model MB-601HT). A 75-foot length of heated 3/8-inch Teflon® tubing transferred the exhaust sample from the rake to the filter and pump. The pump directed the exit flow through 25 feet of heated 3/8-inch Teflon® tubing to a sampling manifold located in a mobile laboratory next to the test cell. The mobile lab is shown on-site next to Test Cell 11 in Figure 5. A tee in the sample line before the filter allowed a stream of hot, unfiltered exhaust to be transported directly to a diluter vessel in the mobile lab. The entire sampling system was maintained at 150°C. Each component of the system was interconnected via heated Teflon® lines. The stainless steel ball valves, tees, and manifolds were

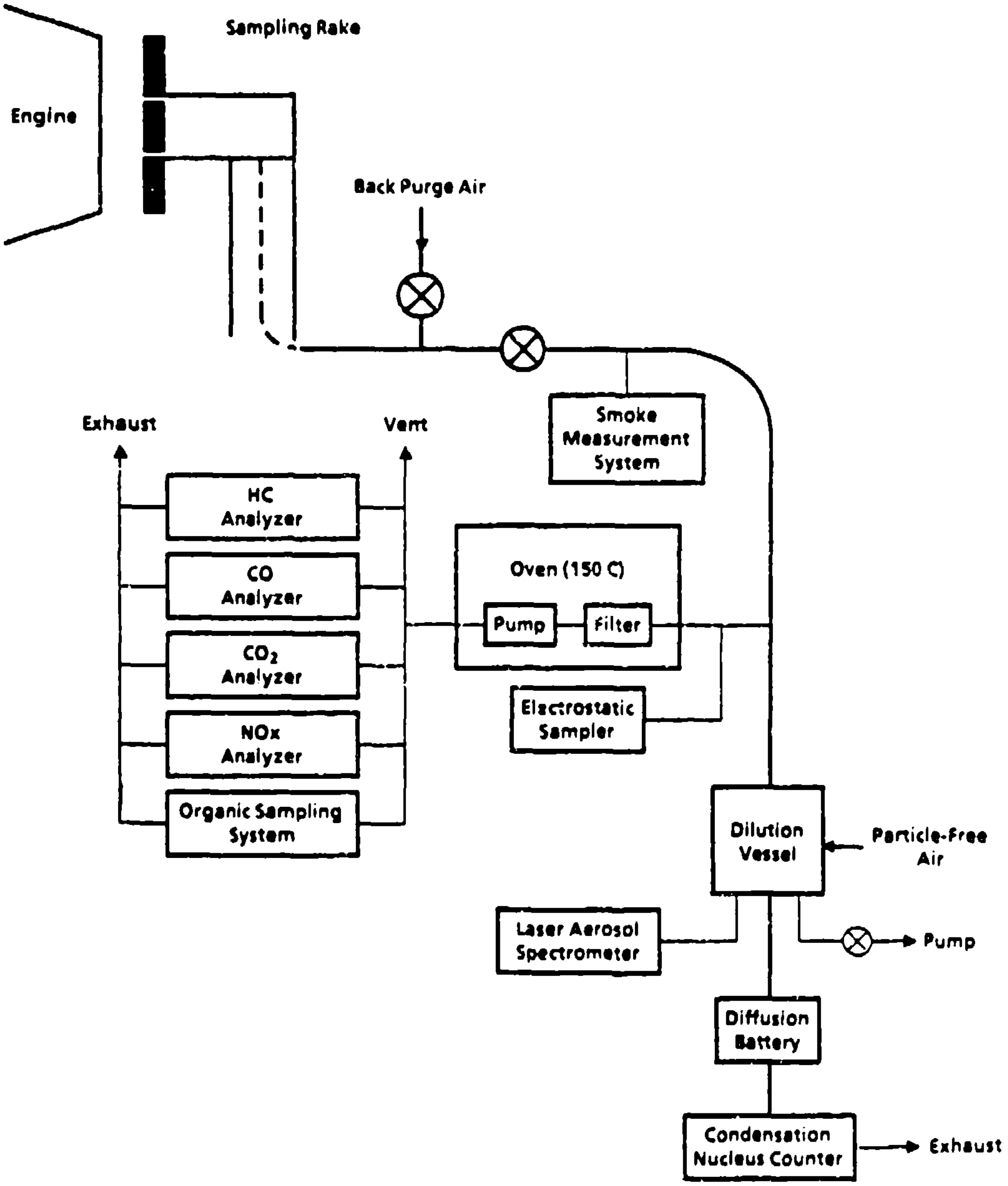

Figure 3. Schematic Diagram of Exhaust Sampling System and Measurement Apparatus

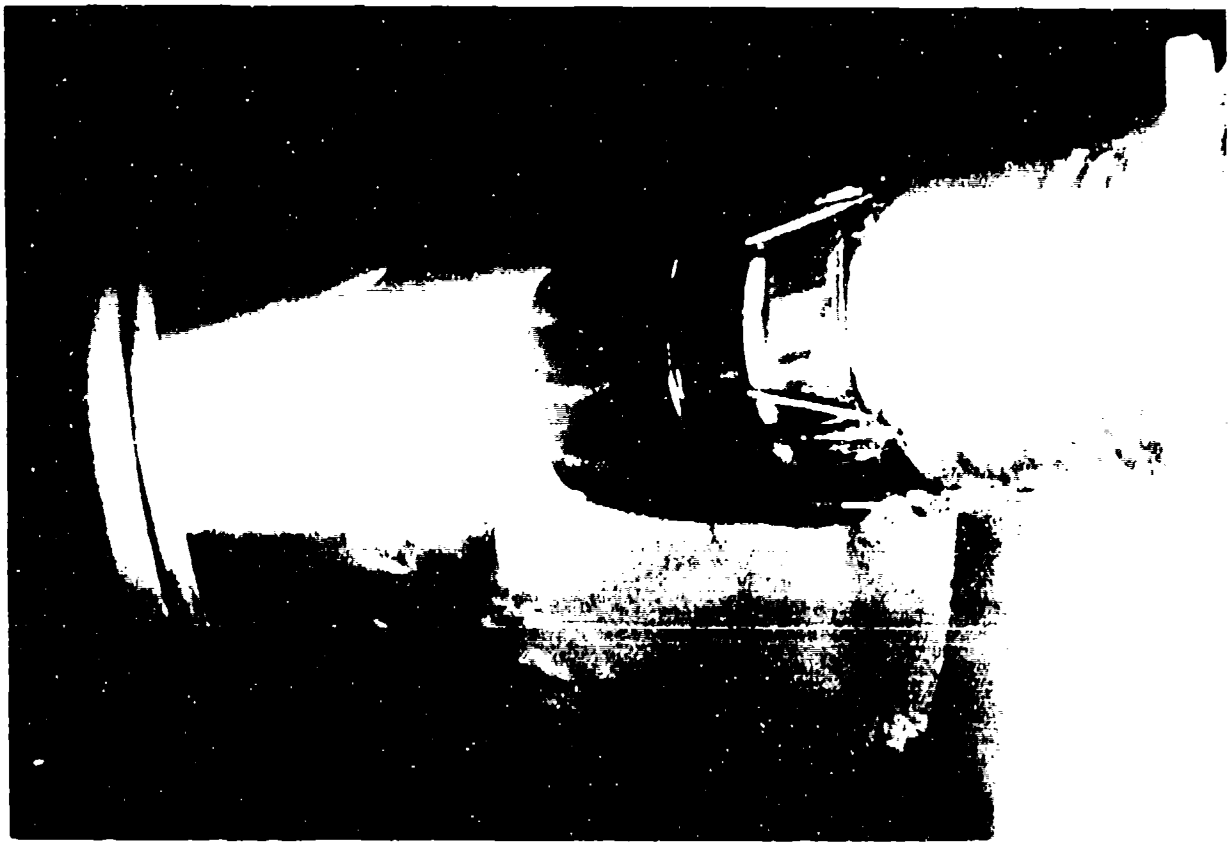

Figure 4. F110 Engine Operations With Augmented Power

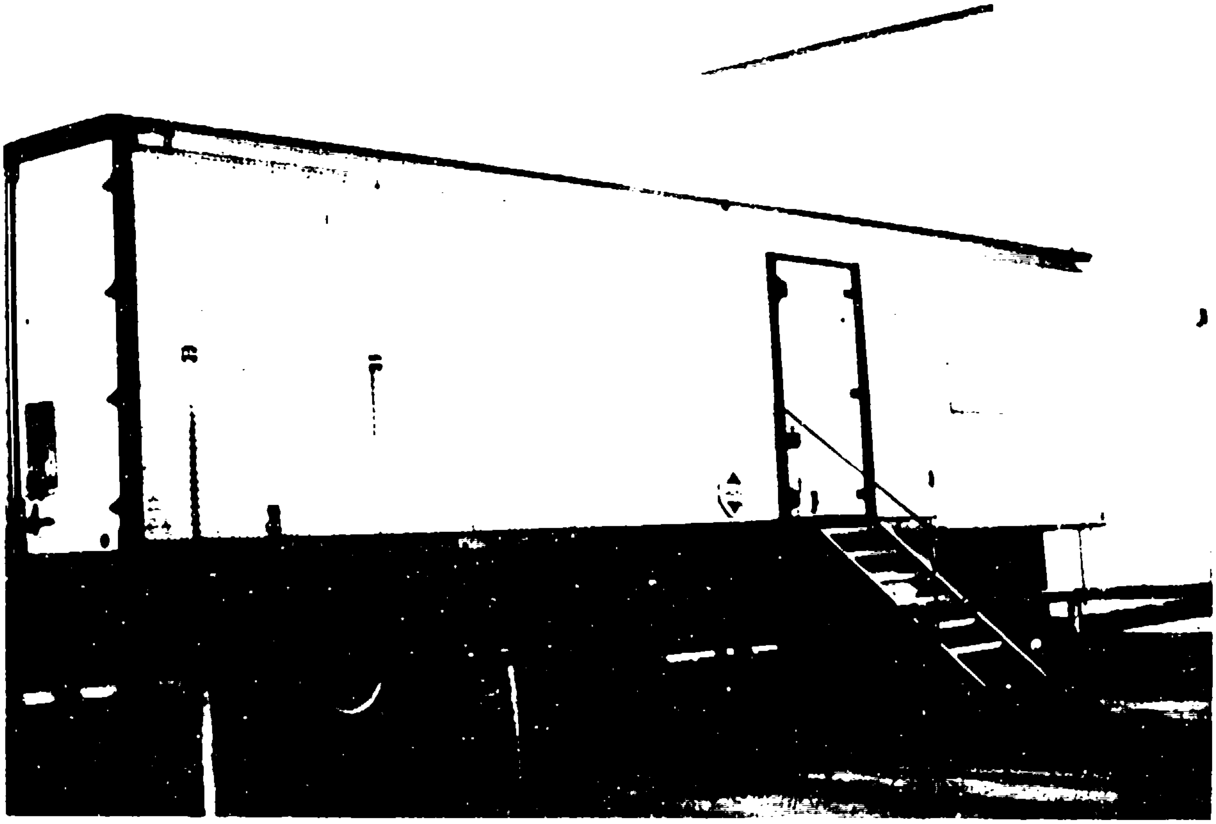

Figure 5. Mobile Laboratory Used for Engine Emissions Measurements At Tinker AFB

wrapped with heating tape. Thermocouples were positioned throughout the system to check actual temperatures.

A variety of techniques were used to sample and analyze the engine emissions. Some instruments operated in a continuous mode, while other techniques employed integrated sample collection. Both gaseous species and particulate matter were collected. Table 1 lists the sampling methods employed during this study, along with the rate, duration, volume, estimated detection limit, and estimated accuracy for each technique. The gas-sampling techniques are described in the remainder of this section.

The instruments used to monitor CO, CO_2, NO, NO_x, and total hydrocarbon (THC) in the exhaust are identified in Table 2. Exhaust samples for the Beckman 402 hydrocarbon monitor and the Beckman 955 NO/NO_x monitor were pumped from the sampling manifold into the instruments through individual Teflon® sampling lines and pumps heated to 150°C. The CO and CO_2 sample passed through a water trap (0°C) before measurement. The output from these instruments was recorded with dual-channel strip chart recorders. The gaseous emissions analyzers were zeroed and spanned at least once a day with certified mixtures of propane in air, CO and CO_2 in nitrogen, and NO in nitrogen. Each analyzer was calibrated every day during the emissions tests with multiple concentrations to cover the range of concentrations of the exhaust samples. Each calibration gas is certified by the vendor to an accuracy of ± 2 percent and is compared with Standard Reference Materials (SRM) from the National Bureau of Standards.

TABLE 2. CONTINUOUS ANALYZERS FOR EXHAUST MEASUREMENTS

SPECIES	INSTRUMENT	RANGE
Total Hydrocarbon	Beckman 402	0-10,000 ppmC
NO/NO_x	Beckman 955	0-10,000 ppm
CO	Beckman 864-11	0-1,000 ppm
CO_2	Beckman 864-23	0-5 percent

The Organic Sampling System in Figure 3 represents three separate sampling techniques designed to cover a wide range of organic compound

TABLE 1. SAMPLING PERIOD OF EACH METHOD DURING A TEST RUN

METHOD	SAMPLING RATE, lpm	SAMPLING DURATION, MIN	TOTAL SAMPLE VOLUME, LITERS	ESTIMATED DETECTION LIMIT, ppm	ESTIMATED ACCURACY, PERCENT
XAD-2	28	20	560	0.001	± 20
DNPH/Impingers	1	20	20	0.001	± 20
Canister/Cryogenic GC	0.6	20	12	0.001	± 20
THC Analyzer	<———	Continuous	———>	0.1	± 15
NO/NO_x Analyzer	<———	Continuous	———>	0.1	± 15
CO Analyzer	<———	Continuous	———>	1	± 15
CO_2 Analyzer	<———	Continuous	———>	100	± 15
Particulate Filter	50 (nominal)	30	1,500 (nominal)	50 $\mu g/m^3$	± 20
Smoke Number	14	1,2,4,6	182	NA	NA
Diffusion Battery/ Condensation Nucleus Counter	4	20	80	NA	NA
Electrostatic Particle Sampler	5	25	125	NA	NA
Laser Aerosol Spectrometer (LAS)	.09	20	1.8	NA	NA

classes and molecular weights. The sampling procedures include: (1) collection on XAD-2 resin, (2) collection in stainless steel canisters, and (3) collection in a liquid derivatizing reagent. These techniques are described below.

1. Solid Adsorbent Sampling On XAD-2 Resin

Exhaust samples collected on XAD-2 resin were used to determine polycyclic aromatic hydrocarbons (PAH). Each test employed a 22-gram portion of XAD-2 resin which had been prepurified by Soxhlet® extraction with dichloromethane for 16 hours. A background check after cleaning showed each batch of XAD-2 resin contained less than 5 μg of total chromatographable organic material per gram of resin. The XAD-2 resin is held in a glass sampling module thermostatted at 54°C. Exhaust samples were collected from the sampling manifold at a rate of 0.028 m^3 min^{-1} for 20 minutes, for a total volume of 0.56 m^3. After collection, the trap was capped with glass connectors and returned to the laboratory for analysis. The glass traps were wrapped with foil both before and after sampling to exclude light. The XAD-2 resin samples were extracted for 16 hours with dichloromethane immediately after receipt at the laboratory. The extracts were Kuderna-Danish (K-D) concentrated to 1 mL and stored at -78°C in the dark until analysis.

A Mettler ME-30 microbalance was used to determine the extractable organic mass. A 25 μL aliquot of each of the concentrated sample extracts was transferred to a tared aluminum pan and the pan placed under a heat lamp at a distance of approximately 8 cm. After allowing 1 minute for the solvent to evaporate, the pan was reweighed. Heating and weighing cycles were repeated until the weight change was less than 1 to 2 μg. The residue weight of the aliquot analyzed was then scaled to the total quantity in the original sample extract.

The XAD-2 sample extracts were analyzed by Electron Impact (EI) GC/MS with conventional splitless injection to determine the selected polynuclear aromatic hydrocarbons (PAH) in the multiple-ion detection (MID) mode. A Finnigan TSQ GC/MS system interfaced with a Finnigan INCOS 2300 data system was used for these analyses. The GC column used was an Ultra 2 crosslinked phenylmethyl silicone column with the outlet of the column located at the inlet of the MS ionization source. The instrument conditions used are as follows:

Chromatography:	Injection:	splitless, 1 µL, 45 sec.
	Column:	50 m x 0.32 mm (I.D.), 0.5 µm film thickness
	Carrier:	Helium, 3 psi head pressure, average velocity 30 cm/sec.
	Temperature Program:	50°C (2 min) to 290°C at 8°C/min.
Mass Spectrometry:	70 eV EI, multiplier gain approximately 10^5, multiple ion detection mode. Acquisition started at the start of temperature program.	

The identification of the target PAH was based on both GC retention time and the molecular ion mass. The quantification of each target compound was based on the comparisons of the respective integrated ion current response of the molecular ion to that of the internal standard. The internal standard 9-phenylanthracene, was added to the standard solutions and sample extracts at a concentration of 0.5 ng/µL prior to analysis. Standard solutions containing the PAH compounds of interest were analyzed to determine the exact mass of each target compound and to derive calibration curves. The sample extracts were analyzed concurrently with the standard solutions. The calibration response curves were generated from response to four concentrations (0.05 to 1.0 ng/µL) of each target compound. Quantification of each target compound was based on the following equation:

$$Cs = \frac{A_s \times C_{is} \times F_v}{A_{is} \times R_f \times V}$$

where

C_s = Concentration of target compound found in XAD-2 sample, µg/m^3

A_s = Molecular ion area count of the target compound

C_{is} = Concentration of the internal standard, 0.5 ng/µL

F_v = Final total volume of the sample extract, mL

A_{is} = Molecular ion area count of the internal standard

R_f = Response factor of target compound

V = total sample volume, m^3.

