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**AIRCRAFT EMISSIONS
CHARACTERIZATION:
TF41-A2, TF30-P103, AND TF30-P109
ENGINES**

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FIELD	GROUP	SUB-GROUP										
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19. ABSTRACT (Continue on reverse if necessary and identify by block number) Assessment of the environmental impact of aircraft operations is required by Air Force regulations. This program was undertaken with the aim of quantifying the gaseous and particulate emissions associated with three Air Force turbine engines. These engines were TF41-A2, TF30-P103, and TF30-P109. 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, 100 percent, and afterburner (where appropriate). 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, CO₂, total hydrocarbons, NO, NO₂, 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 work was performed between December, 1985 and March, 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 Drs. M. R. Kuhlman and 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.



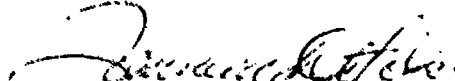
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SECTION I

INTRODUCTION

A. OBJECTIVE

Assessment of the environmental impact of aircraft operations is required by Air Force regulations. 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. The engines are TF41-A2, TF30-P103, and TF30-P109. Tests were conducted using JP-4 fuel at engine power settings of idle, 30 percent, 75 percent, 100 percent, and afterburning (Zone 1) power. The exhaust sampling was carried out in an indoor test cell 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).

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 9. A diagram of the test cell is shown in Figure 1. The engine exhaust flows through an 84-foot long steel augmentor tube, the last 30 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 3-foot diameter vent tubes in the ceiling of the blast room. The test cell is instrumented to record the numerous engine performance parameters included in this report.

Figure 1 shows the position of the exhaust sampling rake at the inlet of the augmentor tube. This position was used for normal engine operating modes. For afterburner operation, a probe was located in one of the exhaust vents on the roof of the test cell above the blast room. This location is noted 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 which were clamped to the inlet cone of the augmentor tube. Schematic top and side views of the test cell are 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 common sample line passes down the support strut where it joins an

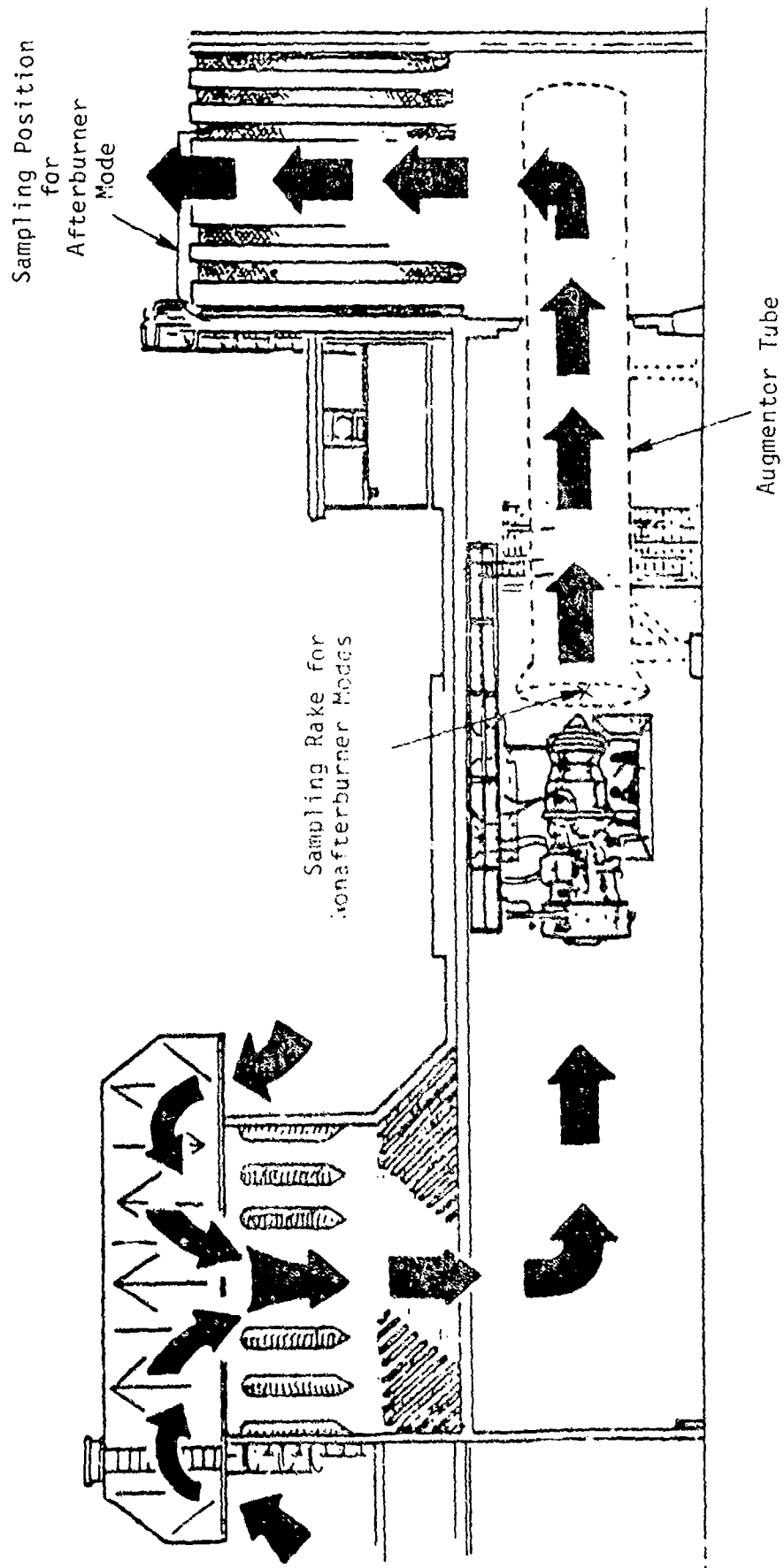


Figure 1. Test Cell Cross Section

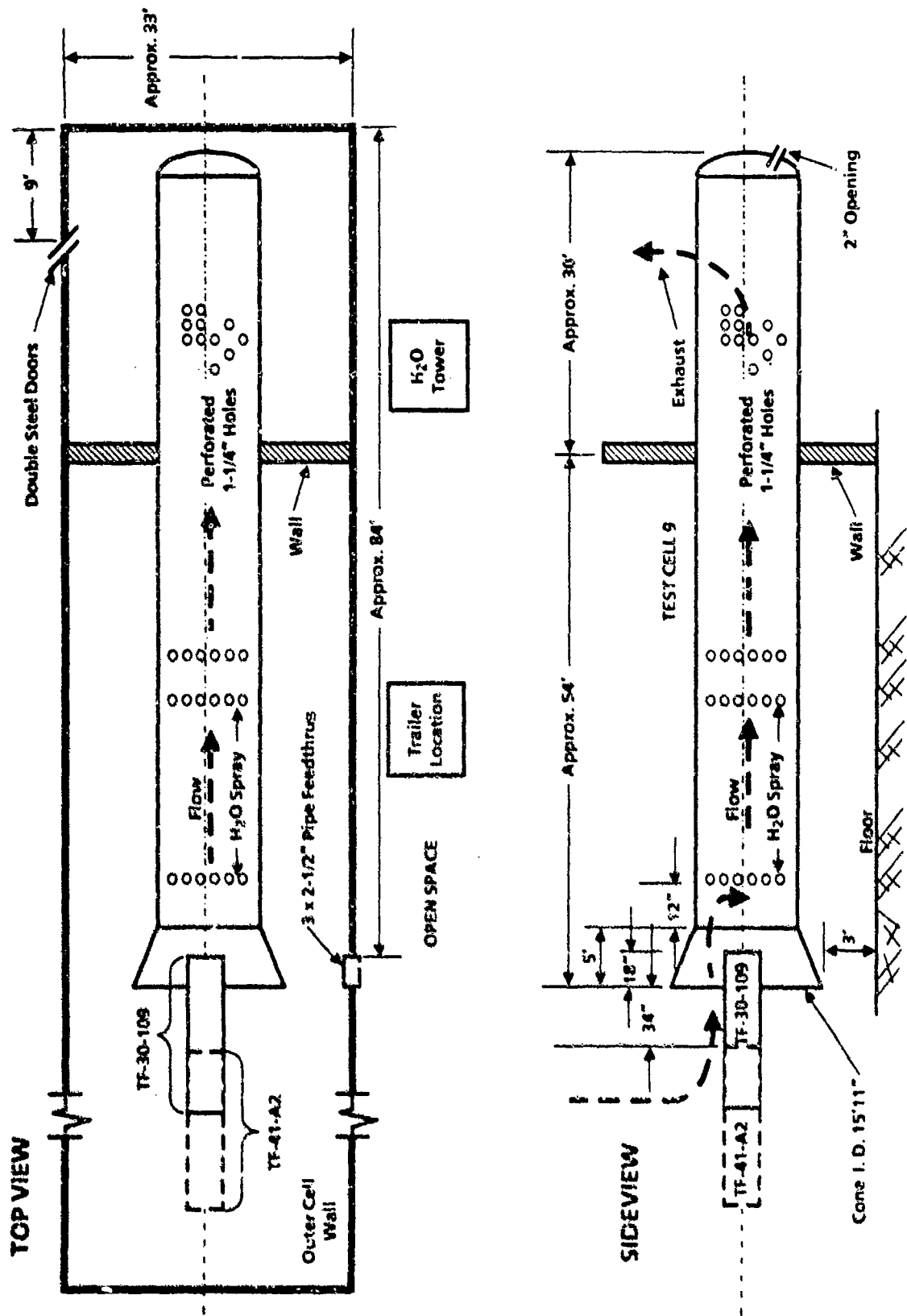


Figure 2. Top View and Side View of Test Cell

electrically heated, flexible Teflon[®] line. At this point, the sample line was connected by a tee to a clean-air purge line and pumping station. A diagram of the sampling apparatus is included in Figure 3.

For afterburner measurements, exhaust samples were collected from one of the test cell exhaust vents located on the roof of the cell (see Figures 1 and 2). 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 Zone 1 afterburner power. Higher afterburner power settings require augmentor tube cooling by water spray, and emission measurements were not practical under these conditions.

In addition to afterburner emission measurements, one rooftop sampling test was run at 100 percent thrust. 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 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.

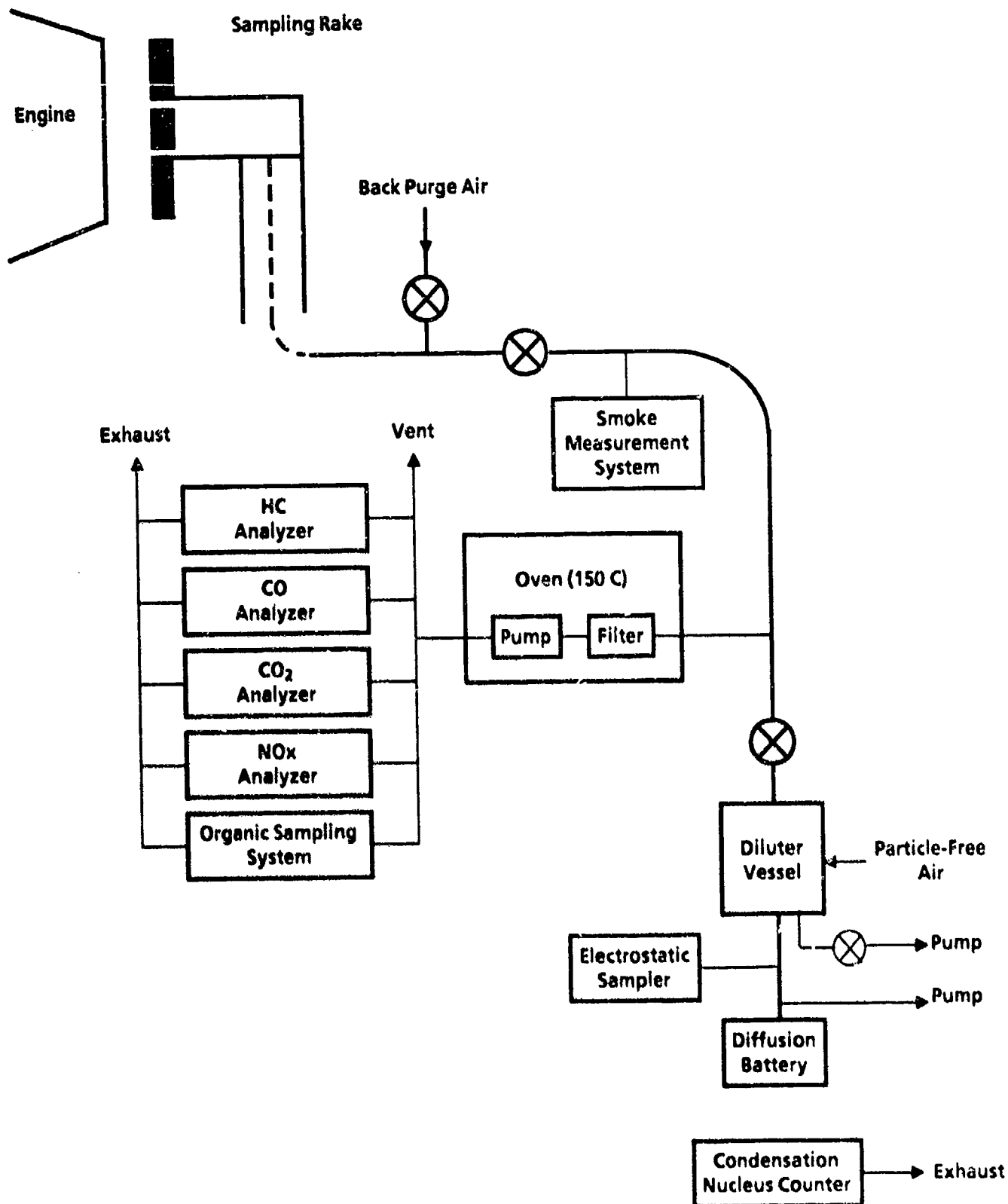


Figure 3. Sampling System

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	70	30	2100	50 µg/m ³	+ 20
Smoke Number	14	20	280	NA	NA
Diffusion Battery/ Condensation Nucleus Counter	4	20	80	NA	NA
Electrostatic Particle Sampler	5	2,5,10	10,25,50	NA	NA

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, CO₂, 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 CO₂ 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 CO₂ in nitrogen, and NO in nitrogen. Each analyzer was calibrated every other 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 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 methylene chloride extraction. 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 $0.028 \text{ m}^3 \text{ min}^{-1}$ 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 methylene chloride 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. Selected extracts were fractionated into aliphatic, aromatic, and polar fractions by silica gel column chromatography. The aromatic fraction was further concentrated to 300 μL with a N_2 gas stream. The aromatic fractions were analyzed by electron impact ionization GC-MS to determine the polycyclic aromatic hydrocarbons using the procedures described in Reference 2. Some extracts were diluted and reanalyzed to quantify the more abundant PAH compounds.

