SPAWAR
Systems Center
San Diego

TECHNICAL REPORT 1881
March 2002

Characterization of Jet Engine Exhaust Particulates for the F404, F118, T64, and T58 Aircraft Engines

L. A. Shumway

SSC San Diego

TECHNICAL REPORT 1881
March 2002

Characterization of Jet Engine Exhaust Particulates for the F404, F118, T64, and T58 Aircraft Engines

L. A. Shumway

SSC San Diego
San Diego, CA 92152–5001

SSC SAN DIEGO
San Diego, California 92152–5001

P. A. Miller, CAPT, USN
Commanding Officer

R. C. Kolb
Executive Director

ADMINISTRATIVE INFORMATION

The work described in this report was prepared for the U.S. Navy Aircraft Environmental Support Office by the SSC San Diego Marine Environmental Quality Branch (Code 2362).

Released by
J. G. Grovhoug, Head
Marine Environmental Quality Branch

S. J. Harrell, Head
Marine Environmental Support Office

Under authority of
R. H. Moore, Head
Environmental
Sciences Division

EXECUTIVE SUMMARY

Jet engine exhaust particulate samples collected from four military aircraft engines were analyzed for particle morphology. Particulate emissions from three of the engines were also analyzed for polycyclic aromatic hydrocarbons (PAHs). The F118, F404, T58, and T64 engines were tested in four modes: approach, idle, military, and intermediate. The F404 engine was also tested in afterburner mode.

Micrographs from a scanning electron microscope (SEM) showed individual particles measured between 22 and 120 nanometers. Particles were discrete in the approach and idle engine modes, and tended to agglomerate as they became denser in the military and intermediate modes. Additional, larger (1 to 40 micrometer) particles were observed in lesser quantities in the military, intermediate, and afterburner modes.

An Electron Dispersive X-ray (EDX) was used for metals analysis of the larger particles located with the SEM. These particles exhibited widely differing morphologies and spectra. Planar particles registered no spectra; these particles were assumed to be elemental carbon. Larger conglomerate particles contained up to 10 metals.

PAHs detected in the particles correlated well with other published results of PAHs detected from sampling jet engine exhaust gases. Higher molecular weight PAHs (generally considered slower to biodegrade and more carcinogenic) were detected in engine exhaust particulates only when the engine was in idle mode. Lighter molecular weight PAHs were detected in the approach, intermediate, and military modes. More types of PAHs and greater amounts of PAHs were found on the T64 filters (the T58 filters were not analyzed for PAHs). The T64 engine is an older design; those filters were visibly many times more heavily laden with particulates.

Benzo[a]pyrene (BAP) is the most studied carcinogenic PAH and is traditionally used as an indicator of overall PAH content (Bjφrseth, 1983). No BAP was detected in the F118 samples. BAP was detected in the F404 and T64 idle mode samples only, at an insignificant value below the Minimum Detection Limit (MDL) of the analysis method.

CONTENTS

Figures

Tables

1. INTRODUCTION

New air pollution particulate standards designed to clear smog and soot from the atmosphere were approved by Congress and released by the U.S. Environmental Protection Agency (USEPA) in 1998. The new standards include regulation of airborne particulate matter smaller than 2.5 microns (PM2.5). Prior standards had regulated particulate matter less than 10 microns (PM10).

USEPA and others have made an intense effort to gather more scientific data about PM2.5 since this legislation was passed. The National Air Monitoring System has been collecting 24-hour PM2.5 particulate samples for gravimetric analysis since January 1999. In late 1999, new monitors became available to collect PM2.5 samples for chemical speciation. Many studies of the health effects and toxicity of PM2.5 are underway.

Particulate matter less than 2.5 microns are emitted from all combustion sources. Jet engine aircraft emit submicron particulates in their exhaust as a byproduct of the combustion process. The following analysis is a first attempt to physically and chemically characterize particulate emissions from jet engine aircraft burning JP8 or JP5 fuel. In the past, military aircraft were fueled with JP4, a napthalene-based fuel. The JP4 fuel has been replaced with kerosene-based fuels. The JP8 fuel has the same basic formula as commercial aviation fuel Jet A1, with additives for anti-corrosivity, anti-icing, and anti-static. Shipboard detachments, or locations with an increased fire hazard, use JP5 fuel because it has a higher flashpoint.

In this study, particulate emissions from four aircraft engines are characterized. The F118 and F404 engines were tested at Edwards Air Force Base in November and December 1997. Four F118 engines power the B-2 bomber, and two F404 engines power the F-117A fighter and F/A-18 fighter/attack aircraft. The T64 engine was tested at Cherry Point Naval Aviation Depot (NADEP) in January 1998. The T58 engine was tested at Cherry Point NADEP in November 1999. The T58 and T64 engines power the CH46 and CH53 helicopters. The T58 and T64 engines are an older engine design; filterable particulate emissions were much greater than from the newer F118 and F404 engines.

This work was funded by the U.S. Navy Aircraft Environmental Support Office (AESO). Analysis results will be used to refine future sampling and analysis efforts. The jet engine exhaust particulate samples on glass fiber filters analyzed in this report were collected as part of a larger testing effort by the Air Force and Navy to develop emission standards for military aircraft under differing load conditions.

2. MATERIALS AND METHODS

2.1 SAMPLE COLLECTION

Samples analyzed in this report are from the F404, F118, T58, and T64 engines. All sample filters analyzed for this report from the F404, F118, and T64 engines collected 60 minutes of emission particulates. Collection periods varied during testing of the T58 engine. Particulate filters used during this testing were Whatman™ 47- or 90-mm glass fiber filters, P/N 934-AH. Environmental Quality Management, Inc. (EQM), Cincinnati, Ohio, and Roy F. Weston, West Chester, PA, performed sampling of the F118, F404, and T64 engines. Pacific Environmental Services Inc., Baldwin Park, CA, performed the T58 sampling.

All filter collections were part of a larger effort for source particulate sampling. Source sampling was performed according to EPA Method 5–Determination of Particulate Emissions from Stationary Sources.

2.2 LABORATORY ANALYSES

Particulate filters for the F118, F404, and T64 engines were 90-mm-diameter glass fiber filters. Filters were cut with a razor blade into three sections for different analyses. Approximately 75% of the filter was reserved for PAH analysis. Portions of the remaining 25% were used for Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray (EDX) analysis.

Filters for the T58 engines were 47-mm-diameter glass fiber filters. Some experimentation was done with Teflon® filters for the T58 sampling. This type of filter provides superior results for metals analysis.

Figures 1 through 4 are photographs of the sampled filters.

2.2.1 Scanning Electron Microscope

A 1-cm (approximate) square was sliced from the glass fiber filters with a razor blade. The particulate layer was not homogeneous on the F118 and F404 filters due to the perforated filter backer support (see Figures 1 and 2) used during sample collection. The 1-cm-square areas selected for SEM analysis were taken from the outer edge of the sample, where the particulate layer was densest. Samples were prepped by tacking the 1-cm square to an aluminum stub and then gold-sputter-coating the sample with a Technics Hummer™ Sputter Coater. The gold plasma was applied with a current of 6 mA for 6 minutes in 100-mtorr pressure. This application resulted in a standard coating of approximately 30 nm. After coating, a colloidal graphite bridge (ground) was applied between the stub and the sample.

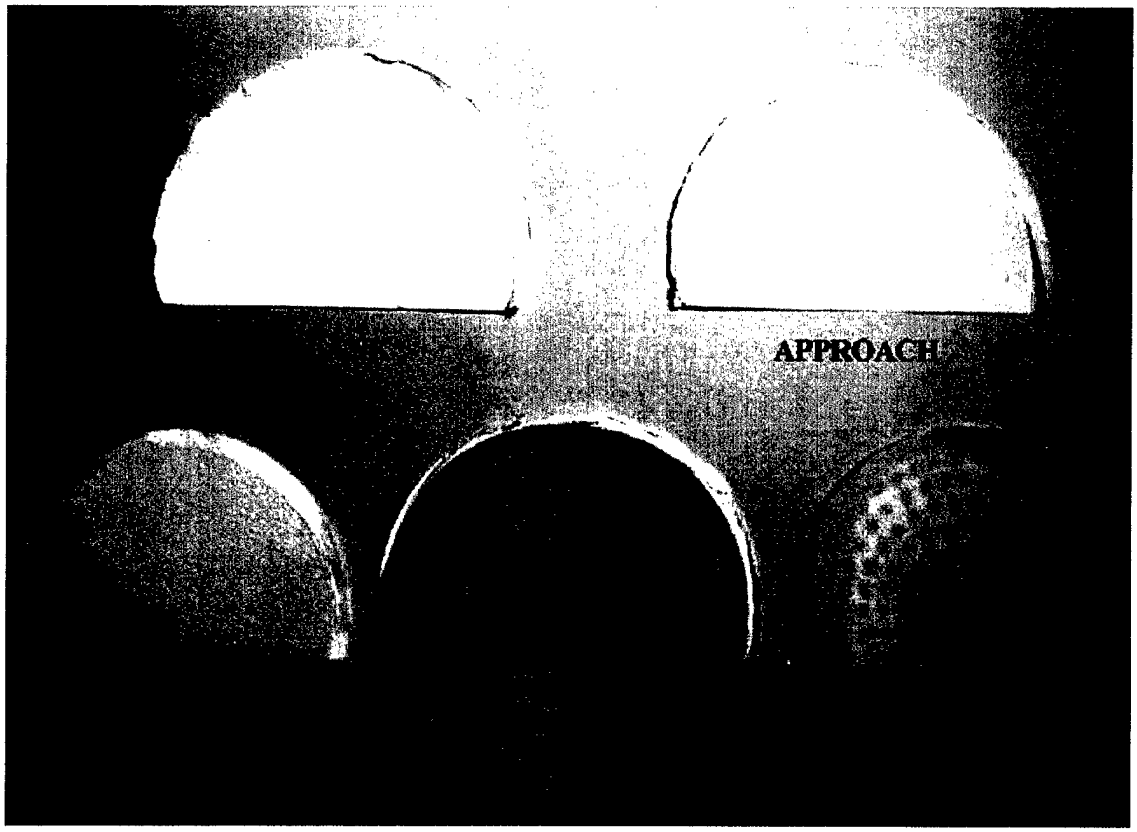


Figure 1. F118 filters (60-minute runs).