2. Canister Sampling for Hydrocarbon Determination

Methane and C_2-C_{15} hydrocarbons were determined by cryogenic preconcentration and capillary column GC analysis of whole air samples collected in surface-passivated canisters. Previous studies have demonstrated excellent stability of C_1-C_{15} hydrocarbons in these canisters. The canisters were analyzed at Battelle's Columbus laboratory following the engine tests. The canisters were under vacuum at the start of each sampling period, and were filled at a constant rate over the 20-minute test period. The sampling rate was controlled by a contamination-free Metal Bellows pump and Tylan mass flow controller. The details of this sampling system have been reported in Reference 5.

A Hewlett-Packard Model 5890 gas chromatograph with microprocessor control and integration capabilities was used for analysis of canisters for C_1 to C_{15} hydrocarbons. The analysis procedure involved collection of a specific volume of air (usually 100 cc) through a freeze-out sample trap (15 cm long by 0.2 cm i.d. stainless steel tubing) filled with 60/80 mesh silanized glass beads. Two traps were used in this study, for separate analyses of C_2 to C_5 and C_4 to C_{15} hydrocarbons. Methane was determined separately. Sampling was initiated by immersing each trap in a dewar of liquid argon (-186°C) and collecting a known volume of air from the canister. Injections were accomplished by transferring the collected sample from each trap through a heated (150°C) six-port valve (Carle Instruments Model 5621) and onto the analytical column. The components in each trap were flash-evaporated into the gas chromatograph by rapidly heating a thermocouple wire which is wound around the sampling trap. During normal operations, the trap is heated from -186°C to 150°C within 20 seconds. The sample lines and traps were back-flushed with zero-grade N_2 after each test run.

The GC was equipped with two flame-ionization detectors. The C_2 through C_5 hydrocarbons were resolved with a 6-meter by 0.2-centimeter i.d. column packed with phenylisocyanate on 80/100-mesh Porasil®C. The column is housed in an oven external to the GC. Isothermal operation at 45°C provides adequate resolution of these species. Methane was determined using this same column and detector. In this case, a separate sample was analyzed without cryogenic preconcentration. A 50-meter OV-1 wide-bore fused-silica column (Hewlett-Packard) was used to separate the C_4 through C_{15} organic species. Optimum results in component resolution were achieved by temperature programming from -50° to 150°C at 8 degrees/minute. This two-column analytical approach was necessary to resolve the major C_2 to C_{15} organic species. Calibration of the gas chromatographic systems made use of an external standard mixture. The standard mixtures were referenced to several NBS primary standard "propane and benzene in air" calibration mixtures.

Selected canister samples were analyzed by GC-MS to identify or confirm the identities of peaks observed in the normal chromatographic analysis.

3. Liquid Impinger Sampling for Carbonyl Compounds

Carbonyl compounds in the exhaust stream were collected in liquid impingers containing 2,4-dinitrophenylhydrazine (DNPH), wherein the DNPH derivatives are formed. The derivatives were returned to the laboratory, extracted into an organic solvent, concentrated, and analyzed by high-performance liquid chromatography (HPLC) using a UV detector. Two impinger samples were collected simultaneously over each 20-minute test, to provide a backup sample in the event of sample loss during analysis.

The impinger procedure uses a solution consisting of 250 mg of 2,4-dinitrophenylhydrazine and 0.2 mL of 98 percent sulfuric acid dissolved in 1 liter of acetonitrile (ACCN). This reagent was prepared just before departing for the engine tests and was stored in a sealed 1-gallon metal can containing a layer of charcoal. During emissions testing, two impingers, each containing 10 mL of the ACCN/DNPH reagent, were placed in series in an ice bath (because of the elevated temperature of the exhaust stream) and samples were collected for 20 minutes at 1 liter/minute. The impinger contents were transferred to a 20 mL glass vial having a Teflon®-lined screw cap, and the impinger rinsed with 1-2 mL of ACCN which was added to the vial. The vial was labeled, sealed with Teflon® tape, and placed in a charcoal-containing metal can for transport back to the laboratory.

In the laboratory, the volume of the organic extract was adjusted to 5 mL. A 10 μL aliquot was analyzed by HPLC with UV detection at 360 nm. The amount of each aldehyde was determined from response factors for pure DNPH derivatives. A Zorbax® ODS (4.6 x 25 cm) column and 60/40 acetonitrile/water mobile phase was used for the HPLC separation. Some samples were also analyzed using a methanol/water mobile phase to achieve better separation of acetone and propanal. The instrument was calibrated daily by injecting a standard containing 2 mg/L of each DNPH derivative of interest.

C. PARTICLE-SAMPLING SYSTEM

A particle-sampling system was designed to determine the size distribution and mass loading of particles in the engine exhaust. The components of this system are shown schematically in Figure 3. They consist of a smoke meter, a filter preceding the main sampling pump (for mass determination), and a dilution system followed by particle sizing instrumentation.

Particulate mass was determined gravimetrically from the filter preceding the pump. This filter was maintained at 150°C during sampling. The sample tubing between the rake and the filter also was held at 150°C during sampling. The sample tubing consisted of 125 feet of electrically grounded carbon-impregnated Teflon® tubing designed to minimize buildup of static charge. Bends in the tubing were kept to a minimum and were of large radius to minimize particle loss. Filter sampling was initiated when the valve to the rake was opened (about 10 minutes before the start of a test) and continued through the 20-minute sample collection period. Between 0.3 and 1.5 m^3 of exhaust was sampled through the filter for each test, depending on power setting. A 6-inch diameter Teflon® coated glass fiber filter was used for particle sampling. The filters were equilibrated for 24 hours at 40 percent relative humidity prior to weighing, both before and after sample collection. After collection, each filter was folded in half and sealed in a glassine envelope within a polyethylene zip-lock bag, for transport back to the laboratory. The filters were stored in a freezer before equilibration and weighing. Several blank filters were handled in the field in the same manner as the actual samples.

Smoke number was determined by sampling exhaust through a Whatman Number 4 filter according to the procedures recommended in ARP 1179A and CFR

Title 40 Part 87. After sampling, smoke spot analysis was performed with a reflectometer, and the smoke number was determined from semilog plots of smoke number versus W/A, where W is the sample mass and A is the filter spot area. A semiautomatic instrument manufactured by Roseco Corp. was used to collect smoke samples. This instrument was on loan from Wright-Patterson AFB. CFR Title 40 Part 87 specifies sampling times and volumes for determination of smoke number, and it also specified a reference ratio of exhaust gas mass to filter spot area (W/A) for reporting smoke number. Our apparatus operated at higher W/A ratios than the reference value, even for the minimum permitted sampling time of 1 minute. Even at higher W/A values, F110 and F101 engines produced very minimal stains on the filter. To provide some information on smoke emissions for these two engines, it was decided to report a "smoke value", which we define as the smoke number at a W/A of 0.080 lbs/in^2. This is higher than the reference W/A of 0.0230 lbs/in^2 specified in CFR Part 87, so that the smoke values reported here are not directly comparable with official smoke numbers. Values reported here, at a higher W/A than the reference value, are expected to be biased on the high side. Nevertheless, the reported values are still quite low.

The instrumentation used for determination of the aerosol size distribution is a condensation nucleus counter (CNC), coupled with a diffusion battery (DB) and automatic switching station. The CNC provides a real-time measurement of particle concentration over a very wide range of concentrations. In the photometric mode it covers the range 10^3 to 10^7 particles/cm^3, and, in the single particle mode, it can be used for even lower concentrations. When coupled with the DB, the CNC can resolve the aerosol size distribution in the 0.002-0.2 μm aerodynamic size range. Up to 10 size increments are selectable in this range, in addition to a total number concentration of submicron particles. Samples of the exhaust particulate matter were taken, using an electrostatic aerosol sampler, to provide for determination of particles larger than 0.2 μm. This device deposits exhaust particles directly on a substrate for subsequent sizing by Scanning Electron Microscopy (SEM). This technique also yields an electron micrograph of the sample so that particle morphology can be examined.

The DB/CNC requires dilution and cooling of the exhaust before measurement. The cooling must be accomplished in a manner which avoids condensation of water vapor on the exhaust particles. Our approach was to dilute an exhaust sample with dry particle-free air in a constant volume vessel. For this purpose we used a sealed 220-liter steel drum mounted in the mobile laboratory. Before each test, the drum was purged with ambient air which had been dried and cleaned by passing it through Drierite and an absolute filter. After confirming (with the CNC) that the dilution air in the drum contained negligible levels of particles, the drum inlet was opened to the exhaust stream and a pump downstream of the drum was used to pull several liters of exhaust into the drum. This typically required 1 to 2 minutes, and resulted in a tenfold to thirtyfold dilution of the exhaust. As soon as the dilution was complete, the DB/CNC sampling was initiated. After sampling was complete, the exhaust monitors for CO and CO_2 were switched to monitor the diluted sample in the drum. The ratios of the CO and CO_2 concentrations in the drum to those in the undiluted exhaust were used to determine the dilution factor.

For a typical test, the DB/CNC scanned each diluted exhaust sample three times, providing three separate measurements of the size distribution. An exhaust sample was diluted and analyzed at the beginning and end of each test to check for changes in particle emissions over the 20-minute test period, so that each test typically resulted in six separate particle size determinations by the DB/CNC system.

The electrostatic sampler was used to collect exhaust particles for scanning electron microscopy (SEM). Based on the results of previous studies (Reference 3) the exhaust was sampled directly, without dilution. Polycarbonate filters (Nuclepore) were used as the collection surface for the electrostatic SEM samples. Samples typically were collected at a flow rate of 5 L/min for at least 25 minutes. The electrostatic particle samples were analyzed by scanning electron microscopy using an International Scientific Instruments, Inc. Model S-IIIA SEM.

D. DATA REDUCTION METHODOLOGY

The procedures used to reduce the data generated in the experimental program generally have been described in Reference 2. Procedures not described in Reference 2 include determination of smoke number, particle size distribution, emission rates, and emission indices. For this study, smoke number was derived according to the procedures recommended in Reference 6, with the exceptions noted above.

The data obtained from the diffusion battery-condensation nucleus counter represent the concentration of aerosol particles penetrating the various stages of the diffusion battery. These data cannot be interpreted without further processing. The results reported in this document are derived from a program which utilizes theoretical penetration efficiency equations for each stage of the battery, and predicts the form of the resulting data based upon an assumed initial size distribution. These resulting "data" are compared against the actual measured values to derive a better estimate of the actual distribution. This process is repeated until a satisfactory fit of the input data is obtained. This fitted distribution is then used to represent the measured aerosol size distribution.

Emission rates and emission indices for power settings other than afterburner, were derived using the equations provided in Reference 7. For afterburner emissions we used a modified version of the procedures recommended by Lyon et al. (Reference 8). Their procedure, which was developed for outdoor downwind measurements of afterburning engine emissions, consists of axial probing of the exhaust plume and linear regression of the pollutant concentrations against the concentration of CO_2. The afterburner measurements made during this study were performed well downstream of the exhaust nozzle, as recommended in Reference 7, so that thermal reactions in the exhaust gas are largely quenched. However, unlike the measurements of Lyon et al. (Reference 8), our samples were obtained in a confined exhaust stream which passed through the augmentor tube and roof vent, as noted in Figure 1. In this mode, the exhaust was diluted with entrained ambient air in the augmentor tube, and was turbulently mixed in the tube, blast room, and roof vents. Due to the turbulent mixing, the exhaust was considered to be well-mixed by the time it reached the rooftop sample probe, and axial probing of the exhaust was judged to be unnecessary. Excellent agreement between emission indices obtained at high power at the exhaust exit nozzle and the rooftop location has confirmed the validity of this sampling strategy (Reference 2). Therefore, rather than develop a linear regression of pollutant concentration versus CO_2 concentration, we used the time-averaged, background-corrected ratio of pollutant concentration to CO_2 concentration. The measured species concentrations were constant over the afterburner test interval, confirming the homogeneity of the exhaust. The equations used to derive emission indices (in lb/1000 lb fuel) are given below (Reference 8):

$$EI_{CO} = \frac{2.801\ (b_{CO})}{(M_C + n\ M_H)\ \left(1 + \frac{b_{CO} + b_{HC}}{10^4}\right)} \qquad (1)$$

$$EI_{HC} = \frac{0.10\ (b_{HC})}{1 + \frac{b_{CO} + b_{HC}}{104}} \qquad (2)$$

$$EI_{NO} = \frac{4.601\ (b_{NO})}{(M_C + n\ M_H)\ \left(1 + \frac{b_{CO} + b_{HC}}{10^4}\right)} \qquad (3)$$

$$EI_{NO_x} = \frac{4.601\ (b_{NO_x})}{(M_C + n\ M_H)\ \left(1 + \frac{b_{CO} + b_{HC}}{10^4}\right)} \qquad (4)$$

where b_z represents the ratio of the time-averaged, background-corrected concentration of species z to CO_2, n is the hydrogen to carbon atomic ratio of the fuel, M_C is the atomic weight of carbon, M_H is the atomic weight of hydrogen, and concentrations are in units of percent for CO_2, ppmC for hydrocarbons, and ppm for NO, NO_x, and CO.

Emission rates in lb/hour were calculated using Equation (5),

$$ER_z = 0.001\ (EI_z)\ (F_f) \qquad (5)$$

where ER_z and EI_z are the emission rate (lb/hr) and emission index (lb/1000 lb fuel) for species z, respectively, and F_f is the total engine fuel flow rate in lb/hr.

SECTION III

RESULTS

A. ENGINE OPERATION

Engine emissions measurements were carried out from June 14 to June 17, 1988, at Tinker AFB in Oklahoma City, OK. The two engines examined during these tests are listed in Table 3. The environmental conditions and engine operating variables are given in Tables 4 and 5 for the two engines F110 and F101. The data on operating conditions represent the average of two measurements made at the beginning and end of each 20-minute sampling period.

TABLE 3. ENGINES USED IN EMISSIONS TESTS

ENGINE	SERIAL NO.
F110	509153
F101	470135

B. FUEL ANALYSIS

All emissions tests employed JP-4 fuel from the standard Tinker AFB commercial supplier. Fuel samples were collected each test day. The fuel samples were analyzed by vaporizing 1 μL of fuel into helium in a heated cylinder (80°C) and analyzing a 1 cc sample of the cylinder contents by capillary column gas chromatography. Table 6 lists the percent composition of the major organic species identified in the fuel samples. Approximately 60 percent of the mass was identified as specific compounds. A representative chromatogram of JP-4 fuel is shown in Figure 6. Compared to JP-4 fuel used for prior emissions tests (References 2 and 3), the relative abundance of the more volatile species was greater for these fuel samples.

TABLE 4. ENGINE OPERATING CONDITIONS
ENGINE F110 (S/N 509153)

Test No.	1-6-15	2-6-15	3-6-15	4-6-15
Date	6-15-88	6-15-88	6-15-88	6-15-88
Location/Test Cell	TAFB/11	TAFB/11	TAFB/11	TAFB/11
Engine nominal power setting	Idle	30%	63%	Intrmdt
Time (CDT)	1324	1515	1658	1829
Initial engine inlet temperature (C)	30	29.444	26.111	27.777
Final engine inlet temperature (C)	28.333	27.222	27.222	27.777
Initial barometric pressure (in. Hg)	28.875	28.835	28.8	28.778
Final barometric pressure (in. Hg)	28.875	28.835	28.8	28.778
Engine inlet total pressure (psia)	14.18	14.155	14.12	14.08
Engine inlet static pressure (psia)	13.99	13.6	12.76	11.4
Fuel	JP-4	JP-4	JP-4	JP-4
Engine time since overhaul (hr)	0	0	0	0
Pass performance test	Yes	Yes	Yes	Yes
Fuel flow (lb/hr)	1059.5	2473.5	5523	9954
Air flow (lb/sec)	86	131.75	193.5	254.05
Fuel/air ratio	0.003422	0.005215	0.007929	0.010884
Rated thrust (lb)[a] (Intermediate-high mach)	16007	16007	16007	16007
Measured thrust (lb)(a)	700	4095.5	9681	16778
Fuel flow (lb/hr)(a)	1104.5	2587.5	5793.5	10673
Air flow (lb/hr)(a)	86.65	132.8	194.9	260.45
Fuel/air ratio(a)	0.003541	0.005412	0.008257	0.0113831
Turbine blade temperature (C)(a)	--	--	--	806.667
Fan speed (rpm)(a)	3301.5	5223	7002	8184
Core speed (rpm)(a)	10651.5	12226.5	13710.5	14643.5
Actual thrust (% intermediate)(a)	4.37	25.59	60.48	104.82

(a) Corrected to standard day.

TABLE 5. ENGINE OPERATING CONDITIONS
ENGINE F101 (S/N 470135)

Test No.	1-6-17	2-6-17	3-6-17	4-6-17
Date	6-17-88	6-17-88	6-17-88	6-17-88
Location/Test Cell	TAFB/12	TAFB/12	TAFB/12	TAFB/12
Engine nominal power setting	Idle	44%	75%	Intrmdt
Time (CDT)	1025	1209	1322	1448
Initial engine inlet temperature (C)	25	27.222	28.333	28.889
Final engine inlet temperature (C)	25	27.778	28.889	29.444
Initial barometric pressure (in. Hg)	28.69	28.665	28.665	28.605
Final barometric pressure (in. Hg)	28.69	28.665	28.645	28.605
Engine inlet total pressure (psia)	14.09	14.055	14.025	14
Engine inlet static pressure (psia)	13.78	12.895	11.96	11.04
Fuel	JP-4	JP-4	JP-4	JP-4
Engine time since overhaul (hr)	0	0	0	0
Pass performance test	Yes	Yes	Yes	Yes
Fuel flow (lb/hr)	1012	3605	6336	9266.5
Air flow (lb/sec)	125.8	236.1	304.25	350.85
Fuel/air ratio	0.002235	0.004241	0.005785	0.007337
Rated thrust (lb)(a) (Intermediate)	17390	17390	17390	17390
Measured thrust (lb)(a)	1033	7836.5	13432	18723.5
Fuel flow (lb/hr)(a)	1065	3726	6544.5	9976.5
Air flow (lb/sec)(a)	126.3	236	304.15	353.8
Fuel/air ratio(a)	0.002342	0.004386	0.005977	0.007833
Turbine blade temperature (C)(a)	--	--	743.33	878.61
Fan speed (rpm)(a)	3274.5	5913	6877	7370
Core speed (rpm)(a)	10372	12601.5	13597.5	14410.5
Actual thrust (% intermediate)(a)	5.94	45.06	77.24	107.67

(a) Corrected to standard day.