2. Canister Sampling for Hydrocarbon Determination

Methane and $\text{C}_2\text{-C}_{15}$ 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 $\text{C}_1\text{-C}_{15}$ hydrocarbons in these canisters. The canisters were analyzed onsite following each test. The canisters were vacuum baked onsite in our mobile laboratory before sampling. The canisters were under vacuum at the start of each sampling period, and 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 3.

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 C₂ to C₅ and C₄ to C₁₅ 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 then 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 N₂ after each test run.

The GC was equipped with two flame-ionization detectors. The C₂ through C₅ 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 C₄ through C₁₅ 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 C₂ to C₁₅ 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 μ L 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. 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^R 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. Approximately 50 ft³ of exhaust was sampled through the filter for each engine/power setting. A 6-inch diameter quartz 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 10³ to 10⁷ particles/cm³, 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 μ m 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 μ m, 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.

Both the DB/CNC and electrostatic sampler require 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 and electrostatic sampling were initiated. After sampling was complete, the exhaust monitors for CO and CO₂ were switched to monitor the diluted sample in the drum. The ratios of the CO and CO₂ 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 resulted in six separate particle size determinations by the DB/CNC system.

Particle loading on the collection surface is important in determining size distributions from SEM photomicrographs. Without prior knowledge of the particle concentrations, we attempted to optimize particle loading by collecting three samples of different duration during each test. In some tests the exhaust was sampled directly, without dilution. The sample whose photomicrograph showed the most appropriate loading was to be used for particle sizing. However, in actual practice, our sampling procedure collected an insufficient number of particles for valid size determination for most tests. This is discussed more fully in Section III.

The collection surface used for the electrostatic SEM samples was stainless steel or stainless steel covered with double-stick tape. Samples typically were collected at a flow rate of 5 Lpm for various periods between 8 and 20 minutes when the test period allowed.

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 4.

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 5. For afterburner emissions we used a modified version of the procedures recommended by Lyon et al. (Reference 6). 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 CO₂. The afterburner measurements made during this study were performed well downstream of the exhaust nozzle, as recommended in Reference 6, so that thermal reactions in the exhaust gas are largely quenched. However, unlike the measurements of Lyon et al. (Reference 6), 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. Therefore, rather than develop a linear regression of pollutant concentration versus CO₂ concentration, we used the time-averaged, background-corrected ratio of pollutant concentration to CO₂ 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 6):

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

$$EI_{HC} = \frac{0.10 (b_{HC})}{1 + \frac{b_{CO} + b_{HC}}{10^4}} \quad (2)$$

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

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

where b_z represents the ratio of the time averaged, background corrected concentration of species z to CO₂, 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 CO₂, 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 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 6 to June 10, 1986, at Tinker AFB in Oklahoma City, OK. The three engines whose emissions were 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 TF41-A2, TF30-P103, and TF30-P109. 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.
TF41-A2	142528
TF30-P103	658703
TF30-P109	676723

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 μ L 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 TF 41-A2 (S/N 142528)

Test No.	1-6-6	2-6-6	3-6-6	4-6-6
Date	6-6-86	6-6-86	6-6-86	6-6-86
Location/Test Cell	TAFB/9	TAFB/9	TAFB/9	TAFB/9
Engine nominal power setting	Idle	30%	75%	100%
Time (CDT)	1030	1130	1340	1415
Initial compressor inlet temperature (°C)	25.7	27.3	29.6	29.8
Final compressor inlet temperature (°C)	26.2	27.6	30.0	30.2
Initial barometric pressure (in. Hg)	28.505	28.495	28.475	28.450
Final barometric pressure (in. Hg)	28.505	28.495	28.475	28.430
Initial humidity (gr H ₂ O/lb dry air)	106	106	102.5	102.5
Final humidity (gr H ₂ O/lb dry air)	106	106	102.5	110.0
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)*	460	3,818	9,554	12,937
Turbine discharge pressure (in. Hg)	30.1	38.8	54.8	64.4
Fuel flow (lb/hr)*	1,047	2,704	5,810	8,086
Air flow (lb/sec)*	48.8	147.3	219.3	250.8
Engine pressure ratio (EPR)*	1.108	1.436	2.044	2.419
Fuel/air ratio*	.005956	.004820	.007342	.008956
Turbine outlet temperature (°C)*	379	319	455	518
Low speed rotor (rpm)*	2,350	5,570	7,498	8,314
High speed rotor (rpm)*	6,794	10,326	11,601	12,210

* Corrected to standard day.

TABLE 5. ENGINE OPERATING CONDITIONS
ENGINE TF 30-PI03 (A/N 658703)

Test No.	1-6-9	2-6-9	3-6-9	4-6-9	7-6-10
Date	6-9-86	6-9-86	6-9-86	6-9-86	6-10-86
Location/Test Cell	TAFB/9	TAFB/9	TAFB/9	TAFB/9	TAFB/9
Engine nominal power setting	30%	75%	100%	Idle	A/B Zone 1
Time (CDT)	1315	1410	1515	1618	1645
Initial compressor inlet temperature (°C)	27.9	29.1	28.8	29.9	28.6
Final compressor inlet temperature (°C)	27.8	29.2	29.2	29.9	24.8
Initial barometric pressure (in. Hg)	28.495	28.460	28.450	28.415	28.465
Final barometric pressure (in. Hg)	28.460	28.455	28.435	28.415	28.465
Initial humidity (gr H ₂ O/lb dry air)	114.0	118.5	114.0	118.5	123.0
Final humidity (gr H ₂ O/lb dry air)	118.5	114.0	118.5	118.5	123.0
Fuel	JP-4	JP-4	JP-4	JP-4	JP-4
Engine time since overhaul (hr)	0	0	0	0	0
Pass performance test	yes	yes	yes	yes	yes
Measured thrust (lb)*	2,934	7,317	9,785	518	13,348
Turbine discharge pressure (in. Hg)	36.0	47.2	53.6	29.3	58.3
Fuel flow (lb/hr)*	2,003	4,119	5,541	826.8	14,292
Air flow (lb/sec)*	127.4	200.5	226.6	87.0	230.8
Engine pressure ratio (EPR)*	1.268	1.673	1.904	1.034	2.068
Fuel/air ratio*	.004367	.005707	.006792	.002640	.01720
Turbine inlet temperature (°C)*	678	838	949	473	1,020
Low speed rotor (rpm)*	5,889	8,169	9,026	3,922	9,190
High speed rotor (rpm)*	11,658	12,960	13,526	9,370	13,740

* Corrected to standard day.

TABLE 6. ENGINE OPERATING CONDITIONS
ENGINE TF 30-P109 (S/N 676723)

Test No.	1-6-10	2-6-10	3-6-10	4-6-10	5-6-10	6-6-10
Date	6-10-86	6-10-86	6-10-86	6-10-86	6-10-86	6-10-86
Location/Test Cell	TAFB/9	TAFB/9	TAFB/9	TAFB/9	TAFB/9	TAFB/9
Engine nominal power setting	Idle	30%	75%	100%	100%	A/B Zone 1
Time (CDT)	0900	1005	1105	1225	1437	1515
Initial compressor inlet temperature (°C)	23.9	24.7	26.9	28.5	30.6	31.3
Final compressor inlet temperature (°C)	24.2	24.9	27.4	29.4	30.7	31.3
Initial barometric pressure (in. Hg)	28.480	28.510	28.500	28.510	28.495	28.450
Final barometric pressure (in. Hg)	28.400	28.510	28.500	28.510	28.495	28.450
Initial humidity (gr H ₂ O/lb dry air)	114.0	118.5	127.0	127.0	123.0	123.0
Final humidity (gr H ₂ O/lb dry air)	114.0	118.5	127.0	127.0	123.0	123.0
Fuel	JP-4	JP-4	JP-4	JP-4	JP-4	JP-4
Engine time since overhaul (hr)	0	0	0	0	0	0
Pass performance test	yes	yes	yes	yes	yes	yes
Measured thrust (lb)*	563	3,200	7,998	10,633	10,668	14,352
Turbine discharge pressure (in. Hg)	29.5	36.6	49.0	56.0	56.0	59.8
Fuel flow (lb/hr)*	864.3	2,138	4,550	6,246	6,284	16,052
Air flow (lb/sec)*	88.0	150.8	206.6	232.3	233.5	234.6
Engine pressure ratio (EPR)*	1.035	1.290	1.734	1.985	1.989	2.125
Fuel/air ratio*	.002728	.004540	.006118	.007469	.007476	.01901
Turbine inlet temperature (°C)*	468	689	865	988	990	1,045
Low speed rotor (rpm)*	3,986	6,047	8,378	9,263	9,269	9,370
High speed rotor (rpm)*	9,524	11,838	13,126	13,768	13,766	13,950

* 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. DATE ANALYSIS	1		2		3	
		6-6-86		6-9-86		6-10-86	
		1	2	1	2	1	2
n-butane		.26	.43	.36	.36	.38	.34
iso-pentane		1.00	1.19	1.08	.97	1.00	.92
n-pentane		1.21	1.23	1.15	1.13	1.20	1.07
2-methylpentane		2.69	2.66	2.59	2.39	2.51	2.59
3-methylpentane		2.34	2.45	2.41	2.25	2.30	2.26
n-hexane		4.05	4.11	4.10	3.91	4.01	3.81
methylcyclopentane		1.94	1.82	1.71	1.63	1.77	1.71
benzene		.30	.33	.23	.22	.21	.21
cyclohexane		2.00	1.90	1.84	1.69	1.91	1.80
2-methylhexane		3.86	3.67	3.48	3.38	3.43	3.28
3-methylhexane		3.33	2.96	2.97	2.72	2.92	2.88
1,2-dimethylpentane		.45	.44	.93	.88	.90	.89
n-heptane		4.73	4.70	4.69	4.57	4.50	4.26
methylcyclohexane		7.16	7.16	7.20	6.70	7.03	6.85
toluene		1.74	1.85	1.96	1.89	1.80	1.65
2-methylheptane		3.34	3.30	3.18	3.15	3.52	3.06
3-methylheptane		4.83	4.64	5.42	5.13	5.75	5.17
n-octane		4.80	4.95	4.80	4.39	4.82	4.53
ethylbenzene		.32	.63	.71	.52	.30	.46
m&p-xylene		2.19	1.97	1.50	1.33	1.79	2.01
o-xylene		1.54	1.50	1.20	1.08	1.41	1.11
n-nonane		3.34	3.36	3.05	3.20	3.38	3.17
n-decane		2.68	2.63	2.36	2.59	2.65	2.59
n-undecane		2.36	2.33	2.72	2.87	2.36	2.45
n-dodecane		2.57	2.35	2.75	2.77	2.52	2.72
n-tridecane		2.71	2.60	2.94	3.20	3.13	3.14
n-tetradecane		1.84	1.91	2.37	2.20	2.11	2.13

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

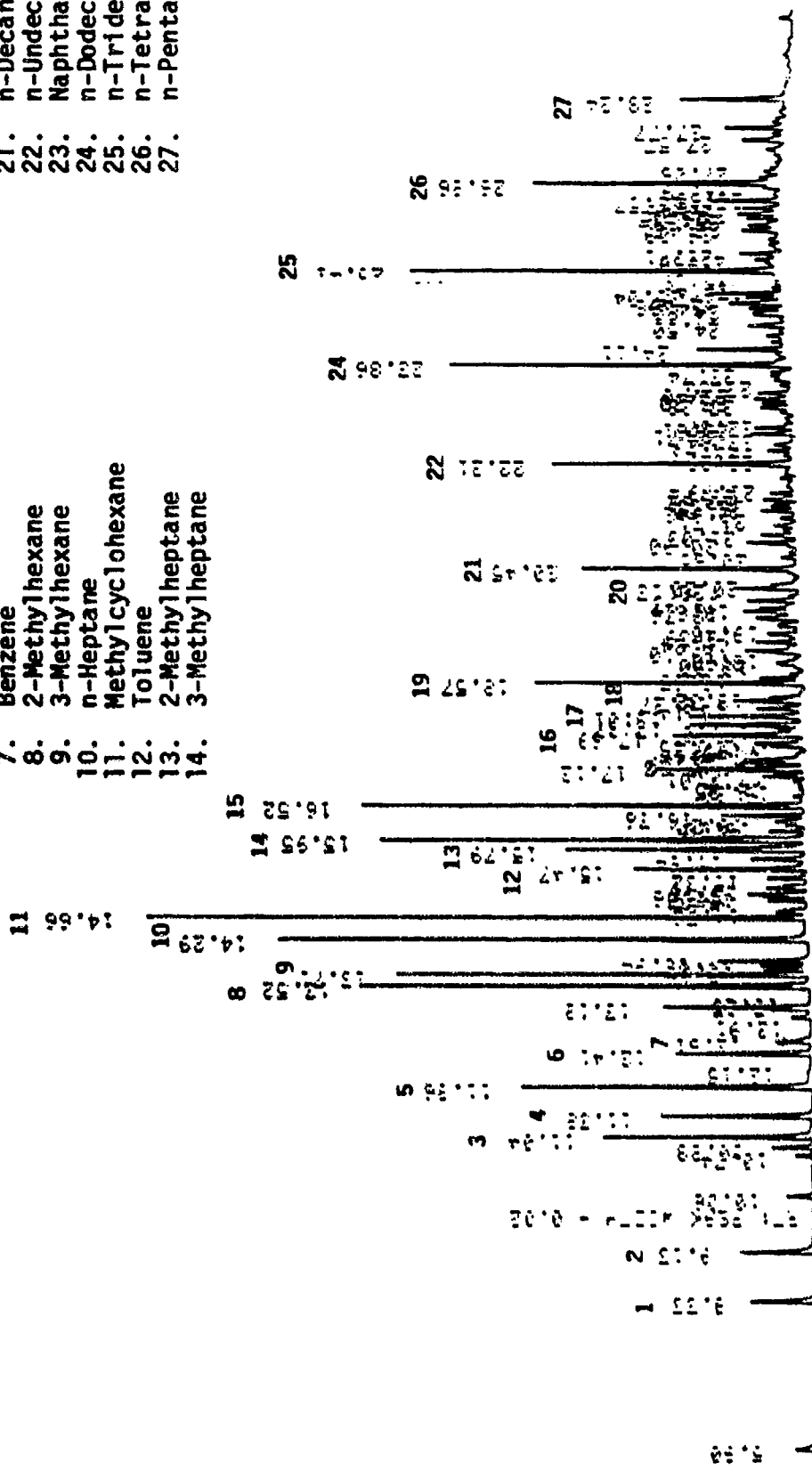


Figure 4. GC/FID Chromatogram for JP-4 Fuel

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. Measurements also were made in Zone 1 afterburning mode for the two afterburning engines, TF30-P103 and TF30-P109. The exhaust concentrations of CO, CO₂, total hydrocarbons, NO_x, and NO are listed in Table 9. The afterburner measurements and test 5-6-10 at 100 percent power were performed at the test cell roof vent, rather than at the exhaust nozzle exit. The exhaust from these three tests, which are noted by an asterisk in Table 9, was diluted by entrainment of ambient air in the augmentor tube. As a consequence, the results from these three 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 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 TF41-A2 engine, the data for the TF30-P103 engine are given in Table 11, and the results for the TF30-P109 engine are shown in Table 12. The tables list hydrocarbons, oxygenated species, and the distribution of compound classes for each engine power setting. The power setting AB refers to Zone 1 afterburner power. As noted above, the afterburner measurements represent dilute exhaust concentrations and should only be compared with other power settings in a relative sense. 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 Table 13. Cases where the samples were diluted before analysis are noted with an asterisk. All concentrations in Table 13 are in units of $\mu\text{g}/\text{m}^3$.