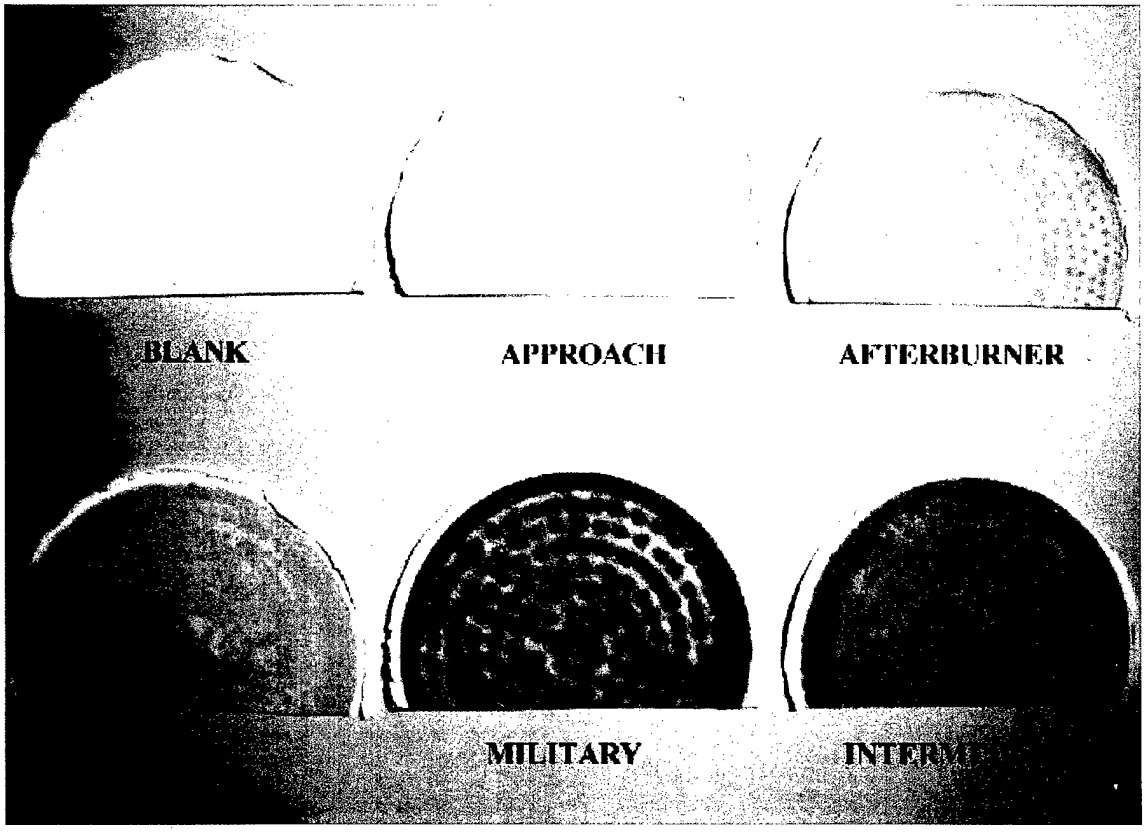


Figure 2. F404 filters (60-minute runs).

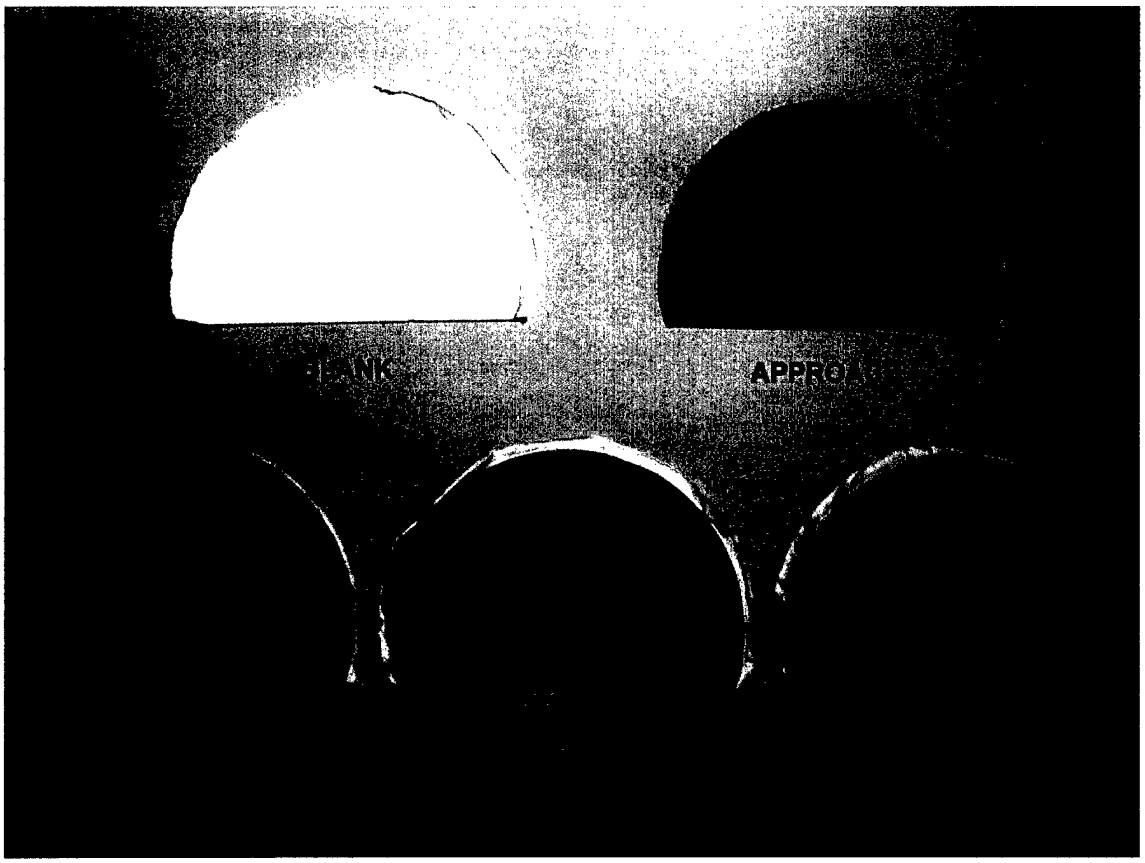


Figure 3. T64 filters (60-minute runs).

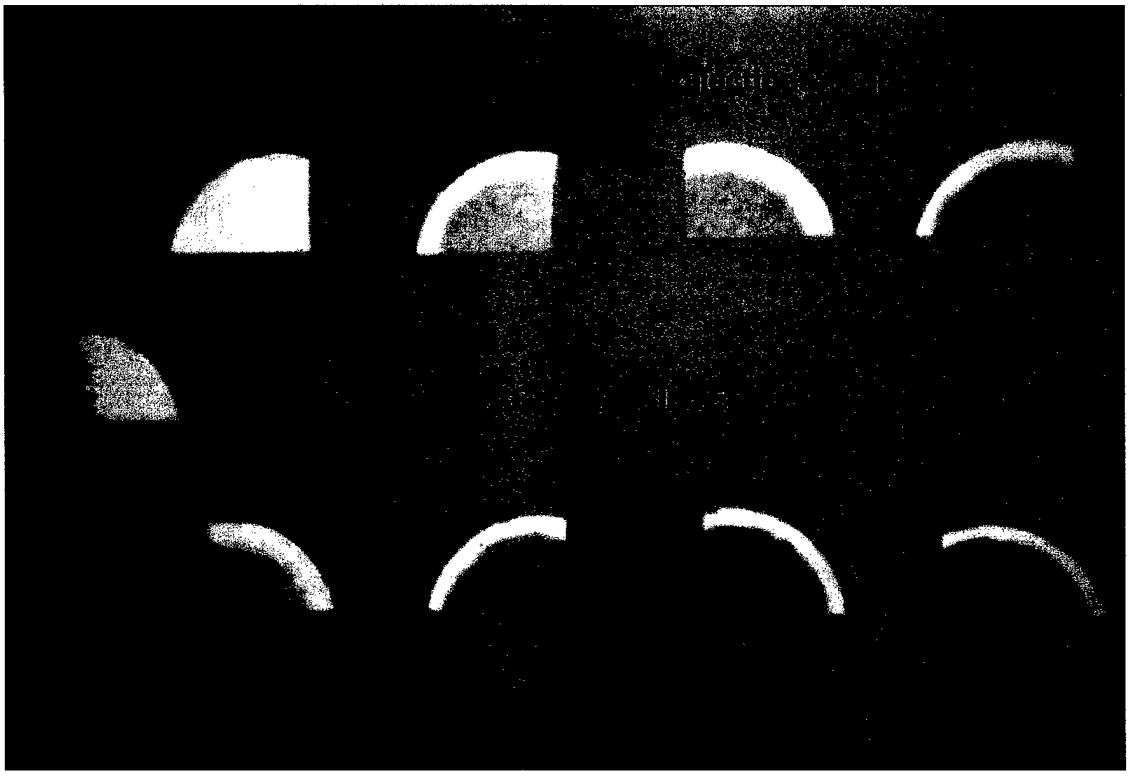


Figure 4. T58 filters (1- and 5-minute runs).

A Cambridge Instruments Model Stereoscan® 360 Scanning Electron Microscope at the Scripps Institution of Oceanography Research Facility was used to analyze and photograph the samples. Working distance from the electron emitter to the sample was 8 mm, the shortest distance that could be achieved with this SEM and these samples. The SEM focused on most particles at magnifications up to 45,000 times at this working distance. The Extra High Tension (EHT is a British term for voltage) was 20.0 kilovolts. The SEM photographs are not representative of the actual color of the samples.

2.2.2 Electron Dispersive X-Ray Metals Analysis

In conjunction with the SEM, a LINK QX2000 Energy Dispersive Spectrometry System X-Ray was used. The low end element is sodium for this machine. The 1-cm-square (approximate) samples were glued onto graphite stubs, and were not sputter-coated. A colloidal graphite bridge (ground) was applied between the stub and the sample.

Conglomerate particles, or particles larger than the 22- to 120-nm average ranges, were located with the SEM. The x-ray beam was directed at these particles, and the resultant metal spectrum was recorded. Working distance was 19 to 21 mm for these samples.

The height of the detection peaks in the spectra graphs is not a measure of metal concentration. This x-ray method can quantify metals in these particles only when microscopic slices of materials are prepared to remove edge effects and present material thin enough for the x-ray to penetrate.

2.2.3 Polycyclic Aromatic Hydrocarbons

A. D. Little (ADL) of Cambridge, MA, completed the PAH analysis. The following method description is summarized from their report[1].