TABLE 6. PERCENT COMPOSITION OF MAJOR ORGANIC SPECIES IN JP-4 FUEL USED FOR EMISSIONS TESTS (WEIGHT PERCENT)

HYDROCARBON	FUEL SAMPLE DATE JUNE 15, 1988	 JUNE 17, 1988
iso-pentane	.45	.34
n-pentane	.93	.78
2-methylpentane	2.37	2.12
3-methylpentane	1.73	1.53
n-hexane	5.29	4.85
methylcyclopentane	3.33	3.28
benzene	.79	.70
cyclohexane	3.25	3.16
2-methylhexane	3.06	3.49
3-methylhexane	3.27	3.74
dimethylcyclopentane	4.18	4.25
n-heptane	6.01	6.25
methylcyclohexane	7.20	7.23
toluene	2.40	2.02
2-methylheptane	2.70	2.85
3-methylheptane	1.59	1.71
n-octane	4.41	4.68
ethylbenzene	1.03	1.06
m&p-xylene	2.88	2.60
o-xylene	.49	.61
n-nonane	2.00	2.04
n-decane	1.11	.80
n-undecane	.58	.45
n-dodecane	.26	.36
n-tridecane	--	1.83

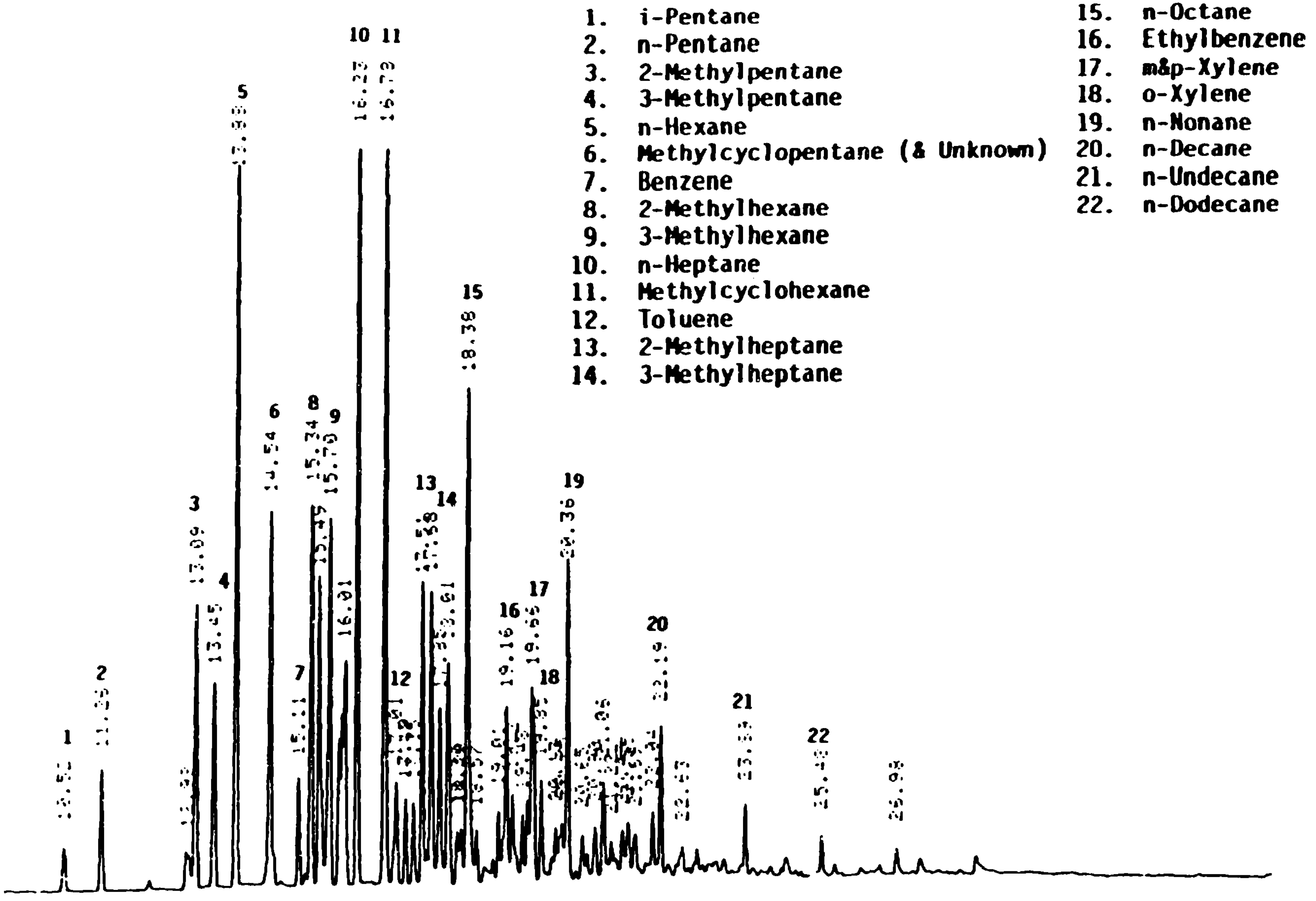

Figure 6. Representative GC/FID Chromatogram for JP-4 Fuel Used in Emissions Tests

C. GASEOUS EMISSIONS

Gaseous emissions were measured at four power settings for each engine by sampling at the exhaust nozzle exit. The nominal power settings used for the F101 engine were idle, 44 percent, 75 percent, and intermediate (high mach). The F110 tests were run at nominal settings of idle, 30 percent, 63 percent, and intermediate (high mach). Emissions measurements also were made at Stage 1 augmentation (afterburner) power, by sampling the exhaust from the roof of the engine test cell (see Figure 1). The exhaust concentrations of total hydrocarbon, NO_x, NO, CO, and CO_2 are reported in Table 7.

As noted above, the measurements made at Stage 1 augmentation power were performed at the test cell roof vent, rather than at the exhaust nozzle exit. The exhaust from these tests, which are noted by an asterisk in Table 7, was diluted by entrainment of ambient air in the augmentor tube. As a consequence, the results from these tests represent engine exhaust which has been diluted significantly. As noted in Section II, these dilute exhaust results are treated in a special manner to derive emission indices and emission rates.

The gaseous organic species measured in the exhaust from the two engines are listed in Tables 8 and 9. Concentrations are given in parts per million carbon (ppmC) for all species. Table 8 shows results for the F110 engine. The results for the F101 engine are shown in Table 9. The tables list hydrocarbons, oxygenated species, and the distribution of compound classes for each engine power setting. As noted above, the measurements made at afterburner power represent diluted exhaust concentrations and should be compared with other power settings with this in mind. Representative chromatograms of the exhaust analysis for hydrocarbon species and carbonyl species are provided in Figures 7-9.

D. POLYCYCLIC AROMATIC HYDROCARBON EMISSIONS

The results of GC-MS analysis of the XAD-2 samples for polycyclic aromatic hydrocarbons are shown in Tables 10 and 11 for the two engines. All concentrations in Tables 10 and 11 are in units of $\mu g/m^3$. Extractable organic mass is listed in Table 12. The XAD-2 sample trap for Test 3-6-17 was broken, so no PAH or extractable mass results are reported for this test.

TABLE 7. ENGINE EMISSIONS DATA

POWER SETTING	TEST NO.	THC ppmC	NO_x ppm	NO ppm	CO ppm	CO_2 PERCENT
		F110 ENGINE				
Idle	TAFB-1-6-15	7	13.8	11.2	85	0.98
30 Percent	TAFB-2-6-15	6	30	28	23	1.25
63 Percent	TAFB-3-6-15	3	97	92	13	2.35
Intermediate	TAFB-4-6-15	3.5	243	227	15	3.17
Augmentation(a) (Stage 1)	TAFB-5-6-15	335	21.5	3.7	178	0.41
Intermediate (Rooftop)(a)	--	<7	26	25	6	0.28
		F101 ENGINE				
Idle	TAFB-1-6-17	6.5	6.9	5	50	0.5
44 Percent	TAFB-2-6-17	3.5	28.5	25.5	8	0.98
75 Percent	TAFB-3-6-17	2.5	68	62	8	1.52
Intermediate	TAFB-4-6-17	3	140	133	11	2.02
Augmentation(a) (Stage 1)	TAFB-5-6-17	287	21.8	7.2	110	0.32

(a) Measurements made on diluted exhaust.

TABLE 8. ORGANIC EMISSIONS FROM F110 ENGINE WITH JP4 FUEL (CONCENTRATIONS IN ppmC)

Organic Species	Test NO.:	1-6-15	2-6-15	3-6-15	4-6-15	5-6-15
	Date:	6-15-88	6-15-88	6-15-88	6-15-88	6-15-88
	Power Setting:	Idle	30%	63%	Intermediate[a]	Stage 1 Augmentation[b]
Methane		1.766	1.462	1.098	0.674	4.046
Ethane		0.033	0.022	0.024	0.013	0.436
Ethylene		0.497	0.089	0.127	0.230	34.194
Propane		0.026	0.023	0.009	0.005	0.071
Acetylene		0.208	0.020	0.011	0.007	3.570
Propene		0.082	0.017	0.022	0.048	20.046
1-Butene + 1,3-Butadiene		0.034	0.016	0.016	0.009	5.429
1-Pentene		0.006	0.002	0.003	0.001	1.847
C5-ene		0.001	<0.001	<0.001	<0.001	0.520
n-Pentane		0.011	0.012	0.005	0.001	1.809
C5-ene		<0.001	<0.001	<0.001	<0.001	0.392
C5-ene		<0.001	<0.001	<0.001	<0.001	0.213
2-Methylpentane		0.009	0.021	0.008	0.001	4.433
3-Methylpentane		0.008	0.012	0.004	0.001	2.981
1-Hexene		0.003	0.004	0.005	0.002	1.526
n-Hexane		0.018	0.032	0.008	0.004	8.395
Methylcyclopentane + unk		0.010	0.018	0.005	0.002	4.601
Benzene		0.079	0.023	0.017	0.011	5.544
2-Methylhexane		0.005	0.011	0.002	<0.001	2.886
3-Methylhexane		0.017	0.019	0.012	0.009	3.679
n-Heptane		0.013	0.028	0.005	0.002	7.842
Methylcyclohexane		0.016	0.034	0.006	0.002	8.992
Toluene		0.985	0.032	0.012	0.007	6.949
2-Methylheptane		0.008	0.011	0.001	<0.001	3.818
3-Methylheptane		0.000	0.009	0.008	0.007	2.573
n-Octane		0.010	0.023	0.004	<0.001	5.855
Ethylbenzene		0.024	0.006	0.002	0.001	1.393
m+p-Xylene		0.086	0.021	0.006	0.003	4.813
Styrene		0.005	0.009	0.002	<0.001	1.300
o-Xylene		0.030	0.007	0.002	0.001	1.410
n-Nonane		0.015	0.025	0.002	<0.001	3.642
p-Ethyltoluene		0.007	0.007	0.002	0.001	0.940
1,2,4-Trimethylbenzene		0.015	0.013	0.002	0.001	1.903
n-Decane		0.025	0.033	0.002	0.001	2.527
Methylbenzaldehyde+C10H14		0.006	0.007	0.001	<0.001	0.695
Undecane		0.021	0.022	0.002	0.001	2.345
Naphthalene		0.005	0.002	0.000	<0.001	0.611
Dodecane		0.019	0.015	0.002	0.001	1.967
Tridecane		0.037	0.017	0.004	0.001	1.266
Tetradecane		0.007	0.029	0.007	0.004	0.758
DNPH/IMPINGER COLLECTION						
Formaldehyde		0.305	0.162	0.095	0.090	9.942
Acetaldehyde		0.140	0.080	0.042	0.032	0.704
Acrolein		0.015	<0.001	0.009	0.003	3.222
Propanaldehyde		0.066	0.012	<0.001	<0.001	0.204
Acetone		0.060	0.072	0.084	0.024	<0.001
Benzaldehyde + unk		<0.001	<0.001	<0.001	<0.001	1.488
Glyoxal		0.064	<0.001	0.004	0.016	0.304
Methylglyoxal		0.051	0.003	0.012	0.018	0.185
Biacetyl		<0.001	<0.001	<0.001	<0.001	<0.001
IDENTIFIED SPECIES						
Paraffins		2.075	1.879	1.219	0.728	74.923
Acetylene		0.208	0.020	0.011	0.007	3.570
Olefins		0.622	0.129	0.174	0.291	64.168
Aromatics		1.242	0.128	0.045	0.026	25.559
Aldehydes		0.641	0.257	0.162	0.159	15.050
Ketones		0.060	0.072	0.084	0.024	0.000
TOTAL SPECIES		4.848	2.485	1.695	1.235	184.269

(a) At high mach; equivalent to 105 percent

(b) Concentrations in dilute exhaust, see text.

TABLE 9. ORGANIC EMISSIONS FROM F101 ENGINE WITH JP4 FUEL (CONCENTRATIONS IN ppmC)

Organic Species	Test NO.:	1-6-17	2-6-17	3-6-17	4-6-17	5-6-17
	Date:	6-17-88	6-17-88	6-17-88	6-17-88	6-17-88
	Power Setting:	Idle	44%	75%	Intermediate[a]	Stage 1 Augmentation[c]
Methane		1.865	1.542	1.302	1.231	2.837
Ethane		0.042	0.016	0.009	0.011	0.458
Ethylene		0.671	0.058	0.078	0.103	13.834
Propane		0.023	0.021	0.015	0.014	0.086
Acetylene		0.242	0.005	0.003	0.008	2.346
Propene		0.172	0.005	0.013	0.019	6.441
1-Butene + 1,3-Butadiene		0.012	0.002	0.005	0.049	2.461
1-Pentene		0.013	0.001	0.001	0.002	0.858
C5-ene		0.001	<0.001	<0.001	<0.001	0.288
n-Pentane		0.025	0.005	0.003	0.005	2.386
C5-ene		<0.001	0.006	0.002	0.001	0.210
C5-ene		<0.001	<0.001	<0.001	<0.001	0.111
2-Methylpentane		0.039	0.011	0.005	0.009	5.731
3-Methylpentane		0.022	0.002	0.003	0.007	3.983
1-Hexene		0.009	0.003	0.002	0.002	0.783
n-Hexane		0.056	0.005	0.008	0.019	11.518
Methylcyclopentane + unk		0.030	0.003	0.005	0.010	6.397
Benzene		0.104	0.011	0.007	0.013	3.643
2-Methylhexane		0.014	0.001	0.004	0.006	3.992
3-Methylhexane		0.026	0.006	0.008	0.017	5.725
n-Heptane		0.030	0.006	0.008	0.018	10.901
Methylcyclohexane		0.036	0.004	0.008	0.021	14.035
Toluene		0.070	0.016	0.009	0.015	6.656
2-Methylheptane		0.010	0.003	0.002	0.005	4.241
3-Methylheptane		0.008	0.008	0.006	0.012	3.578
n-Octane		0.017	0.003	0.007	0.013	8.501
Ethylbenzene		0.008	(b)	0.002	0.003	1.893
m+p-Xylene		0.028	0.005	0.005	0.008	5.736
Styrene		0.005	0.018	0.002	0.004	2.035
o-Xylene		0.008	0.006	0.002	0.009	1.671
n-Nonane		0.009	0.003	0.004	0.007	5.503
p-Ethyltoluene		0.005	0.002	0.002	0.002	1.160
1,2,4-Trimethylbenzene		0.007	0.004	0.002	0.003	2.439
n-Decane		0.007	0.011	0.003	0.005	3.862
Methylbenzaldehyde+C10H14		0.002	0.003	0.001	0.001	0.960
Undecane		0.009	(b)	0.003	0.004	3.255
Naphthalene		<0.001	(b)	<0.001	<0.001	0.349
Dodecane		0.004	0.010	0.002	0.003	2.767
Tridecane		0.004	0.015	0.002	0.003	1.793
Tetradecane		0.007	0.010	0.001	0.002	1.008
DNPH/IMPINGER COLLECTION						
Formaldehyde		0.328	0.044	0.044	0.050	6.009
Acetaldehyde		0.160	0.040	0.032	0.028	3.036
Acrolein		0.006	<0.001	<0.001	<0.001	1.272
Propanaldehyde		0.078	<0.001	<0.001	<0.001	1.776
Acetone		0.087	0.063	0.054	0.054	0.516
Benzaldehyde		<0.001	<0.001	<0.001	<0.001	0.546
Glyoxal		0.016	0.004	<0.001	<0.001	<0.001
Methylglyoxal		0.012	<0.001	<0.001	<0.001	<0.001
Biacetyl		0.008	<0.001	<0.001	<0.001	<0.001
IDENTIFIED SPECIES						
Paraffins		2.284	1.685	1.408	1.423	102.556
Acetylene		0.242	0.005	0.003	0.008	2.346
Olefins		0.878	0.075	0.101	0.176	24.987
Aromatics		0.238	0.065	0.031	0.058	26.542
Aldehydes		0.608	0.088	0.076	0.078	12.639
Ketones		0.087	0.063	0.054	0.054	0.516
TOTAL SPECIES		4.336	1.981	1.673	1.796	169.587

(a) At high mach; equivalent to 107 percent.