TABLE 8. RESULTS FOR STANDARD FUEL ANALYSES

PARAMETER	TEST	ANALYSIS
Gravity, API	D287	56.2
Visual Appearance	HDBK-200	C&B
Freezing Point, °C	D2386	Below -58
Odor	--	Usual
Color	--	Light Straw
Distillation	D86	
Initial Boiling Point, °C		63
10%		84
20%		96
50%		138
90%		221
End Point		254
Recovery, vol %		98.5
Residue, vol %		0.7
Loss, vol %		0.8
Vapor Pressure, KPa (PSI)	D323	17 (2.4)
Existent Gum, mg/100 ml	D381	1.6
Visible Free Water, mL/gal	HDBK-200	0.0
Particulate Matter, mL/gal	D2276	1.0
Fuel Icing Inhibitor, %	--	0.08

TABLE 9. ENGINE EMISSIONS DATA

POWER MODE	RUN NO.	CO, ppm	CO ₂ , %	TOTAL HYDROCARBON, ppmC	NO _x , ppm	NO, ppm
		<u>TF 41-A2</u>				
Idle	1-6-6	772	0.74	850	10.5	6.1
30%	2-6-6	200	0.89	87.5	23.5	9.3
75%	3-6-6	40	1.74	1.5	120	97.5
100%	4-6-6	34	2.12	1.6	202	170
		<u>TF 30-P103</u>				
Idle	4-6-9	276	0.51	413	6.5	2.4
30%	1-6-9	168	0.93	98.6	19.3	6.2
75%	2-6-9	32	1.18	3.5	51.4	42.0
100%	3-6-9	15	1.45	1.2	84.2	75.0
Afterburning (Zone 1)*	7-6-10*	170	0.44	125	15.0	8.0
		<u>TF 30-P109</u>				
Idle	1-6-10	283	0.52	318	7.0	2.5
30%	2-6-10	134	0.97	35.3	23.0	11.0
75%	3-6-10	22	1.30	2.0	58.9	51.9
100%	4-6-10*	8	1.59	1.3	103	95.0
Afterburning (Zone 1)*	6-6-10*	128	0.42	143	16.2	4.3
100%*	5-6-10*	1	0.20	**	14.0	12.5

* Measurements made on diluted exhaust.

** No value reported due to sample contamination.

TABLE 10. ORGANIC EMISSIONS FROM TF41-A2 ENGINE WITH JP-4 FUEL (CONCENTRATIONS IN ppmC)

Organic Species	Test No.: 1-6-6	2-6-6	3-6-6	4-6-6
	Date: 6-6-66	6-6-86	6-6-86	6-6-86
CANISTER COLLECTION	Power Setting: IDLE	30%	75%	100%
Methane	16.204	4.684	0.963	1.240
Ethane	4.355	0.479	0.010	0.007
Ethylene	77.613	15.246	0.271	0.059
Propane	0.745	0.115	0.007	0.004
Acetylene	28.170	6.443	0.159	0.033
Propene	35.319	5.477	0.052	0.010
1-Butene	17.262	1.907	0.031	0.038
1,3-Butadiene	11.324	0.487	<0.001	0.027
1-Pentene	5.462	0.568	0.004	0.005
C5-ene	2.312	0.208	0.018	<0.001
n-Pentane	2.670	0.243	0.011	<0.001
C5-ene	1.473	<0.001	<0.001	<0.001
C5-ene	0.708	0.003	<0.001	<0.001
2-Methylpentane	6.471	0.467	0.015	<0.001
3-Methylpentane	4.993	0.474	0.015	0.011
1-Hexene	5.231	0.456	0.005	0.008
n-Hexane	8.341	0.643	0.019	0.002
Methylcyclopentane+unk	3.993	0.385	0.017	0.032
Benzene	13.291	2.342	0.047	0.015
2-Methylhexane	9.646	0.563	0.012	<0.001
3-Methylhexane	6.834	0.525	0.009	0.007
n-Heptane	10.369	0.658	0.016	0.009
Methylcyclohexane	14.199	0.835	0.018	0.002
Toluene	15.492	1.896	0.029	0.007
2-Methylheptane	8.322	0.500	0.007	<0.001
3-Methylheptane	12.773	0.690	0.011	<0.001
n-Octane	12.156	0.605	0.012	0.005
Ethylbenzene	3.306	0.349	0.003	0.008
m,p-Xylene	16.636	1.424	0.006	<0.001
Styrene	5.657	0.361	<0.001	<0.001
o-Xylene	5.481	0.419	<0.001	<0.001
n-Nonane	9.854	0.398	0.006	<0.001
p-Ethyltoluene	4.098	0.260	0.015	0.008
1,2,4-Trimethylbenzene	8.617	0.372	0.014	0.018
n-Decane	10.521	0.325	<0.001	0.006
Methylbenzaldehyde+C10H14	4.115	0.120	<0.001	0.004
Undecene	10.092	0.361	<0.001	0.007
Naphthalene	3.618	0.308	0.011	0.008
Dodecene	8.904	0.258	0.013	0.008
Tridecene	6.848	0.199	0.015	0.011
Tetradecene	3.639	0.179	0.017	0.010
DNPH/IMPINGER COLLECTION				
Formaldehyde	17.850	6.500	0.575	<0.001
Acetaldehyde	1.030	2.680	0.150	<0.001
Propionaldehyde/Acrolein	2.285	0.525	0.044	<0.001
Acetone	0.225	0.405	0.015	<0.001
Benzaldehyde	1.155	0.700	0.032	<0.001
Glyoxal	0.255	0.565	0.040	<0.001
Methyl glyoxal	3.833	1.950	0.068	<0.001
Biacetyl	0.380	0.040	<0.001	<0.001
IDENTIFIED SPECIES	464.127	65.597	2.782	1.609
Paraffins	171.929	13.586	1.193	1.361
Acetylene	28.170	6.443	0.159	0.033
Olefins	155.704	24.352	0.381	0.147
Aromatics	80.311	7.851	0.125	0.068
Aldehydes	26.788	12.960	0.909	0.000
Ketones	0.225	0.405	0.015	<0.001
TOTAL SPECIES	681.715	81.265	4.026	2.696

TABLE 11. ORGANIC EMISSIONS FROM TF30-P103 ENGINE WITH JP-4 FUEL (CONCENTRATIONS IN ppmC)

Organic Species	Test No.:	4-6-9	1-6-9	2-6-9	3-6-9	7-6-10
	Date:	6-9-86	6-9-86	6-9-86	6-9-86	6-10-86
	Power Setting:	IDLE	30%	75%	100%	AB *
CANISTER COLLECTION						
Methane		6.740	2.964	1.326	0.865	24.617
Ethane		1.858	0.302	0.016	0.008	0.694
Ethylene		32.736	10.102	0.802	0.079	12.844
Propane		0.182	0.032	0.010	0.007	0.123
Acetylene		12.499	3.680	0.337	0.053	2.712
Propene		15.703	5.349	0.136	0.007	6.296
1-Butene		7.068	2.082	*	0.043	3.098
1,3-Butadiene		5.022	1.244	*	<0.001	1.540
1-Pentene		2.272	0.692	*	<0.001	0.822
C5-ene		0.952	0.254	*	<0.001	0.414
n-Pentane		1.718	0.083	*	0.004	0.707
C5-ene		0.750	0.092	*	<0.001	0.266
C5-ene		0.490	0.035	*	<0.001	0.189
2-Methylpentane		3.988	0.198	*	0.002	1.683
3-Methylpentane		3.325	0.296	0.088	0.024	1.476
1-Hexene		2.141	0.600	0.032	<0.001	0.737
n-Hexane		5.585	0.288	0.012	0.003	2.153
Methylcyclopentane+unk		2.660	0.160	0.016	0.033	0.155
Benzene		5.195	1.773	0.636	0.019	2.353
2-Methylhexane		5.942	0.330	0.012	<0.001	1.913
3-Methylhexane		4.387	0.420	0.120	0.001	1.657
n-Heptane		6.744	0.428	0.028	0.017	2.389
Methylcyclohexane		9.291	0.490	<0.001	<0.001	3.082
Toluene		7.891	1.451	0.052	0.011	3.283
2-Methylheptane		5.286	0.032	<0.001	<0.001	1.741
3-Methylheptane		8.025	0.488	<0.001	0.003	2.531
n-Octane		7.587	0.455	0.012	0.008	2.254
Ethylbenzene		1.146	0.117	0.024	0.003	0.635
m,p-Xylene		9.337	1.363	0.040	0.006	3.244
Styrene		3.116	0.420	0.032	0.021	0.926
o-Xylene		3.066	0.117	0.008	0.012	0.211
n-Nonane		5.675	0.378	<0.001	<0.001	1.557
p-Ethyltoluene		2.058	0.324	<0.001	0.006	0.301
1,2,4-Trimethylbenzene		3.738	0.587	0.060	0.014	1.281
n-Decane		5.100	0.405	0.064	0.044	1.358
Methylbenzaldehyde+C10H14		1.919	0.239	<0.001	<0.001	0.242
Undecane		4.902	0.441	0.064	0.018	1.116
Naphthalene		1.784	0.402	0.040	0.001	0.432
Dodecane		4.384	0.380	0.012	0.010	0.942
Tridecane		2.969	0.260	0.024	0.016	0.502
Tetradecane		1.656	0.124	0.024	0.018	0.200
DNPH/IMPINGER COLLECTION						
Formaldehyde		9.300	6.395	0.073	<0.001	*
Acetaldehyde		3.440	2.550	0.045	0.030	*
Propanaldehyde/Acrolein		1.001	0.675	0.011	0.006	*
Acetone		0.825	0.495	0.005	<0.001	*
Benzaldehyde		0.770	0.455	0.004	<0.001	*
Glyoxal		1.615	0.913	0.009	0.005	*
Methyl glyoxal		5.550	3.503	0.005	<0.001	*
Biacetyl		0.045	0.011	<0.001	<0.001	*
IDENTIFIED SPECIES						
Paraffins		239.433	54.874	4.179	1.397	94.676
Acetylene		98.004	8.954	1.828	1.081	52.850
Olefins		12.499	3.680	0.337	0.053	2.712
Aromatics		67.134	20.450	0.970	0.129	26.206
Aldehydes		39.250	6.793	0.892	0.093	12.908
Ketones		21.721	14.502	0.147	0.041	*
		0.825	0.495	0.005	<0.001	*
TOTAL SPECIES		376.924	71.596	4.577	2.304	142.977

* Afterburner results are for diluted exhaust (see text).

TABLE 12. ORGANIC EMISSIONS FROM TF30-P109 ENGINE WITH JP-4 FUEL (CONCENTRATIONS IN ppmC)

Organic Species	Test No.:	1-6-10	2-6-10	3-6-10	4-6-10	6-6-10
	Date:	6-10-86	6-10-86	6-10-86	6-10-86	6-10-86
	Power Setting:	IDLE	30%	75%	100%	AB [*]
CANISTER COLLECTION						
Methane		5.261	2.146	1.088	0.746	4.206
Ethane		1.280	0.131	0.016	0.007	0.548
Ethylene		27.776	7.450	0.121	0.034	13.842
Propane		0.209	0.032	0.014	0.003	0.107
Acetylene		8.159	2.205	0.084	0.010	3.114
Propene		14.324	2.409	0.014	0.004	6.998
1-Butene		6.130	0.812	0.023	0.019	3.130
1,3-Butadiene		4.662	0.526	0.009	<0.001	1.588
1-Pentene		2.022	0.240	0.068	0.048	0.941
C5-ene		0.803	0.090	0.022	0.017	0.439
n-Pentane		1.100	0.025	0.004	0.002	0.707
C5-ene		0.740	0.021	<0.001	<0.001	0.194
C5-ene		0.507	0.007	0.005	0.003	0.064
2-Methylpentane		2.717	0.045	0.004	0.003	1.705
3-Methylpentane		2.215	0.132	0.003	0.048	1.396
1-Hexene		1.914	0.197	0.032	0.018	0.816
n-Hexane		3.668	0.077	0.007	0.004	2.094
Methylcyclopentane+unk		0.180	0.092	0.126	0.151	0.184
Benzene		4.357	1.016	0.021	0.008	2.429
2-Methylhexane		3.581	0.092	0.004	0.002	1.854
3-Methylhexane		3.059	0.046	0.003	0.005	1.631
n-Heptane		4.692	0.106	0.025	0.026	2.303
Methylcyclohexane		6.435	0.113	0.006	0.003	2.919
Toluene		5.978	0.616	0.016	0.010	3.480
2-Methylheptane		3.818	0.090	0.007	<0.001	1.181
3-Methylheptane		5.805	0.116	0.004	0.003	2.415
n-Octane		5.543	0.105	0.007	0.028	2.161
Ethylbenzene		1.371	0.105	0.004	0.002	0.680
m,p-Xylene		7.237	0.434	0.012	0.006	3.467
Styrene		2.477	0.149	0.012	0.008	0.927
o-Xylene		2.477	0.035	0.014	0.010	1.256
n-Nonane		4.368	0.026	0.004	0.001	1.481
p-Ethyltoluene		1.615	0.040	<0.001	<0.001	0.693
1,2,4-Trimethylbenzene		3.029	0.177	0.025	0.018	1.254
n-Decane		4.084	0.082	<0.001	<0.001	1.266
Methylbenzaldehyde+ClOHD		1.561	0.059	<0.001	<0.001	0.570
Undecane		4.016	0.009	0.050	0.039	1.045
Naphthalene		1.527	0.153	0.008	0.005	0.496
Dodecane		3.719	0.067	<0.001	<0.001	0.932
Tridecane		2.561	0.053	0.010	0.007	0.505
Tetradecane		1.386	0.038	0.009	0.007	0.124
DNPH/IMPINGER COLLECTION						
Formaldehyde		8.975	3.305	0.125	<0.001	6.450
Acetaldehyde		3.140	1.290	0.090	0.030	2.870
Propanaldehyde/Acrolein		1.023	0.305	0.023	0.060	0.609
Acetone		0.645	0.165	<0.001	<0.001	0.585
Benzaldehyde		0.700	0.224	<0.001	<0.001	0.455
Glyoxal		1.385	0.170	0.005	0.010	0.495
Methyl glyoxal		7.058	2.063	<0.001	0.002	4.170
Butacetyl		0.080	<0.001	<0.001	0.007	0.380
IDENTIFIED SPECIES						
Paraffins		191.374	27.773	2.124	1.412	93.141
Acetylene		69.702	3.510	1.391	1.085	30.744
Olefins		8.159	2.205	0.084	0.010	3.114
Aromatics		58.878	11.752	0.294	0.143	28.012
Aldehydes		31.629	2.784	0.112	0.085	15.257
Ketones		22.361	7.357	0.243	0.109	15.429
		0.645	0.165	<0.001	<0.001	0.585
TOTAL SPECIES		288.414	34.062	2.782	1.539	140.357

* Afterburner results are for diluted exhaust (see text).