Samples were extracted within 7 days from receipt as per ADL standard operating procedures (SOPs) and quality control (QC) standards. Samples were prepared along with a laboratory procedural blank and two laboratory control samples (blank spikes) following ADL SOPs 2017.00, 1016.00, and 5802.00 for the extraction of organic contaminants in solids using sonication and shaker table techniques. The field and QC samples were spiked with appropriate spiking solutions sonicated three times for 2 minutes each with 60 ml of dichloromethane (DCM) and sodium sulfate followed by 1 hour on a shaker table. The resulting extracts were decanted over sodium sulfate and reduced to less than 1 mL before extract cleanup using alumina column chromatography and HPLC-GPC fractionation to target the PAH analytes. Final extracts were spiked with recovery standards and brought to a final volume of 0.5 mL before submitting for analysis.

Sample extracts were analyzed on a Hewlett–Packard® Gas Chromatograph Mass Spectrometer (GCMS) Model 5890 in the Single-Ion Monitoring Mode (SIM) following modified EPA method 8270. Extracts were analyzed with a five-point calibration, along with a National Institute of Standards and Technology (NIST) standard reference material 1491 and a laboratory oil reference standard to verify instrument precision and accuracy.

Sample results are reported in units of ng/filter. Subsequent reporting limits, which are determined from the propagation of the lowest calibration standard through final volume and sample split corrections, are 25 ng/filter. Weights were taken and reported separately.

The calculation for determining the minimum reporting limit is as follows:

MRL = (Low Std * Split * PIV)/ Size

MRL = (25 ng/ml * 2 * 0.5)/(1 filter) = 25 ng/filter

where,

MRL	= Minimum Reporting Limit
Low Std	= Low Standard Concentration (25 ng/mL)
Split	= Sample Split Factor (2)
PIV	= Pre-Injection Volume (0.5 mL)
Size	= Sample Size (1 filter)

[1] Arthur D. Little. Environmental Monitoring and Analysis Unit. 1999. PAH Analysis of Particulate from Jet Engine Exhaust. Draft Technical Report prepared under SSC San Diego Contract N66001-96-D-0050. Determination of Contaminant Levels in Environmental Samples.

All samples have a split of 2 and a particle image velocity (PIV) of 1 mL. No further dilutions were performed.

A laboratory procedural blank was analyzed and cleaned within laboratory data quality objectives (DQOs). A laboratory control spike and control spike duplicate were analyzed with all results meeting the DQOs. All QC and field samples were spiked with surrogate standards to monitor extraction efficiency.

All QC and field sample surrogate recovery results were within DQOs, except samples T64 Approach (98D2765) and T64 military (98D2766). The d12-benzo[a]pyrene surrogate was not recovered for these two samples. Sample T64 Military also had recovery below acceptance criteria for d10-phenanthrene. Since no corresponding target analytes were present in these samples, and since the overall QC data were excellent, and the entire sample was consumed in the analysis, no corrective actions were taken. ADL has previously experienced poor recovery of d12-benzo[a]pyrene in low-level analyses and suspects that the analyte, and corresponding target analyte benzo[a]pyrene, may be affected, somewhat inconsistently, by active sites on the glass fibers.

Table 1. Blank spiked PAH analysis.

Field ID	Sample Blank	Procedural Blank	Blank Spike	Blank Spike Duplicate	North Slope Crude
Laboratory ID	98D2758	BV-S-64PB	BV-S-65BS	BV-S-66SD	BM91
Laboratory Batch	BO133	BO133	BO133	BO133	BO133
File	DZ6080.D	DZ6077.D	DZ6078.D	DZ6079.D	DZ6076.D
Sample Type	SAMP	QC	QC	QC	QC
Matrix	Glass fiber	Filter	Filter	Filter	Oil
Filter Weight	0.28g	NA	NA	NA	NA
Sample Size	1 filter	1 filter	1 filter	1 filter	5 mg
Weight Basis	Dry	Dry	Dry	NA	Oil
Associated Blank	BV-S-64PB	NA	BV-S-64PB	BV-S-64PB	NA
Field Date	08/25/98	NA	NA	NA	NA
Extract Date	09/02/98	09/02/98	09/02/98	09/02/98	NA
Analysis Date	09/16/98	09/16/98	09/16/98	09/16/98	09/16/98
Minimum Reporting Limit	25	25	25	25	5
Units	ng/filter	ng/filter	ng/filter	ng/filter	mg/kg
PAH					
Napthalene	14 JB	10 J	980	980	750
C1- Napthalenes	21J	ND	15 J	20 J	1700
C2- Napthalenes	ND	ND	ND	ND	2200
C3- Napthalenes	ND	ND	ND	ND	1800
C4- Napthalenes	ND	ND	ND	ND	1000
Acenaphthylene	ND	ND	880	890	ND
Acenaphthene	ND	ND	1000	1000	ND

Table 1. Blank spiked PAH analysis. (continued)

Field ID	Sample Blank	Procedural Blank	Blank Spike	Blank Spike Duplicate	North Slope Crude
Biphenyl	ND	ND	ND	ND	210
Fluorene	ND	ND	990	970	91
C1-Fluorene	ND	ND	ND	ND	240
C2-Fluorene	ND	ND	ND	ND	340
C3-Fluorene	ND	ND	ND	ND	400
Anthracene	ND	ND	760	800	ND
Phenanthrene	6.4 JB	7.8 J	790	820	270
C1-Phenanthrenes/anthracenes	ND	ND	ND	ND	590
C2-Phenanthrenes/anthracenes	ND	ND	ND	ND	700
C3-Phenanthrenes/anthracenes	ND	ND	ND	ND	530
C4-Phenanthrenes/anthracenes	ND	ND	ND	ND	380
Dibenzothiphene	ND	ND	6.9 J	6.9 J	230
C1- Dibenzothiphenes	ND	ND	ND	ND	520
C2- Dibenzothiphenes	ND	ND	ND	ND	700
C3- Dibenzothiphenes	ND	ND	ND	ND	680
Fluoranthene	2.7 JB	2.9J	910	930	ND
Pyrene	ND	ND	920	900	13
C1- Fluoranthenes/pyrenes	ND	ND	ND	ND	94
C2- Fluoranthenes/pyrenes	ND	ND	ND	ND	150
C3- Fluoranthenes/pyrenes	ND	ND	ND	ND	190
Benzo[a]anthracene	ND	ND	910	890	ND
Chrysene	ND	ND	880	910	50
C1- Chrysenes	ND	ND	ND	ND	91
C2- Chrysenes	ND	ND	ND	ND	120
C3- Chrysenes	ND	ND	ND	ND	110
C4- Chrysenes	ND	ND	ND	ND	77
Benzo[b]fluoranthrene	ND	ND	1400	1300	6.4
Benzo[k]fluoranthrene	ND	ND	1200	1000	ND
Benzo[e]pyrene	ND	ND	ND	ND	12
Benzo[a]pyrene	ND	ND	1200	1200	ND
Perylene	ND	ND	ND	ND	ND
Indeno[1,2,3,-c,d]pyrene	ND	ND	1400	1200	ND
Dibenzo[a,h]anthracene	ND	ND	1300	1200	ND
Benzo[g,h,I]perylene	ND	ND	1300	1300	3.8 J
Total Priority Pollutants	23	21	NA	NA	1200
Total PAH	44	21	NA	NA	14000
%%d8-Naphthalene	64	89	91	95	100
%%d10-Acenaphthene	70	85	87	88	101
%%d10-Phenanthrene	97	103	103	100	97
%%d12-Benzo[a]pyrene	62	63	68	68	108

3. RESULTS AND DISCUSSION

3.1 SCANNING ELECTRON MICROSCOPE ANALYSIS

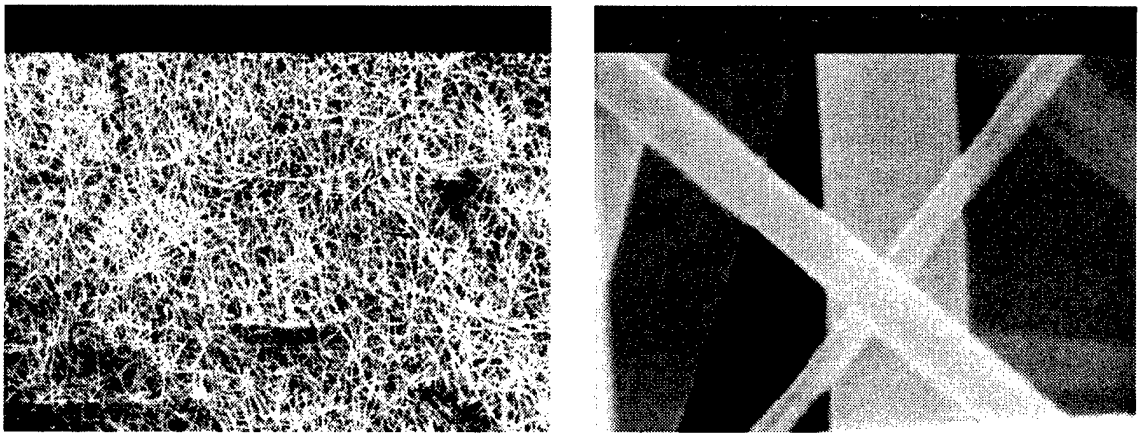
The T64 helicopter engine was tested at ground idle, 75% of normal, normal, and military. To make comparisons with the F118 and F404 aircraft, 75% normal was equated to approach, and normal was considered intermediate. The T58 engine was tested at 65, 80, 90, and 100% ratings. These were equated to idle, approach, intermediate, and miltary. Only the F404 engine was tested in afterburner mode.

Table 2 summarizes the observed particles and size ranges of discrete (not conglomerate) particles.

Table 2. Summary of observed particles and size range of discrete particles.