(b) Data missing due to sample contamination.

(c) Concentrations in dilute exhaust; see text.

1. Propene
2. Acetaldehyde
3. 1-Butene
4. 1,3-Butadiene
5. Acrolein
6. Acetone
7. 1-Pentene
8. C5-ene
9. n-Pentane
10. C5-ene
11. C5-ene
12. 2-Methyl-2-propenal
13. 2-Methylpentane
14. 3-Methylpentane
15. 1-Hexene
16. n-Hexane
17. Methylcyclopentane+unk
18. Benzene
19. 2-Methylhexane
20. 3-Methylhexane
21. n-Heptane
22. Methylcyclohexane
23. Toluene
24. 2-Methylheptane
25. 3-Methylheptane
26. n-Octane
27. Ethylbenzene
28. m&p-Xylene
29. Styrene
30. o-Xylene
31. n-Nonane
32. Benzaldehyde
33. p-Ethyltoluene
34. 1,2,4-Trimethylbenzene
35. n-Decane
36. Methylbenzaldehyde+C10H14
37. Undecane
38. Napthalene
39. Dodecane
40. Tridecane
41. Tetradecane

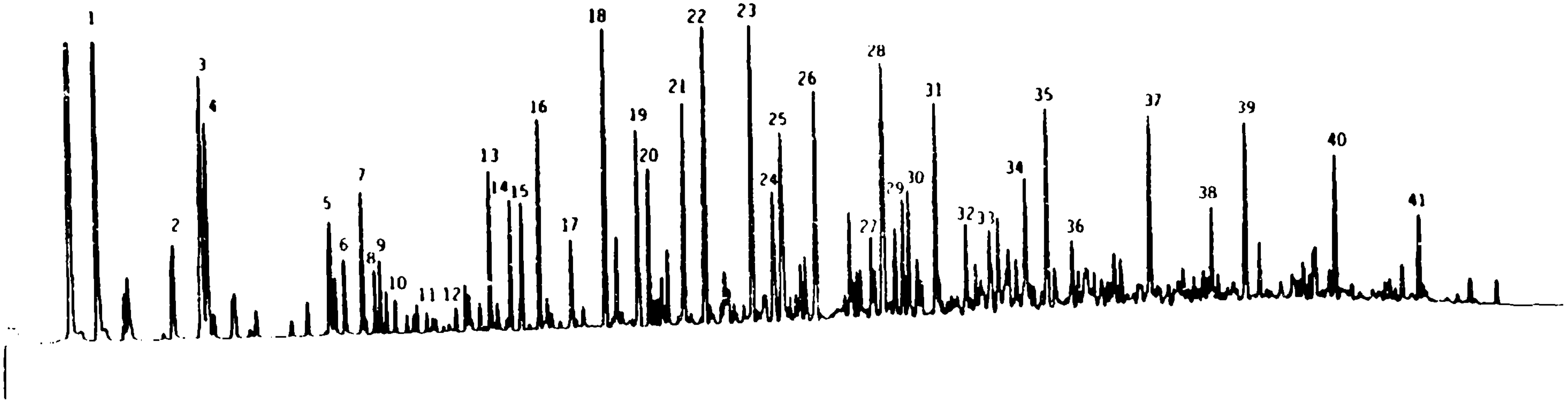

Figure 7. Representative GC/FID Chromatogram for Exhaust from a Turbine Engine Operating With JP-4 Fuel

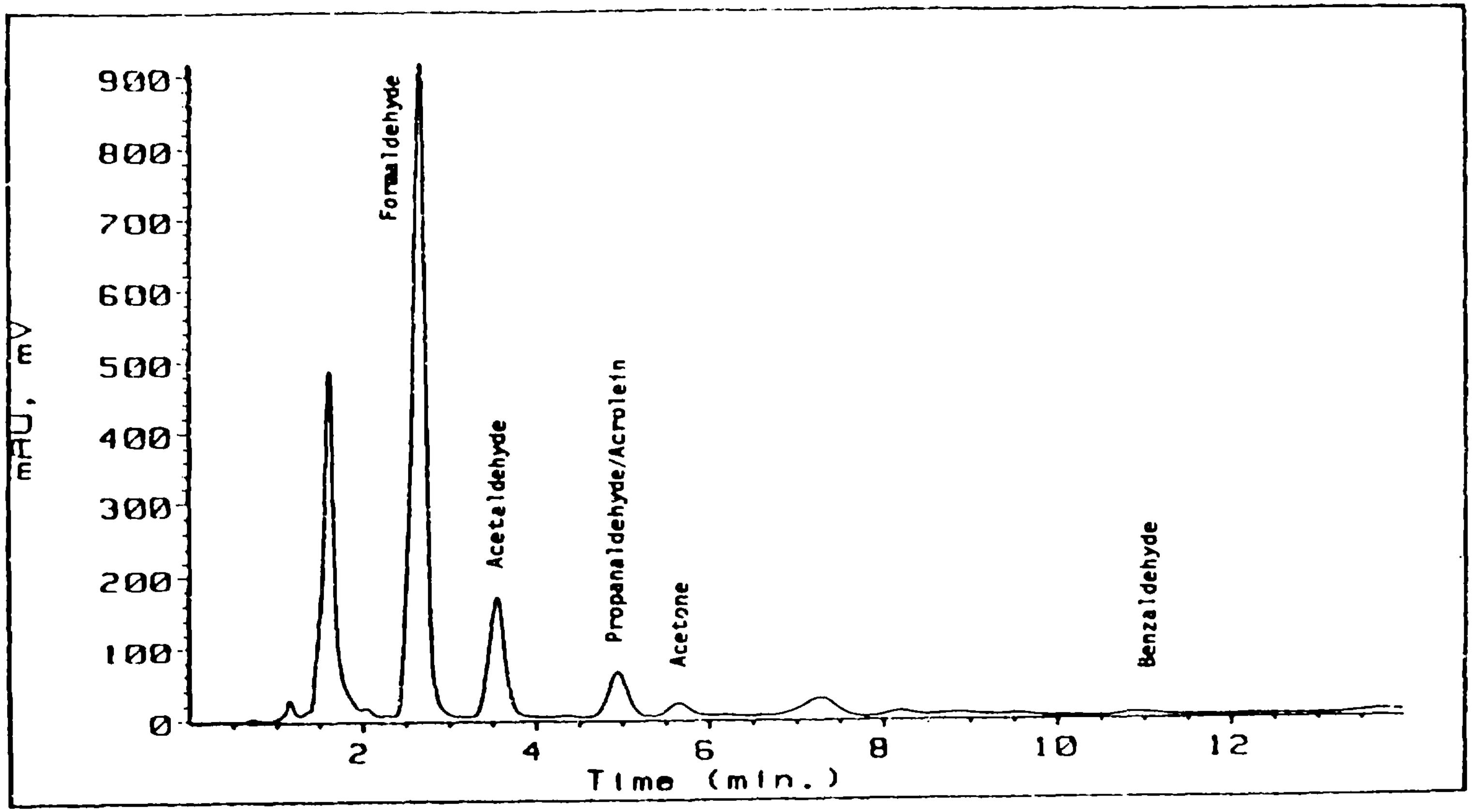

Figure 8. Representative Chromatogram from Analysis of Jet Engine Exhaust for Aldehydes

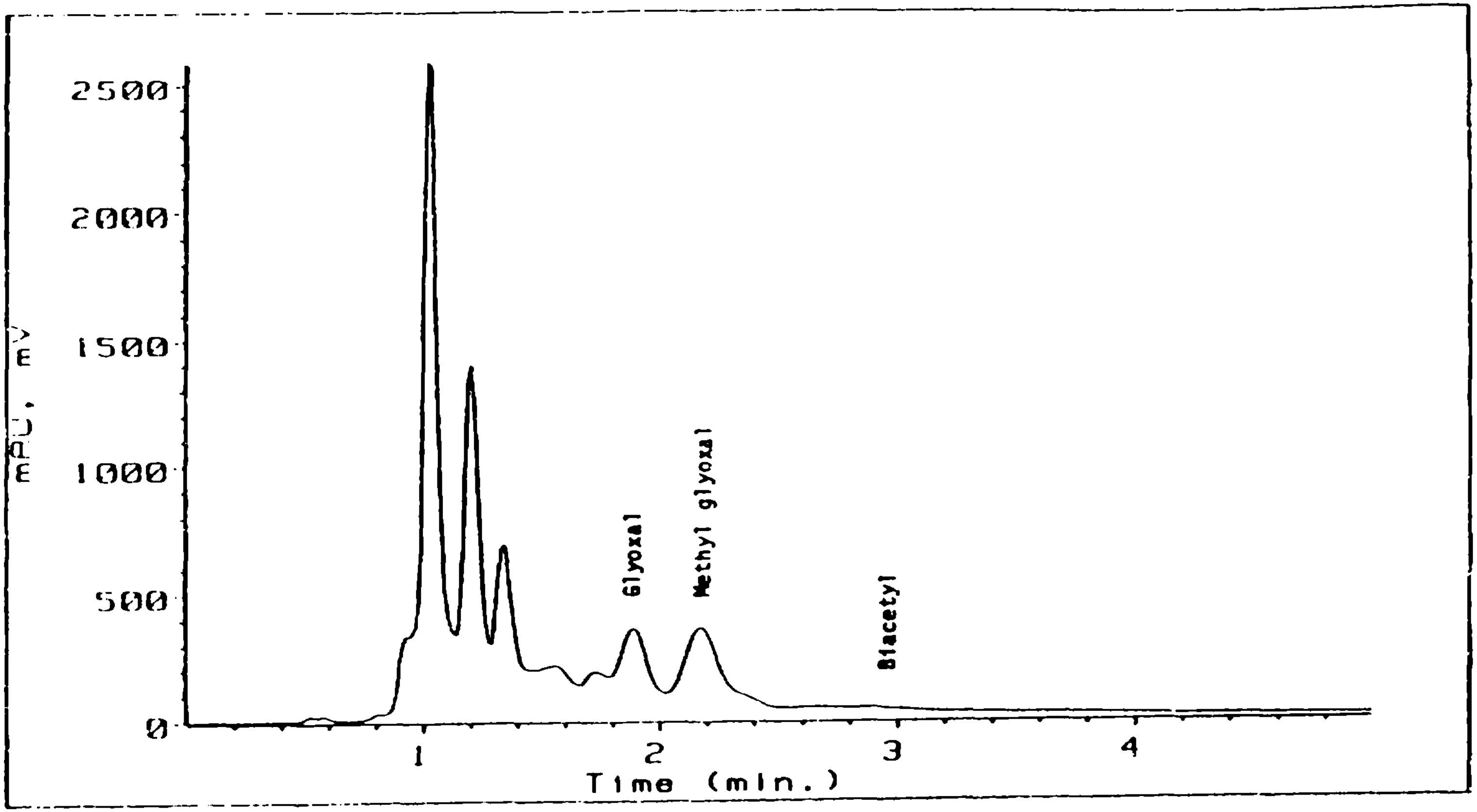

Figure 9. Representative Chromatogram from Analysis of Jet Engine Exhaust for Dialdehydes

TABLE 10. POLYCYCLIC AROMATIC HYDROCARBON (PAH) RESULTS FOR F110 ENGINE (CONCENTRATION IN $\mu g/m^3$)

	ENGINE:	F110	F110	F110	F110	F110
	POWER SETTING:	Idle	30%	63%	INTERMEDIATE	AUGMENTATION(a)
COMPOUND	TEST NO.:	1-6-15	2-6-15	3-6-15	4-6-15	5-6-15
Naphthalene		4.7	2.9	1.4	1.1	190
1-Methylnaphthalene		6.0	4.2	1.1	0.60	280
2-Methylnaphthalene		4.3	2.9	0.75	0.38	190
1,2-Dimethylnaphthalene		3.5	2.4	0.56	0.31	77
Dimethylnapthalene		7.1	5.0	1.3	0.72	140
1,4&2,3-Dimethylnaphthalene		2.0	1.3	0.42	0.22	39
2,6-Dimethylnaphthalene		0.54	0.42	0.10	0.067	11
Acenaphthylene		0.31	0.28	0.077	0.045	1.9
Acenaphthene		0.21	0.13	0.077	0.050	1.1
Dibenzothiophene		0.089	0.045	0.052	0.036	0.57
Phenanthrene		1.3	0.70	0.80	0.55	1.8
Anthracene		0.12	0.047	0.049	0.041	0.096
Fluoranthene		0.51	0.40	0.22	0.19	0.39
Pyrene		0.61	0.40	0.22	0.15	0.36
Cyclopenta[c,d]pyrene		0	0	0	0	0.028
Benz[a]anthracene		0.038	0.019	0.022	0.019	0.033
Chrysene		0.064	0.056	0.035	0.026	0.048
Benzofluoranthenes		0.096	0.038	0.045	0.033	0.051
Benzo[e]pyrene		0.057	0.020	0.022	0.017	0.026
Benzo[a]pyrene		0.073	0.021	0.028	0.022	0.039
Indeno[1,2,3-c,d]pyrene		0.054	0.011	0.023	0.024	0.029
Dibenzo[a,h]anthracene		0.064	0.011	0.030	0.036	0.024
Benzo[g,h,i]perylene		0.045	0.011	0.023	0.026	0.033

(a) Concentrations are for dilute exhaust collected from test cell roof.

TABLE 11. POLYCYCLIC AROMATIC HYDROCARBON (PAH) RESULTS FOR F101 ENGINE (CONCENTRATION IN $\mu g/m^3$)

	ENGINE:	F101	F101	F101	F101
	POWER SETTING:	Idle	44%	75%	AUGMENTATION(a)
COMPOUND	TEST NO.:	1-6-17	2-6-17	3-6-17	5-6-17
Naphthalene		2.8	1.1	0.77	120
1-Methylnaphthalene		2.2	0.67	0.40	180
2-Methylnaphthalene		1.4	0.38	0.20	130
1,2-Dimethylnaphthalene		0.72	0.26	0.13	59
Dimethylnapthalene		1.5	0.50	0.38	110
1,4&2,3-Dimethylnaphthalene		0.51	0.20	0.13	30
2,6-Dimethylnaphthalene		0.099	0.065	0.016	7.9
Acenaphthylene		0.093	0.034	0.017	1.2
Acenaphthene		0.057	0.053	0.030	0.68
Dibenzothiophene		0.096	0.036	0.038	0.38
Phenanthrene		0.81	0.46	0.53	1.1
Anthracene		0.051	0.029	0.069	0.059
Fluoranthene		0.22	0.16	0.13	0.23
Pyrene		0.22	0.19	0.20	0.22
Cyclopenta[c,d]pyrene		0	0	0	0.026
Benz[a]anthracene		0.026	0.021	0.16	0.018
Chrysene		0.042	0.041	0.030	0.038
Benzofluoranthenes		0.051	0.046	0.028	0.041
Benzo[e]pyrene		0.030	0.031	0.024	0.014
Benzo[a]pyrene		0.033	0.036	0.032	0.044
Indeno[1,2,3-c,d]pyrene		0.033	0.031	0.020	0.019
Dibenzo[a,h]anthracene		0.045	0.041	0.024	0.030
Benzo[g,h,i]perylene		0.030	0.031	0.017	0.024

(a) Concentrations are for dilute exhaust collected from test cell roof.

TABLE 12. TOTAL EXTRACTABLE ORGANIC MATTER

ENGINE	POWER SETTING	TEST NO.	TOTAL EXTRACTABLE ORGANIC MASS, mg	TOTAL SAMPLED[a] VOLUME m^3	CONCENTRATION OF EXTRACTABLE ORGANIC MASS, mg/m^3
F110	Idle	1-6-15	0.24	0.3133	0.77
F110	30%	2-6-15	0.32	0.4259	0.75
F110	63%	3-6-15	0.20	0.4268	0.47
F110	Intermediate	4-6-15	0.36	0.4189	0.86
F110	Augmentation	5-6-15	3.7	0.3349	11
F101	Idle	1-6-17	0.20	0.3339	0.60
F101	44%	2-6-17	0.20	0.4175	0.48
F101	75%	3-6-17	0.20	0.4941	0.40
F101	Augmentation	5-6-17	2.8	0.3383	8.3

(a) The sample volume of each XAD-2 sample was corrected at STP conditions.

E. PARTICLE EMISSIONS

Several procedures were employed in an attempt to gather information on the particulate emissions from turbine engines. The procedures include determination of smoke number, gravimetric determination of mass loading, and size distribution measurements by two different techniques. The results from these measurements are described below.

1. Smoke Emissions

Smoke emission was determined by the procedures described in Section IIC. The smoke emissions from these engines were so low, that it was necessary to sample a larger volume of exhaust than the reference procedure specifies, in order to obtain a smoke measurement. Because these measurements were taken at higher (exhaust mass)/(filter spot area) ratios than standard, they will be biased high. See Section IIC for an explanation. The final smoke values for the two engines examined in these tests are listed in Table 13. In spite of the high bias, the reported values are quite low compared with smoke emissions measured for other engines.

TABLE 13. SMOKE VALUES AS FUNCTION OF POWER SETTING

ENGINE	POWER SETTING	SMOKE VALUE(a)
F110	Idle	1
	30%	0
	63%	4
	Intermediate	11
F101	Idle	1
	44%	4
	75%	9
	Intermediate	16

(a) SMOKE VALUE taken at W/A = 0.080 lbs/in^2 (see Section IIC).

