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AIRCRAFT EMISSIONS CHARACTERIZATION

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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 three Air Force turbine engines (TF33-P3, TF33-P7, and J79 [smokeless]). 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 power settings of idle, 30 percent, 75 percent, and 100 percent. Measurements were made of detailed organic composition, CO, CO_2, NO, NO_x, smoke number, particle concentration, and particle size distribution. 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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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 the different engines 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.

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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 three turbine engines. This work was performed between September, 1986 and July, 1987. The AFESC project officers were Lt. Glenn D. Seitchek and Lt. 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 Messrs. G. F. Ward and R. A. Severance, 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 and Mr. David Schley. 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.

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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 three 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 catalogue 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.

C. SCOPE

This study was initiated to determine the gas and particle composition of exhaust from three turbine engines. These engines are J79 (smokeless), TF33-P3, and TF33-P7. Tests were conducted using JP-4 fuel at engine power settings of idle, 30 percent, 75 percent, and 100 percent power. The exhaust sampling was carred 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 1), and used to determine the emissions from a TF39 and a CFM56 engine (Reference 2), as well as TF41-42, TF30-P103, and TF30-P109 engines (Reference 3).

SECTION II

EXPERIMENTAL METHODS

A. ENGINE TEST FACILITY

Engine emissions sampling was performed in an indoor test cell at Tinker Air Force Base, Oklahoma City, OK. The three engines examined in this study were operated in Test Cell 8. A diagram of a generic test cell is shown in Figure 1. The engine exhaust flows through a 75-foot long steel augmentor tube, the last 18 feet of which are perforated with numerous 1-1/4 inch holes. This portion of the tube runs into a separate "blast room" vented to the outside. The hot exhaust passes through these holes and out of the test cell through fifty-six 2.5-foot square vent tubes in the ceiling of the blast room. The test cell is instrumented to record numerous engine performance parameters included in this report.

Measurements under afterburner power conditions were desired; however, the operating procedures for Test Cell 8 require a water spray for cooling the augmentor tube when these engines are operated under afterburner power. Measurements in afterburner mode were precluded because measurements under afterburner power would have to be made downstream of the water spray and our measurement systems are incompatible with liquid water in the air sample.

B. EMISSIONS SAMPLING

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 which were clamped to the inlet cone of the augmentor tube. A schematic side view of the test cell is shown in Figure 2. Because different engines require specific positioning relative to the augmentor tube, the rake mounting was adjustable, to allow the rake to be centered 1-2 feet behind the exhaust nozzle of each engine.

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

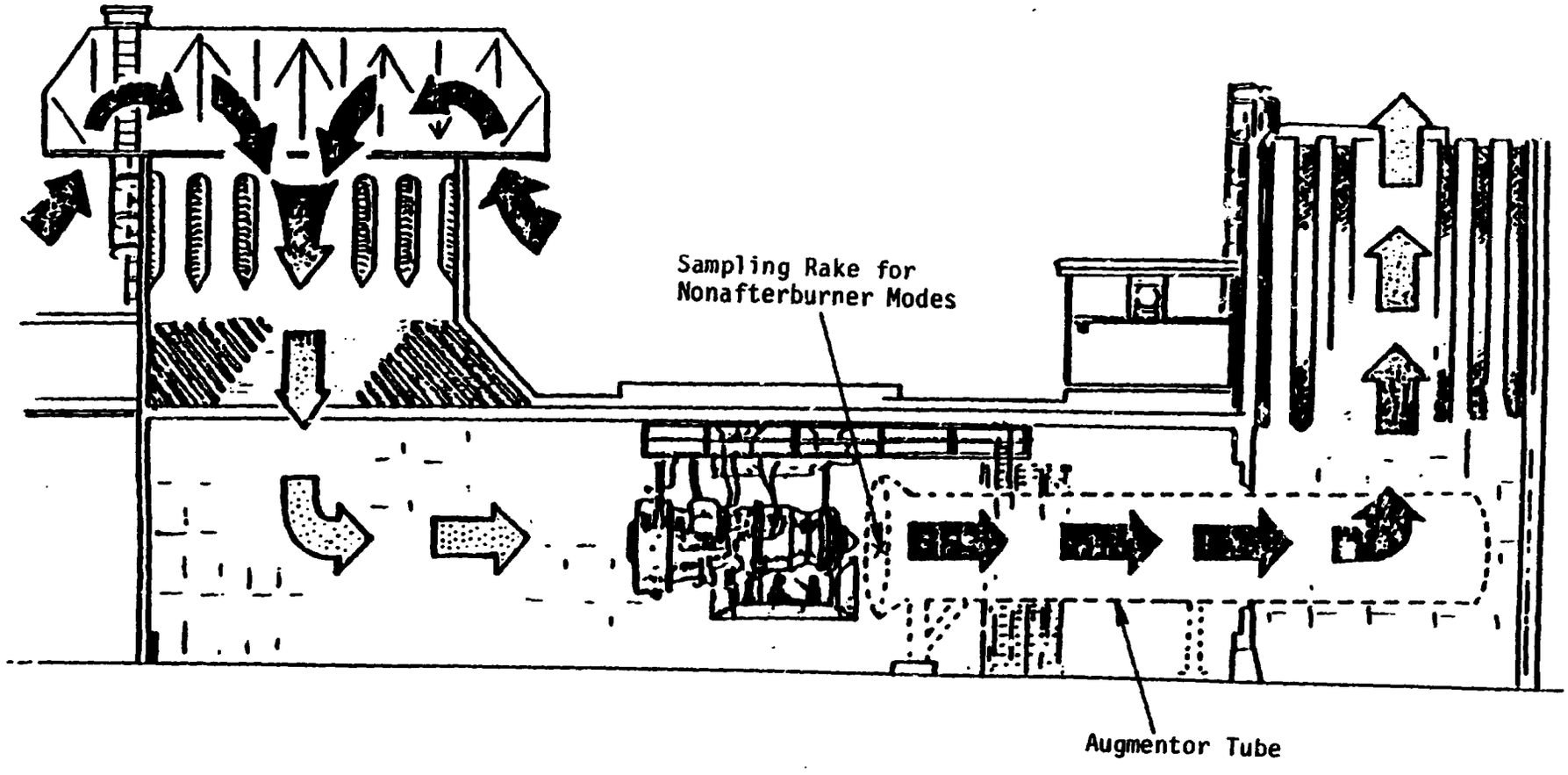

Figure 1. Test Cell Cross Section

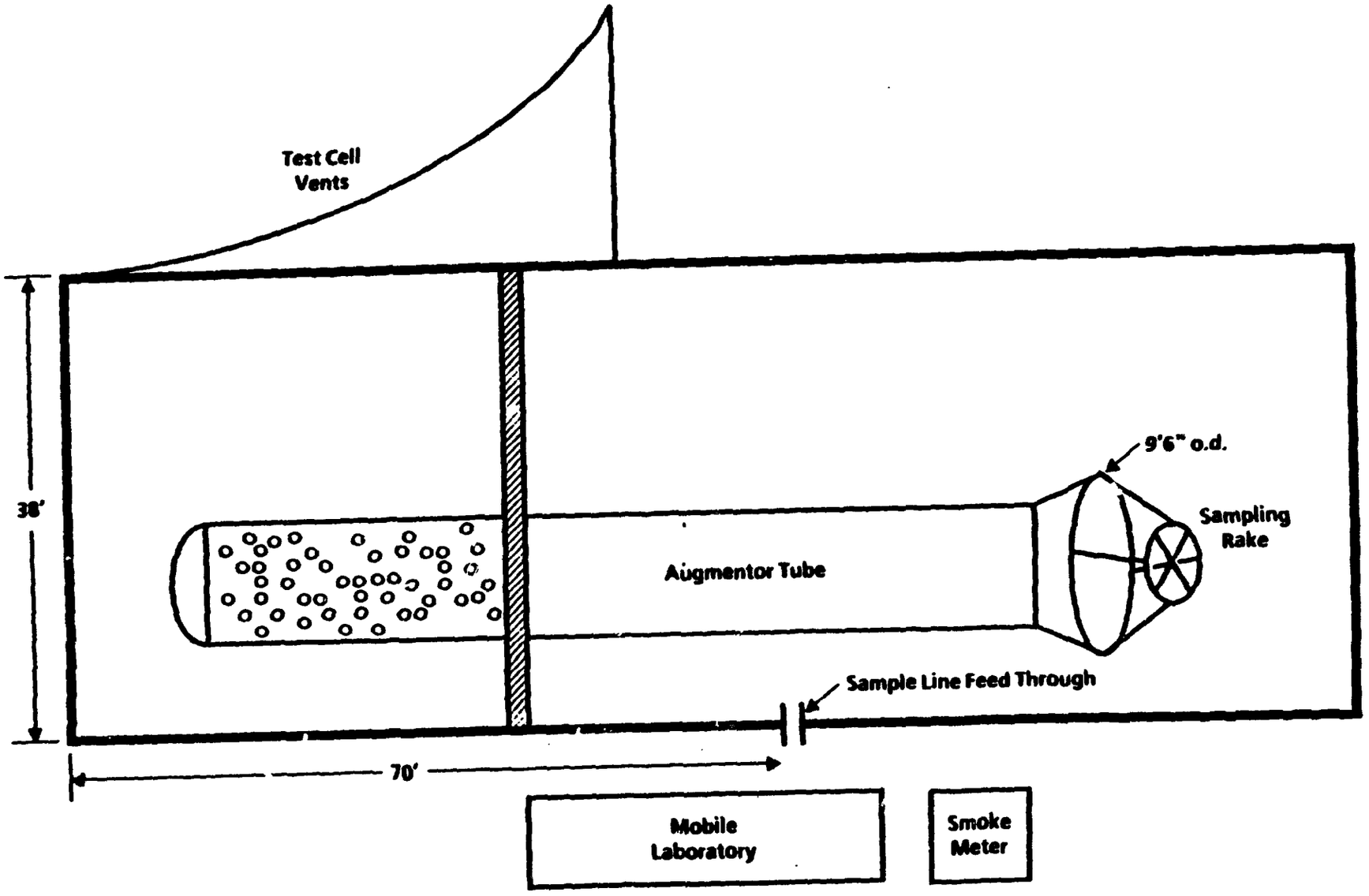

Figure 2. Schematic Diagram of Test Cell 8 (Side View)

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.

The 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). The pump directs the exit flow through 80 feet of heated 3/8-inch Teflon® tubing to a sampling manifold located in a mobile laboratory next to the test cell. 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 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 filtered exhaust stream was pumped through a heated Teflon® sample line to a heated glass manifold, to which the continuous gas analyzers and the organic compound sampling system were connected.

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 other

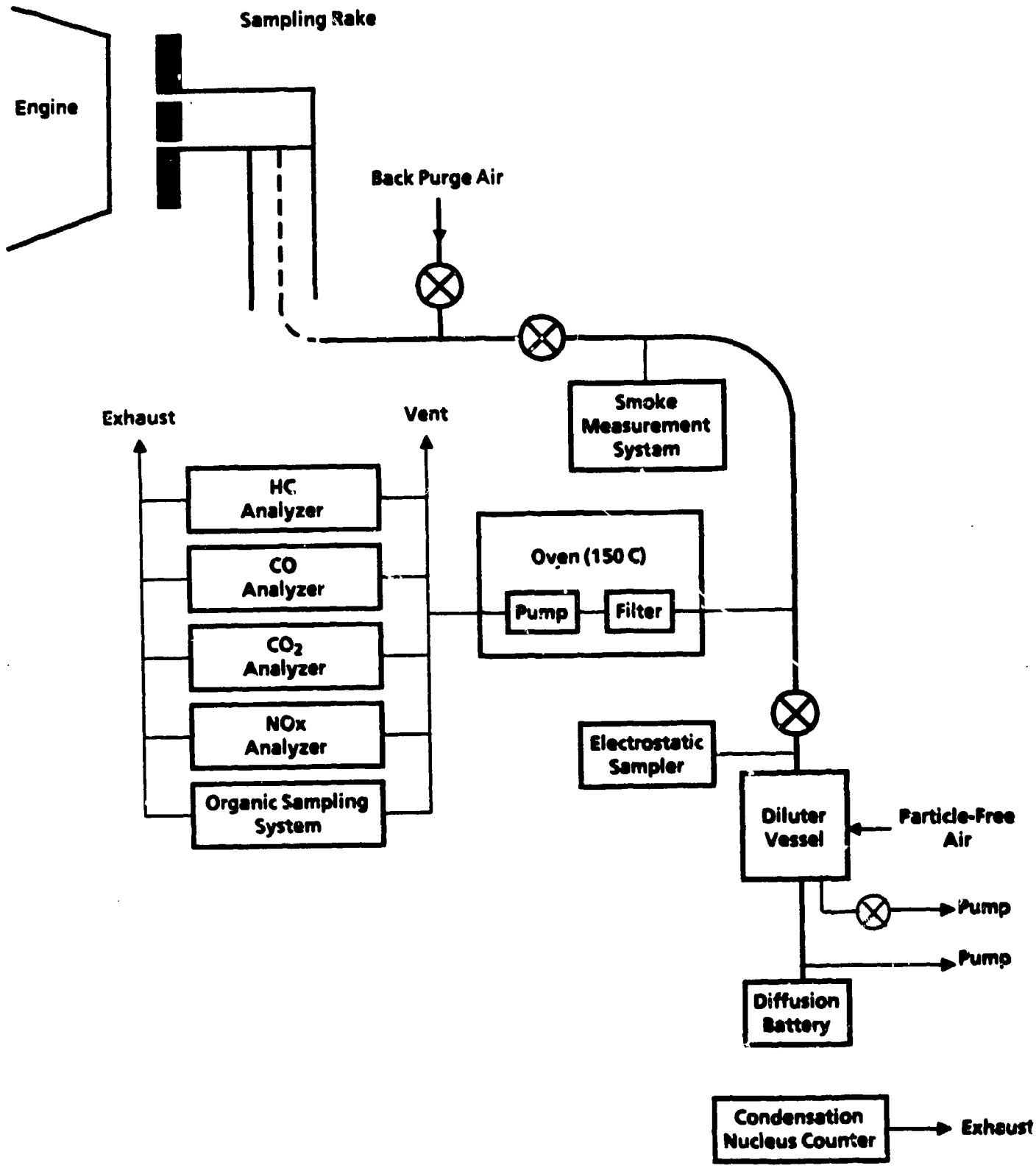

Figure 3. Sampling System

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 (nominal)	50	30	1,500	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

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

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 $\pm$ 2 percent and is compared with Standard Reference Materials (SRM) from the National Bureau of Standards.