	F118 Engine	F404 Engine	T64 Engine	T58 Engine
Idle	30 to 70 nm	70 to 100 nm	70 nm	22 to 65 nm
	Single layer, little aggregation	Single layer, little aggregation	Cake was less thick than approach	Some aggregate particles
Approach	30 to 70 nm	70 to 100 nm	120 nm	22 to 87 nm
	Very sparse, discrete	Very sparse, discrete	Thick cake—difficult to size particles	Increasing aggregation of particles
Intermediate	50 to 70 nm	50 to 100 nm	70 to 100 nm	22 to 87 nm
	Sparse, discrete, a few conglomerates present	Aggregation. particles attracted more to each other than to filter	Thick cake of particles on filter	Aggregate—start to see larger number of particles and larger clumps of particles
Military	50 to 70 nm	50 to 100 nm	70 to 100 nm	22 to 87 nm
	Some aggregation in chainlike formations; conglomerates up to 15 μm	Aggregation. chains and clumps of particles; fewer particles than intermediate mode.	Thick cake of particles on filter	Aggregation, many chains and clumps of particles up to 10 μm
Afterburner	N/A	50 to 70 nm	N/A	N/A
		Large conglomerates up to 40 μm; particles tend to aggregate		

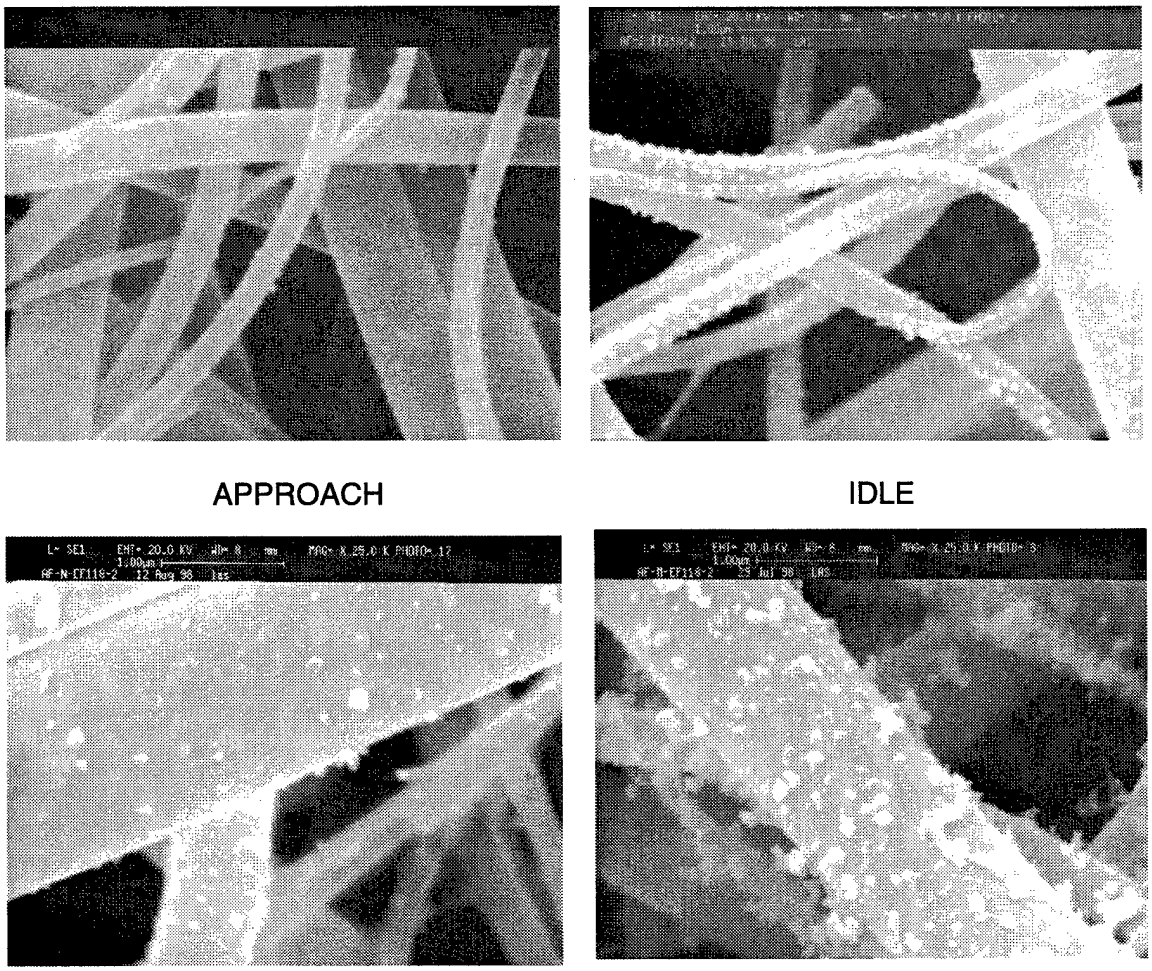
A sample blank filter showed no contamination. Figure 5 verifies that the fibers were clean and free of particles.



100X MAGNIFICATION 25000X MAGNIFICATION

Figure 5. Sample blank glass fiber filters.

Figures 6 and 7 are micrographs of the filter particles from the F118 and F404 engines at 25,000 times magnification.



APPROACH IDLE

INTERMEDIATE MILITARY

Figure 6. F118 engine (four modes at 25,000X magnification).

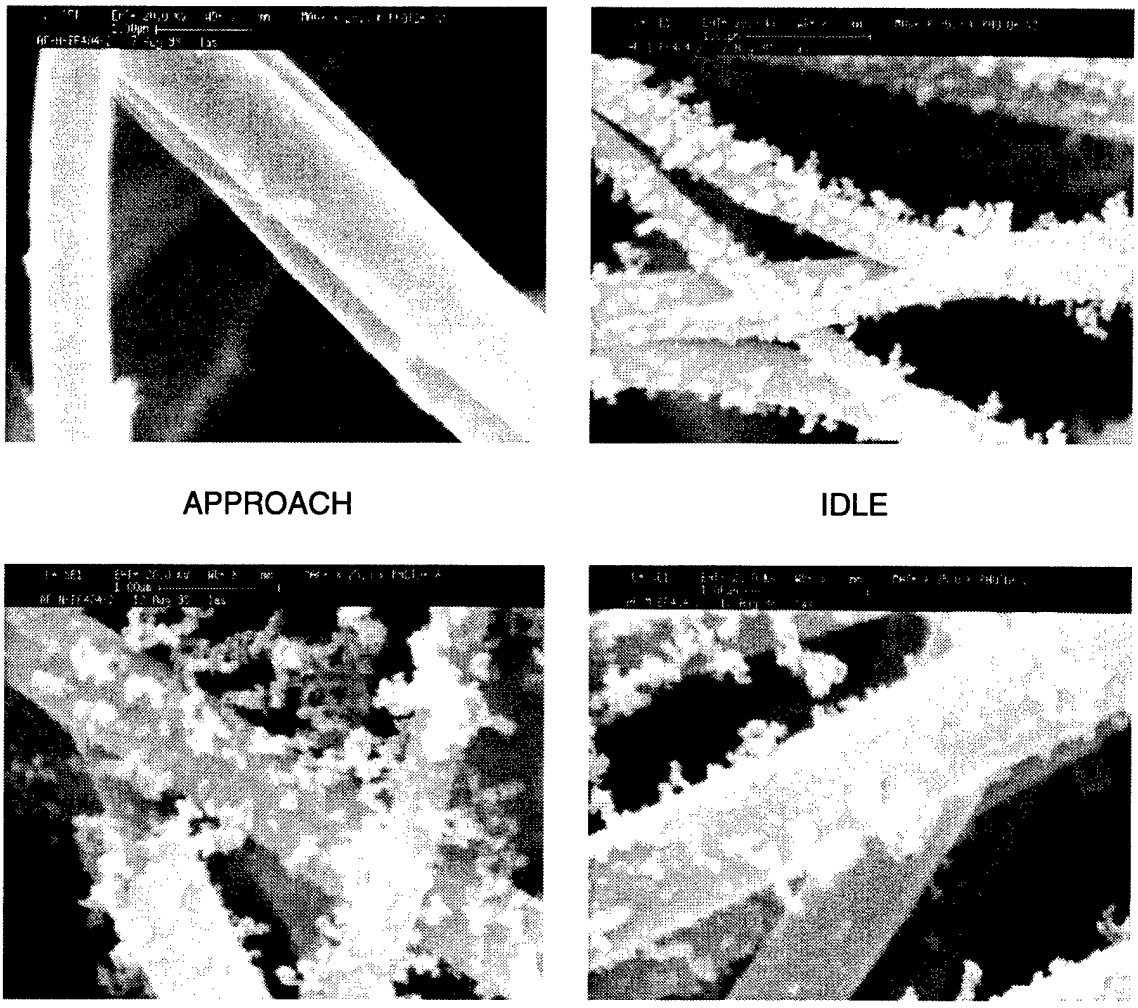
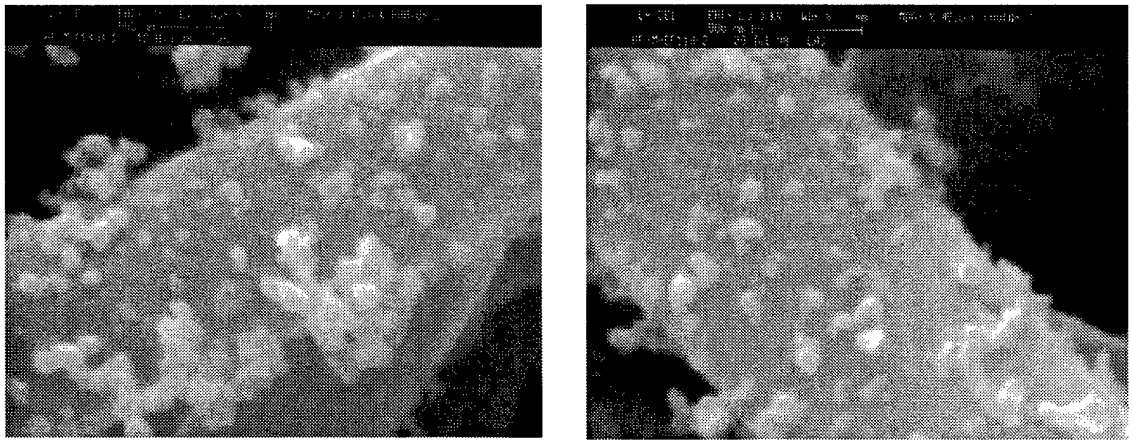


Figure 7. F404 engine (four modes at 25,000X magnification).

Figure 8 is the F118 and F404 military-made emissions at 45,000X magnification. F404 particulates appear slightly larger and denser.



F404 PARTICULATES F118 PARTICULATES

Figure 8. F404 and F118 particle size (45,000X magnification).

The T64 filters were so laden with sample, it was difficult to discern individual particles. Future particulate testing should allow shorter run times for this engine. All T64 samples had a sooty, black, cake-like layer of particulates (Figures 3 and 9). Differences in particle density between the engine modes could not be determined due to the thick layers of particles. There were aggregate 1- to 20-μm-diameter "clumps" of particles on the surface of the particle layer. It is not known whether these "clumps" were emitted from the engine, or whether the particles tended to attract each other on the filter. The T64 and T58 engines had many times the filterable particulate emissions of the newer F118 and F404 engines.