2. Gravimetric Analysis

As noted in Section II, a Teflon®-coated glass fiber filter was used to collect particulate material in the exhaust for gravimetric analysis. The filter and filter holder were maintained at 150°C during sampling. After each test, the filter was removed from the holder, sealed, and transported to the laboratory for equilibration and weighing. The filter masses were corrected to account for the mass change of handled blank filters. These blanks were handled in the same manner as the samples, including heating for 45 minutes at 150°C in the stainless steel filter holder, but without exhaust flow through the filter. The results from the gravimetric analysis of the filters are shown in Table 14. The particle mass concentrations in Table 14 are all below the detection limit· The very low particle mass emissions in Table 14 are consistent with the low smoke numbers reported above, and confirm the cleanliness of these engines in terms of particle emissions.

TABLE 14. PARTICLE MASS EMISSIONS

ENGINE	POWER SETTING	TEST NO.	EXHAUST VOLUME(a), m^3	PARTICULATE MASS CONCENTRATION, mg/m^3
F110	Idle	1-6-15	1.39	<0.4
F110	30%	2-6-15	1.05	<0.4
F110	63%	3-6-15	1.05	<0.4
F110	Intermediate	4-6-15	1.41	<0.4
F101	Idle	1-6-17	0.51	<1
F101	30%	2-6-17	0.49	<0.4
F101	75%	3-6-17	1.05	<0.4
F101	100%	4-6-17	0.64	<0.4

(a) Corrected to NTP.

3. Particle Concentration and Size Distribution

Information on particle concentrations and size distributions in the exhaust from the test engines was obtained using the dilution apparatus, diffusion battery, and condensation nucleus counter noted earlier in Section II. The results from these measurements are presented in Table 15. The table shows particle concentration (in thousands of particles per cubic centimeter of air) in eight size ranges. Also listed are the total particle

TABLE 15. PARTICLE SIZE DISTRIBUTION AND TOTAL PARTICLE CONCENTRATION IN TURBINE ENGINE EXHAUST (THOUSANDS OF PARTICLES/cc)

MEAN PARTICLE DIAMETER (μM)		F101				F110			
	POWER SETTING:	IDLE	44%	75%	INTERMEDIATE	IDLE	30%	63%	INTERMEDIATE
0.004		1.5	23	<0.1	8.6	ND(a)	<0.1	<0.1	<0.1
0.008		170	83	<0.1	<0.1	ND	<0.1	<0.1	<0.1
0.013		430	210	220	<0.1	ND	<0.1	<0.1	<0.1
0.024		330	50	12	200	ND	<0.1	2.1	116
0.042		<0.1	81	51	150	ND	1.0	27	350
0.075		<0.1	<0.1	250	81	ND	15	25	70
0.133		<0.1	<0.1	32	180	ND	<0.1	4.3	23
0.237		<0.1	<0.1	3.1	27	ND	<0.1	<0.1	16
≥0.237		0.1	0.4	27	61	ND	1.0	3.0	18
Total Number Concentration		900	440	500	630	ND	14	58	510

(a) ND = no data.

concentration and the concentration of particles of mean diameter greater than 0.237 μm. These data are shown for each engine and power setting. The total number count is an observed value, whereas the size distributions are based on a model fit to the data. For this reason, the sum of the concentrations at the different particle sizes does not exactly correspond to the total number concentration listed in the table.

The final technique used for particle collection was an electrostatic sampler. As described in Section II, the electrostatic sampler collects particles on a substrate, which is then analyzed by scanning electron microscopy (SEM). The electrostatic sampler was used to determine whether particles larger than the upper limit of size discrimination capability of the diffusion battery/CNC were present. For the system used in this study, particles larger than 0.24 μm are counted, but no size information is determined. The electrostatic sampler was used to collect particles from the undiluted exhaust. These samples were returned to the laboratory and analyzed by SEM, initially at magnifications from 1000X to 2000X. The SEM analysis revealed that only a very few particles were visible at this magnification. This confirms the DB/CNC results from Table 15, which indicate that there are relatively small numbers of particles of diameter greater than 0.24 μm.

SECTION IV

OBSERVATIONS

A. CARBON BALANCE

An important aspect of this project is the accountability of organic species in turbine engine exhaust. Until recently, less than 40 percent of the organic emissions from turbine engines has been accounted for. However, a recent study which employed multiple sampling and analysis techniques was able to account for 98 ± 10 percent of the total organic emissions (Reference 1). In the current study, emission measurements were made on the F110 and F101 engines. These engines were operated with JP-4 fuel at five power settings from idle through Stage 1 augmentation (afterburner).

The normal method of accountability for organic species in turbine engine exhaust involves carrying out a carbon balance. Ideally, the carbon balance is defined as the ratio of the sum of all individual organic species measured in the exhaust to the total organic carbon concentration measured by a total carbon monitoring system. In this study, the total organic carbon instrument, a Beckman 402 Analyzer, employs a flame-ionization detector (FID) to continuously measure the sum of organic species concentration. This monitor is essentialy a carbon-counting instrument; however, it does not respond to oxygenated carbon. Because of this, formaldehyde is not detected, only one of the two acetaldehyde carbons is counted, etc. To compare the species sum with the total FID response, the species sum must be adjusted to eliminate contributions from oxygenated carbon.

The carbon balances achieved for the engines and test conditions in the current study are summarized in Table 16. The species data have been corrected for oxygenated compound response as described above and in earlier reports (References 1 and 2). As noted in the table, the response of the continuous total organic monitor becomes rather uncertain at concentrations less than about 10 ppmC, due to zero and span drift. As a consequence, the carbon balance at exhaust concentrations less than 10 ppmC is highly uncertain. At these low concentrations, the species summation is generally a more accurate representation of the exhaust organic concentration than the continuous FID value.

TABLE 16. COMPARISON OF TOTAL ORGANICS BY SPECIATION METHODS VERSUS CONTINUOUS FID (ppmC)

ENGINE	THRUST SETTING	TOTAL ORGANICS SPECIATION METHODS[a]	TOTAL ORGANICS CONTINUOUS FID	CARBON BALANCE[b]
F110	Idle	6.3	7	0.9
	30%	3.2	6	0.5
	63%	2.1	3	0.7
	Intermediate	2.4	3.5	0.7
	Augmentation (Stage 1)	256	335	0.8
F101	Idle	4.7	6.5	0.7
	44%	3.1	3.5	0.9
	75%	2.1	2.5	0.8
	Intermediate	2.4	3	0.8
	Augmentation (Stage 1)	274	287	1.0

(a) Adjusted for response of oxygenated carbon, as noted in text.

(b) Continuous FID organic measurements below about 10 ppmC are uncertain, and therefore the resulting carbon balances may be misleading.

B. INDIVIDUAL ORGANIC SPECIES

The individual organic species quantified in the emissions have been presented in Tables 8 and 9. In previous studies (References 1, 2, and 3), we have found that four species (ethene, acetylene, propene, and formaldehyde) are the dominant emissions at idle power, accounting for 20-30 percent of the organic concentration. This is also true for the F110 and F101 engines. Indeed, these species account for about 35 percent of the nonmethane organic compound (NMOC) concentration for the F110 engine at idle, and 60 percent of idle power NMOC for the F101 engine. At higher power settings up to intermediate power, the exhaust constituents present at the highest concentrations are methane, ethene, and formaldehyde. The emissions pattern under augmented power was different for the two engines. A substantial fraction of the organic emissions at Stage 1 augmentation was unburned fuel hydrocarbon for the F101 engine. On the other hand, the augmented power emissions from the F110 engine had a much higher contribution of combustion cracking products and products of incomplete combustion.

Examination of the data in Tables 8 and 9 reveal that the organic emissions are reduced as the engine power is increased from idle to intermediate power. The organic emissions increase substantially when the engines are operated in the augmented power (afterburner) mode. Exhaust organic concentrations for these two engines are much lower than for other engines we have tested (References 1, 2, and 3).

C. DISTRIBUTION OF EMISSIONS BY COMPOUND CLASS

The bottom portions of Tables 8 and 9 show the exhaust organic distribution according to major compound classes for each of the engines tested. This distribution is based only on identified compounds. The most significant compound classes are paraffins, olefins, aromatics, and aldehydes, with the relative contribution of these classes varying with power level. The distribution of organic emissions by compound class and for power settings from idle to intermediate is shown in Figure 10 for the F110 engine and in Figure 11 for the F101 engine. Compound class emissions for augmented power are shown for both engines in Figure 12.

D. DISTRIBUTION OF EMISSIONS BY CARBON NUMBER

The distribution of emissions by volatility is important because these data most clearly distinguish the cracking and partial oxidation products from the unburned fuel. The carbon number distributions for each of the engines tested are presented in Table 17. The results are plotted in Figures 13, 14, and 15.

E. EMISSION FACTORS

1. Nitrogen Oxide Emissions

The nitrogen oxide emissions from the F110 and F101 engines are shown in Table 18. Also shown in this table is the ratio of NO_2 to NO_x. The emissions of NO_2 are of concern because it is a Criteria Pollutant, regulated by the U.S. Environmental Protection Agency. The federal ambient

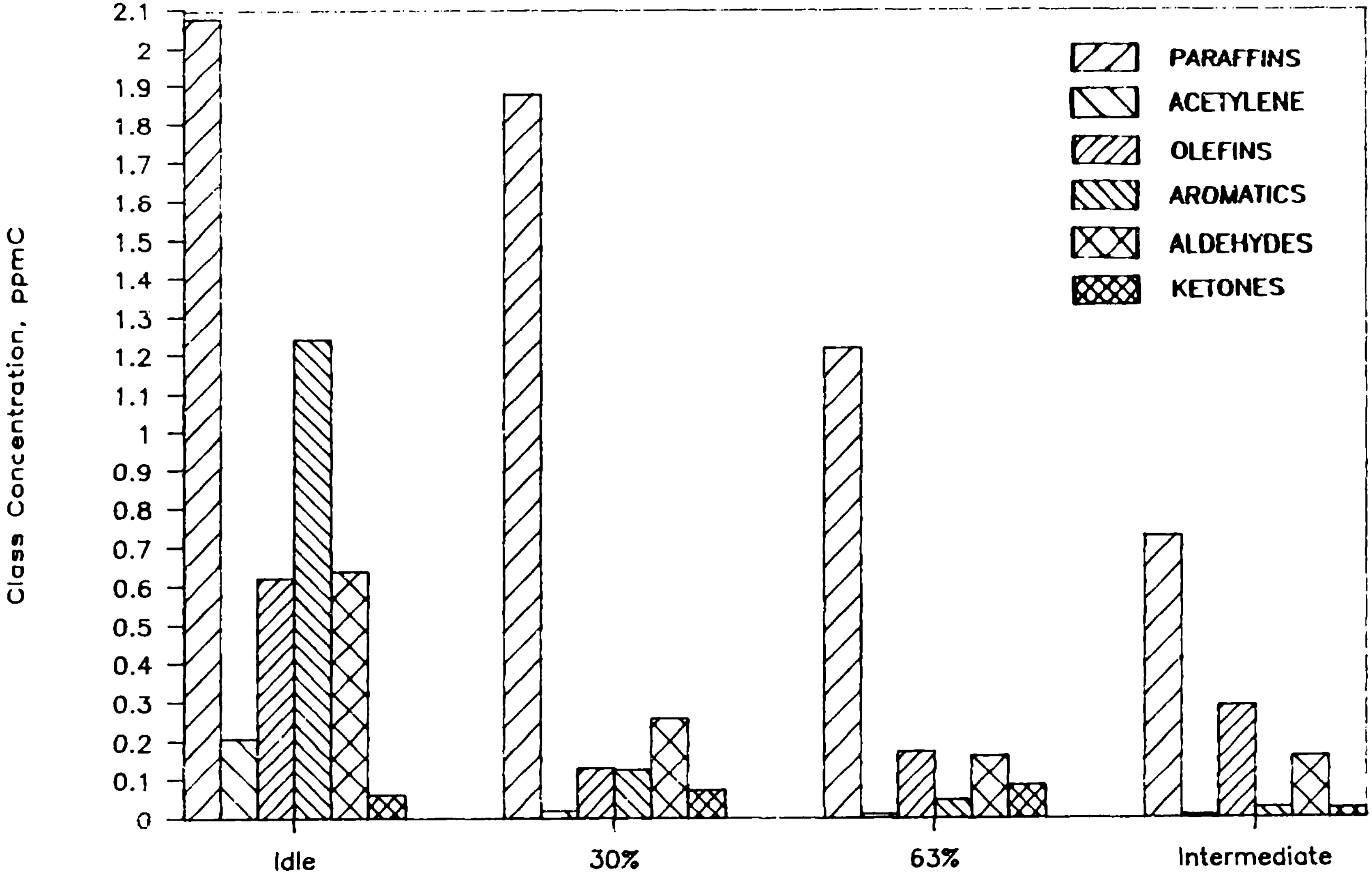

Figure 10. Exhaust Organic Compound Distribution by Compound Class for F110 Engine for Idle Through Intermediate Power Settings

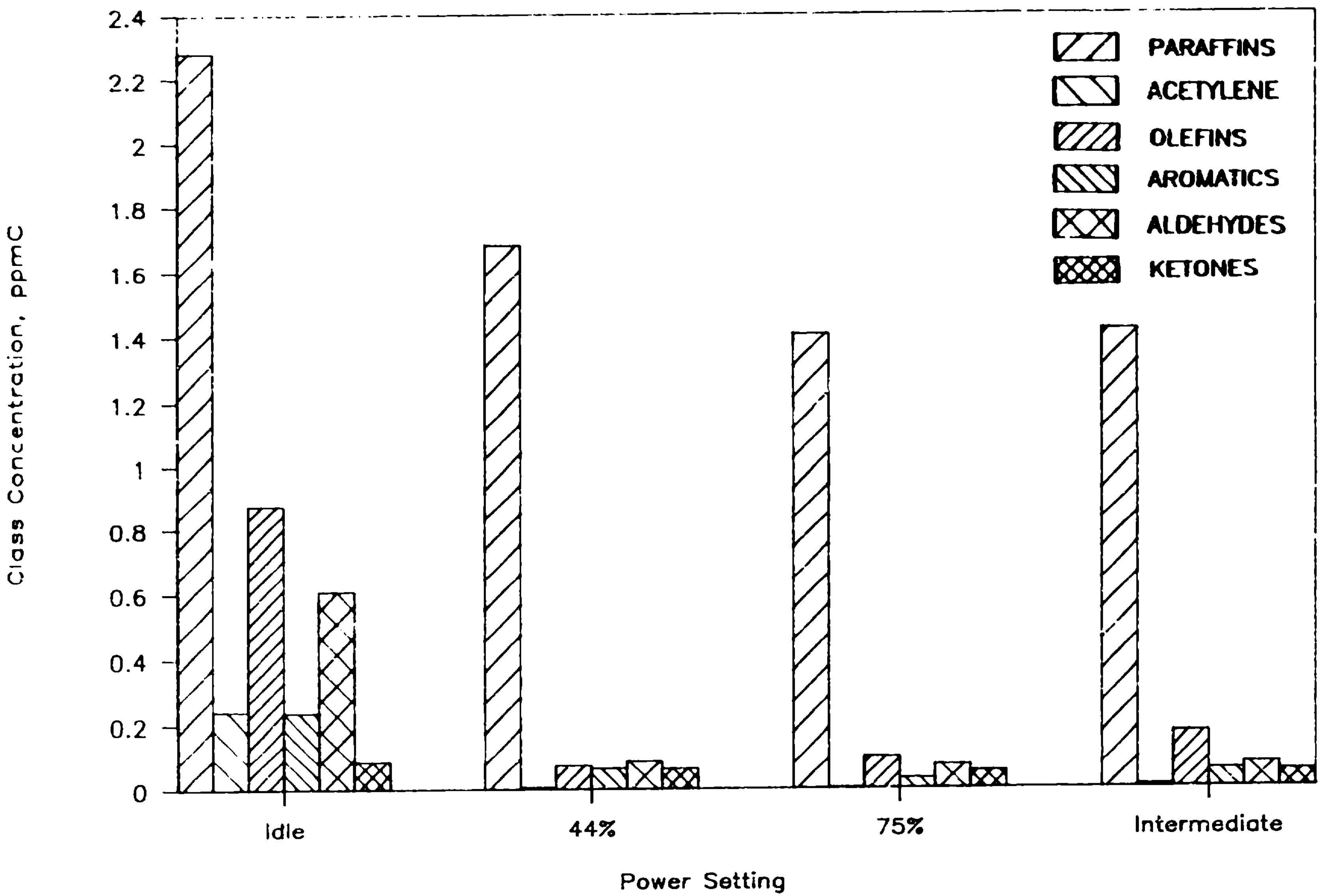

Figure 11. Exhaust Organic Compound Distribution by Compound Class for F101 Engine for Idle Through Intermediate Power Settings