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

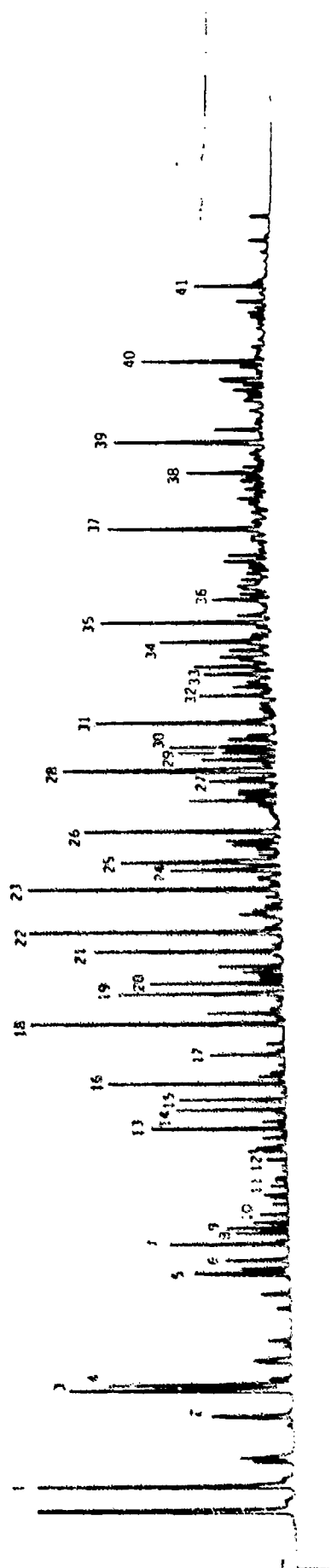


Figure 5. Representative GC/FID Chromatogram for Exhaust from a Turbine Engine Operating With JP-4 Fuel

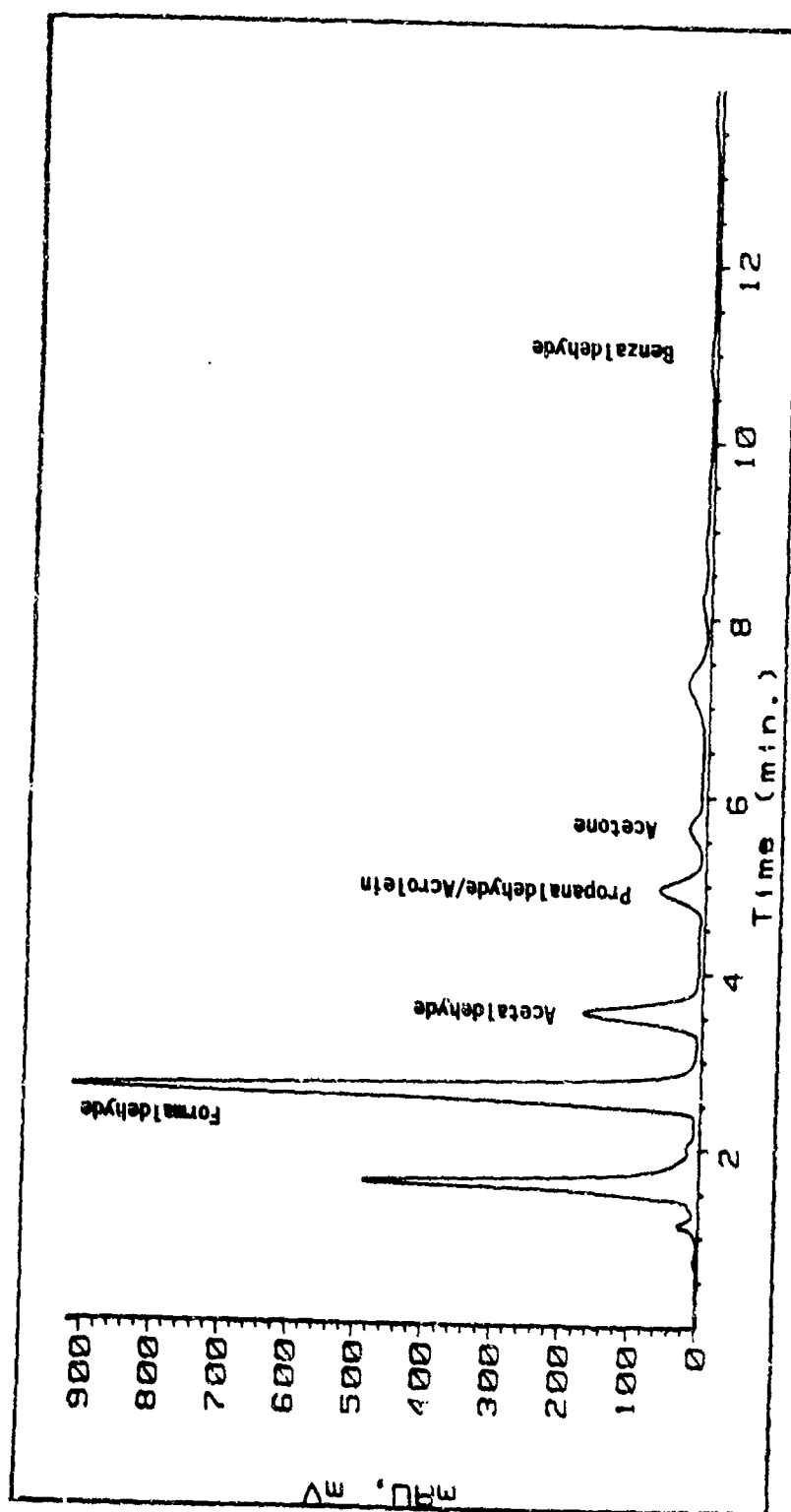


Figure 6. Representative Chromatogram from Analysis of Jet Engine Exhaust for Aldehydes

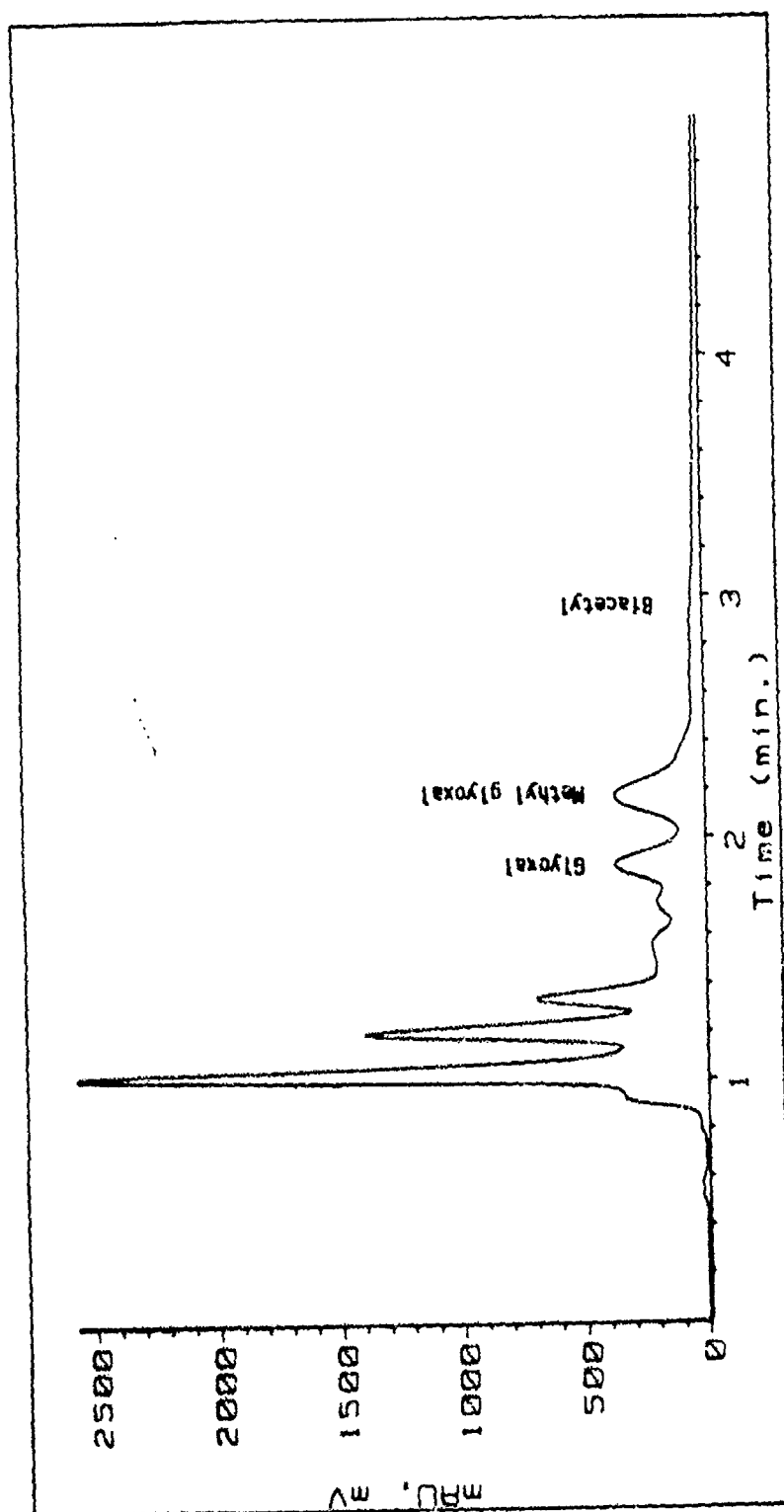


Figure 7. Representative Chromatogram from Analysis of Jet Engine Exhaust for Dialdehydes

TABLE 13. RESULTS OF PAH ANALYSIS FOR SELECTED SAMPLES

Compound	Engine: Thrust: Sample:	CONCENTRATION IN EXHAUST, $\mu\text{g}/\text{m}^3$					
		TF-41 30%	TF-41 75%	TF 30-103 Idle	TF 30-109 Idle		
Napthalene							
1-Methyl napthalene	1-6-6	2-6-6	3-6-6	4-6-9	1-6-10		
2-Methyl napthalene	1150*	146*	2.82	444*	364*		
1,2-Dimethyl naphthalene	1190*	336*	0.785	278*	233*		
1,4+2,3-Dimethyl naphthalene	695*	93.5*	0.492	165*	138*		
2,6-Dimethyl naphthalene	369*	24.2	0.199	158*	188		
Dimethyl naphthalene isomer	504*	33.6	0.314	232*	264		
Dimethyl naphthalene isomer	150*	10.6	0.105	63.6*	91.0		
Dimethyl naphthalene isomer	82.0*	5.65	0.042	33.6*	38.2		
Dimethyl naphthalene isomer	314*	22.2	0.244	125*	118		
Dimethyl naphthalene isomer	60.7*	4.52	0.065	27.6*	29.4		
Phenanthrene	57.3*	4.24	0.055	24.1*	24.9		
Anthracene	38.1	5.32	0.242	6.61	5.94		
Fluoranthene	4.56	0.35	0.177	0.629	0.591		
Pyrene	10.6	3.71	0.201	0.610	1.43		
Benz[a]anthracene	9.93	4.17	0.201	0.420	1.18		
Chrysene	0.0086	0.088	0.054	0.571	0.061		
Benzo[e]pyrene	2.49	0.159	0.160	0.035	0.047		
Benzo[a]pyrene	0.026	ND**	ND**	ND**	ND**		
Perylene	0.023	ND	ND	ND	ND		
Coronene	0.026	ND	ND	ND	ND		
	ND**	ND	ND	ND	ND		

* Data from analysis of diluted sample extracts.

** ND = Not Detected.

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 Numbers, 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 Numbers were 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 14. In general, for all three engines, the Smoke Numbers were quite low at idle and increases with higher thrust. Smoke Number measurements were not made in the afterburner power mode because the sampling configuration precluded accurate smoke number measurements.

2. Gravimetric Analysis

As noted in Section II, a quartz 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 exhaust sampling process caused the quartz fibers to adhere to the edges of the stainless steel filter holder, and our quality assurance tests demonstrated that the mass loss due to this problem was highly variable. For this reason, the gravimetric results are highly uncertain and are not presented. Following this study, we tested and then switched to a Teflon[®]-coated glass fiber filter, which has demonstrated excellent capability for collection and gravimetric analysis of turbine engine particulate emissions.

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 15. The table shows particle concentration (in thousands of

TABLE 14. SMOKE NUMBERS AS FUNCTION OF POWER SETTING

POWER SETTING	SMOKE NUMBER
<u>TF41-A2</u>	
Idle	0.2
30%	14.4
75%	39.2
100%	53.9
<u>TF30-P103</u>	
Idle	0.0
30%	18.8
75%	23.4
100%	40.9
<u>TF30-P109</u>	
Idle	0.2
30%	30.3
75%	37.7
100%	32.4

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 $0.237\text{ }\mu\text{m}$. 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 last two columns list measurements made with the TF30-P109 engine at 100 percent and afterburner power. These measurements were made from the rooftop vent of the test cell, so the exhaust had experienced considerable dilution before sampling. The longer lines required for sampling at this location also may have caused some particle loss. However, the ratio of total particle concentrations between the samples collected at the exhaust nozzle and the roof vent at 100 percent power was about 8, which is the same as the dilution factor calculated from the CO , CO_2 , and NO_x concentrations in Table 9. Therefore, sample line losses of particles seems minimal. Although the particle

concentrations for the samples collected from the roof vent have been influenced by dilution, the relative size distribution should be valid. These results are listed in the last two columns of Table 15.