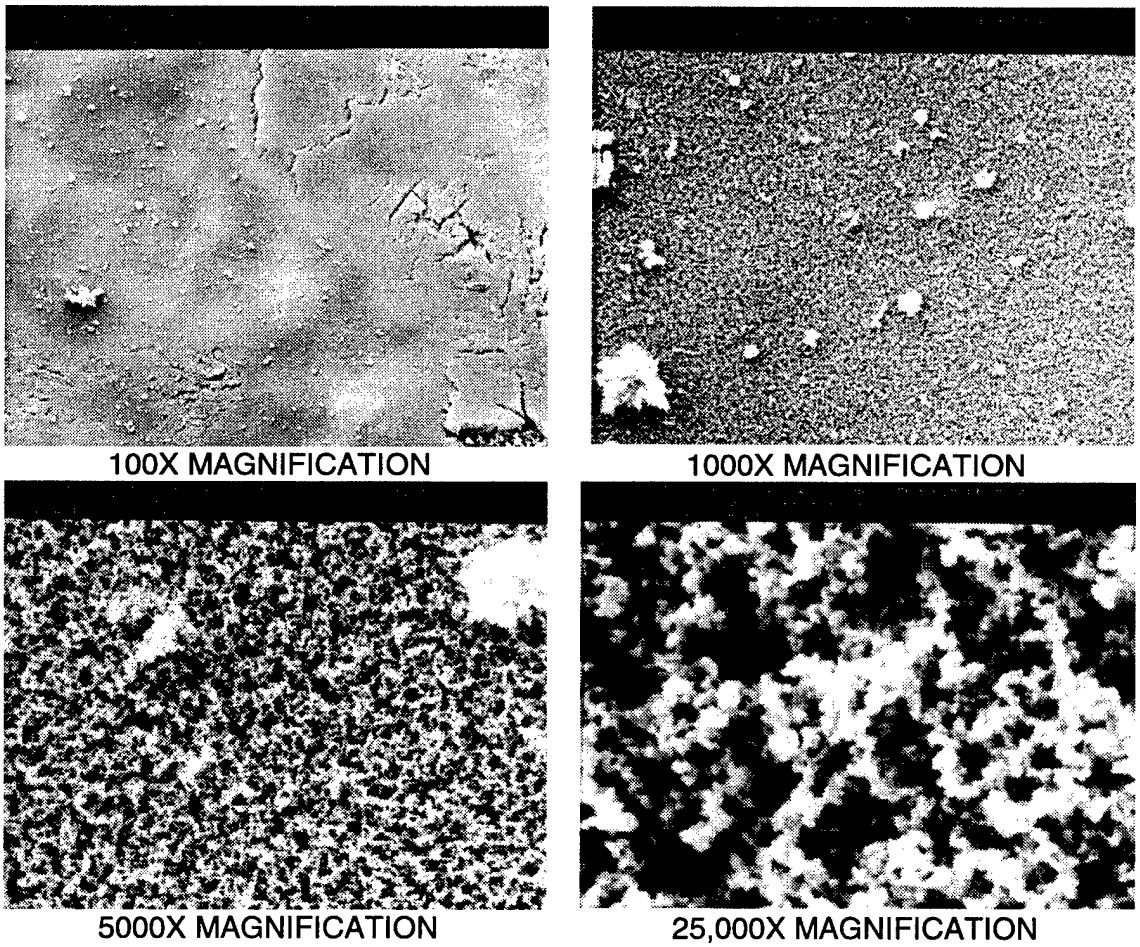
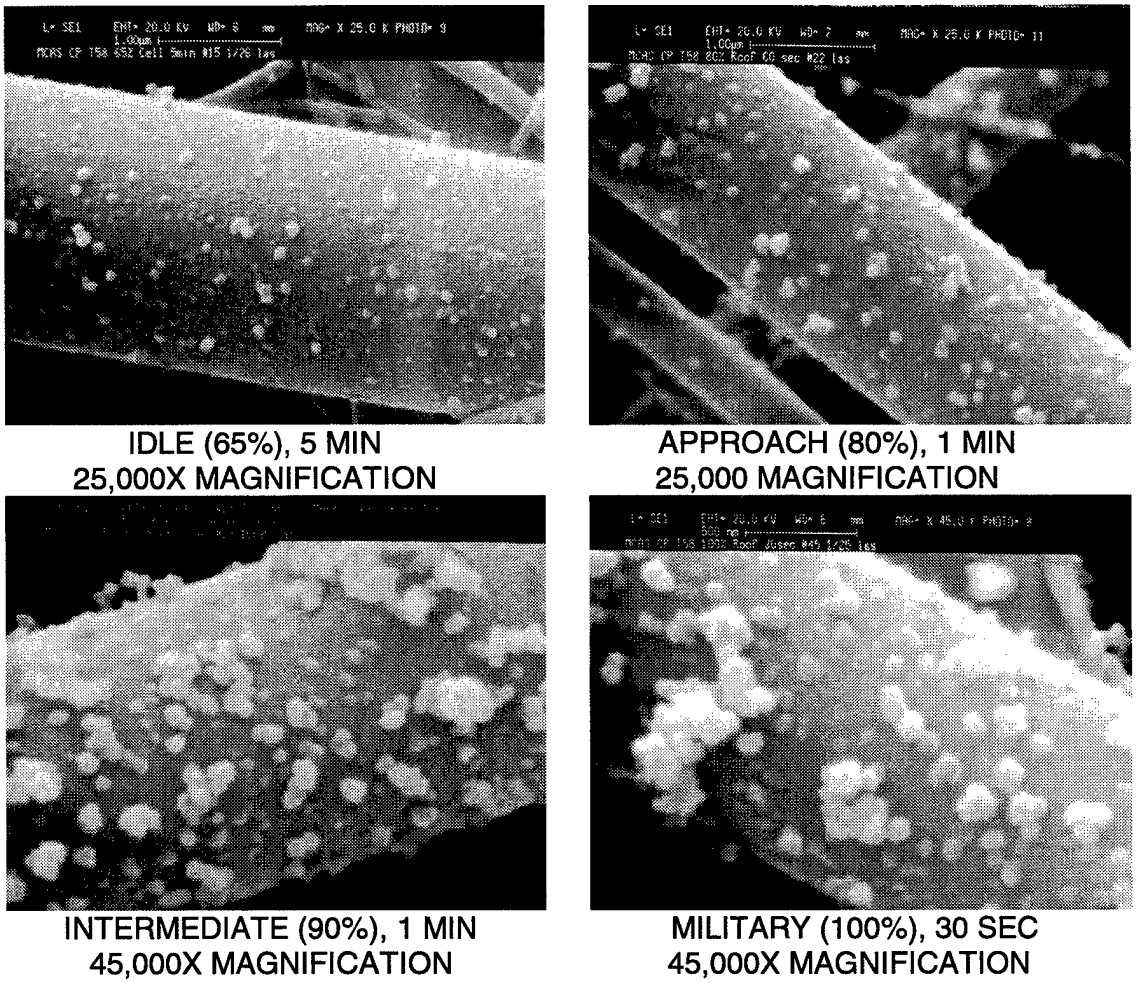


Figure 9. T64 approach mode.

T58 filters were sampled for varying times (Figure 10) to allow for better viewing with the SEM. The number of discrete particles emitted, and the number and size of the agglomerate particles increased as the engine speed increased. More particles emitted by the engine results in more and larger agglomerate particles due to the higher probability of small particles hitting each other and sticking together. These increases correlate well with the fuel usage amounts in Table 3.



IDLE (65%), 5 MIN
25,000X MAGNIFICATION

APPROACH (80%), 1 MIN
25,000 MAGNIFICATION

INTERMEDIATE (90%), 1 MIN
45,000X MAGNIFICATION

MILITARY (100%), 30 SEC
45,000X MAGNIFICATION

Figure 10. T58 particulates in four engine modes.

Table 3. Fuel usage (pounds/hour) during sample collection.

	F118 Engine[2]	F404 Engine[2]	T64 Engine[2]	T58 Engine[3]
Idle	1097	685	298	185
Approach	3773	3111	941	308
Intermediate	6350	6464	1698	550
Military	10887	7739	1848	959
Afterburner	N/A	15852	N/A	N/A

Fuel usage per hour was much higher for the newer jet engines than the helicopter engines, but the helicopter engines emitted much more particulate.

Teflon® filters were used for some of the T58 sample runs. However, the Teflon® filters were difficult to analyze on the SEM and could not be used during higher revolutions per minute (rpm) engine runs. The composition of the Teflon® filters made it difficult to discern individual particles from the filter background. Intermediate and military engine modes created exhaust temperatures high enough to melt the Teflon® filters.

3.2 METALS ANALYSIS: EDX

Particles much larger than the discrete 22- to 120-nm sizes were located on the filters. Some of the particles were aggregates—amorphous clumps or chains made of smaller particles. Other large particles appeared solid and made up of differing materials. These larger particles were located by scanning the filter samples with the SEM, and then when 'aiming' at the particle, using the EDX to detect the metals spectrum for that particle. This method is not a practical one for determining total metal content for the sample, but does give insight into the chemical makeup of some of the particles present.

Silicon alone was detected when blank filters and filters with 'typical' particles of 22 to 120 nm (or aggregates of these discrete particles) were x-rayed. These filters were x-rayed from varying distances and the result was always a single silicon peak. Typical particles are most probably all carbon. Carbon is below the low end element (sodium) on the periodic table, and so is not detected.

There were many different resultant spectra from the x-ray of the larger particles. Larger particles ranged from 1 to 40 microns. Some had discrete planar edges and others were amorphous (Figure 11). Some had discrete planar edges and others were amorphous (Figure 11). Solid, large particle spectra appeared primarily fuel-based (sulfur) and/or metallic (iron, chromium, nickel).

---

[2] Environmental Quality Management, Inc. and Roy F. Weston, Inc. 1998. Aircraft Engine and Auxiliary Power Unit Emissions Testing Report. Draft Scientific and Technical Report prepared under the Air Force Occupational and Environmental Health Assessments Contract F41624-95-D-9019, vols. 1–4.

[3] Pacific Environmental Services, Inc. 1999. Marine Corps Air Station Cherry Point Field Data Sheets. Prepared under contract to the U.S. Navy Aircraft Environmental Support Office.