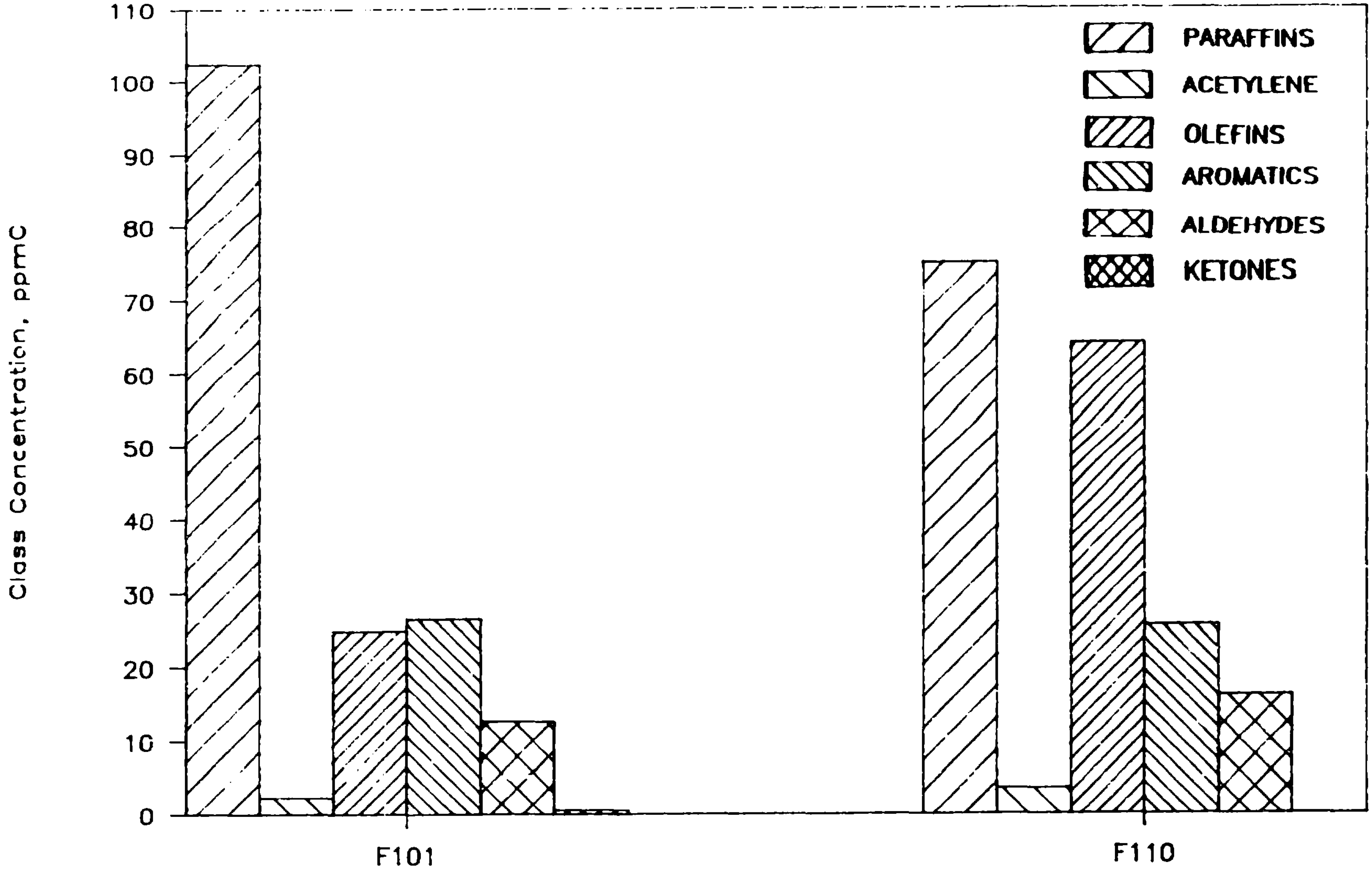

Figure 12. Exhaust Organic Compound Distribution by Compound Class for F101 and F110 Engine Operating With Stage 1 Augmented Power (Concentrations are for Dilute Exhaust Measured at Roof of Test Cell)

TABLE 17. DISTRIBUTION OF ORGANIC EMISSIONS BY CARBON NUMBER FOR F101 AND F110 ENGINES AT VARIOUS POWER SETTINGS (CONCENTRATIONS IN ppmC)

Engine	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	Total
F-101 Idle	2.193	1.131	0.378	0.143	0.222	0.331	0.205	0.115	0.071	0.038	0.029	0.015	0.147	0.012	0.128	5.158
F-101 44 %	1.586	0.123	0.089	0.216	0.217	0.229	0.086	0.171	0.122	0.084	0.031	0.052	0.050	0.043	0.055	3.154
F-101 75 %	1.346	0.122	0.082	0.074	0.191	0.067	0.048	0.048	0.039	0.021	0.046	0.076	0.007	0.002	0.022	2.191
F-101 100 %	1.281	0.150	0.087	0.072	0.369	0.119	0.103	0.074	0.060	0.023	0.014	0.100	0.007	0.002	0.001	2.462
F-101 AB(a)	8.846	19.674	10.091	7.324	16.597	51.154	54.655	37.204	24.788	13.854	7.876	6.098	4.197	2.114	0.593	265.065
F-110 Idle	2.071	0.942	0.300	0.298	0.267	0.168	1.070	0.259	0.529	0.165	0.088	0.055	0.091	0.346	0.193	6.840
F-110 30 %	1.624	0.211	0.127	0.338	0.234	0.162	0.157	0.130	0.145	0.116	0.051	0.030	0.041	0.053	0.026	3.445
F-110 63 %	1.193	0.208	0.136	0.055	0.228	0.077	0.053	0.041	0.029	0.018	0.012	0.005	0.013	0.012	0.008	2.089
F-110 100 %	0.764	0.298	0.098	0.061	0.140	0.036	0.030	0.022	0.019	0.009	0.007	0.002	0.007	0.005	0.002	1.502
F-110 AB(a)	13.888	39.208	23.729	14.565	15.888	42.341	31.666	37.419	17.680	11.115	8.308	6.451	4.524	2.188	0.509	285.579

(a) Augmented Power (Stage 1); concentrations are for dilute exhaust.

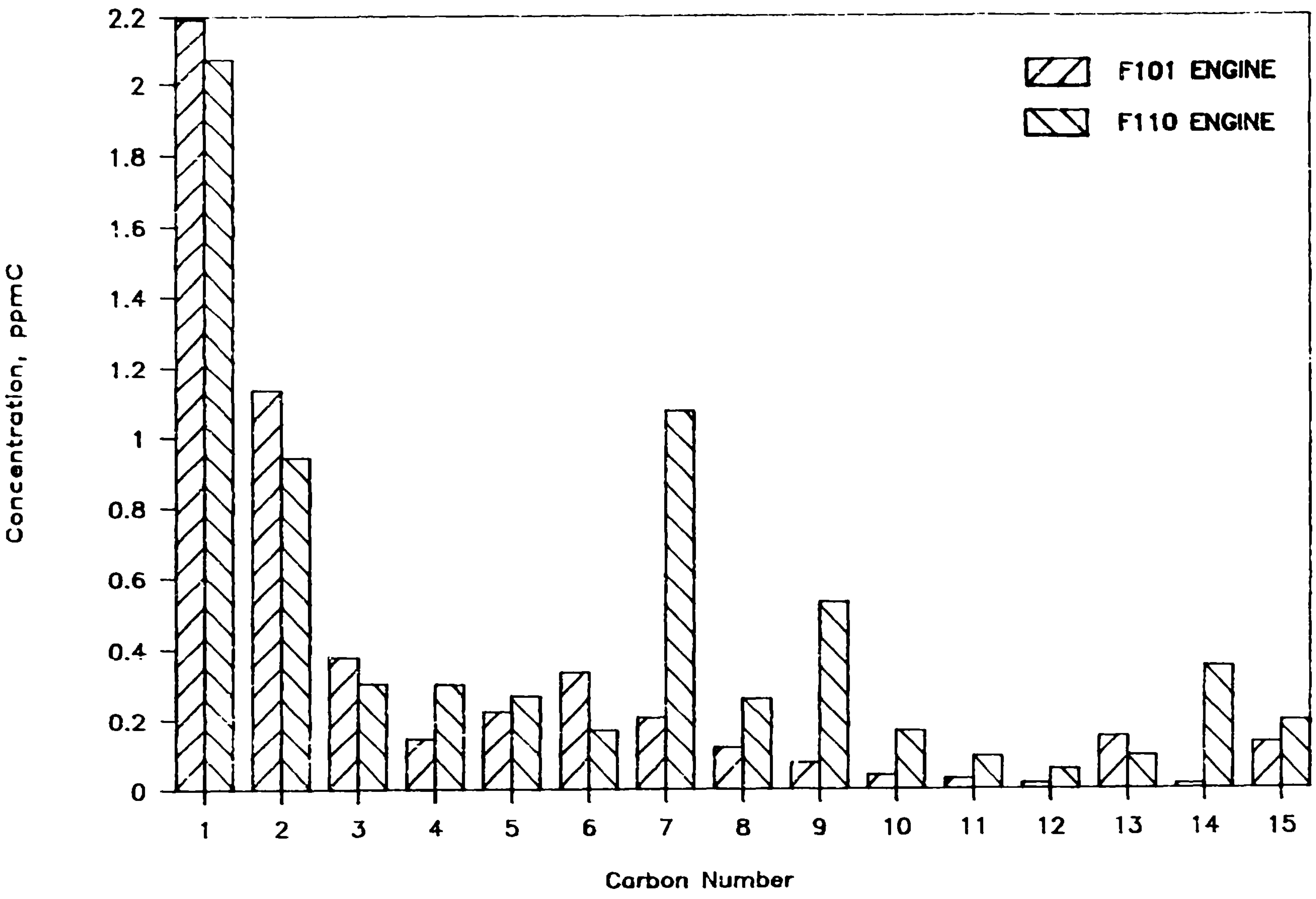

Figure 13. Exhaust Organic Species Concentrations by Carbon Number at Idle

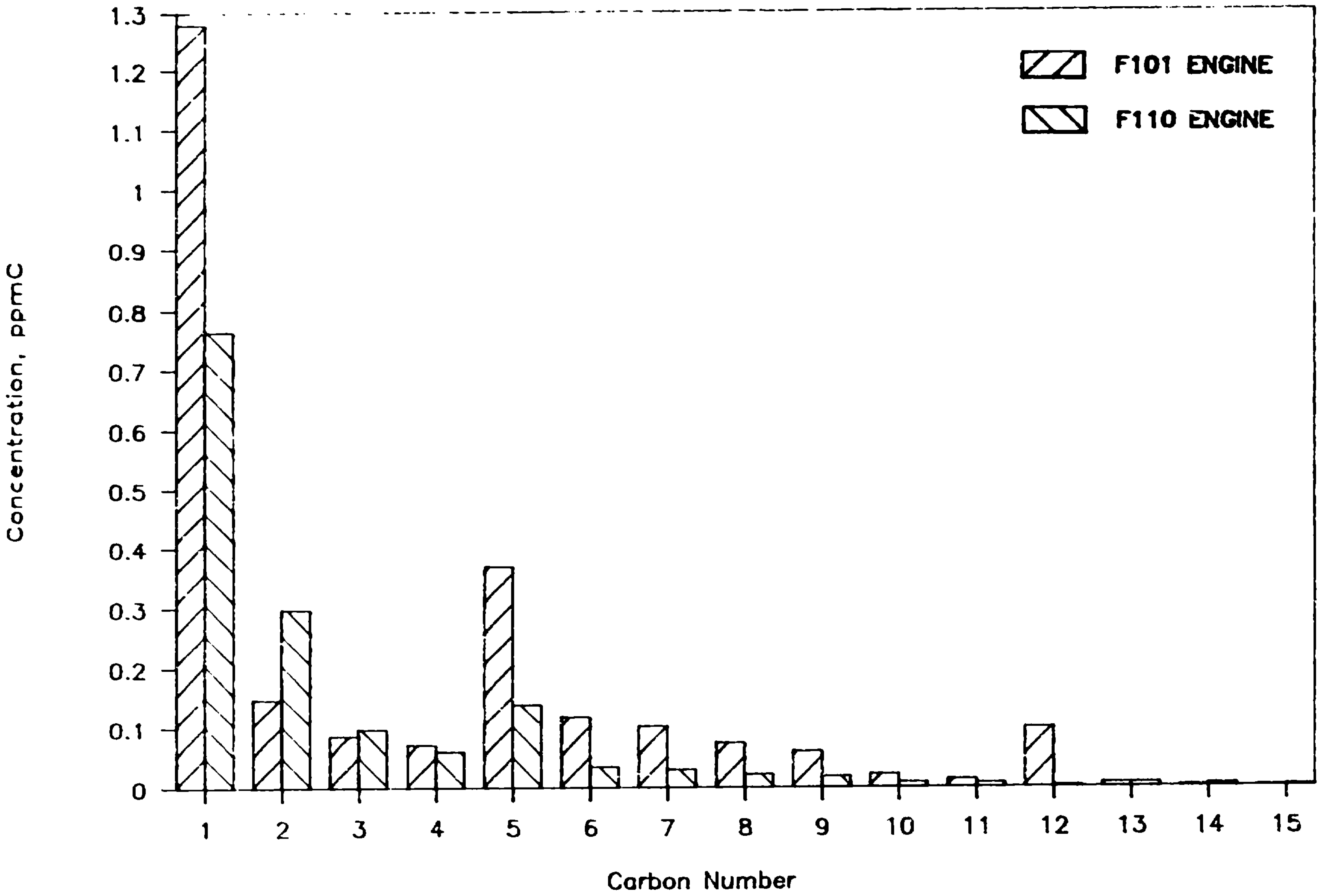

Figure 14. Exhaust Organic Species Concentrations by Carbon Number at Intermediate Power

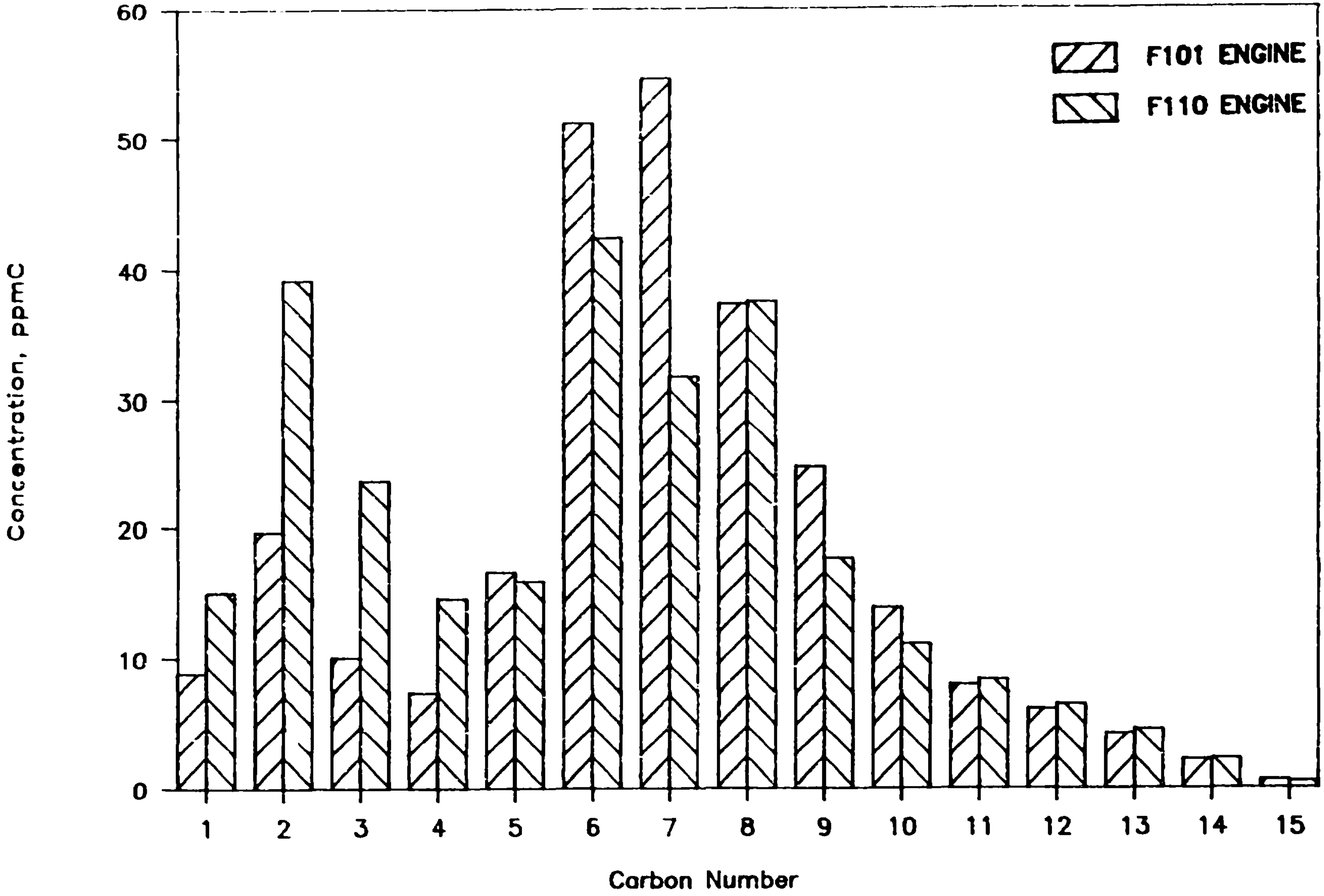

Figure 15. Exhaust Organic Species Concentrations by Carbon Number with Augmented Power (Concentrations are for Dilute Exhaust Measured at Roof of Test Cell)

air standard currently is based on annual average concentration. California has enacted a short-term NO_2 standard and has expressed concern over NO_2 emissions from engine test cells due to visibility impairment.

The data in Table 18 show that the concentrations of both NO and NO_x increase with power setting from idle to intermediate power. The data for afterburner power were taken at the test cell rooftop, where the exhaust stream has been diluted with entrained ambient air. Therefore, the concentrations of NO and NO_x are lower for the afterburner power settings than for intermediate power. However, even though the exhaust sampled at afterburner power has been diluted, it still yields the highest NO_2 concentration for both engines. The final column of Table 18 shows the NO_2/NO_x ratio, which decreases as power increases up to full intermediate power, and then increases abruptly at augmented power. This same phenomenon was observed during tests with TF30-P103 and TF30-P109 engines (Reference 2). One mechanism of NO_2 formation in engine exhaust is oxidation of NO by peroxy radicals. The concentration of peroxy radicals is expected to be enhanced in fuel-rich combustion, where organic species are available for peroxy radical formation. Table 7 shows that organic emissions are much higher under augmented power than at any other power setting. This may account for the higher ratio of NO_2/NO_x at afterburner power, and at idle.