The Organic Sampling System in Figure 3 represents three separate sampling techniques designed to cover a wide range of organic compound 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 which is 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 -20°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. An Extranuclear GC/MS system interfaced with a Finnigan INCOS 2300 data system was used for these analyses. The GC column used was a thin film bonded phase methyl silicone (HP-1) 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:	25 m x 0.32 mm (I.D.), 0.17 µ film thickness
	Carrier:	Helium, 3 psi head pressure, average velocity 55 cm/sec.
	Temperature Program:	80°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 corresponding internal standard. The internal standards used for each target compound are as follows:

Target Compound	Internal Standard
Naphthalene	D_8 -Napathalene
Methyl Naphthalene	D_8 -Napathalene
Dimethyl Naphthalene	D_8 -Naphthalene
Phenanthrene	D_{10}-Phenanthrene
Anthracene	D_{10}-Phenanthrene
Fluoranthene	D_{10}-Pyrene
Pyrene	D_{10}-Pyrene

Target Compound	Internal Standard
Benz[a]anthracene	D_{12}-Chrysene
Chrysene	D_{12}-Chrysene
Benzo[e]pyrene	D_{12}-Benzo[e]pyrene
Benzo[a]pyrene	D_{12}-Benzo[a]pyrene
Perylene	D_{12}-Benzo[e]pyrene
Coronene	D_{12}-Benzo[e]pyrene

The standard solutions containing target PAH were prepared at 1 μg/mL level. Prior to GC/MS analysis, the internal standards were added to the standard solution and the extracts at a constant concentration level of 1 μg/mL. The results of the analysis of the standard solutions were used to calculate the response factor for each target compound.

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

where

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

A_s = Molecular ion area of the sample

C_{is} = Concentration of the internal standard, 1 μg/mL

F_v = Final total volume of the sample extract, mL

A_{is} = Molecular ion area 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, onsite, following each test. The canisters were vacuum-baked onsite in the mobile laboratory before sampling. 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 is controlled by a contamination-free Metal Bellows pump and Tylan mass flow controller. The details of this sampling system have been reported in Reference [4].

A Hewlett-Packard Model 5890 gas chromatograph with microprocessor control and integration capabilities was used for onsite 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 is necessary to resolve the major C_2 to C_{15} organic species. Calibration of the gas chromatographic systems was accomplished by injecting an external standard mixture into each GC. The standard mixtures were referenced to several NBS primary standard "propane and benzene in air" calibration mixtures.

Following the field tests, selected canister samples were returned to the laboratory for GC-MS analysis to identify or confirm the identities of peaks observed in the field 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 25 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 40 CFR 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.

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. To provide for determination of particles larger than 0.2 μm, samples of the exhaust particulate matter were taken using an electrostatic aerosol sampler. 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 was dried and cleaned by passing 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. The collection surface used for the electrostatic SEM samples was stainless steel covered with double-stick tape. Samples typically were collected at a flow rate of 5 Lpm 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 numbers were derived according to the procedures recommended in Reference 5.

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 were derived using the equations provided in References 5 and 6. The equations used to derive emission indices (in lb/1000 lb fuel) are given below:

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

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

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

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

where b_z represents the ratio of the time-averaged, background-corrected concentration of species z to the concentration of 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

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

where ER_z and EI_z are the emission rate (lb/hr) and emission index (lb/1000 lbs 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 October 7 to October 17, 1986,at Tinker AFB in Oklahoma City, OK. The three engines examined during these tests are listed in Table 3. The environmental conditions and engine operating variables are given in Tables 4-6 for the three engines J-79-17G, TF 33-P3, and TF 33-P7. 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.
J79-17G	453869
TF33-P3	642697
TF33-P7	651687

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 2 μL of fuel into helium in a heated cylinder (80°C) and analyzing duplicate 1 cc samples of the cylinder contents by capillary column gas chromatography. Table 7 lists the percent composition of the major organic species identified in the fuel samples. Approximately 70 percent of the mass was identified as specific compounds. A representative chromatogram of JP-4 fuel is shown in Figure 4. The relative abundance of methylcyclohexane was much greater in these fuel samples than in other JP-4 samples we have analyzed; the composition of other fuel constituents appeared normal.

TABLE 4. ENGINE OPERATING CONDITIONS

ENGINE J79-17G (S/N 453869)

Test No.	4-10-7	1-10-7	2-10-7	3-10-7
Date	10-7-86	10-7-86	10-7-86	10-7-86
Location/Test Cell	TAFB/8	TAFB/8	TAFB/8	TAFB/8
Engine nominal power setting	Idle	30%	75%	100%
Time (CDT)	1530	1030	1130	1430
*Initial compressor inlet temperature (°C)	21.7	18.0	19.0	21.4
*Final compressor inlet temperature (°C)	21.9	18.7	19.7	21.4
*Initial barametric pressure (in. Hg)	28.715	28.810	28.810	28.745
*Final barametric pressure (in. Hg)	28.700	28.810	28.810	28.725
Initial dew point (°C)	15.6	13.9	14.4	16.1
Final dew point (°C)	16.1	14.4	15.0	15.5
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
Measured thrust (lb)	290	3,072	7,458	9,964
Turbine discharge pressure (in. Hg)	**	**	**	**
Fuel flow (lb/hr)*	1,198	2,485	5,807	8,263
Air flow (lb/sec)*	45.2	97.7	143.6	164.8
Engine pressure ratio (EPR)*	**	**	**	**
Fuel/air ratio	.00735	.00707	.01124	.01393
Turbine outlet temperature (°C)*	315	314	507	609
Rotor speed (R/min)*	5,008	6,176	6,824	7,147
Actual thrust (% normal rated)	2.8	29.0	70.8	95.6

* Corrected to standard day.
** Engine not instrumented for these measurements

TABLE 5. ENGINE OPERATING CONDITIONS

ENGINE TF33-P3 (S/N 642697)

Test No.	1-10-14	2-10-14	3-10-14	5-10-14
Date	10-14-86	10-14-86	10-14-86	10-14-86
Location/Test Cell	TAFB/8	TAFB/8	TAFB/8	TAFB/8
Engine nominal power setting	Idle	30%	75%	100%
Time (CDT)	1120	1330	1400	1645
Initial compressor inlet temperature (°C)	12.1	15.3	15.0	15.6
Final compressor inlet temperature (°C)	13.0	14.9	15.0	15.6
Initial barametric pressure (in. Hg)	28.760	28.755	28.740	28.725
Final barametric pressure (in. Hg)	28.760	28.740	28.740	28.725
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
Measured thrust (lb)*	981	4,344	10,848	14,575
Turbine discharge pressure (in. Hg)	32.2	33.9	42.4	48.6
Fuel flow (lb/hr)*	1,052	2,256	5,182	7,105
Air flow (lb/sec)*	81.2	187.5	285.3	318.2
Engine pressure ratio (EPR)*	1.024	1.132	1.417	1.624
Fuel/air ratio*	.003635	.003335	.00505	.00620
Turbine outlet temperature (°C)*	276	304	380	425
Low speed rotor (R/min)*	1,945	3,805	5,458	6,075
High speed rotor (R/min)*	5,625	7,932	9,066	9,497
Actual thrust (% normal rated)*	6.8	30.0	74.8	100

* Corrected to standard day.

TABLE 6. ENGINE OPERATING CONDITIONS

ENGINE TF33-P7 (S/N 651687)

Test No.	4-10-15	3-10-15	2-10-15	1-10-15
Date	10-15-86	10-15-86	10-15-86	10-15-86
Location/Test Cell	TAFB/8	TAFB/8	TAFB/8	TAFB/8
Engine nominal power setting	Idle	30%	75%	100%
Time (CDT)	1700	1630	1500	1400
Initial compressor inlet temperature (°C)	20.8	19.0	18.8	18.5
Final compressor inlet temperature (°C)	19.9	18.6	18.5	18.3
Initial barametric pressure (in. Hg)	28.880	28.890	28.890	28.910
Final barametric pressure (in. Hg)	28.880	28.890	28.890	28.905
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
Measured thrust (lb)*	1,786	5,401	13,516	18,063
Turbine discharge pressure (in. Hg)	30.6	33.8	44.2	52.1
Fuel flow (lb/hr)*	1,110	2,532	6,310	8,847
Air flow (lb/sec)*	85.1	185.0	313.2	369.5
Engine pressure ratio (EPR)*	1.023	1.129	1.479	1.742
Fuel/air ratio*	.00362	.00381	.00559	.00665
Turbine outlet temperature (°C)*	282	288	362	417
Low speed rotor (R/min)*	1,703	3,479	5,032	5,572
High speed rotor (R/min)*	5,384	7,721	8,824	9,224
Actual thrust (% normal rated)*	9.9	30.0	75.0	100.3

* Corrected to standard day.

TABLE 7. PERCENT COMPOSITION OF MAJOR ORGANIC SPECIES IN JP-4 FUEL USED FOR EMISSIONS TESTS (WEIGHT PERCENT)

HYDROCARBON	SAMPLE NO.	1		2		3	
	DATE	10-7-86		10-14-86		10-15-86	
	ANALYSIS	1	2	1	2	1	2
n-butane		.38	.36	.45	.40	.57	.31
iso-pentane		.85	.78	.85	1.03	.99	1.00
n-pentane		.95	.79	1.10	.95	1.26	1.00
2-methylpentane		2.16	2.04	2.19	2.27	2.25	2.14
3-methylpentane		1.79	1.73	1.74	1.74	1.78	1.98
n-hexane		3.26	3.21	3.20	3.22	3.39	3.38
methylcyclopentane		1.57	1.52	1.57	1.56	1.95	1.82
benzene		0	.61	.41	.35	.42	.32
cyclohexane		1.60	1.72	1.71	1.57	1.88	1.97
2-methylhexane		4.53	4.48	4.63	4.45	5.33	5.38
3-methylhexane		3.94	3.91	4.04	4.02	4.55	4.48
1,2-dimethylpentane		.87	.93	.36	.39	1.19	1.11
n-heptane		5.00	4.80	4.95	4.88	5.99	5.81
methylcyclohexane		6.24	6.31	6.12	6.04	7.42	7.43
toluene		1.50	1.52	1.50	1.38	1.83	2.13
2-methylheptane		3.15	3.30	3.28	3.19	3.75	3.93
3-methylheptane		5.05	5.06	5.29	5.13	6.21	6.17
n-octane		4.04	4.05	4.45	4.38	5.22	5.30
ethylbenzene		.20	.51	.31	.26	.28	.31
m&p-xylene		1.61	1.87	1.81	1.85	1.47	1.54
o-xylene		.96	1.03	1.25	1.10	1.31	1.25
n-nonane		2.45	2.39	2.66	2.87	3.15	3.41
n-decane		2.09	2.04	2.09	2.01	2.21	2.19
n-undecane		2.88	3.07	2.35	2.39	1.90	1.70
n-dodecane		3.42	3.60	3.22	3.12	1.72	1.68
n-tridecane		4.42	3.93	4.01	3.77	2.57	2.42
n-tetradecane		3.12	2.32	2.56	2.67	2.21	2.07

1. i-Pentane
2. n-Pentane
3. 2-Methylpentane
4. 3-Methylpentane
5. n-Hexane
6. Methylcyclopentane (& Unknown)
7. Benzene
8. 2-Methylhexane
9. 3-Methylhexane
10. n-Heptane
11. Methylcyclohexane
12. Toluene
13. 2-Methylheptane
14. 3-Methylheptane
15. n-Octane
16. Ethylbenzene
17. m&p-Xylene
18. o-Xylene
19. n-Monane
20. C_{10}/C_3-Benzene
21. n-Decane
22. n-Undecane
23. Naphthalene
24. n-Dodecane
25. n-Tridecane
26. n-Tetradecane
27. n-Pentadecane