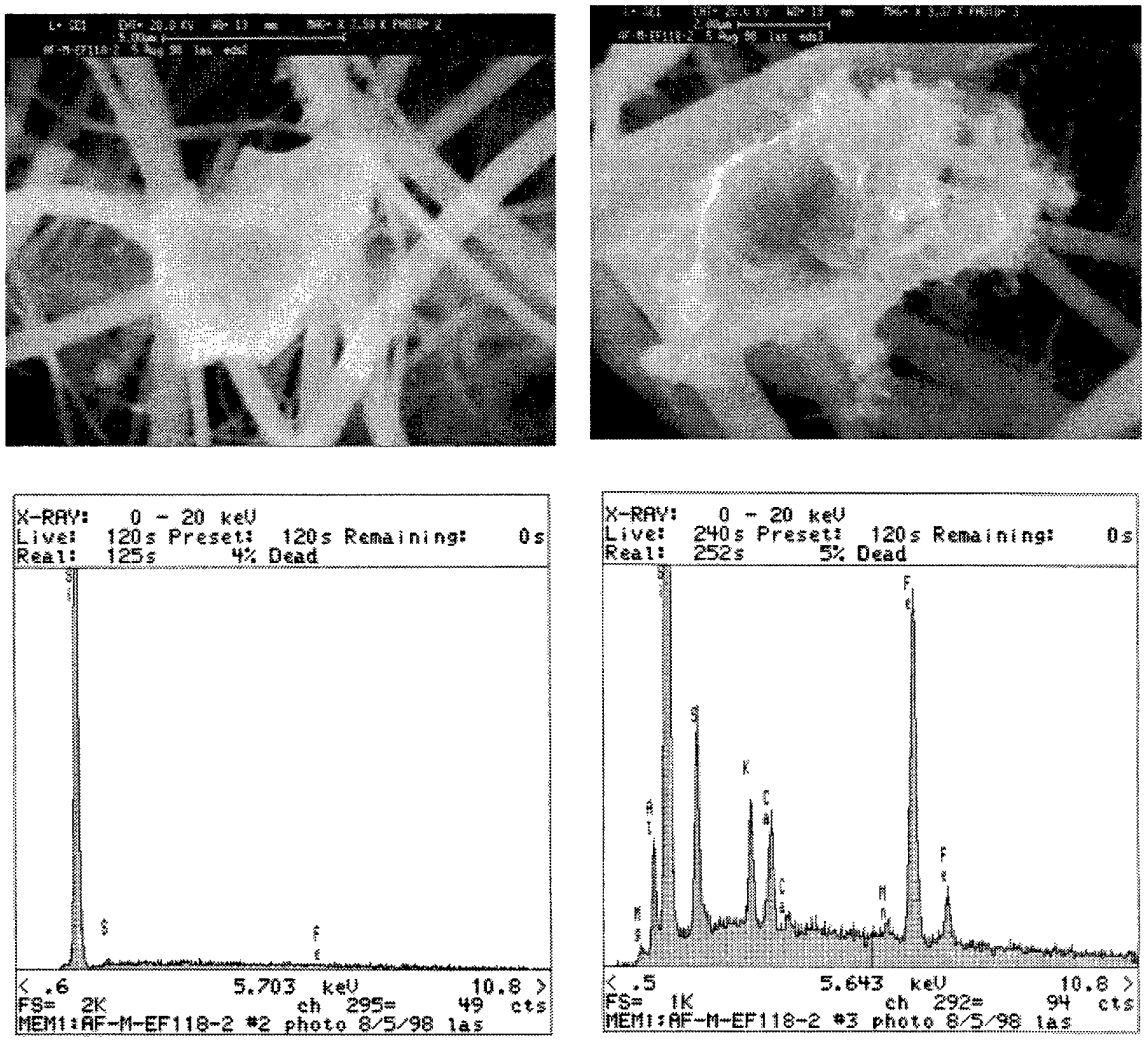
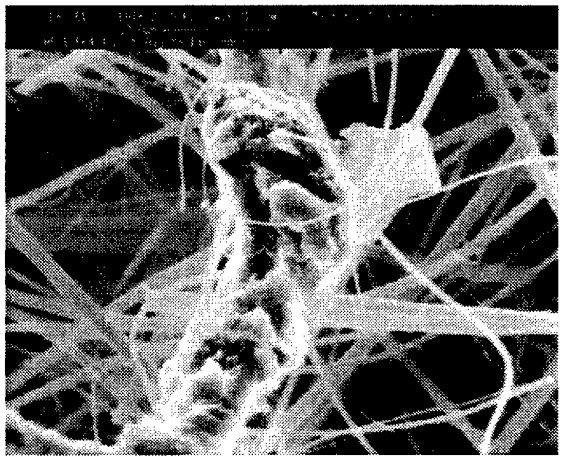


Figure 11. F118 military mode x-ray analysis.

The largest particle (Figure 12) located was on the F404 afterburner mode filter. This conglomerate particle was approximately 40 microns in length, and was composed of aluminum, sulfur, chlorine, potassium, calcium, barium, titanium, chromium, iron, and zinc in addition to the silicon background. This conglomerate is probably composed of engine material or a coating on the blades that breaks free when the engine is run at the high afterburner temperatures and rpms.



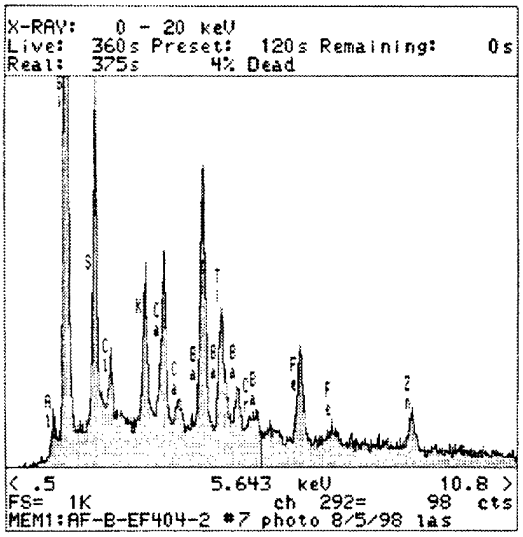


Figure 12. F404 afterburner mode x-ray analysis.

3.3 PAH ANALYSIS

A. D. Little performed the PAH analysis[4]. Tables 4 through 6 present measured PAHs for the three different engines. Results found below the minimum reporting limit are qualified as estimated (J). Results found in samples corresponding to a result found in the laboratory procedural blank are qualified with a (B) when the result in the sample is less than five times the result found in the procedural blank. Note that the results found in the blank are well below the minimum reporting limit. Results not detected are qualified as (ND).

Except for three values measured in the idle mode, the detected PAHs for the F118 and F404 were below MDLs. Measurements of this low magnitude may confirm the presence of the compounds, but are not reliable for quantitative purposes.

The F118 engine had few PAHs detected. Naphthalene was measured above MDLs in idle mode. Naphthalene is the lightest of the PAHs. It biodegrades readily and does not have a high carcinogenic potential. The F404 engine had two measurable PAHs in idle mode, indeno[1,2,3,-c,d]pyrene and benzo[g,h,i]perylene. These PAHs are two of the heaviest; they do not biodegrade readily but their carcinogenic potential is low compared to other heavy PAH compounds.

Benzo[a]pyrene (BAP) is the most studied carcinogenic PAH, and is traditionally used as an indicator of overall PAH content (Bjϕseth, 1983). No BAP was detected in the F118 samples. BAP was detected in the F404 and T64 idle mode samples only, at a value below the MDL. This result needs to be verified in future tests with other filters; BAP recovery was poor for the spiked samples. A. D. Little believes that BAP recovery is affected by active sites on the glass fiber filters (see footnote 1).

The T64 engine had many more PAHs present in the samples than the newer engines. Significant amounts of naphthalene were measured in the approach and military modes. Biphenyl, phenanthrene, and dibenzothiohene (lighter molecular weight PAHs) were detected above the MDLs. Like the F404 engine, indeno[1,2,3,-c,d]pyrene and benzo[g,h,i]perylene were measured above the MDLs in the idle mode.

[4] Arthur D. Little. PAH Analysis of Particulate from Jet Engine Exhaust. Draft.

Table 4. F118 engine PAH analysis.

Field ID	F118 Idle	F118 Military	Sample Blank
Laboratory ID	98D2758	98D2760	98D2758
Laboratory Batch	BO133	B0133	B0133
File	DZ6080.D	DZ6082.D	DZ6080.D
Sample Type	Samp	Samp	Samp
Matrix	Glass fiber filter	Glass fiber filter	Glass fiber filter
Filter Weight	0.20 g	0.25 g	0.28 g
Sample Size	1 filter	1 filter	1 filter
Weight Basis	Dry	Dry	Dry
Associated Blank	BV-S-64PB	BV-S-64PB	BV-S-64PB
Field Date	08/25/98	08/25/98	08/25/98
Extract Date	09/02/98	09/02/98	09/02/98
Analysis Date	09/16/98	09/16/98	09/16/98
Minimum Reporting Limit	25	25	25
Units	ng/filter	ng/filter	ngfFilter
PAH			
Napthalene	19 JB	23 JB	14JB
C1- Napthalenes	36	22 J	21J
C2- Napthalenes	ND	ND	ND
C3- Napthalenes	ND	ND	ND
C4- Napthalenes	ND	ND	ND
Acenaphthylene	ND	ND	ND
Acenaphthene	ND	ND	ND
Biphenyl	ND	ND	ND
Fluorene	ND	ND	ND
C1-Fluorene	ND	ND	ND
C2-Fluorene	ND	ND	ND
C3-Fluorene	ND	ND	ND
Anthracene	ND	ND	ND
Phenanthrene	16 JB	17 JB	6.4 JB
C1- Phenanthrenes/anthracenes	ND	ND	ND
C2- Phenanthrenes/anthracenes	ND	ND	ND
C3- Phenanthrenes/anthracenes	ND	ND	ND
C4- Phenanthrenes/anthracenes	ND	ND	ND
Dibenzothiphene	ND	ND	ND
C1- Dibenzothiphenes	ND	ND	ND
C2- Dibenzothiphenes	ND	ND	ND
C3- Dibenzothiphenes	ND	ND	ND
Fluoranthene	5.6 JB	4.9 JB	2.7 JB
Pyrene	ND	4.0 J	ND
C1- Fluoranthenes/pyrenes	ND	ND	ND
C2- Fluoranthenes/pyrenes	ND	ND	ND
C3- Fluoranthenes/pyrenes	ND	ND	ND
Benzo[a]anthracene	ND	ND	ND
Chrysene	ND	ND	ND
C1- Chrysenes	ND	ND	ND
C2- Chrysenes	ND	ND	ND
C3- Chrysenes	ND	ND	ND
C4- Chrysenes	ND	ND	ND

Table 4. F118 engine PAH analysis. (continued)

Field ID	F118 Idle	F118 Military	Sample Blank
Benzo[b]fluoranthrene	ND	ND	ND
Benzo[k]fluoranthrene	ND	ND	ND
Benzo[e]pyrene	ND	ND	ND
Benzo[a]pyrene	ND	ND	ND
Perylene	ND	ND	ND
Indeno[1,2,3,-c,d]pyrene	ND	ND	ND
Dibenzo[a,h]anthracene	ND	ND	ND
Benzo[g,h,I]perylene	ND	ND	ND
Total Priority Pollutants	41	49	23
Total PAH	77	71	44
%%d8-Naphthalene	44	49	64
%%d10-Acenaphthene	57	66	70
%%d10-Phenanthrene	81	91	97
%%d12-Benzo[a]pyrene	46	49	62

Table 5. F404 engine PAH analysis.