2. Fuel/Air Ratios

During the engine tests, fuel flow and air flow to the engines were monitored. These data were reported in Tables 4 and 5, together with the fuel/air ratios for each test. Two fuel/air ratios are reported in the tables, one based on ambient conditions and the other corrected to "standard day" conditions. For comparison data, we will use the corrected fuel/air ratios to be consistent with our earlier reports (References 1, 2, and 3). The measured fuel/air ratios from Tables 4 and 5 are compared with ratios derived from exhaust composition data in Table 19. Ratios derived from composition data are reported as F/A (Calculated) in Table 19. There is greater deviation between the measured and calculated ratios than we have observed in our previous engine emissions studies. The calculated ratio is higher than the measured ratio for all tests but one. The deviation in calculated and measured ratios ranges from 2 percent low to 35 percent high.

TABLE 18. NO_x EMISSION DATA

POWER MODE	RUN NO.	NO_x, ppm	NO, ppm	NO_2, ppm	NO_2/NO_x
		<u>Engine F110 (S/N 509153)</u>			
Idle	1-6-15	13.8	11.2	2.6	0.19
30%	2-6-15	30.0	28.0	2.0	0.07
63%	3-6-15	97.0	92.0	5.0	0.05
Intermediate	4-6-15	243.0	227.0	16.0	0.07
Augmentation (Stage 1)(a)	5-6-15	21.5(a)	3.7(a)	17.8(a)	0.83(a)
		<u>Engine F101 (S/N 470135)</u>			
Idle	1-6-17	6.9	5.0	1.9	0.28
44%	2-6-17	28.5	25.5	3.0	0.11
75%	3-6-17	68.0	62.0	6.0	0.09
Intermediate	4-6-17	140.0	133.0	7.0	0.05
Augmentation (Stage 1)(a)	5-6-17	21.8(a)	7.2(a)	14.6(a)	0.67(a)

(a) Afterburner measurements made on dilute exhaust.

TABLE 19. FUEL/AIR RATIOS

POWER MODE	RUN NO.	F/A (MEASURED)	F/A (CALCULATED)
		<u>Engine F110 (S/N 509153)</u>	
Idle	1-6-15	0.003541	0.004643
30%	2-6-15	0.005412	0.005912
63%	3-6-15	0.008257	0.01116
Intermediate	4-6-15	0.01138	0.01504
		<u>Engine F101 (S/N 470135)</u>	
Idle	1-6-17	0.002342	0.002308
44%	2-6-17	0.004386	0.004605
75%	3-6-17	0.005977	0.007200
Intermediate	4-6-17	0.007833	0.009591

On average, the ratios calculated from exhaust composition are 19 percent higher than measured fuel/air ratios. Differences in the measured and calculated fuel/air ratios could be due to nonrepresentative exhaust sampling, but nonrepresentative sampling with the 12-port sampling rake used in this study would most likely involve sampling of ambient air at the outer edges of the exhaust plume, and this would result in a calculated F/A which was too low, not too high as observed here. The other possibility for deviation relates to measurement error or uncertainty in the fuel flows, air flows, or exhaust composition results. We have reexamined all of these data and the corresponding calibrations, and have found no reason to invalidate any of the results. Consequently, we can not explain the observed differences between the measured and calculated fuel/air ratios. The measured air flow is very sensitive to small errors in pressure measurement, where a 0.1 psia error in pressure measurement can cause a 16 percent error in measured F/A at idle power. It is possible that drift of the output signal from the pressure transducer could be contributing to the F/A ratio discrepancies, but we have no evidence to support this or other alternative explanations.

3. Emission Indices

The emission index, in pounds per thousand pounds of fuel, has been calculated for CO, CO_2, total hydrocarbon, NO, NO_2, and NO_x for power levels from idle to intermediate. The emission index has also been determined under augmented power for CO, NO, NO_x, and total hydrocarbons. The calculation procedures were noted in Section II. The emission indices for the two engines at each power setting are given in Table 20. As noted in the table, all oxidized nitrogen species were calculated using the molecular weight of NO_2, in accordance with the convention employed in such calculations. The emission indices show that emissions of CO and hydrocarbons per thousand pounds of fuel decrease as power is increased from idle to intermediate. Both increase substantially with augmented power. Emission indices for NO and NO_x increase with increasing power from idle to intermediate. The emissions index for NO_2 shows no clear trend with engine power. The CO_2 emission index for the F110 engine shows little trend with power setting, while the index for the F101 increases with power level.

TABLE 20. EMISSION INDICES FOR F110 AND F101 ENGINES

	EMISSION INDEX (LBS/10^3 LB FUEL)					
NO_x(a)	CO	CO_2	HC	NO(a)	NO_2	NO_x(a)
F110 Engine						
Idle	24.0	4352	1.01	5.3	1.2	6.6
30%	4.3	3638	0.57	8.8	0.63	9.4
63%	1.6	4473	0.19	19.0	1.0	20.1
Intermediate (105%)	1.3	4378	0.16	34.3	2.4	36.8
Augmentation (Stage 1)	83.3	--	78.4	2.8	--	16.5
F101 Engine						
Idle	21.7	3408	1.44	3.6	1.4	5.0
44%	1.8	3511	0.41	9.8	1.2	11.0
75%	1.3	3982	0.21	17.5	1.7	19.2
Intermediate (108%)	1.4	4162	0.20	29.7	1.6	31.3
Augmentation (Stage 1)	71.6	--	88.3	7.7	--	23.3

(a) Calculated as NO_2 by convention.

The emission indices for the engines may be used with the fuel flow data in Tables 4 and 5 to calculate emission rates. The emission rates are shown in Table 21 for power settings from idle through Stage 1 augmentation. These rates are given in units of pounds per hour. The emission rates for CO are highest for augmented power, while the rates for CO_2, NO, NO_2, and NO_x increase as engine power is increased from idle to intermediate. The rates for hydrocarbons are low at all power settings from idle to intermediate,and very high in afterburner mode. The CO emission rates for these two engines are significantly lower than the rates for other engines we have tested for power settings below intermediate (Reference 2 and 3). The CO emission rates at intermediate power are fairly similar for all the engines we have examined. The CO_2, NO, and NO_x emission rates for these two engines are generally higher at all power settings than other engines we tested previously (References 2 and 3). Perhaps the greatest difference between these two engines and other engines we have tested is the significantly lower hydrocarbon emissions rate for the F110 and F101 engines at low power, especially at idle. These two engines appear to be substantially more efficient at fuel combustion at low power than engines tested earlier. However, they are significant organic emitters under Stage 1 augmented power. The sampling strategy and data reduction methodology employed for the afterburner emissions were tested in an earlier study (Reference 2), and the results confirmed the utility of this approach.

TABLE 21. EMISSION RATES FOR F110 AND F101 ENGINES

	EMISSION RATES (LB/HR)					
	CO	CO_2 (x 10^3)	HC	NO[a]	NO_2	NO_x[a]
F110 Engine						
Idle	25.4	4.6	1.1	5.6	1.3	7.0
30%	10.5	9.0	1.4	21.7	1.6	23
63%	8.7	24.7	1.0	105	5.7	111
Intermediate (105%)	13.1	43.6	1.6	342	24	366
Augmentation (Stage 1)	1289	--	1213	43.3	--	255
F101 Engine						
Idle	22.0	3.4	1.5	3.7	1.4	5.1
44%	6.6	12.7	1.5	35.3	4.2	40
75%	8.4	25.2	1.4	111	6.1	122
Intermediate (108%)	13.4	38.6	1.9	275	14	290
Augmentation (Stage 1)	1009	--	1244	108	--	328

(a) Calculated as NO_2 by convention.

Care should be exercised in comparing the various engines we have tested, because the engines are not all rated at the same maximum thrust, so the same "power setting" will produce different thrust for each engine. These power output differences should be considered in comparing emissions among engines.

F. RELATIVE EMISSIONS OF TOXIC CHEMICALS

Numerous methods are available to present data on emissions from a source. From jet engines, the emissions can be reported as concentrations, emission indices (g/kg fuel), emission rates (g/hr), mass per unit thrust, and so forth. Because different uses of the data require different presentations, our approach has been to list the data in concentration units, and include all the ancillary information needed to calculate the results in whatever form the user may require.

To provide some general perspective on emission levels of chemicals of toxicological significance, the emissions from these engines were compared with those from other combustion sources for selected chemicals. These comparisons were made on the basis of pollutant mass per mass of fuel consumed, or undiluted exhaust concentration. Other applications may require comparisons on the basis of thrust, miles traveled, unit time, etc. The emissions for benzene and benzo(a)pyrene were calculated by multiplying the weight percent of the constituent in the exhaust by the total organic emissions index from Table 20. This yields emissions in mass per mass of fuel consumed. The weight percent values were derived from the pollutant concentrations (in ppmC) and the total organic emissions (in ppmC). The data in Tables 8 and 9 were used for these calculations. The total species summations in Table 17 were used to determine weight percentage, because these values are considered to be more accurate at the higher power settings than the total hydrocarbon values reported in Table 7.

1. Benzene

Benzene is an environmentally significant compound because it is known to cause leukemia in workers exposed to relatively high levels. The current workplace standard for this chemical is set at 10 ppm (60 ppmC), although this standard is controversial and has been set as low as 1 ppm (6 ppmC) in the recent past. Benzene's route of entry into the body is primarily by inhalation of the gas. Benzene is poorly absorbed through unbroken skin. Other routes include ingestion and eye contact. Acute exposure can lead to headache, dizziness, causea, convulsions, coma, and death in extreme cases. Chronic exposure causes changes in the blood, including aplastic anemia, anemia, leukopenia, and thrombocytopenia. There is strong evidence that benzene causes acute myelogenous leukemia (Reference 9).

Emission levels of benzene from the two study engines were 79 ppbC for the F110 and 104 ppbC for the F101 in the undiluted exhaust at idle power (where exposure of flight line personnel is maximum). These exhaust concentrations are one to two orders of magnitude lower than benzene concentrations in the exhaust from other engines we have examined

(Reference 1-3). At higher engine power levels up through intermediate power, the exhaust concentration of benzene decreases. As noted in Tables 9 and 10, emissions of benzene, as well as other fuel hydrocarbons, increase dramatically in the augmented power mode.

The benzene emissions from the two test engines are compared with emissions from automobiles operating on the 1975 Federal Test Procedure with and without catalytic converters (Reference 10), and eight jet engines studied previously (References 1-3), in Table 22. These two engines produce the lowest benzene emissions per unit mass of fuel consumed of any of the combustion sources listed in Table 22.

TABLE 22. COMPARISON OF BENZENE EMISSIONS FROM VARIOUS MOBILE SOURCES

SOURCE	TYPE	POWER	FUEL	BENZENE EMISSIONS, mg/g OF FUEL
F101	Turbine engine	Idle	JP-4	0.029
F110	Turbine engine	idle	JP-4	0.012
J79 (smokeless)	Turbine engine	Idle	JP-4	0.51
TF33-P3	Turbine engine	Idle	JP-4	0.93
TF33-P7	Turbine engine	Idle	JP-4	0.88
TF39	Turbine engine	Idle	JP-5	0.42
CFM-56	Turbine engine	Idle	JP-4	0.09
TF41-A2	Turbine engine	Idle	JP-4	1.94
TF30-P103	Turbine engine	Idle	JP-4	1.06
Automobile	Catalyst-equipped	Federal driving cycle	--	0.13
Automobile	Noncatalyst	Federal driving cycle	--	0.75

2. Aldehydes

Aldehydes represent one of the most significant classes of compounds emitted by turbine engines from a health perspective (Reference 9). Formaldehyde is a suspected animal carcinogen, a potential occupational carcinogen, and is classified as a hazardous substance by EPA (Reference 9). The route of entry into the body is through inhalation and skin absorption. Gaseous formaldehyde causes severe irritation of mucus membranes in the respiratory tract and the eyes. Inhalation of the gas can cause urticaria; at high concentrations coughing, breathing difficulty, and pulmonary edema can occur. There is evidence that inhalation of formaldehyde causes nasal cancer in rats (Reference 9). Other hazardous aldehydes include acrolein and acetaldehyde, which are irritating to the eyes, skin, and upper respiratory tract at very low levels.

The Occupational Safety and Health Administration (OSHA) standard for formaldehyde is 3 ppm, but National Institute of Occupational Safety and Health (NIOSH) has recommended a ceiling of 0.8 ppm for any 30-minute period (Reference 9). The concentration of formaldehyde in undiluted exhaust at engine idle was 0.31 ppm for the F110 and 0.33 ppm for the F101. The concentrations in diluted exhaust under augmented power were 9.9 and 6.0 ppm. We estimate that the exhaust was diluted by about an order of magnitude, so the actual exhaust concentrations were probably in the range of 50-100 ppm. This represents a very significant localized source of formaldehyde in the atmosphere. Table 23 compares the concentration of formaldehyde in exhaust from several mobile sources (References 1-3,11).

TABLE 23. FORMALDEHYDE CONCENTRATIONS IN EXHAUST FROM MOBILE SOURCES

SOURCE	TYPE	POWER	FUEL	FORMALDEHYDE CONCENTRATION, ppm
F110	Turbine engine	Idle	JP-4	0.31
F101	Turbine engine	Idle	JP-4	0.33
J79 (smokeless)	Turbine engine	Idle	JP-4	15.9
TF33-P3	Turbine engine	Idle	JP-4	15.5
TF33-P7	Turbine engine	Idle	JP-4	16.6
TF39	Turbine engine	Idle	JP-4	14.6
CFM-56	Turbine engine	Idle	JP-4	9.3
TF41-A2	Turbine engine	Idle	JP-4	17.8
TF30-P103	Turbine engine	Idle	JP-4	9.3
TF30-P109	Turbine engine	Idle	JP-4	9.0
Automobile	Noncatalyst	Driving cycle	--	24
Automobile	Catalyst-equipped	Driving cycle	--	3.6
Diesel	Light duty (1978)	Driving cycle	--	5.7
Diesel	Light duty (1980)	Driving cycle	--	7.0

3. Polynuclear Aromatic Hydrocarbons (PAH)

The concentrations in exhaust from turbine engines are generally higher than light duty diesels or catalyst-equipped automobiles, with the exception of the F110 and F101 engines, for which the exhaust concentrations at idle are more than an order of magnitude lower than the other sources listed in Table 23. This comparison is for direct exhaust concentrations; comparisons on the basis of fuel consumption, miles traveled, or emission rates may yield a different perception of the relative emissions from these sources.

The class of compounds known as polynuclear aromatic hydrocarbons (PAH) contains numerous potent carcinogens (Reference 9). Benzo(a)pyrene (BaP) is one of the most common and most hazardous members of this class of compound, and is frequently used as a surrogate for PAH in general. The route of entry for BaP is inhalation and ingestion. BaP has been found in emissions from a variety of combustion sources, in urban air, cigarette smoke, and food sources. BaP produces tumors in all nine animal species which have been tested. It has both a local and a systemic carcinogenic effect (Reference 9). The OSHA standard for BaP is 0.2 mg/m^3 for [illegible] hour time-weighted average (Reference 9). Emissions of BaP from several mobile sources are noted in Table 24 (Reference 12).

TABLE 24. COMPARISON OF BENZO(a)PYRENE EMISSIONS FROM SEVERAL EMISSIONS SOURCES

SOURCE	TYPE	POWER	FUEL	BaP, µg/g OF FUEL
F110	Turbine engine	Idle	JP-4	0.021
F101	Turbine engine	Idle	JP-4	0.018
J79 (smokeless)	Turbine engine	Idle	JP-4	< 0.0013
TF33-P3	Turbine engine	Idle	JP-4	< 0.0013
TF33-P7	Turbine engine	Idle	JP-4	< 0.0013
TF39	Turbine engine	Idle	JP-5	0.0051
CFM-56	Turbine engine	Idle	JP-4	0.024
TF41-A2	Turbine engine	Idle	JP-4	0.0064
TF30-P103	Turbine engine	Idle	JP-4	< 0.0013
Automobile	Diesel	Driving cycle	--	0.03-0.16
Automobile	Internal combustion	Driving cycle	Unleaded	0.014
uck	Diesel	Driving cycle	--	0.0038
uck	Internal combustion	Driving cycle	--	0.065

The data in Table 24 indicate that both the F101 and F110 engines emit more BaP per mass of fuel consumed than most of the other turbine engines for which data are available. On this same comparison basis, diesel automobiles and internal combustion engine trucks show higher emissions. However, the exhaust concentrations of BaP, shown earlier in Tables 10 and 11, are over three orders of magnitude lower than the OSHA standard for an 8-hour time-weighted average exposure.

4. Carbon Monoxide

Carbon monoxide is an odorless, colorless, tasteless gas which is emitted by nearly all combustion sources. Its route of entry is by inhalation. It combines with hemoglobin in the blood to produce carboxyhemoglobin, which reduces the capacity of the blood to carry oxygen, leading to a state of tissue hypoxia. Acute exposure to CO can cause headache, dizziness, drowsiness, nausea, vomiting, coma, and death. Severe carbon monoxide exposure has been reported to permanently damage the extrapyramidal system (Reference 9).

The OSHA standard for CO is 50 ppm for an 8-hour time-weighted average. The EPA ambient air standard is 9 ppm averaged over an 8-hour period, and 35 ppm for 1 hour, not to be exceeded more than once a year (Reference 9). Exhaust concentrations of CO for the study engines are listed in Table 25. These are concentrations at idle power in undiluted exhaust. The concentrations in F110 and F101 exhaust at idle are significantly lower than other engines listed in Table 25. Table 7 shows that the CO concentration decreases significantly at higher power settings below augmented power.