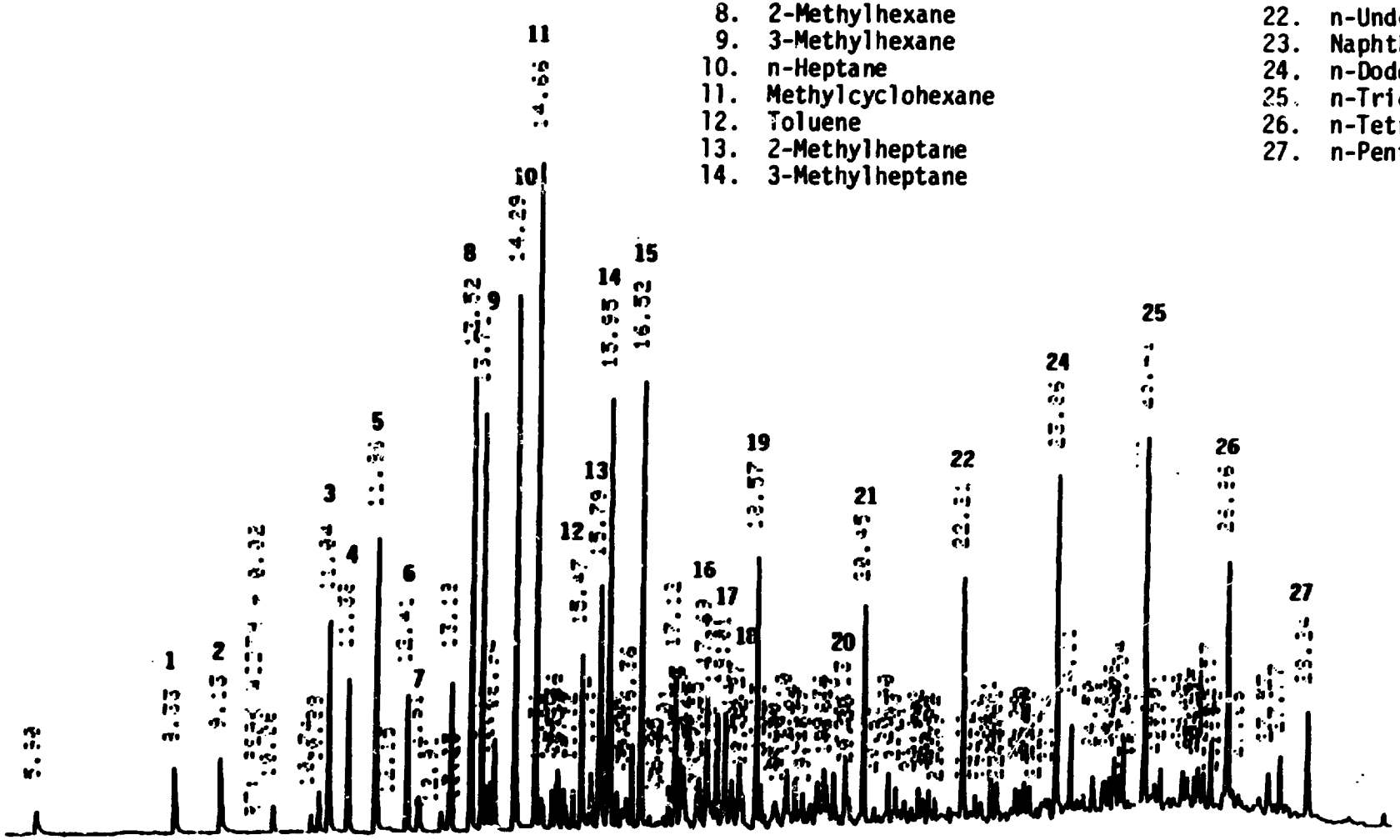

Figure 4. GC/FID Chromatogram for JP-4 Fuel

Additional characterization of the fuel by standardized ASTM procedures was provided by Tinker AFB contractors. These data are given in Table 8.

C. GASEOUS EMISSIONS

Gaseous emissions were measured for all three engines at four power settings: idle, 30 percent, 75 percent, and 100 percent. The exhaust concentrations of CO, CO_2, total hydrocarbons, NO_x, and NO are listed in Table 9.

The gaseous organic species measured in the exhaust from the three engines are listed in Tables 10-12. Concentrations are given in parts per million carbon (ppmC) for all species. Table 10 shows results for the J79-17G engine, the data for the TF33-P3 engine are given in Table 11, and the results for the TF33-P7 engine are shown in Table 12. The tables list hydrocarbons, oxygenated species, and the distribution of compound classes for each engine power setting. Representative chromatograms of the exhaust analysis for hydrocarbon species and carbonyl species are provided in Figures 5-7.

D. POLYCYCLIC AROMATIC HYDROCARBON EMISSIONS

The results of GC-MS analysis of the XAD-2 samples for polycyclic aromatic hydrocarbons are shown in Tables 13-15 for the three engines. All concentrations in Tables 13-15 are in units of $\mu g/m^3$.

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 Number

Smoke Number was determined by the procedures described in Section II. The final Smoke number Values for the three engines examined in these tests are listed in Table 16.

TABLE 8. RESULTS FOR STANDARD FUEL ANALYSES

PARAMETER	TEST	ANALYSIS
Gravity, API	D287	52.8
Visual Appearance	HDBK-200	C&B
Freezing Point, °C	D2386	Below -58
Odor	--	Usual
Color	--	Water white
Distillation	D86	
Initial Boiling Point, °C		64
10%		104
20%		114
50%		140
90%		210
End Point		239
Recovery, vol %		98.2
Residue, vol %		0.7
Loss, vol %		1.1
Vapor Pressure, KPa (PSI)	D323	14 (2.1)
Existent Gum, mg/100 mL	D381	1.0
Visible Free Water, mL/gal	HDBK-200	0.0
Particulate Matter, mg/gal	D2276	1.0
Fuel Icing Inhibitor, %	--	0.12

TABLE 9. ENGINE EMISSIONS DATA

POWER MODE (nominal)	RUN NO.	CO, ppm	CO_2, %	TOTAL HYDROCARBON, ppmC	NO_x, ppm	NO, ppm
			J79 ENGINE			
Idle	4-10-7	700	1.41	355	9.5	4.6
30%	1-10-7	200	1.59	15.7	18.0	7.5
75%	2-10-7	50	2.64	0.7	52.5	44.5
100%	3-10-7	25	3.23	2.2	84.0	76.6
			TF33-P3 ENGINE			
Idle	1-10-14	680	1.30	1350	11.0	3.5
30%	2-10-14	185	1.82	76	24.5	10.7
75%	3-10-14	45	2.50	5.8	56.0	47.0
100%	5-10-14	30	2.82	0.7	73.5	68.0
			TF33-P7 ENGINE			
Idle	4-10-15	930	1.55	1150	11.2	5.5
30%	3-10-15	205	1.80	52	23.0	10.0
75%	2-10-15	35	2.75	2.2	62.8	57.0
100%	1-10-15	15	3.22	1.3	95.5	93.0

TABLE 10. ORGANIC EMISSIONS FROM J79 ENGINE WITH JP4 FUEL (CONCENTRATIONS IN ppmC)

Organic Species	Test No.:	4-10-7	1-10-7	2-10-7	3-10-7
	Date:	10-7-86	10-7-86	10-7-86	10-7-86
J-79	Power Setting:	IDLE	30%	75%	100%
Methane		9.198	3.050	0.704	0.368
Ethane		3.259	0.332	0.022	<0.001
Ethylene		24.499	0.393	0.289	0.055
Propane		0.331	0.024	0.049	<0.001
Acetylene		20.706	4.453	0.249	0.031
Propene		26.013	2.246	0.032	0.011
1-Butene		12.689	0.639	0.054	0.014
1,3-Butadiene		5.314	0.238	0.027	<0.001
1-Pentene		3.718	0.153	<0.001	<0.001
C5-ene		1.407	0.059	<0.001	<0.001
n-Pentane		0.835	0.038	0.014	0.011
C5-ene		0.314	0.003	<0.001	0.004
C5-ene		0.359	0.017	<0.001	0.007
2-Methylpentane		2.447	0.063	<0.001	<0.001
3-Methylpentane		1.622	0.042	0.003	<0.001
1-Hexene		3.520	0.111	<0.001	<0.001
n-Hexane		2.663	0.078	0.002	<0.001
Methylcyclopentane+unk		1.471	0.050	0.030	0.018
Benzene		7.468	1.003	0.030	0.008
2-Methylhexane		5.196	0.108	<0.001	<0.001
3-Methylhexane		3.913	0.085	<0.001	<0.001
n-Heptane		4.616	0.100	<0.001	<0.001
Methylcyclohexane		4.821	0.094	<0.001	<0.001
Toluene		7.033	0.544	0.008	0.003
2-Methylheptane		2.372	0.065	<0.001	<0.001
3-Methylheptane		4.946	0.091	0.005	0.008
n-Octane		4.535	0.078	0.002	<0.001
Ethylbenzene		1.614	0.082	<0.001	<0.001
m&p-Xylene		7.070	0.282	<0.001	<0.001
Styrene		2.511	0.074	<0.001	0.003
o-Xylene		2.523	0.084	0.003	<0.001
n-Nonane		3.474	0.044	<0.001	<0.001
p-Ethyltoluene		1.847	0.055	<0.001	0.002
1,3,4-Trimethylbenzene		3.253	0.076	0.004	0.007
n-Decane		3.566	0.047	0.005	0.006
Methylbenzaldehyde+C10H14		1.585	0.026	<0.001	<0.001
Undecane		4.485	0.041	0.002	<0.001
Naphthalene		1.929	0.103	<0.001	0.007
Dodecane		4.683	0.042	0.004	<0.001
Tridecane		3.776	0.043	<0.001	<0.001
Tetradecane		2.001	0.037	<0.001	0.002
DNPH\IMPINGER COLLECTION					
Formaldehyde		15.920	1.825	0.127	0.027
Acetaldehyde		3.161	0.803	0.035	0.022
Acrolein		1.973	0.286	0.016	<0.001
Propanaldehyde		0.599	0.080	0.004	<0.001
Acetone		<0.001	0.196	0.026	0.014
Benzaldehyde+unk		3.579	0.762	0.112	<0.001
Glyoxal		4.928	0.520	0.044	0.012
Methylglyoxal		8.099	1.194	0.042	0.022
Biacetyl		0.041	0.029	<0.001	<0.001
IDENTIFIED SPECIES		247.882	20.888	1.944	0.662
Paraffins		74.210	4.552	0.842	0.413
Acetylene		20.706	4.453	0.249	0.031
Olefins		77.033	3.859	0.402	0.091
Aromatics		36.833	2.329	0.045	0.030
Aldehydes		38.300	5.499	0.380	0.083
Ketones		<0.001	0.196	0.026	0.014
TOTAL SPECIES		361.839	23.373	2.178	0.791

TABLE 11. ORGANIC EMISSIONS FROM TF33-P3 ENGINE WITH JP-4 FUEL (CONCENTRATIONS IN ppmC)

Organic Species	Test No.:	1-10-14	2-10-14	3-10-14	4-10-14
	Date:	10-14-86	10-14-86	10-14-86	10-14-86
TF33-P3	Power Setting:	IDLE	30%	75%	100%
Methane		37.670	2.425	0.704	0.439
Ethane		5.098	0.336	0.010	0.004
Ethylene		47.405	15.171	1.368	0.164
Propane		0.893	0.026	0.005	<0.001
Acetylene		28.368	3.925	0.374	0.068
Propene		43.344	5.048	0.289	0.041
1-Butene		18.489	1.814	0.107	0.049
1,3-Butadiene		11.981	0.571	0.024	<0.001
1-Pentene		5.818	0.595	0.065	0.042
C5-ene		2.563	0.225	0.017	<0.001
n-Pentane		4.464	0.112	<0.001	<0.001
C5-ene		1.584	0.013	<0.001	<0.001
C5-ene		0.835	0.052	<0.001	<0.001
2-Methylpentane		11.059	0.192	0.005	<0.001
3-Methylpentane		8.438	0.335	0.006	<0.001
1-Hexene		5.587	0.521	0.023	<0.001
n-Hexane		14.688	0.339	0.005	<0.001
Methylcyclopentane+unk		7.834	0.246	0.059	0.077
Benzene		12.499	1.698	0.160	0.029
2-Methylhexane		25.488	0.571	0.012	0.004
3-Methylhexane		20.534	0.589	0.009	0.006
n-Heptane		26.870	0.606	0.016	0.011
Methylcyclohexane		31.824	0.643	0.014	0.007
Toluene		23.270	1.446	0.076	0.022
2-Methylheptane		21.226	0.339	0.013	0.009
3-Methylheptane		31.651	0.687	0.018	0.010
n-Octane		28.915	0.595	0.014	0.009
Ethylbenzene		5.558	0.320	0.017	0.008
m&p-Xylene		30.787	1.332	0.048	0.024
Styrene		11.174	0.380	0.016	0.012
o-Xylene		9.734	0.413	0.016	0.008
n-Nonane		22.406	0.464	0.012	0.010
p-Ethyltoluene		8.352	0.346	0.009	0.016
1,2,4-Trimethylbenzene		15.581	0.566	0.016	0.018
n-Decane		21.715	0.498	0.019	0.014
Methylbenzaldehyde+C10H14		8.179	0.497	0.059	0.062
Undecane		26.179	0.606	0.027	0.042
Naphthalene		10.138	0.395	0.035	0.050
Dodecane		29.261	0.522	0.023	0.066
Tridecane		21.398	0.452	0.034	0.080
Tetradecane		5.011	0.405	0.041	0.184
DNPH\IMPINGER COLLECTION					
Formaldehyde		15.540	4.009	0.423	0.083
Acetaldehyde		1.802	1.564	0.211	0.036
Acrolein		1.833	0.501	0.051	<0.001
Propanaldehyde		0.461	0.268	0.019	0.005
Acetone		<0.001	0.432	0.067	0.025
Benzaldehyde+unk		3.903	1.668	0.200	<0.001
Glyoxal		1.680	1.368	0.126	0.024
Methylglyoxal		5.310	0.817	0.077	0.032
Biacetyl		0.542	0.257	0.024	0.013
IDENTIFIED SPECIES		734.939	57.198	4.963	1.803
Paraffins		402.622	10.986	1.046	0.972
Acetylene		28.368	3.925	0.374	0.068
Olefins		137.606	24.010	1.893	0.296
Aromatics		135.272	7.393	0.452	0.249
Aldehydes		31.071	10.452	1.131	0.193
Ketones		<0.001	0.432	0.067	0.025
TOTAL SPECIES		1259.692	77.818	6.008	3.180