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. For most tests, the electrostatic sampler sampled the same cooled and diluted exhaust as did the DB/CNC unit. For selected tests, the electrostatic sampler was also used to collect particles from the undiluted exhaust. These samples were returned to the laboratory and analyzed by SEM at magnifications from 1000X to 2000X. Only the samples collected from undiluted exhaust produced high enough particle loadings to yield informative photomicrographs. A representative micrograph is included in Section IV, along with a discussion of the particle size distribution.

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

MEAN DIAMETER, μ m	TF41-A2				TF30-P103				TF30-P109				TF30-P109	
	IDLE	30%	75%	100%	IDLE	30%	75%	100%	IDLE	30%	75%	100%	100%*	AB*
0.004	6.2	0	0	0	0	0	162	0	0	0	0	93	0	0
0.008	1339	0	0	10	0	0	0	0	111	0	0	0	0	0
0.013	50	0	0	39	213	0	0	0	536	0	0	0	0	0
0.024	41	664	0	0	139	0	0	0	503	1658	0	0	2	113
0.042	1771	1952	0	0	174	1980	0	0	877	2158	0	0	206	141
0.075	345	594	74	0	0	3957	2571	1542	149	2	801	865	88	150
0.133	35	523	3278	1185	0	74	2875	2855	22	0	3022	2036	32	62
0.237	16	166	490	3506	0	410	88	15	12	371	34	64	34	17
>0.237	52.1	216	837	1469	0	617	750	590	27	237	589	436	29	32
Total Number Count	3310	3760	3316	4260	492	5957	5178	3975	2167	3684	3444	2818	345	480

* Measurements made at rooftop .ent on diluted exhaust.

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 ± 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 TF41-A2, TF30-P103, and TF30-P109 engines. These engines were operated with JP-4 fuel at thrust settings of idle, 30, 75, and 100 percent, and afterburning (if applicable).

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 16. The species data have been corrected for oxygenated compound response as described above and in earlier reports (References 1 and 2). An average carbon balance of 83 ± 12 percent was obtained from the eight test runs at idle, 30 percent

TABLE 16. 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
<u>TF41</u>				
	Idle	659	850	0.78
	30%	71.1	87.5	0.81
	75%	3.27	1.50*	2.18*
	100%	2.70	1.60*	1.69*
<u>TF30-P103</u>				
	Idle	360	413	0.87
	30%	60.2	98.6	0.61
	75%	4.48	3.50*	1.28*
	100%	2.28	1.20*	1.90*
	AB	131	125	1.05
<u>TF30-P109</u>				
	Idle	271	318	0.85
	30%	28.4	35.3	0.80
	75%	2.58	2.00*	1.29*
	100%	1.49	1.30*	1.15*
	AB	129	143	0.90

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

and afterburning thrust settings. This average is in reasonable agreement with the earlier Battelle study (Reference 2). The carbon balances at the two higher thrust settings (75 and 100 percent) are much greater than 100 percent. The imbalance at the higher thrust is caused by analytical inaccuracies resulting from the much lower total hydrocarbon content of exhaust at these test points. Similar variability at higher thrusts was also observed during earlier studies (Reference 2).

B. INDIVIDUAL HYDROCARBON SPECIES

The individual hydrocarbon species quantified in the emissions have been presented in Tables 10-12. The predominant species at idle thrust condition are ethylene, acetylene, propene and formaldehyde. Generally, these four species account for 20-30 percent of the total hydrocarbon emissions at idle. As shown in Table 10, hydrocarbon concentrations in

the exhaust from the TF41-A2 engine are generally higher than those from the TF30-P103 and TF30-P109 engines. Examination of the data in Tables 10-12 reveals that the total hydrocarbon emissions are greatly reduced at the 30, 75, and 100 percent thrust conditions. At the 75 and 100 percent thrust settings, all of the individual hydrocarbon species, with the exception of methane, are present at very low concentration.

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. Table 10 shows higher levels in each compound class for the TF41-A2 engine, as compared to the TF30-P103 and TF30-P109 engines. These 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 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. The afterburner results in Figures 9 and 10 are from diluted exhaust, and should not be used to make quantitative comparisons among different power settings. The afterburner data for the TF30-P103 engine (Figure 9) does not contain aldehyde results. Aldehydes were not measured because of a pump problem.

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 17-19. The results at idle and 30 percent power are plotted in Figures 11 and 12. As shown by these data, a primary maximum in the distribution of the exhaust hydrocarbons is found in the C₂ to C₃ region, represented predominantly by ethylene. At idle thrust, a secondary maximum is found in the C₇ to C₈ region. This secondary maximum is not seen at higher thrust settings.