5. Nitrogen Dioxide

Nitrogen dioxide (NO_2) is classified as a hazardous substance by EPA. Its route of entry to the body is inhalation, along with skin and eye contact. At high concentrations, NO_2 may cause irritation of the eyes and mucus membrances, and may result in severe pulmonary irritation. Even lower concentrations may produce acute pulmonary edema. Chronic exposure may result in pulmonary dysfunction with decreased vital capacity and signs of emphysema (Reference 9).

TABLE 25. CONCENTRATIONS OF CO IN UNDILUTED ENGINE EXHAUST AT IDLE POWER (JP-4 FUEL)

ENGINE	CO CONCENTRATION, ppm
F110	85
F101	50
J79 (smokeless)	700
TF33-P3	680
TF33-P7	930
TF39	550
CFM-56	640
TF41-A2	772
TF30-P103	276
TF30-P109	283

The OSHA standard for NO_2 is 5 ppm for a time-weighted 8-hour period. The EPA ambient air standard is 0.05 ppm on an annual average basis. The concentrations of NO_2 in exhaust from several turbine engines is shown in Table 26. These concentrations are for undiluted exhaust. As expected, the NO_2 concentrations increase at higher power settings. The NO_2 exhaust concentrations for the study engines are lower than the levels reported for other turbine engines (References 1-3). The relationship between NO_2 emissions and engine power settings was discussed earlier in this report.

TABLE 26. CONCENTRATIONS OF NO_2 IN JET ENGINE EXHAUST

ENGINE	NO_2 CONCENTRATION, ppm	
	IDLE POWER	30 PERCENT POWER
F110	2.6	2.0
F101	1.9	3.0(a)
J79 (smokeless)	4.9	10.5
TF33-P3	7.5	13.8
TF33-P7	5.7	13.0
TF39	5.8	18
CFM-56	5.6	9
TF41-A2	4.4	14.2
TF30-P103	4.1	13.1
TF30-P109	4.5	12.0

(a) 44 percent power.

G. PARTICLE SIZE DISTRIBUTION

The particle size distribution obtained at different power settings for the F110 and F101 turbine engines is provided in Table 15. The table shows that the particle concentrations are quite low for both the F101 and F110 engines. The exhaust particle concentrations from these engines are significantly lower than other engines we have examined (References 2 and 3)), with the exception of the J79 (smokeless) engine, which yielded particle emissions only slightly higher than the F101. For both the F101 and F110 engines, the data in Table 15 indicate that most of the particles have diameters less than 0.1 μm. The particle size distribution for the F101 engine shifts to larger diameter particles at higher power settings, while, for the F110, relatively few particles are found at power settings below intermediate.

An increase in mean particle diameter with increasing power is consistent with results from other engines (References 2 and 3). Table 13 showed that smoke emissions increased with power setting for both of these engines. The fact that the greatest number concentration was observed for the F101 at idle power demonstrates that number concentration alone can not explain light attenuation, upon which smoke observations are based. Light attenuation and light scattering depend strongly on particle size over this range of sizes. Although there are a number of complicating factors, roughly speaking, the attenuation increases with particle volume below about 0.1 μm and with particle surface area above this size. Thus, attenuation increases with particle radius cubed or squared over the size range observed for these engines. Because of this sensitive relationship between attenuation and size, small changes in the size distribution can yield significant changes in light attenuation. This is clearly demonstrated by the F101 data, where the total particle number concentration changes little with increasing power, but the smoke value increases significantly from idle to intermediate power.

The data in Table 15 show that most particles emitted by these engines are smaller than 0.2 μm. This is confirmed by the photomicrographs which resulted from the electrostatically collected exhaust particle samples. These samples were collected to determine whether a significant concentration of large particles ($\geq$ 1 μm) might be present in turbine engine exhaust. Photomicrographs of three exhaust samples are shown in Figures

16-18. Particles were collected on Nuclepore filters as described in Section II, and the filter pores which are visible in these pictures are 0.1 μm diameter. Very small particles (< 0.03 μm) are not visible at these magnifications, and are difficult to find at higher magnifications because the number of particles emitted by these engines is so low, and the field of view is greatly reduced at higher magnification. Our microscopic analysis of the filter samples confirms the negligible number of large particles in the exhaust, and confirms that most particles emitted by these engines have mean diameters less than 0.2 μm.

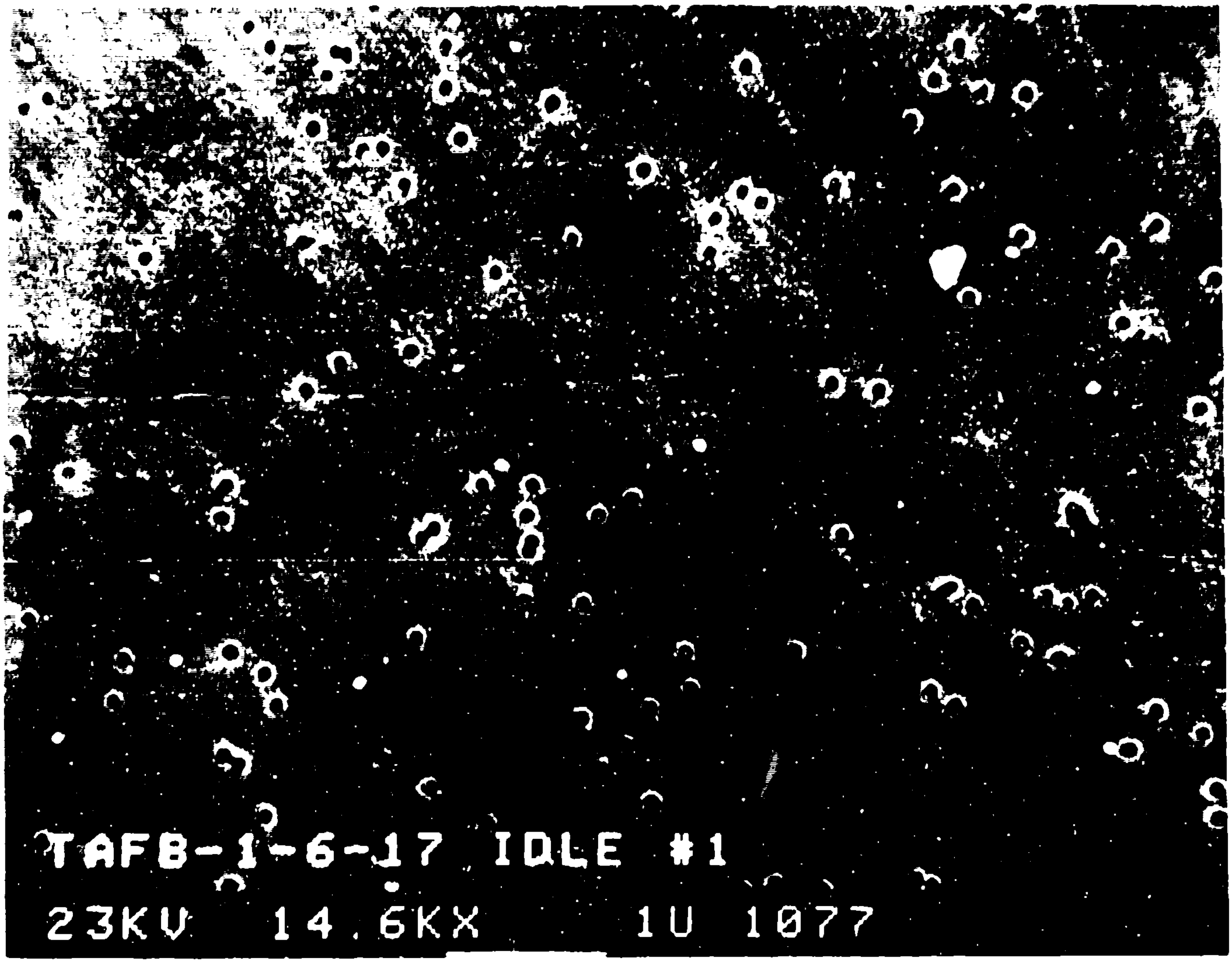

Figure 16. Photomicrograph of Exhaust Particles From F101 Engine At Idle (Filter Pores are 0.1 μm Diameter)

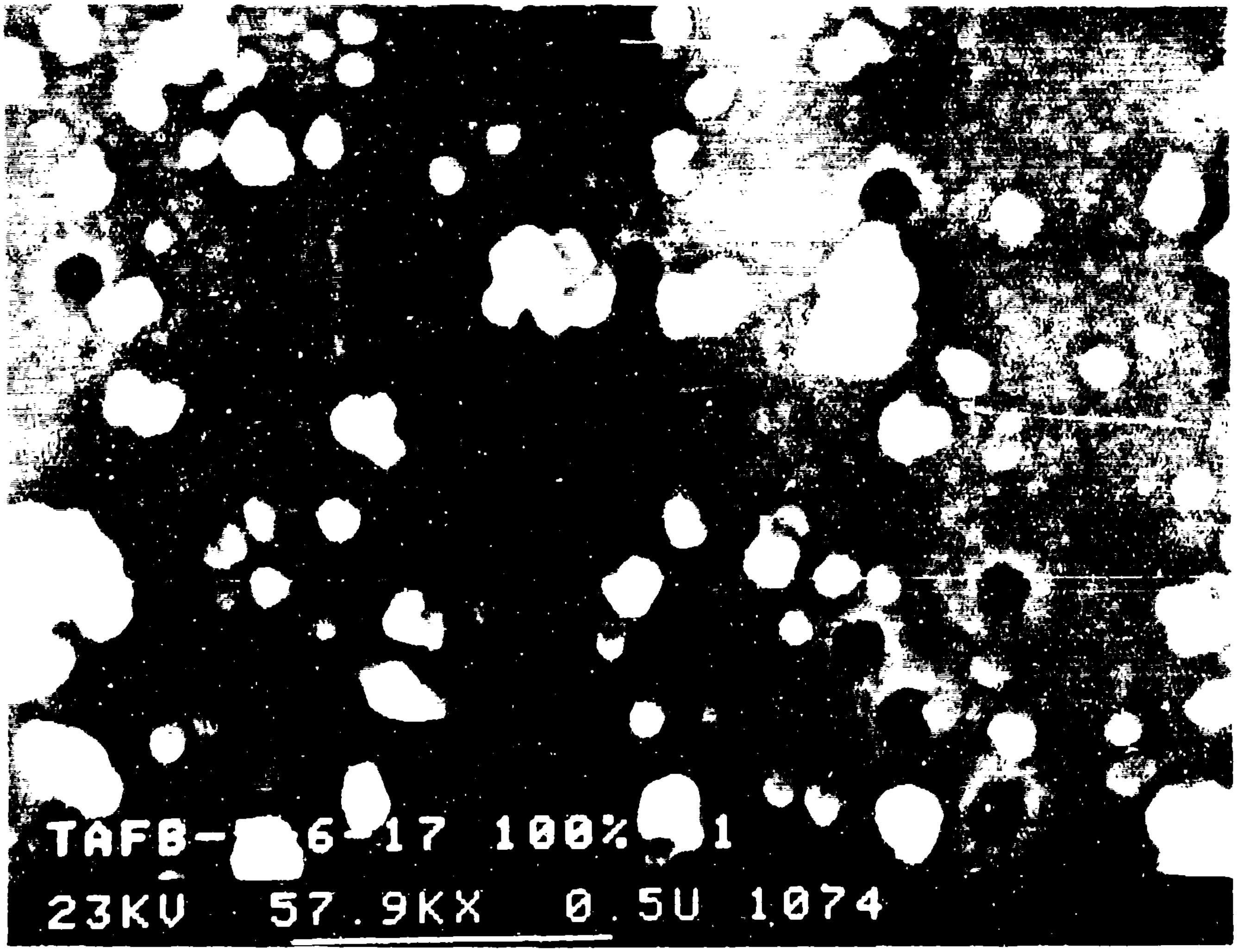

Figure 17. Photomicrograph of Exhaust Particles From F101 Engine At Intermediate Power (Filter Pores are 0.1 μm Diameter)

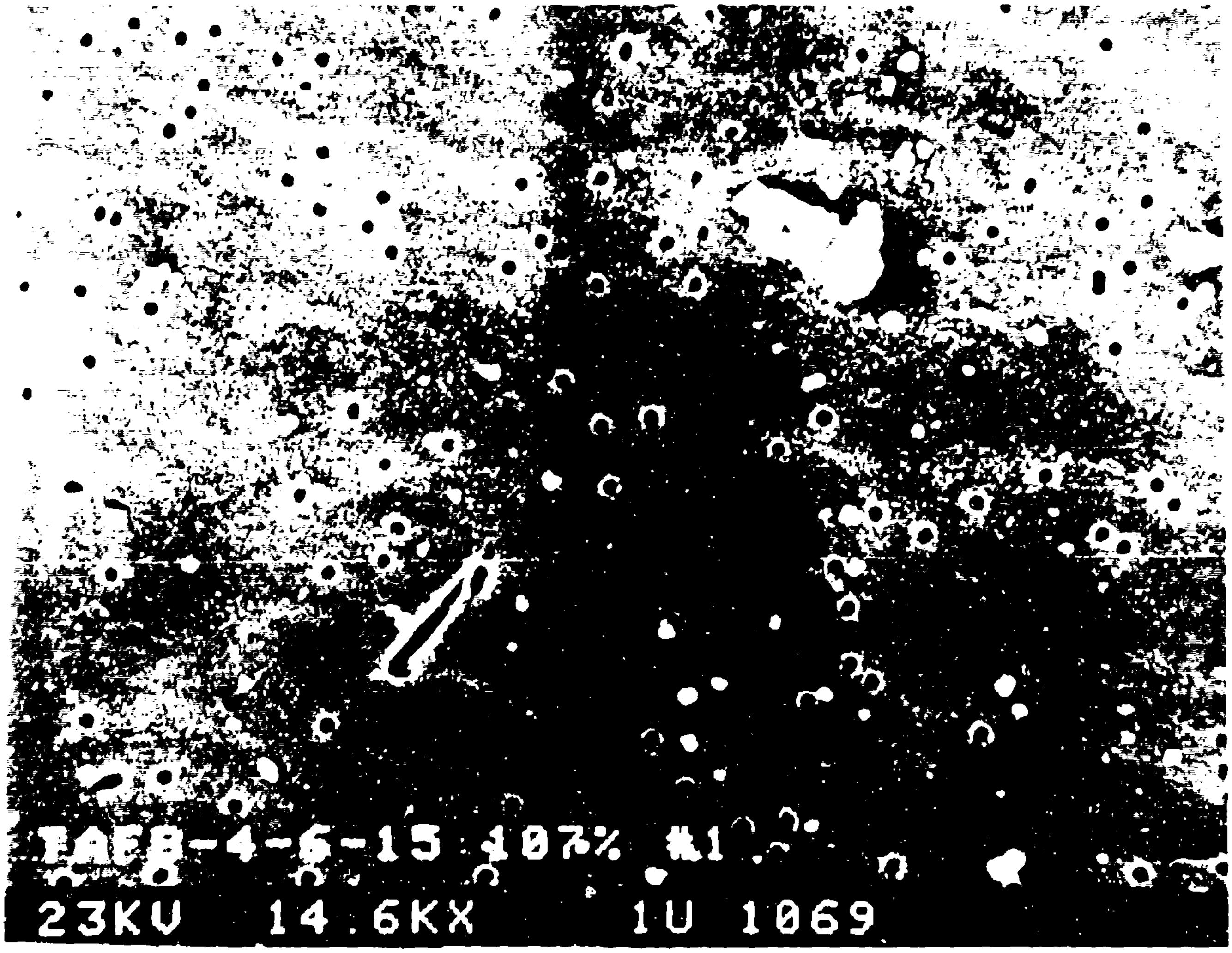

Figure 18. Photomicrograph of Exhaust Particles From F110 Engine At Intermediate Power (Filter Pores are 0.1 μm Diameter)

SECTION V

CONCLUSIONS

This study has characterized the gas and particle composition of exhaust from two Air Force turbine engines: F110 and F101. Measurements were made with the engines operating on JP-4 fuel, at power settings from idle to intermediate. Augmented power (Stage 1) was also studied. Several significant findings resulting from this study are summarized below:

- Emissions of organic species, CO, and particles were very low for both the F101 and F110 engines.
- At idle, four combustion products (ethene, acetylene, propene, and formaldehyde) accounted for 40-60 percent of total nonmethane organic emissions for the F110 and F101 engines. At higher power up to intermediate, ethene and formaldehyde are the dominant nonmethane organic compounds.
- Under augmented (afterburner) power, organic emissions increased dramatically. A larger fraction of the organic emissions at augmented power was unburned fuel for the F101, compared to the F110.
- Aldehydes were present at significant concentrations in the exhaust from both engines.
- Dicarbonyl compounds were observed in the exhaust from each engine, consistent with our earlier studies (References 1-3).
- Particle emissions were so low that particle mass measurements were not feasible using our sampling protocol. Smoke measurements and data on particle number concentrations confirmed the very low particle concentrations in exhaust from these engines.
- Microscopic examination of exhaust particle samples collected electrostatically demonstrated that the vast majority of emitted particles had diameters smaller than 0.2 μm.
- Emission indices and emission rates were determined for CO, CO_2, hydrocarbons, NO, NO_2, and NO_x at power levels from idle to intermediate.

- After accounting for exhaust dilution during augmented-power sampling, the polynuclear aromatic hydrocarbon (PAH) concentrations were highest at this power setting. Measurable levels of PAH were present at all power levels.

- The ratio of NO_2/NO_x was highest under augmented power, second highest at idle, and decreased from idle to intermediate power.

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