TABLE 12. ORGANIC EMISSIONS FROM TF33-P7 ENGINE WITH JP-4 FUEL (CONCENTRATIONS IN ppmC)

Organic Species	Test No.:	4-10-15	3-10-15	2-10-15	1-10-15
	Date:	10-15-86	10-15-86	10-15-86	10-15-86
TF33-P7	Power Setting:	IDLE	30%	75%	100%
Methane		18.567	2.854	0.563	0.382
Ethane		6.120	0.306	0.004	0.004
Ethylene		103.454	10.713	0.346	0.093
Propane		1.144	0.092	0.002	0.002
Acetylene		37.727	4.644	0.122	0.015
Propene		48.223	4.302	0.112	0.013
1-Butene		24.002	1.503	0.026	0.025
1,3-Butadiene		17.492	0.209	<0.001	0.063
1-Pentene		7.584	0.427	0.022	0.028
C5-ene		3.421	0.134	<0.001	0.034
n-Pentane		4.688	0.101	<0.001	0.045
C5-ene		3.119	0.043	0.025	<0.001
C5-ene		1.943	0.016	0.003	0.012
2-Methylpentane		10.315	0.201	<0.001	<0.001
3-Methylpentane		8.116	0.266	0.043	0.076
1-Hexene		7.220	0.365	0.020	0.040
n-Hexane		14.350	0.263	0.005	<0.001
Methylcyclopentane+unk		8.189	0.190	0.029	0.012
Benzene		17.398	1.684	0.043	0.015
2-Methylhexane		25.636	0.396	0.003	0.011
3-Methylhexane		20.285	0.387	0.005	0.020
n-Heptane		25.391	0.389	0.016	0.009
Methylcyclohexane		31.476	0.406	0.004	<0.001
Toluene		26.383	1.240	0.018	0.015
2-Methylheptane		20.599	0.270	0.004	0.005
3-Methylheptane		31.104	0.393	0.002	0.004
n-Octane		27.737	0.340	0.005	0.029
Ethylbenzene		6.456	0.213	0.005	0.009
m&p-Xylene		32.159	0.869	0.014	0.021
Styrene		12.102	0.196	0.010	0.032
o-Xylene		11.421	0.253	0.012	0.009
n-Nonane		24.504	0.204	0.005	0.010
p-Ethyltoluene		9.154	0.176	0.004	<0.001
1,2,4-Trimethylbenzene		18.154	0.253	0.018	0.034
n-Decane		22.142	0.176	0.008	0.018
Methylbenzaldehyde-C10H14		9.859	0.088	0.116	<0.001
Undecane		23.254	0.201	0.027	0.040
Naphthalene		10.057	0.270	0.018	0.022
Dodecane		23.354	0.169	0.020	0.045
Tridecane		17.612	0.134	0.025	0.058
Tetradecane		8.698	0.083	0.023	0.092
DNPH\IMPINGER COLLECTION					
Formaldehyde		16.560	3.550	0.089	0.044
Acetaldehyde		1.475	1.366	0.053	0.021
Acrolein		1.840	0.217	0.010	<0.001
Propanaldehyde		0.356	0.180	<0.001	<0.001
Acetone		<0.001	0.333	0.026	0.018
Benzaldehyde+unk		2.498	1.322	0.025	<0.001
Glyoxal		1.918	1.145	0.049	0.027
Methylglyoxal		2.144	0.409	0.041	0.021
IDENTIFIED SPECIES		808.104	44.140	2.020	1.473
Paraffins		373.281	7.821	0.793	0.862
Acetylene		37.727	4.644	0.122	0.015
Olefins		216.458	17.712	0.554	0.308
Aromatics		153.143	5.242	0.258	0.157
Aldehydes		27.495	8.388	0.267	0.113
Ketones		<0.001	0.333	0.026	0.018
TOTAL SPECIES		1348.097	54.261	2.861	2.940

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. Naphthalene
39. Dodecane
40. Tridecane
41. Tetradecane

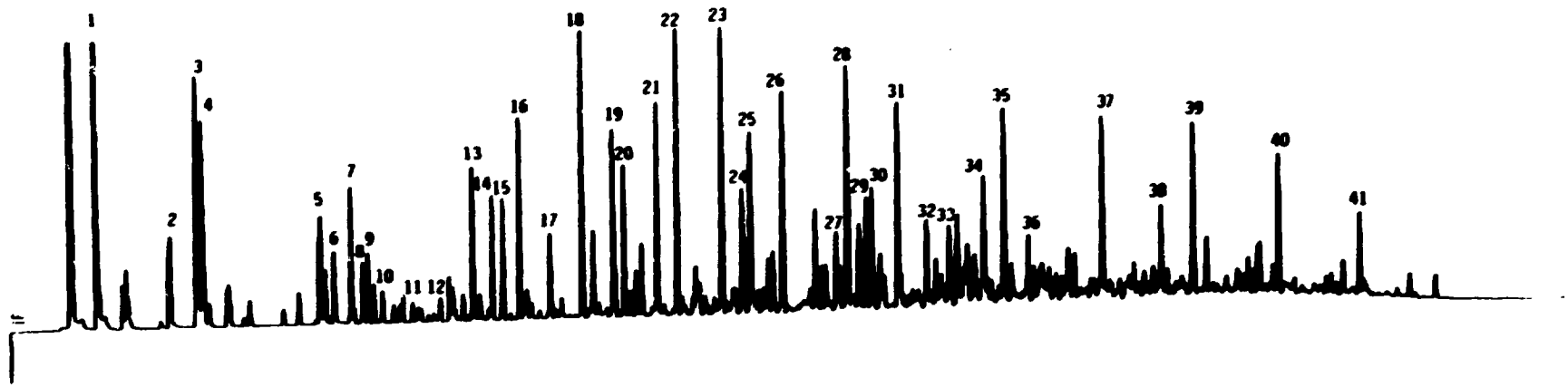

Figure 5. Representative GC/FID Chromatogram for Exhaust from a Turbine Engine Operating With JP-4 Fuel

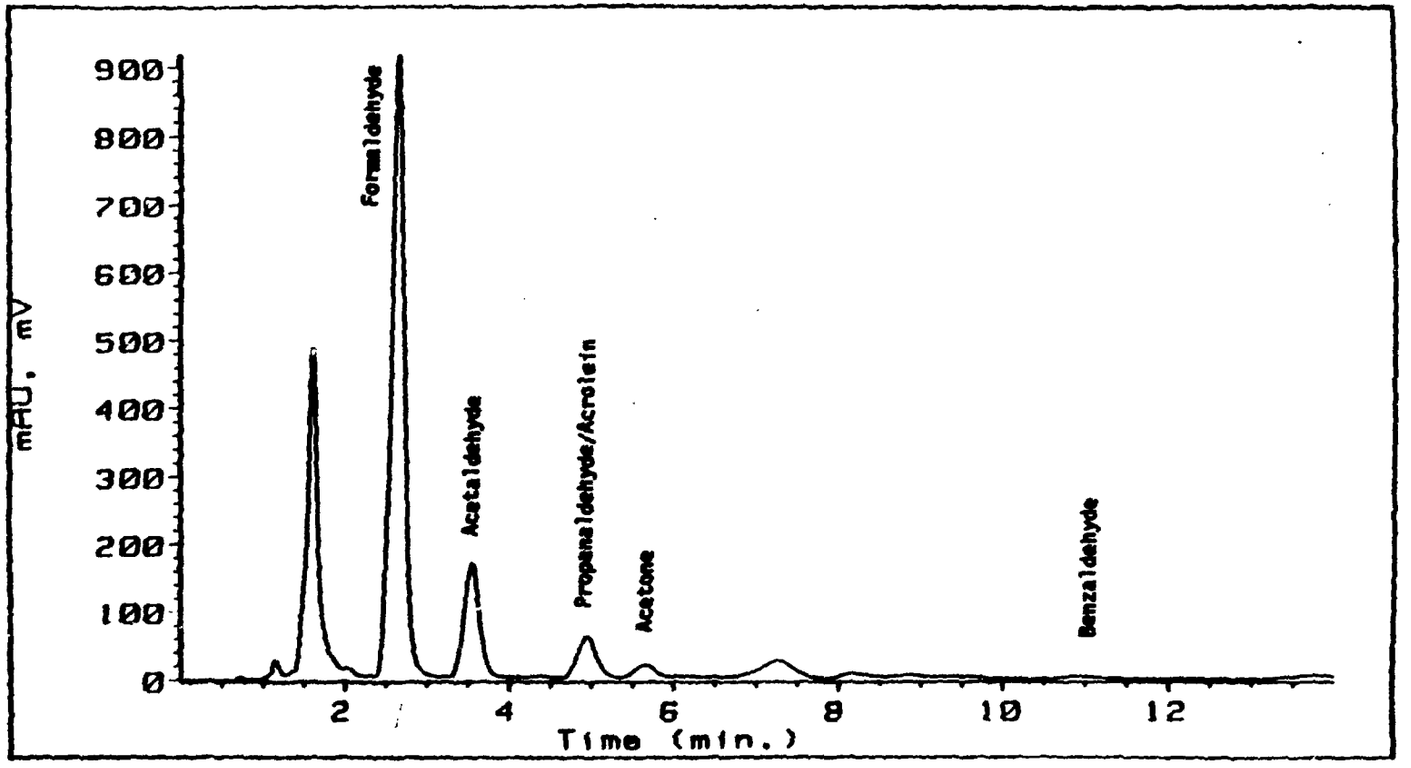

Figure 6. Representative Chromatogram from Analysis of Jet Engine Exhaust for Aldehydes