Field ID	F404 After-Burner	F404 Idle	F404 Military	F404 Intermediate	Sample Blank
Laboratory ID	98D2761	98D2762	98D2763	98D2764	98D2758
Laboratory Batch	BO133	BO133	BO133	BO133	BO133
File	DZ6083.D	DZ6084.D	DZ6085.D	DZ6086.D	DZ6080.D
Sample Type	SAMP	SAMP	SAMP	SAMP	SAMP
Matrix	Glass fiber	Glass fiber	Glass fiber	Glass fiber	Glass fiber
Filter Weight	0.27 g	0.27 g	0.29 g	0.24 g	0.28 g
Sample Size	1 filter	1 filter	1 filter	1 filter	5 mg
Weight Basis	Dry	Dry	Dry	NA	oil
Associated Blank	BV-S-64PB	BV-S64PB	BV-S-64PB	BV-S-64PB	BV-S64PB
Field Date	08/25/98	08/25/98	08/25/98	08/25/98	08/25/98
Extract Date	09/02/98	09/02/98	09/02/98	09/02/98	NA
Analysis Date	09/16/98	09/16/98	09/16/98	09/16/98	09/16/98
Minimum Reporting Limit	25	25	25	25	5
Units	ng/filter	ng/filter	ng/filter	ng/filter	mg/kg
PAH					
Napthalene	15 JB	18 JB	16 JB	13 JB	14 JB
C1- Napthalenes	23 J	ND	18 J	ND	21 J
C2- Napthalenes	ND	ND	ND	ND	ND
C3- Napthalenes	ND	ND	ND	ND	ND
C4- Napthalenes	ND	ND	ND	ND	ND
Acenaphthylene	ND	ND	ND	ND	ND
Acenaphthene	ND	ND	ND	ND	ND
Biphenyl	ND	ND	ND	ND	ND
Fluorene	ND	ND	ND	ND	ND
C1-Fluorene	ND	ND	ND	ND	ND
C2-Fluorene	ND	ND	ND	ND	ND
C3-Fluorene	ND	ND	ND	ND	ND
Anthracene	ND	ND	ND	ND	ND
Phenanthrene	15 JB	8.7 JB	24 JB	27 B	6.4 JB
C1-Phenanthrenes/anthracenes	15 JB	ND	16 J	16 J	ND
C2-Phenanthrenes/anthracenes	ND	ND	ND	ND	ND
C3-Phenanthrenes/anthracenes	ND	ND	ND	ND	ND
C4-Phenanthrenes/anthracenes	ND	ND	ND	ND	ND
Dibenzothiphene	3.5 J	ND	3.8 J	3.9 J	ND
C1- Dibenzothiphenes	14 J	ND	ND	ND	ND
C2- Dibenzothiphenes	ND	ND	ND	ND	ND
C3- Dibenzothiphenes	ND	ND	ND	ND	ND
Fluoranthene	9.4 JB	7.8 JB	12 JB	8.6 JB	2.7 JB
Pyrene	5.8 J	5.6 J	5.5 J	5.5 J	ND
C1- Fluoranthenes/pyrenes	ND	ND	ND	ND	ND
C2- Fluoranthenes/pyrenes	ND	ND	ND	ND	ND
C3- Fluoranthenes/pyrenes	ND	ND	ND	ND	ND

Table 5. F404 engine PAH analysis. (continued)

Field ID	F404 After-Burner	F404 Idle	F404 Military	F404 Intermediate	Sample Blank
Benzo[a]anthracene	ND	ND	ND	ND	ND
Chrysene	ND	ND	ND	ND	ND
C1- Chrysenes	ND	ND	ND	ND	ND
C2- Chrysenes	ND	ND	ND	ND	ND
C3- Chrysenes	ND	ND	ND	ND	ND
C4- Chrysenes	ND	ND	ND	ND	ND
Benzo[b]fluoranthrene	ND	12 J	ND	ND	ND
Benzo[k]fluoranthrene	ND	ND	ND	ND	ND
Benzo[e]pyrene	ND	11 J	ND	ND	ND
Benzo[a]pyrene	ND	7.8 J	ND	ND	ND
Perylene	ND	ND	ND	ND	ND
Indeno[1,2,3,-c,d]pyrene	ND	58	ND	ND	ND
Dibenzo[a,h]anthracene	ND	ND	ND	ND	ND
Benzo[g,h,I]perylene	ND	120	ND	ND	ND
Total Priority Pollutants	45	240	58	54	23
Total PAH	100	250	95	74	44
%%d8-Naphthalene	75	41	78	58	64
%%d10-Acenaphthene	82	52	78	65	70
%%d10-Phenanthrene	103	79	92	91	97
%%d12-Benzo[a]pyrene	61	52	44	48	62

Table 6. T64 engine PAH analysis.

Field ID	T64 Approach	T64 Idle	T64 Military	Sample Blank
Laboratory ID	98D2765	98D2767	98D2766	98D2758
Laboratory Batch	BO133	BO133	BO133	BO133
File	DZ6088.D	DZ6090.D	DZ6089.D	DZ6080.D
Sample Type	Samp	Samp	Samp	Samp
Matrix	Glass fiber	Glass fiber	Glass fiber	Glass fiber
Filter Weight	0.26 g	0.26 g	0.28 g	0.28 g
Sample Size	1 filter	1 filter	1 filter	1 filter
Weight Basis	Dry	Dry	Dry	NA
Associated Blank	BV-S-64PB	NA	BV-S-64PB	BV-S-64PB
Field Date	08/25/98	08/25/98	08/25/98	08/25/98
Extract Date	09/02/98	09/02/98	09/02/98	09/02/98
Analysis Date	09/16/98	09/16/98	09/16/98	09/16/98
Minimum Reporting Limit	25	25	25	25
Units	ng/filter	ng/filter	ng/filter	ng/filter
Naphthalene	510	23 JB	660	14 JB
C1- Napthalenes	380	38	400	21
C2- Napthalenes	330	ND	330	ND
C3- Napthalenes	290	ND	200	ND
C4- Napthalenes	310	ND	ND	ND
Acenaphthylene	7.7 J	ND	7.5 J	ND
Acenaphthene	18 J	ND	17 J	ND
Biphenyl	74	ND	60	ND
Fluorene	ND	ND	ND	ND
C1-Fluorene	ND	ND	ND	ND
C2-Fluorene	ND	ND	ND	ND
C3-Fluorene	ND	ND	ND	ND
Anthracene	ND	ND	ND	ND
Phenanthrene	78	22 JB	44	6.4 JB
C1- Phenanthrenes/anthracenes	30	16 J	ND	ND
C2- Phenanthrenes/anthracenes	ND	ND	ND	ND
C3- Phenanthrenes/anthracenes	ND	ND	ND	ND
C4- Phenanthrenes/anthracenes	ND	ND	ND	ND
Dibenzothiphene	18 J	ND	14 J	ND
C1- Dibenzothiphenes	29	ND	ND	ND
C2- Dibenzothiphenes	ND	ND	ND	ND
C3- Dibenzothiphenes	ND	ND	ND	ND
Fluoranthene	11 JB	14 J	ND	2.7 JB
Pyrene	ND	12 J	ND	ND
C1- Fluoranthenes/pyrenes	ND	ND	ND	ND
C2- Fluoranthenes/pyrenes	ND	ND	ND	ND
C3- Fluoranthenes/pyrenes	ND	ND	ND	ND
Benzo[a]anthracene	ND	ND	ND	ND
Chrysene	ND	ND	ND	ND
C1- Chrysenes	ND	ND	ND	ND
C2- Chrysenes	ND	ND	ND	ND
C3- Chrysenes	ND	ND	ND	ND
C4- Chrysenes	ND	ND	ND	ND
Benzo[b]fluoranthrene	ND	19 J	ND	ND
Benzo[k]fluoranthrene	ND	ND	ND	ND

Table 6. T64 engine PAH analysis. (continued)

Field ID	T64 Approach	T64 Idle	T64 Military	Sample Blank
Benzo[e]pyrene	ND	12 J	ND	ND
Benzo[a]pyrene	ND	15 J	ND	ND
Perylene	ND	ND	ND	ND
Indeno[1,2,3,-c,d]pyrene	ND	59	ND	ND
Dibenzo[a,h]anthracene	ND	ND	ND	ND
Benzo[g,h,I]perylene	ND	110	ND	ND
Total Priority Pollutants	620	270	730	23
Total PAH	2100	340	1700	44
%%d8-Naphthalene	77	71	83	64
%%d10-Acenaphthene	77	70	83	70
%%d10-Phenanthrene	61	90	39	97
%%d12-Benzo[a]pyrene	ND	51	ND	62

Limited information is available on the concentration of PAHs in aircraft exhaust particulates. Figures 13 and 14 compare PAHs detected in the particulate samples to other aircraft engine tests that measured PAHs in the exhaust air. The lower three data sets on each chart are from the particulate analysis. Excepting the EPA data, none of the heavier molecular weight PAHs were present in the approach, intermediate, military, and afterburner modes of the three engines. Those compounds were present only in the idle engine mode.