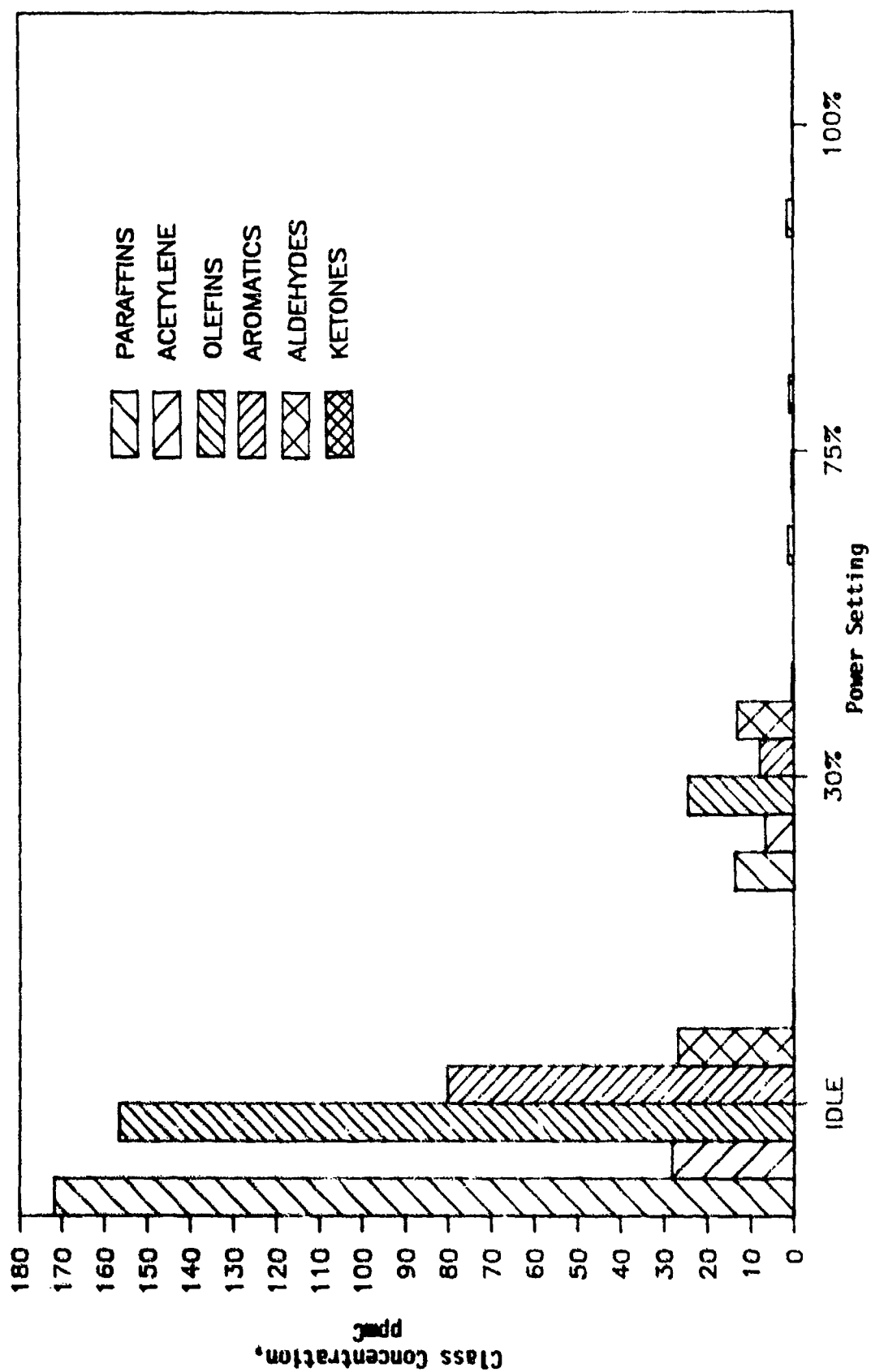


Figure 8. Compound Class Distribution for TF41-A2 Engine

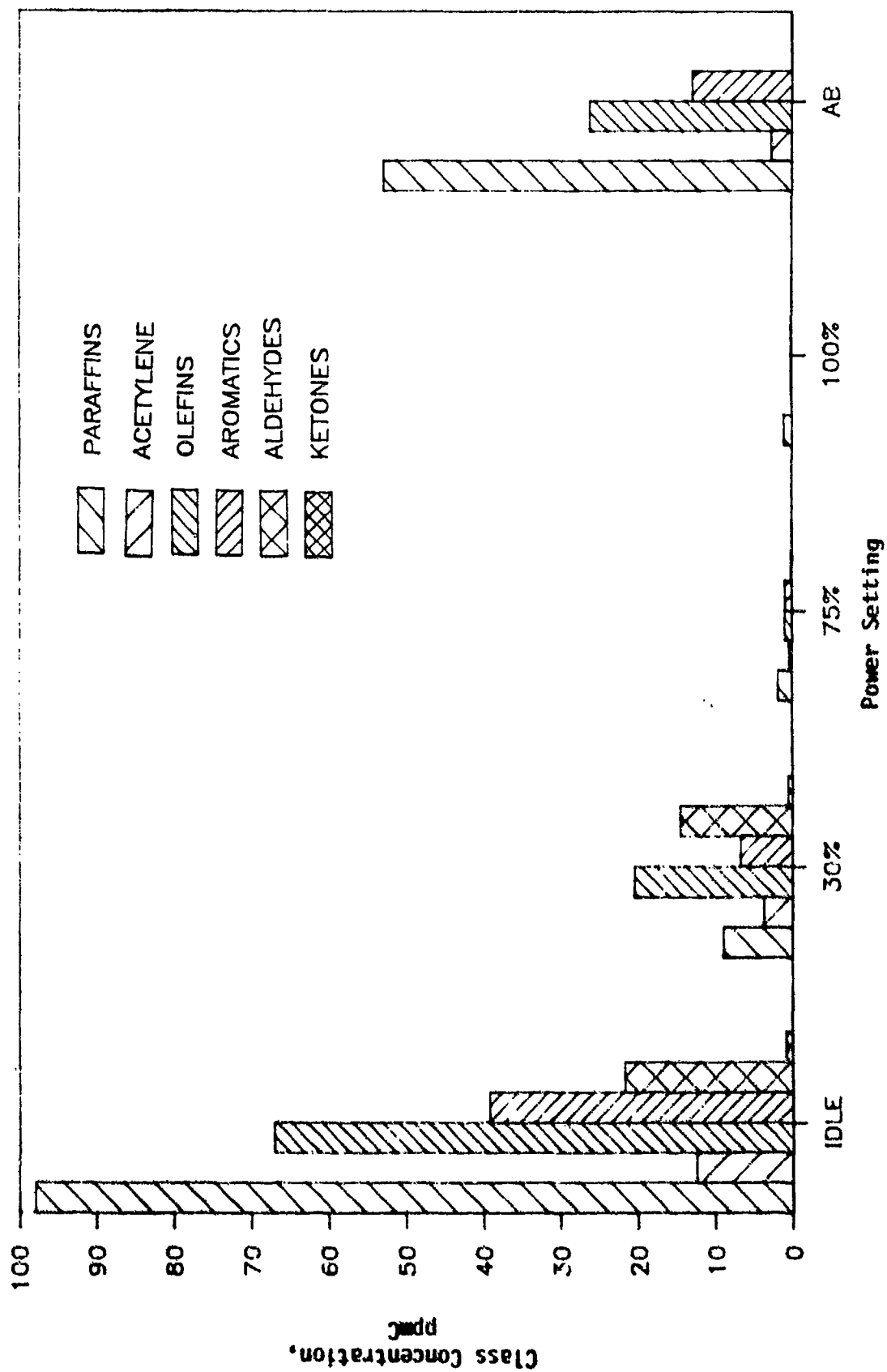


Figure 9. Compound Class Distribution for TF30-P103 Engine

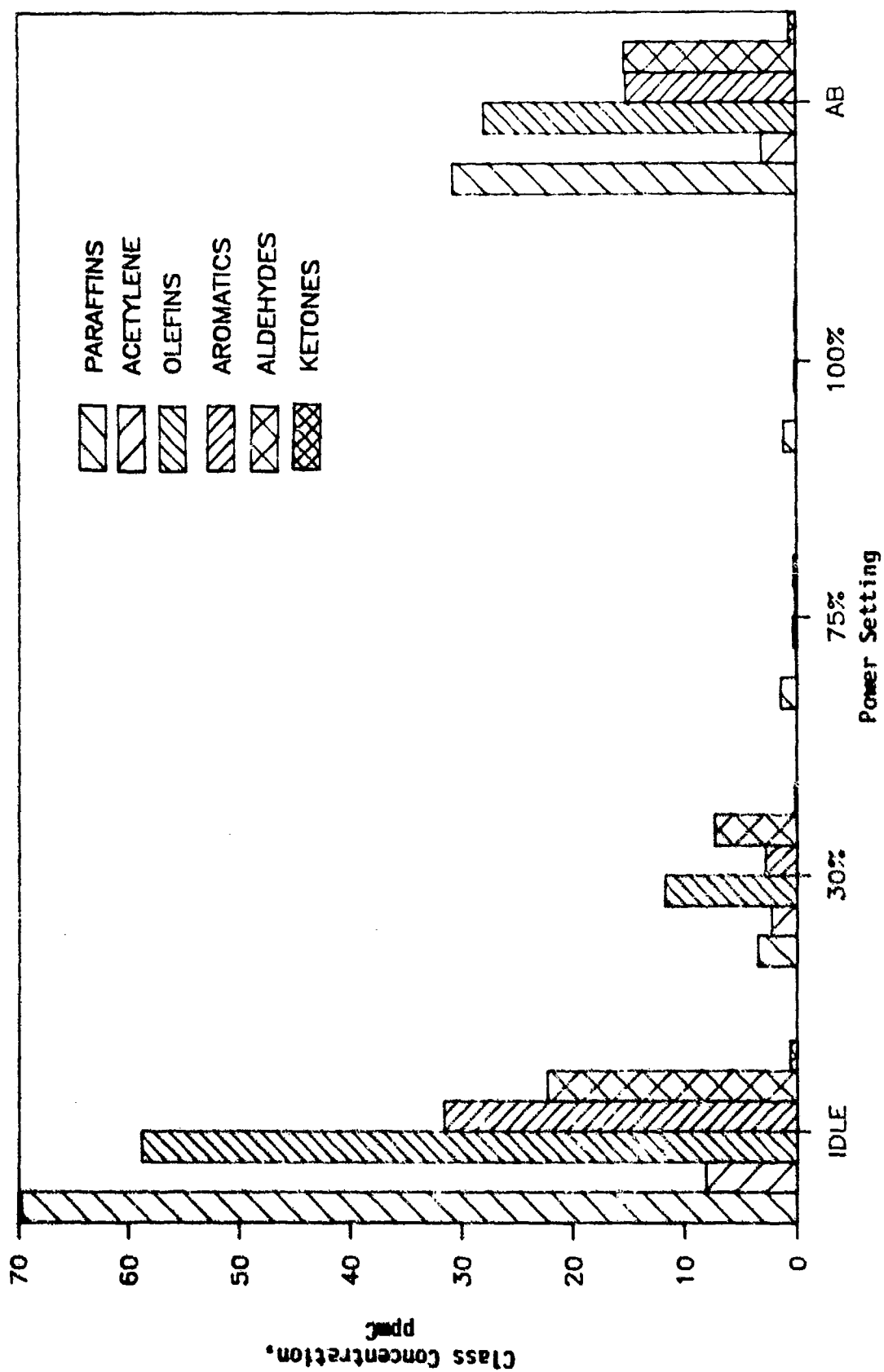


Figure 10. Compound Class Distribution for TF30-P109 Engine

TABLE 17. DISTRIBUTION OF ORGANIC EMISSIONS BY
CARBON NUMBER FOR TF41-A2 ENGINE (ppmC)

CARBON NUMBER	POWER SETTING			
	IDLE	30%	75%	100%
C1	34.054	11.367	1.538	1.240
C2	111.423	25.413	0.630	0.099
C3	42.428	8.472	0.186	0.014
C4	50.361	5.220	0.178	0.178
C5	35.344	3.054	0.126	0.091
C6	61.655	6.391	0.276	0.152
C7	85.050	6.680	0.149	0.073
C8	75.390	4.948	0.127	0.144
C9	53.959	2.952	0.072	0.105
C10	42.167	2.019	0.084	0.123
C11	32.298	1.333	0.098	0.138
C12	27.325	0.854	0.113	0.140
C13	18.775	0.582	0.074	0.067
C14	9.306	0.519	0.061	0.045
C15-ABOVE	2.180	1.461	0.314	0.087

TABLE 18. DISTRIBUTION OF ORGANIC EMISSIONS BY
CARBON NUMBER FOR TF30-P103 ENGINE (ppmC)

CARBON NUMBER	POWER SETTING				
	IDLE	30%	75%	100%	AB*
C1	16.040	9.359	1.398	0.865	24.617
C2	52.148	17.547	1.208	0.175	16.250
C3	23.211	10.053	0.101	0.020	6.419
C4	21.665	6.261	*	0.069	9.403
C5	18.792	3.053	0.202	0.121	8.136
C6	52.830	4.921	0.580	0.051	13.749
C7	50.237	5.352	0.094	0.088	17.876
C8	42.080	4.803	0.136	0.191	14.249
C9	27.891	2.901	0.060	0.054	10.819
C10	22.200	2.455	0.212	0.116	9.141
C11	18.528	2.083	0.128	0.090	5.987
C12	15.794	1.585	0.064	0.069	3.814
C13	9.579	0.694	0.048	0.047	1.675
C14	4.751	0.433	0.050	0.060	0.629
C15-ABOVE	1.178	0.086	0.296	0.288	0.213

* Afterburner measurements made on dilute exhaust.

TABLE 19. DISTRIBUTION OF ORGANIC EMISSIONS BY
CARBON NUMBER FOR TF30-P109 ENGINE (ppmC)

CARBON NUMBER	POWER SETTING				
	IDLE	30%	75%	100%	AB*
C1	14.236	5.541	1.213	0.746	10.656
C2	41.740	11.246	0.407	0.091	20.869
C3	23.259	4.974	0.051	0.069	12.469
C4	18.132	2.226	0.073	0.052	10.536
C5	14.667	1.478	0.233	0.123	8.186
C6	25.491	2.283	0.113	0.047	13.885
C7	36.882	1.747	0.115	0.078	18.128
C8	32.695	1.443	0.100	0.045	14.230
C9	23.458	0.985	0.062	0.026	9.796
C10	18.523	0.742	0.153	0.094	7.920
C11	15.617	0.662	0.114	0.082	5.765
C12	12.163	0.443	0.060	0.034	4.282
C13	6.693	0.165	0.038	0.017	2.821
C14	3.848	0.103	0.021	0.007	0.612
C15-ABOVE	1.010	0.114	0.029	0.028	0.202

* Afterburner measurements made on dilute exhaust.

E. EMISSION FACTORS

1. Nitrogen Oxide Emissions

The nitrogen oxide emissions from the three test engines are shown in Table 20. 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 which is regulated by the U.S. Environmental Protection Agency. The federal ambient air standard currently is based on annual average concentration. The state of 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 20 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 from idle to 100 percent power. This ratio increases abruptly at afterburner power for the two afterburner engines examined in this study. One mechanism of NO_2 formation in engine exhaust is oxidation of NO by peroxy radicals. The concentration of organic peroxy radicals is expected

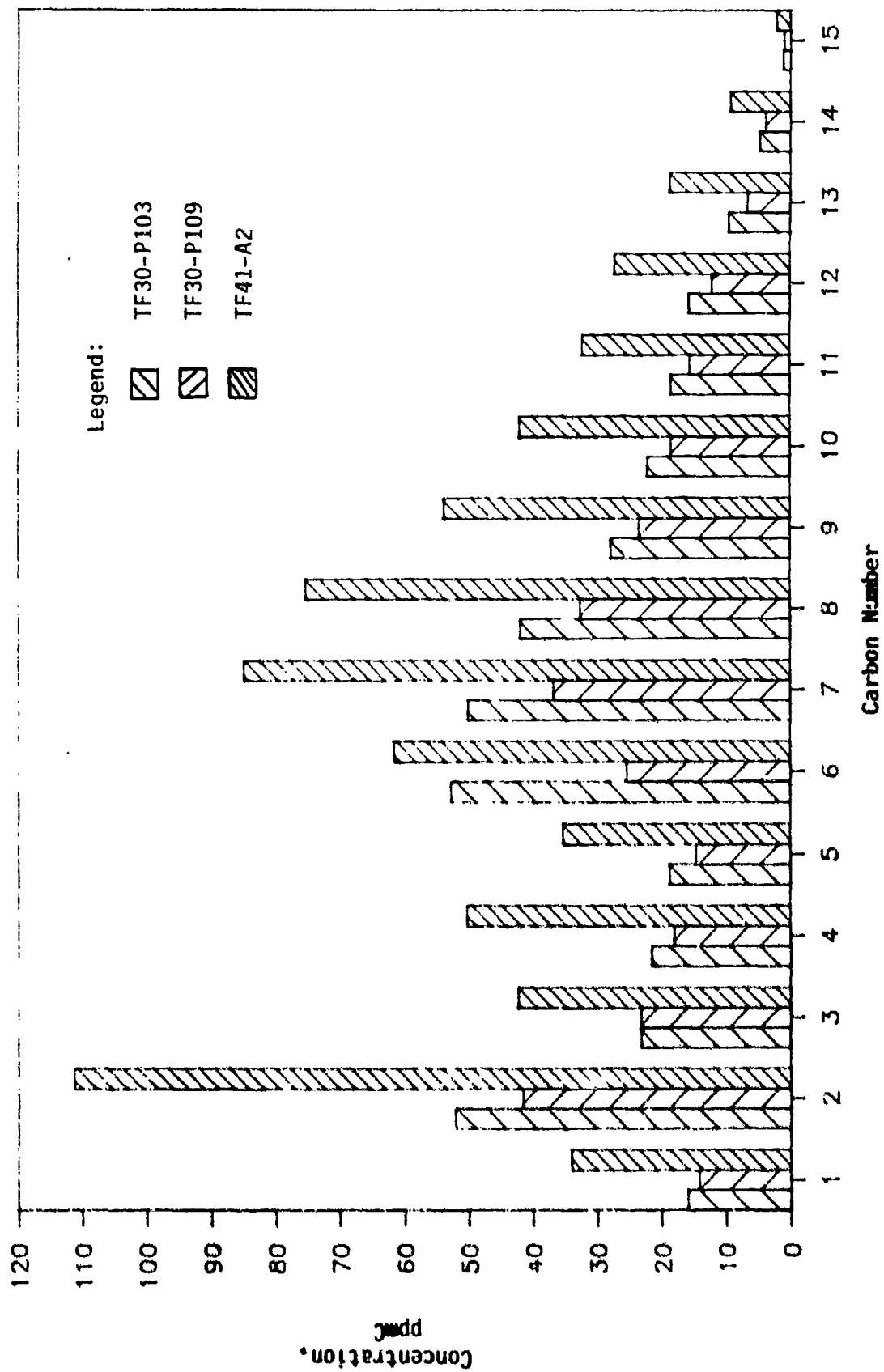


Figure 11. Distribution of Organic Emissions by Carbon Number for Three Engines at Idle Power

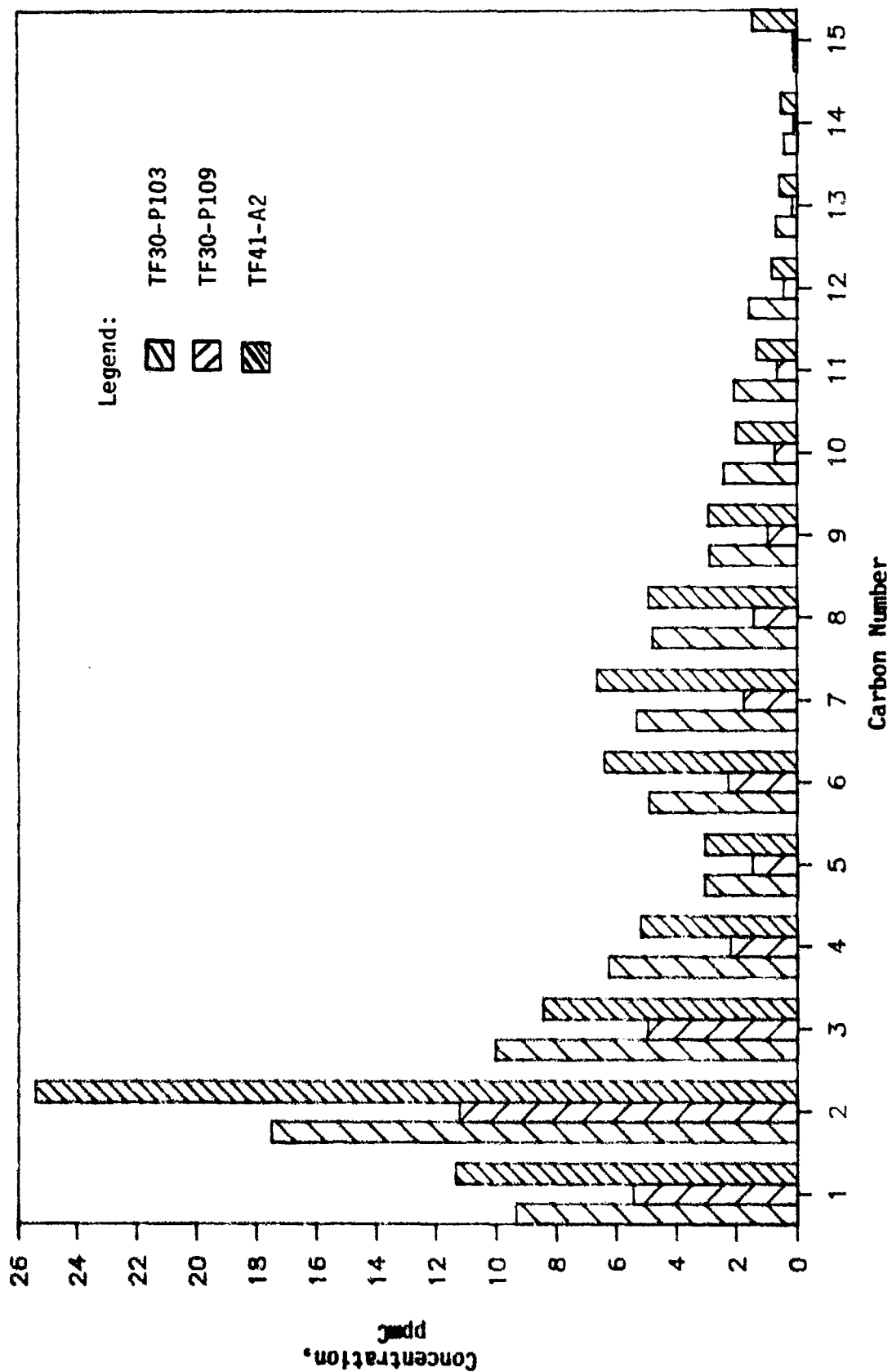


Figure 12. Distribution of Organic Emissions by Carbon Number for Three Engines at 30 Percent Power

TABLE 20. NO_x EMISSION DATA

POWER MODE	RUN NO.	NO _x , ppm	NO, ppm	NO ₂ , ppm	NO ₂ /NO _x
<u>TF 41-A2</u>					
Idle	1-6-6	10.5	6.1	4.4	.42
30%	2-6-6	23.5	9.3	14.2	.60
75%	3-6-6	120	97.5	22.5	.19
100%	4-6-6	202	170	32.0	.16
<u>TF 30-P103</u>					
Idle	4-6-9	6.5	2.4	4.1	.63
30%	1-6-9	19.3	6.2	13.1	.68
75%	2-6-9	51.4	42.0	9.4	.18
100%	3-6-9	84.2	75.0	9.2	.11
AB (Zone 1)	7-6-10	15.0*	8.0*	7.0*	.47*
<u>TF 30-P109</u>					
Idle	1-6-10	7.0	2.5	4.5	.64
30%	2-6-20	23.0	11.0	12.0	.52
75%	3-6-10	58.9	51.9	7.0	.12
100%	4-6-10	103	95.0	8.0	.08
100%	5-6-10	14.0*	12.5*	1.5*	.11*
AB (Zone 1)	6-6-10	16.2*	4.3*	11.9*	.73*

* Dilute exhaust samples collected from test cell roof vent.

to be enhanced in fuel-rich combustion, where organic species are available for peroxy radical formation. This may account for the increasing ratio of NO₂/NO_x at lower power settings and at afterburner power. Table 9 showed that the exhaust organic concentration is highest at idle and afterburner power. The high NO₂/NO_x at 30 percent power may result from the combination of moderate levels of organic species and NO in the exhaust, both of which are necessary to produce NO₂ by this mechanism.