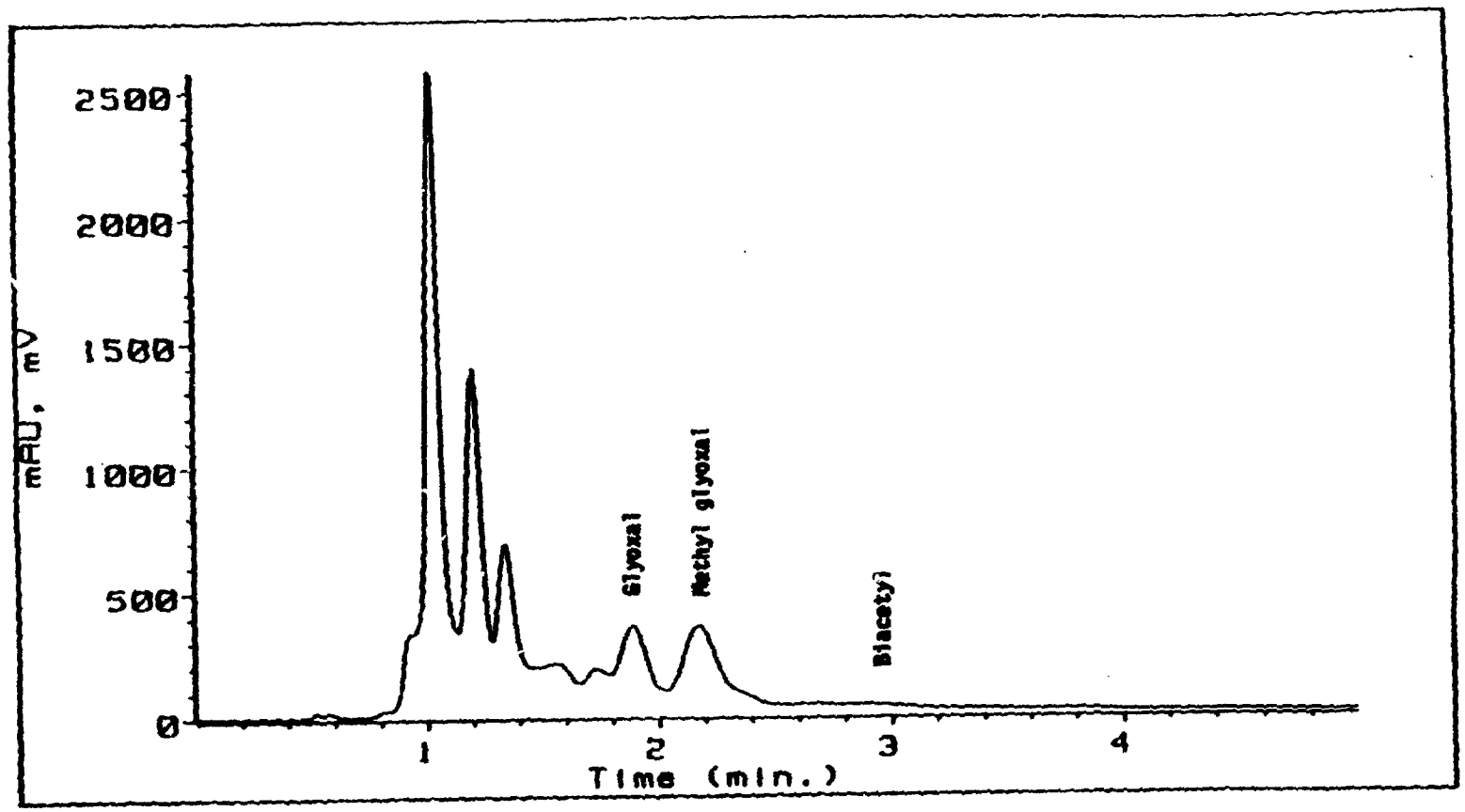

Figure 7. Representative Chromatogram from Analysis of Jet Engine Exhaust for Dialdehydes

TABLE 13. RESULTS OF PAH ANALYSIS
(concentration in exhaust, $\mu g/m^3$)

Engine:	J79	J79	J79	J79
Thrust:	Idle	30%	75%	100%
Sample:	4-10-7	1-10-7	2-10-7	3-10-7
Compound				
Naphthalene	190	49	1.8	1.0
1-methyl naphthalene	98	16	0.27	0.18
2-methyl naphthalene	150	18	0.42	0.21
Dimethyl naphthalene isomer	35	2.1	0.040	0.031
1,2-Dimethyl naphthalene	120	5.2	0.090	0.13
1,4- & 2,3-Dimethyl naphthalene	220	9.4	0.27	0.20
2,6-Dimethyl naphthalene	57	2.6	0.053	0.44
Dimethyl naphthalene isomer	15	0.7	0.027	0.027
Dimethyl naphthalene isomer	26	5.7	0.12	0.089
Phenanthrene	7.3	1.2	0.36	0.24
Anthracene	0.96	0.056	0.011	0.029
Fluoranthene	1.6	0.27	0.20	0.081
Pyrene	1.1	0.11	0.089	0.027
Benz[a]anthracene	0.071	0.012	<0.010	<0.010
Chrysene	0.051	0.017	<0.010	<0.010
Benzo[e]pyrene	<0.010	<0.01	<0.010	ND*
Benzo[a]pyrene	<0.010	<0.01	<0.010	ND*
Perylene	<0.010	<0.01	<0.010	ND*
Coronene	ND*	ND*	ND*	ND*

* ND = Not detected.

TABLE 14. RESULTS OF PAH ANALYSIS
(concentration in exhaust, $\mu g/m^3$)

Engine:	TF33-P3	TF33-P3	TF33-P3	TF33-P3
Thrust:	Idle	30%	75%	100%
Sample:	1-10-14	2-10-14	3-10-14	5-10-14
Compound				
Naphthalene	320	45	9.0	2.3
1-methyl naphthalene	430	33	3.6	1.0
2-methyl naphthalene	350	49	4.5	1.1
Dimethyl naphthalene isomer	53	8.8	0.043	0.064
1,2-Dimethyl naphthalene	320	33	1.8	0.53
1,4- & 2,3-Dimethyl naphthalene	530	53	3.2	1.2
2,6-Dimethyl naphthalene	140	14	0.81	0.29
Dimethyl naphthalene isomer	32	3.3	0.19	0.088
Dimethyl naphthalene isomer	21	11	1.5	0.10
Phenanthrene	40	1.9	0.72	0.22
Anthracene	4.8	0.22	0.045	0.019
Fluoranthene	9.7	0.76	0.32	0.11
Pyrene	8.9	0.64	0.27	0.095
Benz[a]anthracene	0.20	0.012	0.012	0.010
Chrysene	0.20	0.034	0.026	0.021
Benzo[e]pyrene	<0.01	<0.010	<0.010	ND*
Benzo[a]pyrene	<0.01	<0.010	<0.010	ND*
Perylene	<0.01	<0.010	ND*	ND*
Coronene	ND*	ND*	ND*	ND*

* ND = Not detected.

TABLE 15. RESULTS OF PAH ANALYSIS
(concentrations in exhaust, $\mu g/m^3$)

Engine:	TF33-P7	TF33-P7	TF33-P7	TF33-P7
Thrust:	Idle	30%	75%	100%
Sample:	4-10-15	3-10-15	2-10-15	1-10-15
Compound				
Naphthalene	440	77	4.4	1.8
1-methyl naphthalene	350	31	1.9	1.4
2-methyl naphthalene	510	42	2.7	1.9
Dimethyl naphthalene isomer	110	5.0	0.27	0.21
1,2-Dimethyl naphthalene	450	15	1.8	1.3
1,4- & 2,3-Dimethyl naphthalene	760	25	3.2	2.0
2,6-Dimethyl naphthalene	200	7.1	0.65	0.51
Dimethyl naphthalene isomer	46	1.8	0.16	0.12
Dimethyl naphthalene isomer	44	8.8	0.65	0.15
Phenanthrene	47	3.3	0.72	0.71
Anthracene	3.4	0.12	0.036	0.026
Fluoranthene	19	0.38	0.49	0.25
Pyrene	14	0.25	0.34	0.16
Benz[a]anthracene	0.13	0.010	0.023	0.016
Chrysene	0.15	0.10	0.017	0.017
Benzo[e]pyrene	<0.01	<0.010	<0.01	<0.010
Benzo[a]pyrene	<0.01	<0.010	<0.01	<0.010
Perylene	<0.01	<0.010	<0.01	ND*
Coronene	ND*	ND*	ND*	ND*

* ND = Not detected.

TABLE 16. SMOKE NUMBERS AS FUNCTION OF POWER SETTING

ENGINE	POWER SETTING	SMOKE NUMBER
JP-79	Idle	20.3
	30%	24.1
	75%	16.1
	100%	22.6
TF33-P3	Idle	20.4
	30%	36.0
	75%	54.0
	100%	59.4
TF33-P7	Idle	20.0
	30%	35.3
	75%	51.6
	100%	52.5

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 results from the gravimetric analysis of the filters are shown in Table 17. The exhaust volume was corrected to normal conditions of one atmosphere and 25°C. The filter masses were corrected to account for the mass change of four 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 particle mass concentrations in Table 17 range from 0.60 to 36.2 mg/m^3. The mass concentrations generally increase with increasing thrust, consistent with the smoke number results. The particle concentrations in the exhaust from the J79 engine were considerably lower than in either of the TF33 engines. The lower particle emissions from the J79 engine are expected because of the steps that have been taken to make this a "smokeless" engine.

TABLE 17. PARTICLE MASS EMISSIONS

ENGINE	POWER SETTING	TEST NO.	EXHAUST VOLUME*, m^3	PARTICULATE MASS CONCENTRATION, mg/m^3
J79	Idle	4-10-7	0.51	1.73
J79	30%	1-10-7	1.41	0.60
J79	75%	2-10-7	1.48	1.45
J79	100%	3-10-7	1.31	4.22
TF33-P3	Idle	1-10-14	0.61	6.27
TF33-P3	30%	2-10-14	0.35	16.6
TF33-P3	75%	3-10-14	0.57	32.0
TF33-P3	100%	5-10-14	0.61	36.2
TF33-P7	Idle	4-10-15	0.28	7.39
TF33-P7	30%	3-10-15	0.40	11.6
TF33-P7	75%	2-10-15	0.55	24.6
TF33-P7	100%	1-10-15	0.78	20.8

* Corrected to NTP.

3. Particle Concentration and Size Distribution

Information on particle concentrations and size distributions in the exhaust from the three 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 18. The table shows particle concentration (in thousands of particles per cubic centimeter of air) in eight size ranges. Also listed are the total particle 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

TABLE 18. PARTICLE SIZE DISTRIBUTION AND TOTAL PARTICLE CONCENTRATION IN TURBINE ENGINE EXHAUST (THOUSANDS OF PARTICLES/cc)

	J79-17G				TF33-P3				TF33-P7			
MEAN DIAMETER, μm	IDLE	30%	75%	100%	IDLE	30%	75%	100%	IDLE	30%	75%	100%
0.004	0	0	0	0	0	0	0	0	0	0	0	0
0.008	0	0	0	0	0	0	0	0	48	0	0	0
0.013	175	2	0	0	818	0	0	0	3500	120	0	0
0.024	832	198	688	0	2523	845	0	0	790	3641	0	0
0.042	371	162	773	811	361	3050	0	0	930	962	1604	78
0.075	3	23	297	956	1316	432	3225	2293	1518	1487	4073	3381
0.133	0	0	272	14	541	382	5050	2667	25	1236	651	320
0.237	9	0	28	187	18	1105	212	175	0	87	593	181
≥0.237	7	3	81	201	189	575	1250	760	107	359	727	433
Total Number Count	1320	353	1870	1700	5230	5500	7750	4530	6250	7179	6364	3608

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 18, which indicate that there are relatively small numbers of particles of diameter greater than 0.24 μm.

SECTION IV

DISCUSSION

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 had been accounted for. However, a recent study which employed multiple sampling and analysis techniques was able to account for 98 $\pm$ 10 percent of the total organic emissions (Reference 2). During that study, emission measurements were made on TF-39 and CFM-56 engines operating at idle, 30 and 80 percent thrust settings. Both engines utilized JP-4, JP-5 and JP-8 fuels.

In the current study, emission measurements were made on the J79, TF33-P3, and TF33-P7 engines. These engines were operated with JP-4 fuel at thrust settings of idle, 30, 75, and 100 percent.

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 concentration as determined with a continuous total organic carbon monitoring system. In this study, the total organic carbon instrument, a Beckman 402 Analyzer, employs a flame-ionization detector (FID) to continuously measure organics. This monitor is essentially a carbon-counting instrument; however, it does not respond to oxygenated carbon. Because of this, formaldehyde is not detected, and only one of the two acetaldehyde carbons is counted. 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 19. 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.

TABLE 19. COMPARISON OF TOTAL ORGANICS BY SPECIATION METHODS VERSUS CONTINUOUS FID (ppmC)

ENGINE	THRUST SETTING	TOTAL ORGANICS BY SPECIATION METHODS	TOTAL ORGANICS BY CONTINUOUS FID	CARBON BALANCE
J79-17G				
	Idle	333	355	.94
	30%	19.5	15.7	1.24
	75%	1.93	0.7	2.76*
	100%	0.72	2.2	.33*
TF33-P3				
	Idle	1236	1350	.92
	30%	70.3	76.0	.92
	75%	5.22	5.8	.90*
	100%	3.02	0.7	4.31*
TF33-P7				
	Idle	1326	1150	1.15
	30%	48.2	52.0	.93
	75%	2.55	2.2	1.20*
	100%	2.84	1.3	2.18*

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

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.

Excluding samples for which the exhaust organic concentration was less than 10 ppmC, the mean carbon balance for the remaining six engine/power setting combinations was 1.02 $\pm$ 0.14. This is in very good agreement with the study noted above (Reference 2), and demonstrates that our analytical speciation methods are accounting for most of the organic material in the exhaust.

B. INDIVIDUAL ORGANIC SPECIES

The individual organic species quantified in the emissions have been presented in Tables 10-12. In previous studies (References 2 and 3), we have found that four species (ethylene, 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 J79 engine in this study, where these four species account for 24 percent of the organic concentration. However, this observation does not hold for the two TF33 engines. Both the TF33-P3 and TF33-P7 engines show a significant contribution of unburned fuel in the emissions at idle power. The individual species having the highest concentrations for these two engines are still the products of combustion cracking, ethylene and propene, but the sum of the unburned fuel constituents contribute significantly to the organic emissions.

Examination of the data in Tables 10-12 reveal that the organic emissions are greatly reduced as the engine power is increased from idle to 100 percent. It is also noteworthy that exhaust organic concentrations at the two lower power settings, idle and 30 percent, are much lower for the J79 engine compared to the TF33 engines.