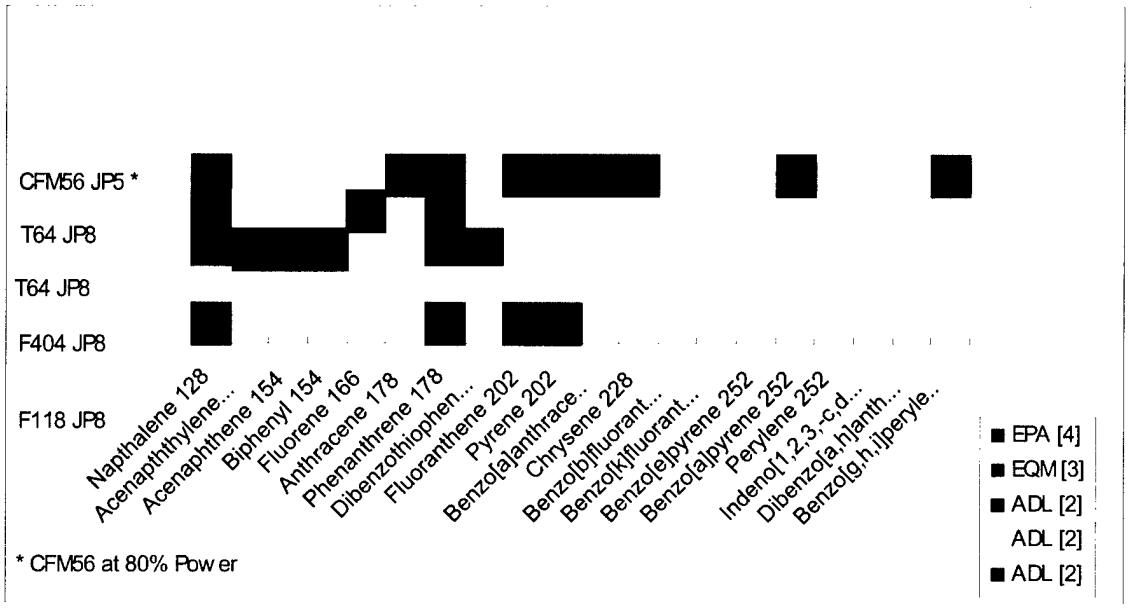


Figure 13. PAHs present in military mode.

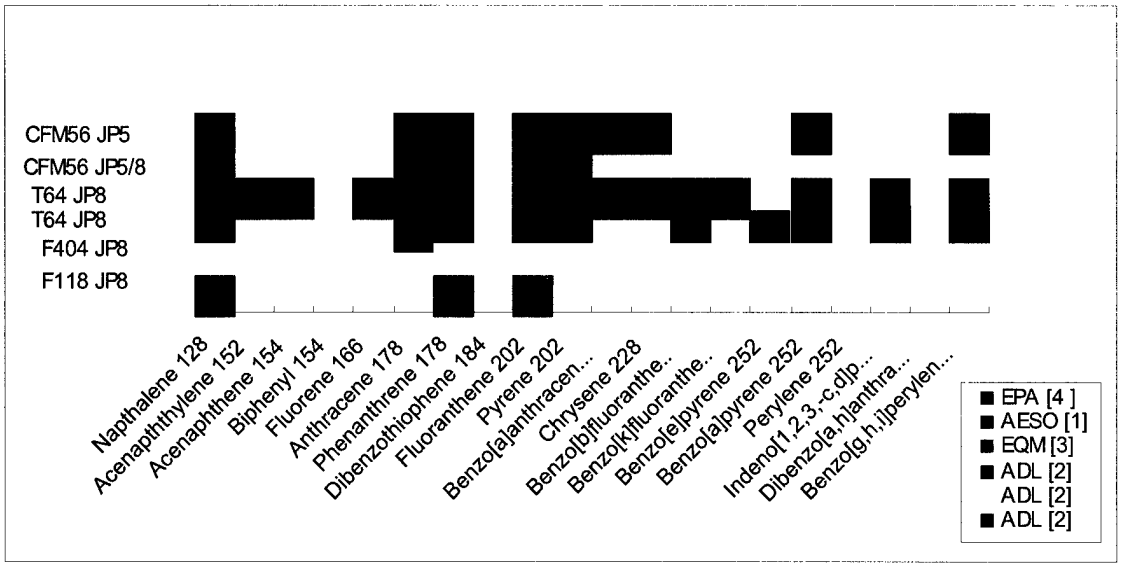


Figure 14. PAHs present in idle mode.

NOTE: Data for Figures 13 and 14 were obtained from the following sources:

1. Aircraft Environmental Support Office (AESO). 1998. Toxic Organic Contaminants in the Exhaust of Gas Turbine Engines: Draft Report. AESO Report No. 12-90 Rev B (Oct). Naval Aviation Depot, Naval Air Station, San Diego, CA.

2. Arthur D. Little Environmental Monitoring and Analysis Unit. 1999. PAH Analysis of Particulate from Jet Engine Exhaust. Draft Technical Report prepared under SSC San Diego Contract N66001-96-D-0050. Determination of Contaminant Levels in Environmental Samples.

3. Environmental Quality Management, Inc. and Roy F. Weston, Inc. 1998. Aircraft Engine and Auxiliary Power Unit Emissions Testing Report. Draft Scientific and Technical Report prepared under the Air Force Occupational and Environmental Health Assessments Contract F41624-95-D-9019, vols 1-

4. U.S. Environmental Protection Agency. 1997. Memorandum from Rich Cook, Assessment and Modeling Division to Joe Touma, Office of Air Quality Planning and Standards, Subject: PAH/VOC Emission Fractions for Aircraft. National Vehicle and Fuel Emissions Laboratory, Ann Arbor, MI.

4. CONCLUSIONS and RECOMMENDATIONS

Jet engine exhaust particulates from a JP8 or JP5 fueled engine range were measured from 22 to 120 nanometers. Larger, sparsely located particles existed in the 1- to 40-micron range in the intermediate, military, and afterburner modes. It is theorized that these larger particles form a buildup on the engine and are dislodged at higher engine rpms and temperatures. Particulates from the T64 and T58 helicopter engines were much denser than those from the F118 and F404 engines. The helicopter engines are a 1970s design; the F404 and F118 engines were designed in the 1980s and incorporated changes to lessen visible exhaust emissions. The 1-hour sample time used for the T64 filters was designed for gravimetric analysis, which resulted in a thick layer of particulate on the filter. This layer was too thick to discern individual particles. Time must be decreased and varied according to engine speed when sampling older engines. This method was used with the T58 engine, and it enabled SEM analysis of individual particles.

Submicron particle sizing and counting requires sophisticated instrumentation. These instruments have concise size and concentration ranges where they can measure accurately. Larger particles are detected with different test apparatus than submicron particles. Real-time particulate sizing and counting will require splitting an exhaust stream and sampling one portion of it for submicron particles and the other for larger particles. The splitting of the size ranges will also enable better correlation of particulate analysis results (metals, PAHs, and carbon fraction) to submicron versus larger particles.

Metals analysis was qualitative only. EDX testing indicated that a significant number of metals were present in the larger nonhomogeneous particles. In the future, use of an impactor with a 1-micron cutpoint would allow for better characterization of the submicron particles. The impactor would also enable separate gravimetric and metals analysis of the particles greater than 1 micron.

Except for three compounds measured in the idle mode, all of the detected PAHs for the F118 and F404 were below MDLs. Measurements of this low magnitude may confirm the presence of the compounds, but are not reliable for quantitative purposes.

Idle mode particulate samples contained many more PAH compounds than any of the other engine modes. Generally, these were the heavier molecular weight compounds. Any measure to lessen the amount of time an aircraft spends idling would lessen particulate and PAH emissions. Many airports are currently reviewing Best Management Practices (BMPs) to minimize environmental contaminants and are including practices to lessen aircraft idle time.

Filters from the F118 and F404 engines had very low loading that may have been caused by sampling at the edge of the stack matrix. Samples collected from a different stack location or for a longer sampling period may provide more information about the PAHs and the metals present.

5. REFERENCES

Aircraft Environmental Support Office (AESO). 1990. "Summary Tables of Gaseous and Particulate Emissions from Aircraft Engines." AESO Report No. 6-90 (Jun). San Diego, CA.

Bjørseth, A. (Editor). 1983. *Handbook of Polycyclic Aromatic Hydrocarbons.* Marcel Dekker, Inc., New York, NY.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-01-0188

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
03–2002	Technical	

4. TITLE AND SUBTITLE
CHARACTERIZATION OF JET ENGINE EXHAUST PARTICULATES FOR THE F404, F118, T64, AND T58 AIRCRAFT ENGINES

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
O&M

6. AUTHORS
L. A. Shumway

5d. PROJECT NUMBER
SV15

5e. TASK NUMBER

5f. WORK UNIT NUMBER
ME83

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SSC San Diego
San Diego, CA 92152–5001

8. PERFORMING ORGANIZATION REPORT NUMBER
TR 1881

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Aircraft Environmental Support Office
Naval Air Station North Island
San Diego, CA 92135

10. SPONSOR/MONITOR'S ACRONYM(S)
AESO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
This is the work of the United States Government and therefore is not copyrighted. This work may be copied and disseminated without restriction. Many SSC San Diego public release documents are available in electronic format at www.spawar.navy.mil/sandiego/.

14. ABSTRACT
In this study, jet engine exhaust particulate samples collected from four military aircraft engines were analyzed for particle morphology. Particulate emissions from three of the engines were also analyzed for polycyclic aromatic hydrocarbons (PAHs). The F118, F404, T58, and T64 engines were tested in four modes: approach, idle, military, and intermediate. The F404 engine was also tested in afterburner mode. Conclusions and recommendations are made based on the test results.

15. SUBJECT TERMS
Mission Area: Environmental Sciences
jet fuels
polycyclic aromatic hydrocarbons
particle morphology
particulate emissions

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			L. A. Shumway
U	U	U	UU	48	19B. TELEPHONE NUMBER *(Include area code)* (619) 553–6171

INITIAL DISTRIBUTION

D0012	Patent Counsel	(1)
D0271	Archive/Stock	(6)
D0274	Library	(2)
D027	M. E. Cathcart	(1)
D0271	E. R. Ratliff	(1)
D0271	D. Richter	(1)

Defense Technical Information Center
Fort Belvoir, VA 22060–6218 (4)

SSC San Diego Liaison Office
C/O PEO-SCS
Arlington, VA 22202–4804

Center for Naval Analyses
Alexandria, VA 22311–1850

Office of Naval Research
ATTN: NARDIC (Code 362)
Arlington, VA 22217–5660

Government-Industry Data Exchange
Program Operations Center
Corona, CA 91718–8000

Leslee Shumway
Washington, DC 20594 (8)

Thomas Delmer, Ph.D.
La Jolla, CA 92037

Naval Aviation Depot
Naval Air Station North Island
San Diego, CA 92135-7058 (11)

Environmental Quality Management
Cincinnati, OH 45240

U.S. Environmental Protection Agency
Research Triangle Park, NC 27711 (2)

Air Force Institute for Environment, Safety,
and Occupational Health Risk Analysis
Brooks AFB, TX 78235-5123

U.S. Army Forces Command
Ft. McPherson, GA 30330-6000 (5)