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 fuel and air flows have been used to determine the fuel/air ratio, reported as

F/A (measured) in Table 21. The fuel/air ratio has also been calculated, based on the exhaust composition. These results are reported in Table 21 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

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

agreement between the measured and calculated fuel to air ratio. With one exception, all the ratios agree to within ± 15 percent. The exception is the Test No. 1-6-6, for which the air flow was so low that it had to be estimated by extrapolation. The uncertainty in the estimated air flow means that the F/A (measured) for this test is less certain than for the other tests, and this uncertainty probably accounts for the disagreement in measured and calculated ratios. The ratios for the TF30-P103 and TF30-P109 engines all agree to better than ± 3 percent.

3. Emission Indices

The emission index, in pounds per thousand pounds of fuel, has been calculated for CO, CO₂, total hydrocarbon, NO, NO₂, and NO_x. The calculation procedures were noted earlier in Section II. The emission indices for the three engines at each power setting are given in Table 22. As noted in the table, all oxidized nitrogen species were calculated using the molecular weight of NO₂, in accordance with the convention employed in such calculations. The emission indices for afterburner power (zone 1) were calculated somewhat differently, as described in Section II. These results are included in Table 23.

Engine emissions indices are often used to derive aircraft emissions for assessment of aircraft operations or airport environmental impacts. The emission indices for a number of turbine engines have been reported by Seitchek (Reference 7) based on emissions measurements made in the 1970s. The data collected in this study update the compilation of Reference 7 for the TF41-A2, TF30-P103, and TF30-P109 engines. In comparing data in Tables 22 and 23 with the emissions listed in Reference 7, it is important to compare emissions at the same power setting, because the emissions can change significantly with small changes

TABLE 21. FUEL/AIR RATIOS

POWER MODE	RUN NO.	F/A (CALCULATED)	F/A (MEASURED)
<u>TF41-A2</u>			
Idle	1-6-6	.004268	.005956*
30%	2-6-6	.004335	.004820
75%	3-6-6	.008322	.007342
100%	4-6-6	.010145	.008956
<u>TF30-P103</u>			
Idle	4-6-9	.002688	.002640
30%	1-6-9	.004519	.004367
75%	2-6-9	.005617	.005707
100%	3-6-9	.006912	.006792
<u>TF30-P109</u>			
Idle	1-6-10	.002692	.002728
30%	2-6-10	.004665	.004540
75%	3-6-10	.006191	.006118
100%	4-6-10	.007584	.007469

* Based on extrapolated air flow--accuracy questionable.

in power setting. In this regard, the thrust and fuel flow data in Tables 4-6 may be useful in comparing data from this report with other emissions data.

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, CO₂, hydrocarbons, NO, NO₂, and NO_x are shown in Table 24 for power settings from idle through 100 percent. Emission rates for afterburner power are listed in Table 23. These rates are given in units of pounds per hour. A plot of emission rate by power setting for the three engines is shown in Figure 13. As anticipated, the CO and hydrocarbon emissions decrease and NO_x emissions increase with increasing power setting. This graph also indicates differences in emissions among engines. Because these engines are not all rated at the same maximum thrust, the same "power setting" will produce different thrust for each engine. The actual thrusts developed by each engine at

TABLE 22. EMISSION INDICES FOR THREE ENGINES

	EMISSION INDEX (LBS/10 ³ LB FUEL)					
	CO	CO ₂	HC	NO*	NO ₂	NO _x *
<u>TF41-A2</u>						
Idle	176	2656	99.6	2.4	1.7	4.0
30%	45.0	3142	10.1	3.5	5.4	8.9
75%	4.7	3186	0.09	19.3	4.5	23.8
100%	3.2	3179	0.08	27.8	5.2	32.9
<u>TF30-P103</u>						
Idle	100	2910	76.9	1.5	2.5	4.0
30%	36.2	3149	10.9	2.2	4.8	7.0
75%	5.5	3211	0.31	12.3	2.8	15.1
100%	2.1	3202	0.09	17.9	2.2	20.1
<u>TF30-P109</u>						
Idle	103	2962	59.1	1.5	2.8	4.3
30%	28.0	3181	3.8	3.9	4.2	8.1
75%	3.4	3207	0.16	13.9	1.9	15.7
100%	1.1	3198	0.09	20.7	1.8	22.5

* Calculated as NO₂ by convention.

TABLE 23. EMISSION INDICES AND EMISSION RATES FOR AFTERBURNING ENGINES

	EMISSION INDICES (LB/10 ³ LBS FUEL)			
	CO	HC	NO*	NO _x *
TF30-P103 (Zone 1 A/B)	77.2	28.0	6.0	11.2
TF30-P109 (Zone 1 A/B)	61.2	33.8	3.4	12.7
	EMISSION RATES (LB/HR)			
	CO	HC	NO*	NO _x *
TF30-P103 (Zone 1 A/B)	1,104	400	85.1	160
TF30-P109 (Zone 1 A/B)	982	542	54.1	204

* Calculated as NO₂ by convention.

ENGINE EMISSION RATES

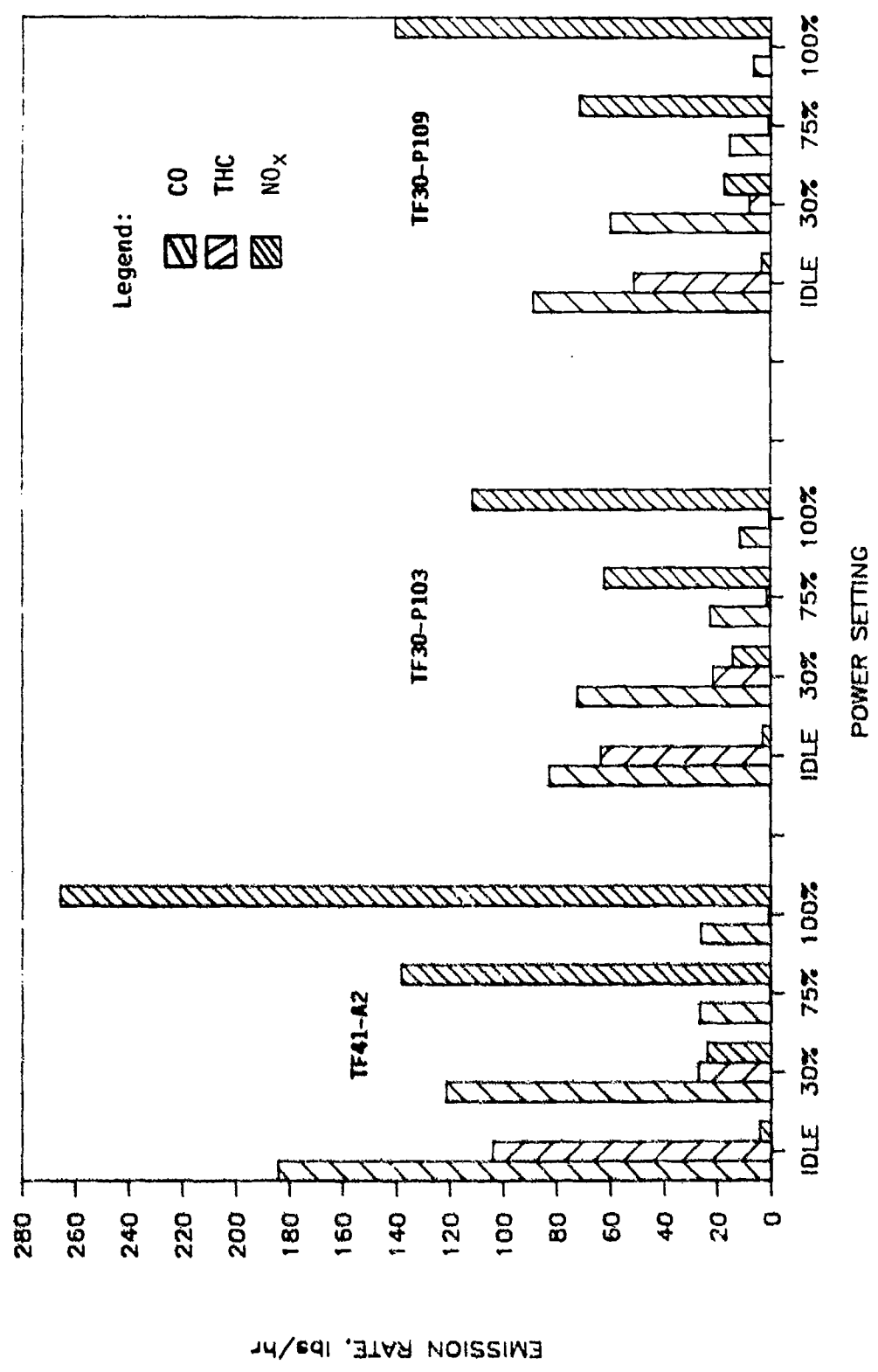


Figure 13. Engine Emission Rates for CO, THC, and NO_x

TABLE 24. EMISSION RATES FOR THREE ENGINES

	EMISSION RATES (LBS/HR)					
	CO	CO ₂ (x 10 ³)	HC	NO*	NO ₂	NO _x *
<u>TF41-A2</u>						
Idle	185	2.8	104	2.4	1.8	4.2
30%	122	8.5	27.3	9.5	14.6	24.1
75%	27.1	18.5	0.5	112	25.9	138
100%	26.2	25.7	0.6	224	42.1	266
<u>TF30-P103</u>						
Idle	82.7	2.4	63.6	1.2	2.1	3.3
30%	72.5	6.3	21.9	4.5	9.6	14.1
75%	22.7	13.2	1.3	50.8	11.4	62.2
100%	11.6	17.7	0.5	99.2	12.2	111
<u>TF30-P109</u>						
Idle	89.0	2.6	51.1	1.3	2.4	3.7
30%	59.8	6.8	8.1	8.3	9.0	17.3
75%	15.4	14.6	0.7	63.0	8.5	71.6
100%	6.7	20.0	0.5	130	10.9	140

* Calculated as NO₂ by convention.

the various power settings are listed in Tables 4-6. These power output differences should be taken into account in comparing emissions among engines.

To test the applicability of our roof vent sampling strategy for afterburner emissions measurements, we measured emissions from the TF30-P109 engine, operating at 100 percent power at both the exhaust nozzle exit, using the rake, and at the rooftop vent from the test cell, using a single-point probe. These locations were noted earlier in Figure 1. All afterburner emissions measurements were made from the roof vent because the exhaust temperature was too high at afterburner power to make accurate measurements at the nozzle exit. The assumption used in making the roof vent measurements was that the exhaust is well-mixed by the time it reaches the vent, so that a representative exhaust sample can be obtained with a single probe. This assumption can be

tested using the data collected at 100 percent power from the two sampling locations. The emission indices obtained at the two sampling locations are shown in Table 25. The agreement between the emission indices obtained at the two locations is quite reasonable, confirming the assumption of exhaust homogeneity at the roof vent. The agreement also confirms the utility of the data reduction procedures used to derive emission index information for the roof vent samples, i.e. using pollutant/CO₂ ratios.

TABLE 25. COMPARISON OF EMISSIONS INDICES FOR CO, NO, AND NO_x FOR TF30-P109 ENGINE AT 100 PERCENT POWER FOR SAMPLES COLLECTED AT EXHAUST NOZZLE AND ROOF VENT

	EMISSION INDEX AT NOZZLE EXIT, LBS/10 ³ LBS FUEL	EMISSION INDEX AT ROOF VENT, LBS/10 ³ LBS FUEL
CO	1.1	1.2
NO	20.7	24.1
NO _x	22.5	26.9

F. RELATIVE EMISSIONS OF TOXIC CHEMICALS

There are numerous ways 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 Tables 22 and 23. 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. 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 4.3 to 13.3 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. However, benzene concentrations are elevated at Zone 1 afterburner power. The concentrations of benzene and other species at afterburner power in Tables 11 and 12 are for diluted exhaust.

A comparison of benzene emissions from automobiles operating on the 1975 Federal Test Procedure with and without catalytic converters (Reference 8), two jet engines studied previously (Reference 2), and the study engines is included in Table 26. On the basis of mass of benzene emitted per mass of fuel consumed, the study engines emit greater quantities of benzene than the other sources.

TABLE 26. COMPARISON OF BENZENE EMISSIONS
FROM VARIOUS MOBILE SOURCES

SOURCE	BENZENE EMISSIONS, mg/g OF FUEL
Automobile, catalyst equipped	0.13
Automobile, non-catalyst	0.75
TF39 engine, at idle (JP-5 fuel)	0.42
CFM-56 engine, at idle (JP-4 fuel)	0.09
TF41-A2 engine, at idle (JP-4 fuel)	1.94
TF30-P103 engine, at idle (JP-4 fuel)	1.06
TF30-P109 engine, at idle (JP-4 fuel)	0.89

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 OSHA standard for formaldehyde is 3 ppm, but 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 27 lists the concentration of formaldehyde in exhaust from several mobile sources (Reference 10).

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

TABLE 27. FORMALDEHYDE CONCENTRATIONS IN EXHAUST FROM MOBILE SOURCES

SOURCE	FORMALDEHYDE CONCENTRATION, ppm
Automobile, non-catalyst	24
Automobile, catalyst equipped	3.6
Light duty diesel (1978)	5.7
Light duty diesel (1980)	7.0
TF39 engine*	14.6
CFM-56 engine*	9.3
TF41-A2 engine*	17.8
TF30-P103 engine*	9.3
TF30-P109 engine*	9.0

* At idle using JP-4 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 an 8-hour time-weighted average (Reference 9). Emissions of BaP from several mobile sources are noted in Table 28 (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 13 showed that BaP was not detected in the exhaust from the TF41-A2 engine at higher power, nor from the TF30-P103 or TF-JOP109 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.