C. DISTRIBUTION OF EMISSIONS BY COMPOUND CLASS

Tables 10-12 also show the exhaust organic distribution according to major compound classes for each of the three engines tested. Comparison of the emissions from the three engines reveals that the most abundant compound classes are usually paraffins and olefins. However, the aromatic hydrocarbons are also an important class of compounds, especially at idle power, and aldehydes are quite significant, particularly at 30 percent power. The compound class data are graphically illustrated in Figures 8-10, where the levels of various compound classes for each of the three engines are plotted. The olefin and aldehyde emissions often increase in abundance relative to other classes as the power setting increases from idle to 30 percent. These two classes are especially significant in terms of photochemical reactivity and health considerations.

D. DISTRIBUTION OF EMISSIONS BY CARBON NUMBER

The distribution of emissions by volatility is of some importance since these data most clearly distinguish the cracking and partial oxidation products from the unburned fuel. The carbon number distributions for each of the three engines tested are presented in Tables 20-22. The results at idle and 30 percent power are plotted in Figures 11 and 12. These data show that the two TF33 engines yield higher organic emissions

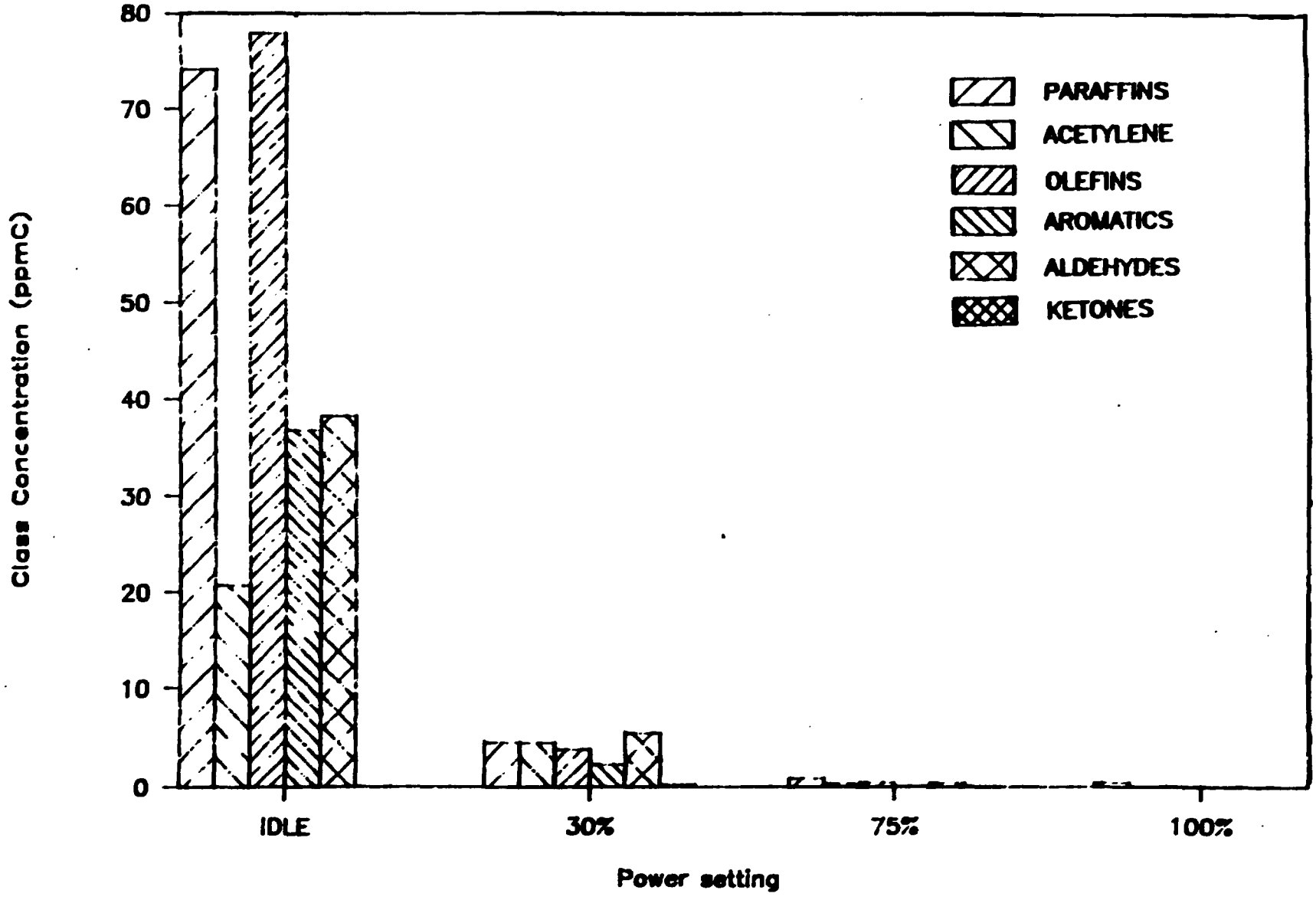

Figure 8. Exhaust Organic Concentration by Compound Class for J79 Engine

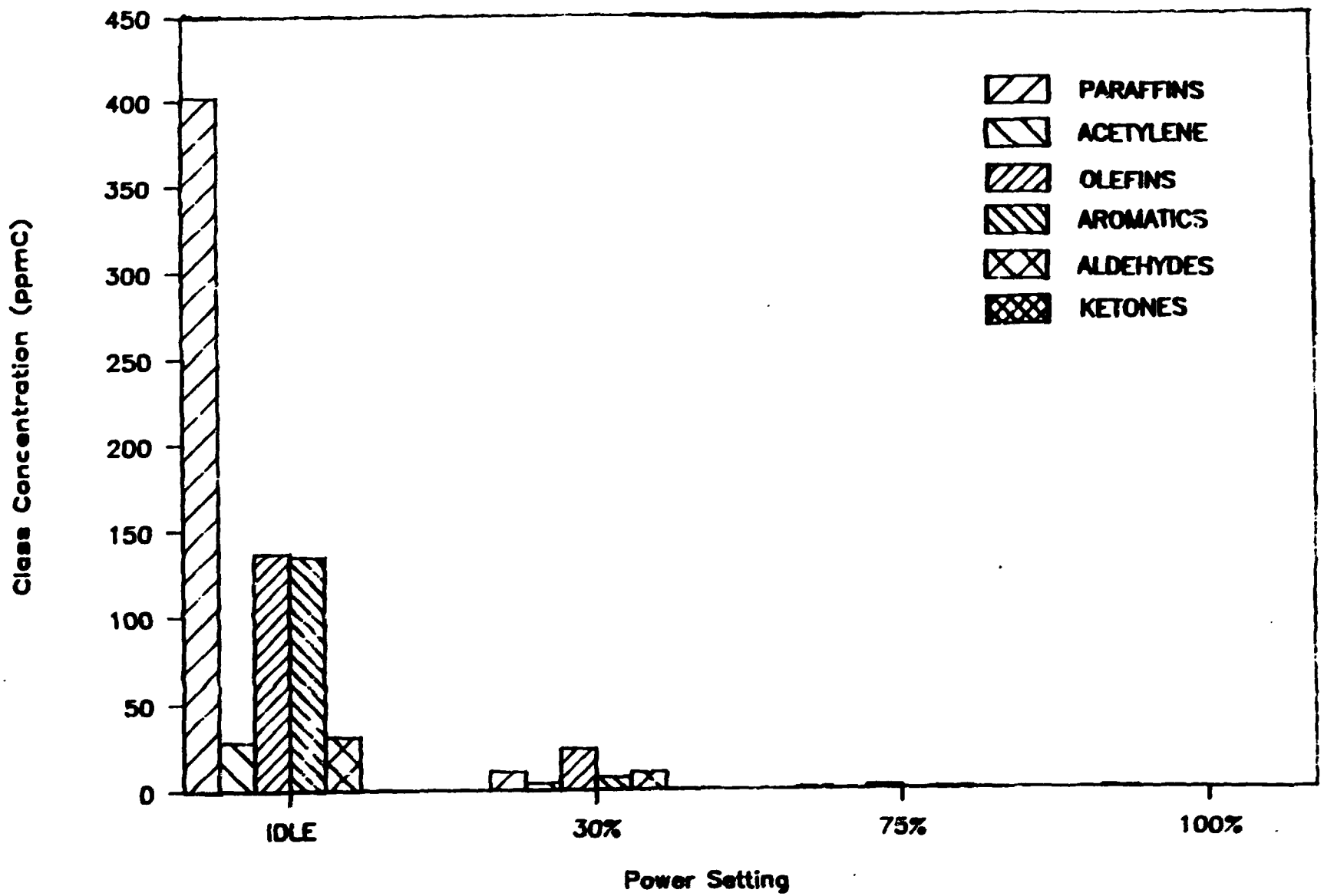

Figure 9. Exhaust Organic Concentration by Compound Class for TF33-P3 Engine

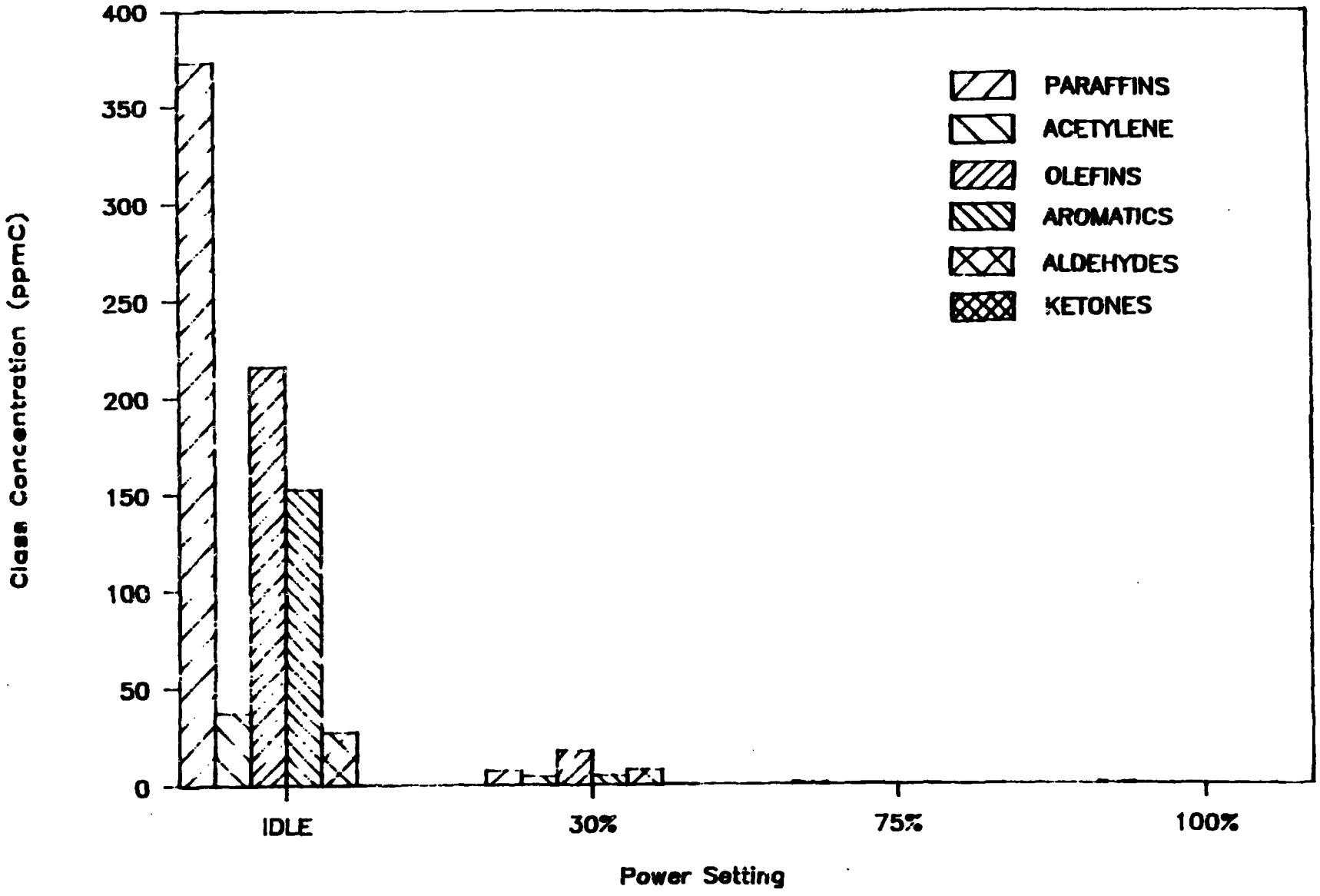

Figure 10. Exhaust Organic Concentration by Compound Class for TF33-P7 Engine

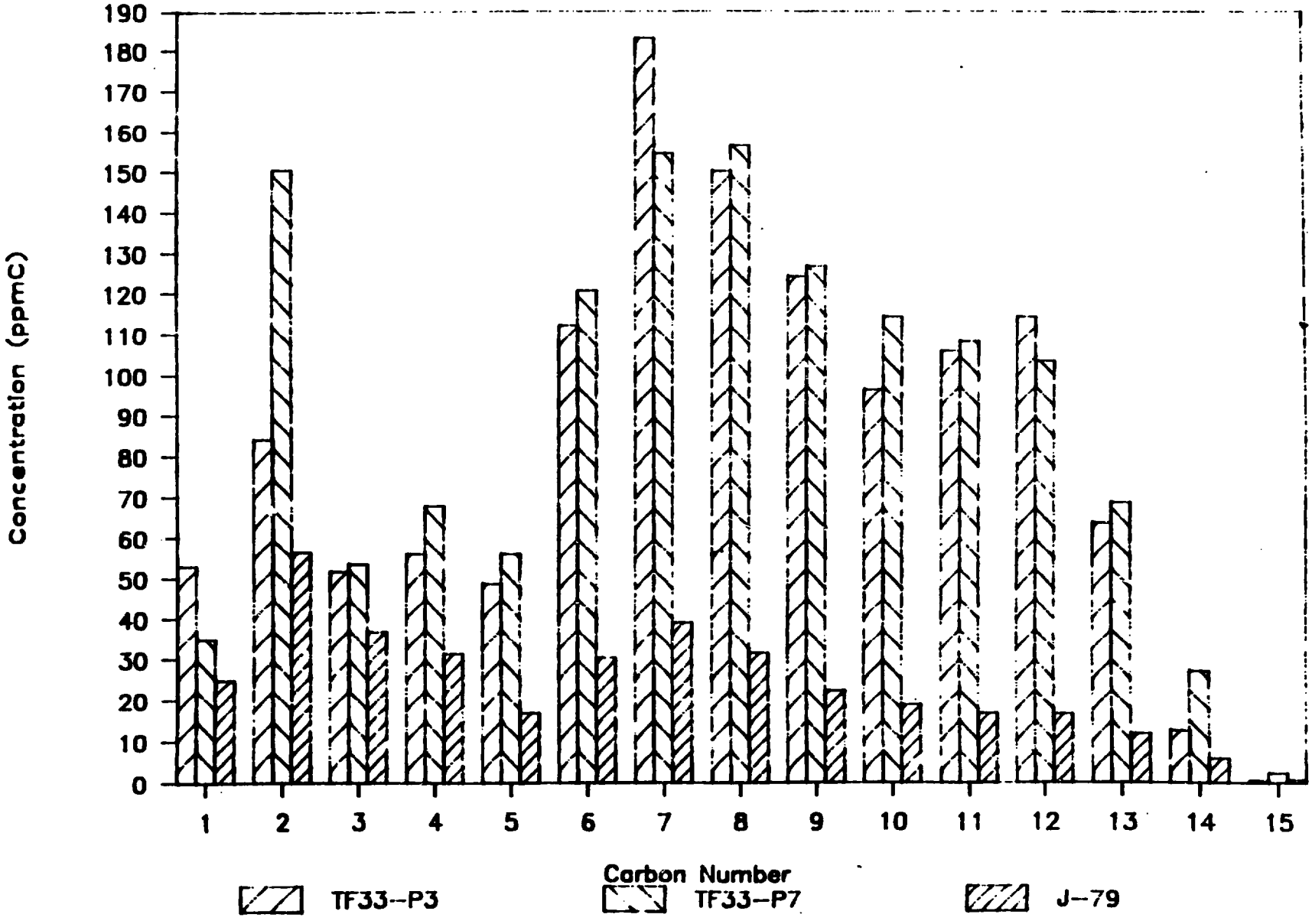

Figure 11. Exhaust Organic Species Concentrations by Carbon Number at Idle Power

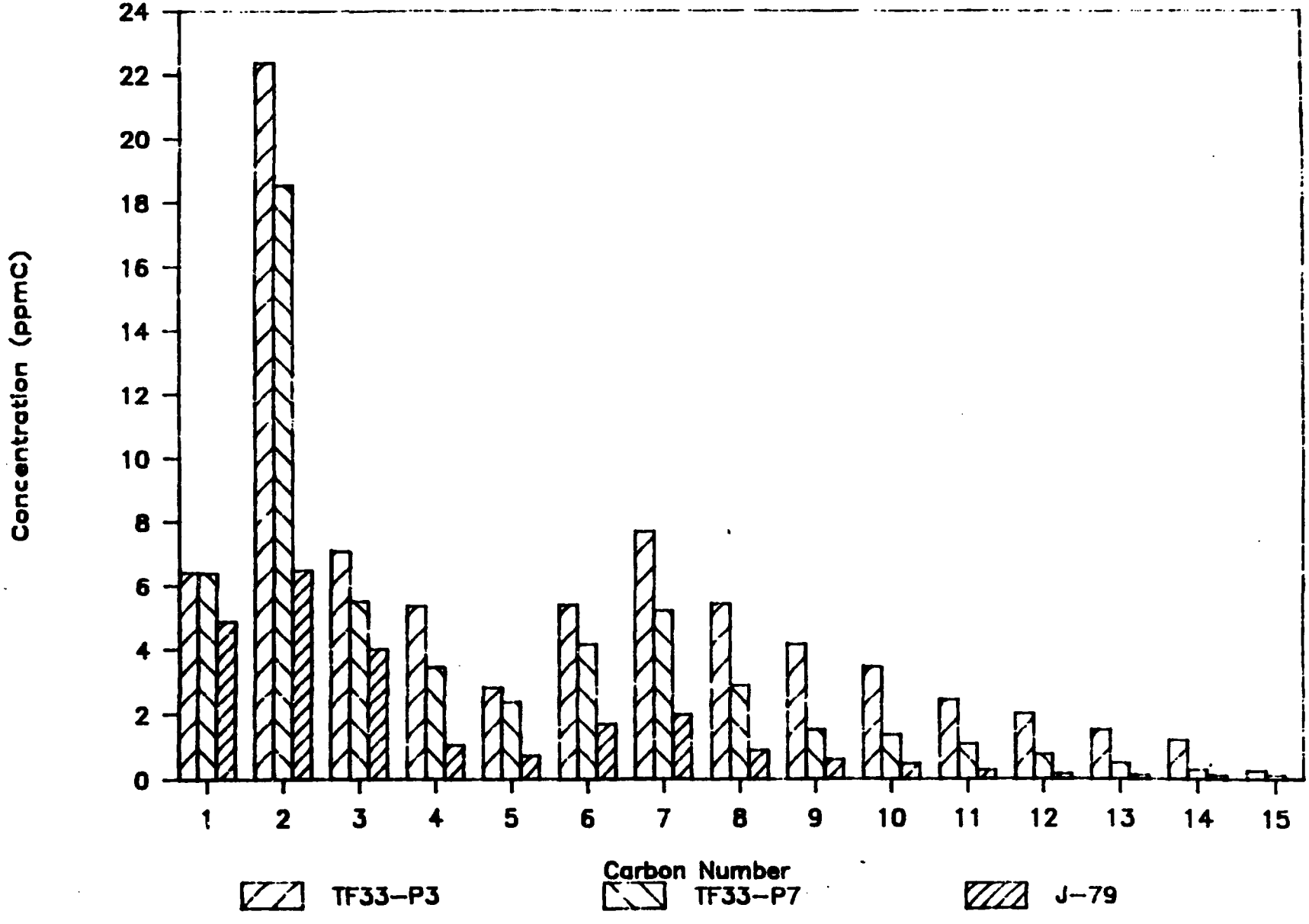

Figure 12. Exhaust Organic Species Concentrations by Carbon Number at 30 Percent Power

TABLE 20. DISTRIBUTION OF ORGANIC EMISSIONS BY CARBON NUMBER FOR J79 ENGINE (ppmC)

CARBON NUMBER	POWER SETTING			
	IDLE	30%	75%	100%
C1	25.118	4.875	0.831	0.395
C2	56.553	6.501	0.639	0.120
C3	37.051	4.026	0.169	0.047
C4	31.458	1.045	0.104	0.052
C5	15.846	0.690	0.053	0.044
C6	30.530	1.695	0.078	0.027
C7	39.222	1.983	0.137	0.011
C8	31.718	0.866	0.021	0.008
C9	22.490	0.576	0.044	0.022
C10	19.004	0.465	0.058	0.019
C11	15.749	0.251	0.028	0.031
C12	16.619	0.145	0.014	0.008
C13	12.091	0.108	0.002	0.003
C14	5.748	0.114	<0.001	0.002
C15-ABOVE	0.642	0.033	<0.001	0.002
TOTAL	361.839	23.373	2.178	0.791

than the J79 at all power settings studied. At idle power, the TF33 engines showed maxima in organic concentrations at C_2 and over the range C_6-C_{12}. The J79 emissions were less variable, but peaked at C_2. At 30 percent power, all three engines showed maximum emissions of C_2 organic species.

E. EMISSION FACTORS

1. Nitrogen Oxide Emissions

The nitrogen oxide emissions from the three test engines are shown in Table 23. 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 air standard currently is based on annual average

TABLE 21. DISTRIBUTION OF ORGANIC EMISSIONS BY CARBON NUMBER FOR TF33-P3 ENGINE (ppmC)

CARBON NUMBER	POWER SETTING			
	IDLE	30%	75%	100%
C1	53.210	6.434	1.127	0.522
C2	84.353	22.362	2.094	0.236
C3	51.841	7.092	0.508	0.103
C4	56.304	5.377	0.437	0.238
C5	48.874	2.846	0.247	0.173
C6	112.530	5.421	0.337	0.183
C7	183.267	7.721	0.274	0.114
C8	150.425	5.441	0.179	0.130
C9	124.520	4.175	0.105	0.160
C10	96.538	3.468	0.170	0.272
C11	105.987	2.451	0.119	0.335
C12	114.627	2.024	0.087	0.365
C13	63.867	1.543	0.096	0.087
C14	12.822	1.206	0.116	0.159
C15-ABOVE	0.527	0.257	0.112	0.103
TOTAL	1259.692	77.818	6.008	3.180

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 23 show that NO and NO_x emissions increase at higher engine power settings, as expected from combustion kinetics. However, the ratio of NO_2 to NO_x generally decreases above 30 percent power.

2. Fuel/Air Ratios

During the engine tests, fuel flow and air flow to the engines were monitored. These data were reported in Tables 4-6. The air flow reported in Tables 4-6 does not include bypass air, which must be included for an accurate comparison with the fuel/air ratio calculated from the emissions measurements. The fuel flow and adjusted air flow

TABLE 22. DISTRIBUTION OF ORGANIC EMISSIONS BY CARBON NUMBER FOR TF33-P7 ENGINE (ppmC)

CARBON NUMBER	POWER SETTING			
	IDLE	30%	75%	100%
C1	35.127	6.404	0.652	0.426
C2	150.694	18.571	0.574	0.160
C3	53.707	5.533	0.191	0.054
C4	68.017	3.475	0.166	0.361
C5	56.203	2.389	0.148	0.390
C6	120.979	4.170	0.194	0.270
C7	154.772	5.238	0.111	0.090
C8	156.599	2.894	0.114	0.246
C9	126.998	1.543	0.062	0.124
C10	114.625	1.371	0.194	0.173
C11	108.390	1.070	0.151	0.205
C12	103.618	0.748	0.083	0.133
C13	68.694	0.483	0.066	0.066
C14	27.275	0.263	0.041	0.114
C15-ABOVE	2.399	0.109	0.114	0.128
TOTAL	1348.097	54.261	2.861	2.940

have been used to determine the measured fuel/air ratio, reported as F/A (measured) in Table 24. The fuel/air ratio has also been calculated based on the exhaust composition. These results are reported in Table 24 as F/A (calculated). Significant differences in the measured and calculated F/A might suggest inaccuracy in one or more of the measured variables, or nonrepresentative sampling of the exhaust. Calculating the relative difference in the ratios using the formula

$$\frac{\text{F/A (calculated)} - \text{F/A (measured)}}{\text{F/A (measured)}}$$

provides information on the agreement between the measured and calculated fuel to air ratio. With one exception, all of the ratios agree to within ± 15 percent. The mean relative difference in ratios for all the tests was 1.8 percent

TABLE 23. NO_x EMISSION DATA

POWER MODE	RUN NO.	NO_x, ppm	NO, ppm	NO_2, ppm	NO_2/NO_x
			J79-17G		
Idle	4-10-7	9.5	4.6	4.9	.52
30%	1-10-7	18.0	7.5	10.5	.58
75%	2-10-7	52.5	44.5	8.0	.15
100%	3-10-7	84.0	76.6	7.4	.09
			TF33-P3		
Idle	1-10-14	11.0	3.5	7.5	.68
30%	2-10-14	24.5	10.7	13.8	.56
75%	3-10-14	56.0	47.0	9.0	.16
100%	5-10-14	73.5	68.0	5.5	.08
			TF33-P7		
Idle	4-10-15	11.2	5.5	5.7	.51
30%	3-10-15	23.0	10.0	13.0	.56
75%	2-10-15	62.8	57.0	5.8	.09
100%	1-10-15	95.5	93.0	2.5	.03

± 8.7 percent. This is adequate agreement, and it demonstrates that representative exhaust samples were collected, and that the emissions measurements are reasonably accurate.