TABLE 28. COMPARISON OF BENZO(a)PYRENE EMISSIONS
FROM SEVERAL EMISSIONS SOURCES

SOURCE	BaP, µg/g FUEL
Automobile, diesel	0.03-0.16
Automobile, unleaded gasoline	0.014
Truck, diesel	0.0038
Truck, gasoline	0.065
TF39 engine, at idle (JP-5 fuel)	0.0051
CFM-56 engine*	0.024
TF41-A2 engine*	0.0064
TF30-P103 engine*	Below detection
TF30-P109 engine*	Below detection

* At idle using JP-4 fuel.

4. Carbon Monoxide

Carbon monoxide is a 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, and death. Severe carbon monoxide 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 29. These are concentrations at idle power in undiluted exhaust. Table 9 shows that the CO concentration decreases significantly at higher power settings.

TABLE 29. CONCENTRATIONS OF CO IN UNDILUTED ENGINE EXHAUST AT IDLE POWER (JP-4 FUEL)

ENGINE	CO CONCENTRATION, ppm
TF39	550
CFM-56	640
TF41-A2	772
TF30-P103	276
TF30-P109	283

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 concentration 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. 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 30. 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 two other turbine engines (Reference 2). The relationship between NO_2 emissions and engine power setting was discussed earlier in this report.

TABLE 30. CONCENTRATIONS OF NO_2 IN JET ENGINE EXHAUST

ENGINE	<u>NO_2 CONCENTRATION, ppm</u>	
	IDLE POWER	30 PERCENT POWER
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 15. These data are presented graphically for the TF41-A2 engine in Figure 14. The figure shows only slight changes in the total number concentration (N_t) at different power settings, but a definite shift in size distribution. Small particles ($\leq 0.05 \mu\text{m}$) dominate the number concentration at idle and 30 percent power, while larger particles ($\geq 0.1 \mu\text{m}$) are more prevalent at power settings of 75 and 100 percent. We find very little information in the literature on the size distribution of particles from turbine engines, and this observation regarding the change in distribution with power setting has apparently not been reported before.

The change in size distribution probably accounts for the dramatic change in smoke number with increasing power. Table 14 showed that smoke number increased from 0.2 to 53.9 for the TF41-A2 engine on increasing power from idle to 100 percent. However, Figure 14 shows that N_t changes very little with increasing power for this engine. The likely explanation is the very 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 $0.2 \mu\text{m}$ 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 14 indicate.

An electrostatic sampler was used to collect exhaust particles during this study. Several variations in sampling strategy were employed in order to obtain samples appropriately loaded for SEM analysis. Some samples were collected, using double-stick tape on the collection surface. While this technique has worked very well in the past, it did not provide satisfactory samples for this study. The reason is unknown. Other samples were collected directly on stainless steel surfaces, and these samples generated usable photomicrographs. Some of these collections were made with dilute exhaust, and some with undiluted exhaust, to obtain

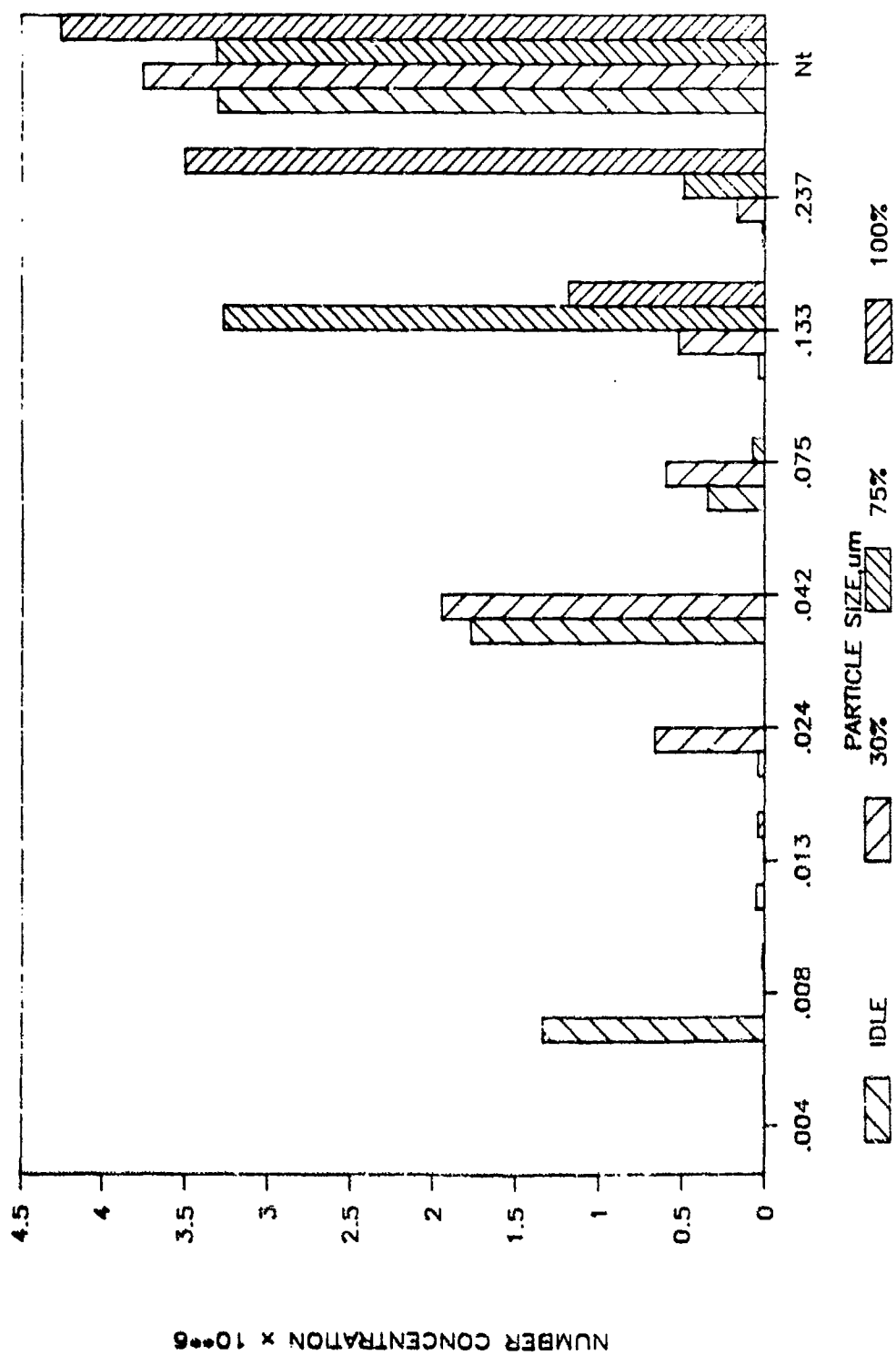


Figure 14. Particle Size Distribution for TF41-A2 Exhaust

appropriate loading for SEM analysis. Only those samples which collected particles from undiluted exhaust and sampled with stainless steel surfaces yielded usable photomicrographs. An example photomicrograph is included in Figure 15 for the TF30-P109 engine operating at 75 percent power. At a magnification of 1000, 1 μ m particles will appear with a diameter of 1 mm. Numerous submicron particles appear on the rough stainless steel substrate surface as small light colored shapes. Some larger dendritic particles are also seen as a result of agglomeration of the smaller primary particles. The size and morphology of the particles evident in Figure 15 suggest combustion generated particles of a carbonaceous nature. The primary reason for employing the electrostatic samples and SEM procedures was the need to determine whether large particles (i.e. >1 μ m) are emitted by turbine engines. There is little evidence of particles greater than 1 μ m in the exhaust, except for those produced by agglomeration of smaller particles noted above.

The electrostatic sampler/SEM procedures employed in this study should be viewed as a preliminary attempt to devise appropriate procedures for such collections. Subsequent studies will use these results to optimize the sample collection and analysis strategy, so that more detailed information on particle size and morphology can be obtained.

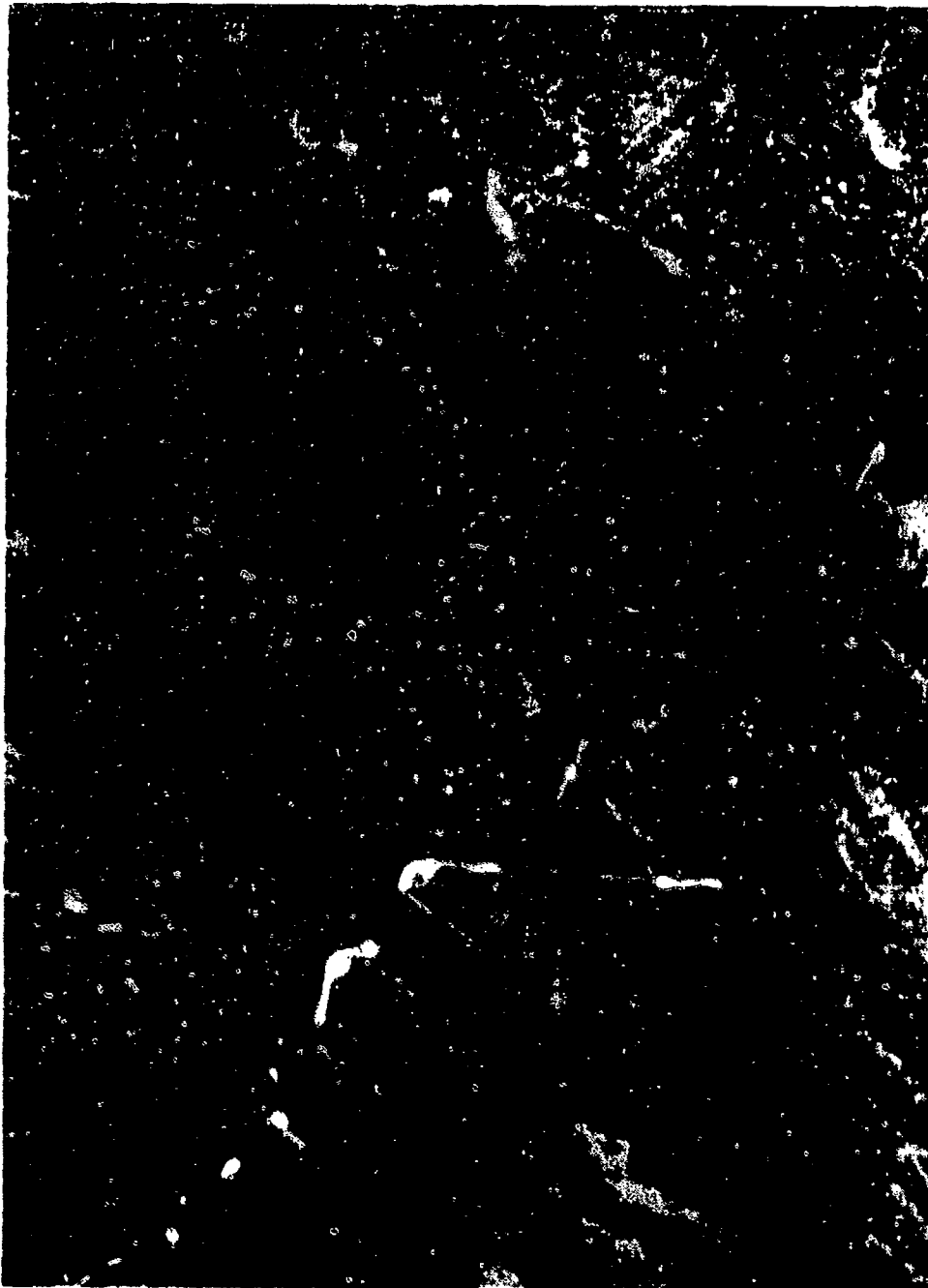


Figure 15. Photomicrograph of Particles in Exhaust from
TF30-P109 Engine at 75 Percent Power
(stainless steel substrate, magnification x1000)

SECTION V

CONCLUSIONS

This study has characterized the gas and particle composition of exhaust from three Air Force turbine engines: TF41-A2, TF30-P103, and TF30-P109. Measurements were made with the engines operating on JP-4 fuel, at power settings from idle to afterburner. 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 83 ± 12 percent of the total organic loading of the exhaust.
- At idle, five cracking products (methane, ethylene, acetylene, propene, and 1-butene) accounted for 20-25 percent of total organic emissions. Most of the remainder is unburned fuel and partial oxidation products.
- 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, methane is the dominant organic component in the exhaust, accounting for about 30 percent of the organic burden at 75 percent power and about 45 percent at 100 percent power. At lower power settings (idle and 30 percent), ethylene is the dominant organic constituent.
- Aldehydes were present at significant concentrations in the exhaust from all three engines. In general, the abundance of aldehydes relative to total organic species increased from ~6 percent at idle to ~20 percent at 30 percent power. The relative abundance of aldehydes generally decreased at higher power settings.
- Dicarbonyl compounds were observed at relatively high concentrations in the exhaust from each engine, consistent with our earlier studies (Reference 2). At low power settings, methyl glyoxal always exceeded glyoxal.
- The distribution of organic emissions by carbon number is bimodal at idle power, with peaks occurring at C₂ and C₇.

- The ratio NO_2/NO_x generally decreases at higher power settings, as NO_x increases. At afterburner power, this ratio increases dramatically. We speculate that organic peroxy radicals formed in the fuel-rich afterburner exhaust oxidize NO to NO_2 .
- With the exception of one test, measured fuel/air ratios agreed with the ratios calculated from exhaust composition to better than ± 15 percent. This indicates that representative exhaust samples were collected. The ratios for the TF30 engines all agreed to better than ± 3 percent.
- Emission indices and emission rates were determined for CO , CO_2 , hydrocarbons, NO , and NO_x at all power settings. In general, the TF41-A2 engine yielded higher emission rates for CO , HC , and NO_x than the TF30 engines.
- Emission indices for CO , NO , and NO_x measured at 100 percent power at the exhaust nozzle (with a multiport rake) and at the roof vent (with a single probe) were in good agreement, confirming the validity of the roof vent sampling strategy.
- Smoke emissions, as measured by light reflectance from an exhaust filter sample, increased from very low values at idle, to high values at higher power settings.
- Particle number concentration in the exhaust was generally in the range 2×10^6 to 6×10^6 particles/cc. The distribution of particle sizes varied with power setting, with small particles ($<0.05 \mu\text{m}$) most prevalent at idle and 30 percent power, and larger particles ($>0.05 \mu\text{m}$) dominant at higher power. Microscopic examination of collected exhaust particles revealed primarily submicrometer particles, and larger agglomerations of these particles.

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