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. The calculation procedures were noted in Section II. The emission indices for the three engines at each power setting are given in Table 25. 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 emissions indices for the three engines may be used with the fuel flow data in Tables 4-6 to calculate emission rates. The emission rates for CO, CO_2, hydrocarbons, NO, NO_2, and NO_x are shown in Table 26

TABLE 24. FUEL/AIR RATIOS

POWER MODE	RUN NO.	F/A (CALCULATED)	F/A (MEASURED)
		J79-17G	
Idle	4-10-7	.00723	.00735
30%	1-10-7	.00768	.00707
75%	2-10-7	.01264	.01124
100%	3-10-7	.01543	.01393
		TF33-P3	
Idle	1-10-14	.00719	.00872
30%	2-10-14	.00882	.00800
75%	3-10-14	.01197	.01212
100%	5-10-14	.01349	.01488
		TF33-P7	
Idle	4-10-15	.00842	.00830
30%	3-10-15	.00872	.00870
75%	2-10-15	.01346	.01280
100%	1-10-15	.01538	.01500

for power settings from idle through 100 percent. These rates are given in units of pounds per hour. As anticipated, the CO and hydrocarbon rates decrease and NO_x rates increase with increasing power setting. Table 26 shows some differences in emissions among engines. These engines are not all rated at the same maximum thrust, so the same "power setting" will produce different thrust for each engine. The actual thrusts developed by each engine at the various power settings are listed in Tables 4-6. 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

TABLE 25. EMISSION INDICES FOR THREE ENGINES

	EMISSION INDEX (LBS/10^3) LB FUEL)					
	CO	CO_2	HC	NO*	NO_2	NO_x*
J79						
Idle	94.1	2978	24.6	1.0	1.1	2.1
30%	25.3	3158	1.0	1.6	2.2	3.8
75%	3.8	3169	0.03	5.8	1.0	6.8
100%	1.6	3167	0.07	8.2	0.8	9.0
TF33-P3						
Idle	92.0	2763	94.0	0.8	1.7	2.5
30%	20.3	3144	4.3	2.0	2.6	4.6
75%	3.6	3171	0.2	6.5	1.2	7.7
100%	2.2	3169	0.03	8.4	0.7	9.1
TF33-P7						
Idle	107	2809	68.5	1.1	1.1	2.2
30%	22.8	3145	3.0	1.9	2.5	4.4
75%	2.5	3098	0.08	7.0	0.7	7.7
100%	0.9	3167	0.04	10.0	0.3	10.3

* Calculated as NO_2 by convention.

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 25. 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 10-12 were used for these calculations.

TABLE 26. EMISSION RATES FOR THREE ENGINES

	EMISSION RATES (LB/HR)					
	CO	CO_2 (x 10^3)	HC	NO*	NO_2	NO_x*
J79						
Idle	113	3.6	29.5	1.2	1.3	2.5
30%	62.8	7.8	2.6	4.0	5.6	9.6
75%	22.2	18.4	0.2	33.8	6.1	39.9
100%	12.9	26.2	0.6	68.1	6.6	74.7
TF33-P3						
Idle	96.7	2.9	98.9	0.8	1.8	2.6
30%	45.9	7.1	9.8	4.5	5.8	10.3
75%	18.8	16.4	1.3	33.6	6.4	40.0
100%	15.2	22.5	0.2	59.3	4.8	64.1
TF33-P7						
Idle	119	3.1	76.0	1.2	1.2	2.4
30%	57.7	8.0	7.6	4.8	6.2	11.0
75%	15.8	19.5	0.5	44.2	4.5	48.7
100%	8.3	28.0	0.4	88.8	2.4	91.2

* Calculated as NO_2 by convention.

The total species summations in Tables 10-12 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 9.

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, nausea, 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 three study engines ranged from 7.5 to 17.4 ppmC in the undiluted exhaust at idle power (where exposure of flight line personnel is maximum). Exhaust concentrations of benzene at higher power settings are much lower.

A comparison of benzene emissions from automobiles operating on the 1975 Federal Test Procedure with and without catalytic converters (Reference 7), five jet engines studied previously (References 2 and 3), and the study engines, is included in Table 27.

TABLE 27. COMPARISON OF BENZENE EMISSIONS FROM VARIOUS MOBILE SOURCES

Source	Type	Power	Fuel	Benzene Emissions, mg/g of Fuel
J79 (smokeless)	-	idle	JP-4	0.51
TF33-P3	-	idle	JP-4	0.93
TF33-P7	-	idle	JP-4	0.88
TF39	-	idle	JP-5	0.42
CFM-56	-	idle	JP-4	0.09
TF41-A2	-	idle	JP-4	1.94
TF30-P103	-	idle	JP-4	1.06
TF30-P109	-	idle	JP-4	0.89
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 2). 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). Concentrations of formaldehyde in undiluted exhaust from the study engines at idle ranged from 9.0 to 17.8 ppm. Table 28 lists the concentration of formaldehyde in exhaust from several mobile sources (References 2,3,10).

TABLE 28. FORMALDEHYDE CONCENTRATIONS IN EXHAUST FROM MOBILE SOURCES

Source	Type	Power	Fuel	Formaldehyde Concentration, ppm
J79 (smokeless)	-	idle	JP-4	15.9
TF33-P3	-	idle	JP-4	15.5
TF33-P7	-	idle	JP-4	16.6
TF39	-	idle	JP-4	14.6
CFM-56	-	idle	JP-4	9.3
TF41-A2	-	idle	JP-4	17.8
TF30-P103	-	idle	JP-4	9.3
TF30-P109	-	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

The concentrations in exhaust from turbine engines are generally higher than light duty diesels or catalyst-equipped automobiles, and approaches the levels in noncatalyst automobiles. 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.

3. Polynuclear Aromatic Hydrocarbons (PAH)

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 8-hour time-weighted average (Reference 9). Emissions of BaP from several mobile sources are noted in Table 29 (Reference 11).

These data indicate that BaP emissions from jet engines are generally lower than from internal combustion engines, when compared on the basis of mass per mass of fuel consumed. Table 29 shows that BaP was not detected in the exhaust from the current study engines at idle power. As a class, nitro-PAHs are much more hazardous than PAHs. Emissions and atmospheric formation of nitro-PAHs in turbine engine exhaust are the subject of a current study which will be reported separately.

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. This can lead to a state of tissue hypoxia. Acute exposure to CO can cause headache, dizziness, drowsiness, nausea, vomiting, coma,

TABLE 29. COMPARISON OF BENZO(a)PYRENE EMISSIONS FROM SEVERAL EMISSIONS SOURCES

Source	Type	Power	Fuel	BaP, μg/g of Fuel
J79 (smokeless)	-	idle	JP-4	< 0.0013
TF33-P3	-	idle	JP-4	< 0.0013
TF33-P7	-	idle	JP-4	< 0.0013
TF39	-	idle	JP-5	0.0051
CFM-56	-	idle	JP-4	0.024
TF41-A2	-	idle	JP-4	0.0064
TF30-P103	-	idle	JP-4	< 0.0013
TF30-P109	-	idle	JP-4	< 0.0013
Automobile	diesel	driving cycle	-	0.03-0.16
Automobile	internal combustion	driving cycle	unleaded	0.014
Truck	diesel	driving cycle	-	0.0038
Truck	internal combustion	driving cycle	-	0.065

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 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 30. These are concentrations at idle power in undiluted exhaust. Table 9 shows that the CO concentration decreases significantly at higher power settings.

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 membranes, and may result in severe pulmonary irritation. Even lower concentrations may produce acute pulmonary edema.

TABLE 30. CONCENTRATIONS OF CO IN UNDILUTED ENGINE EXHAUST AT IDLE POWER (JP-4 FUEL)

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

Chronic exposure may result in pulmonary dysfunction with decreased vital capacity and signs of emphysema (Reference 9).

The OSHA standard for NO_2 is 5 ppm for a 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 jet engines is shown in Table 31. These concentrations are for undiluted exhaust. As expected, the NO_2 concentrations increase at higher power settings. In general, the NO_2 exhaust concentrations for the study engines are similar to the levels reported for other turbine engines (References 2 and 3). The relationship between NO_2 emissions and engine power setting was discussed earlier in this report.

TABLE 31. CONCENTRATIONS OF NO_2 IN JET ENGINE EXHAUST

ENGINE	NO_2 CONCENTRATION, ppm	
	IDLE POWER	30 PERCENT POWER
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

G. PARTICLE SIZE DISTRIBUTION

The particle size distribution obtained at different power settings for the three turbine engines is provided in Table 18. The table shows a very significant difference in particle concentration for the J79 (smokeless) engine compared to the two TF33 engines. Particles with diameters $\leq$0.1 μm dominated the J79 distribution at all power levels. The lower particle concentrations observed from the J79 engine are consistent with the lower smoke number and lower particle mass emissions measured for this engine (Tables 16 and 17).

The data in Table 18 showed relatively little variation in the total particle count with power setting, for the TF33 engines. However, the size distribution varies considerably with power level. As reported in Reference 3 for other turbine engines, the mean particle diameter increases with increasing power. For the TF33 engines, small particles ($\leq$0.05 μm) dominate the number concentration at idle and 30 percent power, while larger particles ($\geq$0.1 μm) are more prevalent at power settings of 75 and 100 percent.

The change in size distribution probably accounts for the change in smoke number with increasing power. Table 16 showed that smoke number increased from 20 to over 50 for the TF33 engines on increasing power from idle to 100 percent. However, Table 18 shows that the particle concentration does not increase smoothly with increasing power for these engines. The likely explanation for the smoke number increasing while the particle concentration stays constant or decreases, is the strong dependence of light attenuation and scattering 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 0.2 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 extremely sensitive relationship between attenuation and size, small changes in the size distribution can yield significant changes in light attenuation. This is precisely what the smoke numbers in Table 16 indicate.

The data in Table 18 indicate that the vast majority of particles emitted by these turbine engines are sub-micron-size, and are typically $\leq$0.24 μm in diameter. This observation was confirmed by the SEM analysis

of the samples collected by electrostatic precipitator. The particle size distributions measured from these engines are qualitatively similar to those reported for three other turbine engines (Reference 3).

SECTION V

CONCLUSIONS

This study has characterized the gas and particle composition of exhaust from three Air Force turbine engines: TF33-P3, TF33-P7, and J79 (smokeless). Measurements were made with the engines operating on JP-4 fuel, at power settings from idle to 100 percent normal rated. Several significant findings resulting from this study are summarized below:

- For exhaust organic concentrations greater than 10 ppmC, the sum of individual organic compounds measured during the study accounted for 102 $\pm$ 14 percent of the total organic loading of the exhaust.

- At idle, four combustion products (ethylene, acetylene, propene, and formaldehyde) accounted for 25 percent of total organic emissions for the J79 engine. For both TF33 engines, the highest concentrations in the exhaust at idle were ethylene and propene, but unburned fuel constituents contributed a major portion of the organic composition.

- Exhaust organic species concentrations and carbon monoxide concentrations decreased dramatically as the engine power setting was increased from idle to 100 percent. Nitrogen oxide concentrations increased with increasing power.

- At the higher power settings of 75 percent and 100 percent, cracking products and partially oxygenated combustion products were the dominant organic constituents in the exhaust.

- Aldehydes were present at significant concentrations in the exhaust from all three engines.

- Dicarbonyl compounds were observed at relatively high concentrations in the exhaust from each engine, consistent with our earlier studies (References 2 and 3). At idle power, methyl glyoxal always exceeded glyoxal.

- The ratio NO_2/NO_x was greater than 0.5 at idle and 30 percent power for all three engines. This ratio decreased at higher power settings, as NO_x increased.

- With the exception of one test, measured fuel/air ratios agreed with the ratios calculated from exhaust composition to better than $\pm$ 15 percent. This indicates that representative exhaust samples were collected. The mean relative difference in ratios for all tests was 1.8 percent.

- Emission indices and emission rates were determined for CO, CO_2, hydrocarbons, NO, and NO_x at all power settings.

- Polynuclear aromatic hydrocarbons (PAH) were measured in the exhaust from all three engines. The highest concentrations were observed at idle power. The concentration of benzo[a]pyrene, which is frequently used as a surrogate for PAH, was below the detection limit.

- The concentration of particulate matter in the exhaust was much lower for the J79 (smokeless) engine compared to the TF33-P3 and TF33-P7 engines. For all three engines, the particle concentration increased with increasing power.

- The smoke number was determined for exhaust from each engine. At idle, the smoke number was similar for all engines. The smoke number increased for the TF33 engines at higher power settings.

- Particle number concentration in the exhaust was in the range 0.4×10^6 to 8×10^6 particles/cc. The particle concentrations in the exhaust from the J79 (smokeless) engine were substantially lower than those from the TF33 engines. The distribution of particle sizes varied with power setting, with small particles (<0.05 μm) most prevalent at idle and 30 percent power, and larger particles (>0.05 μm) dominant at higher power. Microscopic examination of collected exhaust particles confirmed that there were few particles in the exhaust greater than 0.24 μm in diameter.

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