

**UNITED STATES AIR FORCE
IERA**

**Characterization of Aerosols from
JP-8 Fuels in Jet Engine Emissions**

Philip M. Schumacher

**Battelle
505 King Avenue
Columbus, Ohio 43201-2693**

May 1998

20000317 037

*Approved for public release;
distribution is unlimited.*

**Institute for Environment, Safety and
Occupational Health Risk Analysis
Risk Analysis Directorate
Health and Safety Division
2513 Kennedy Circle
Brooks Air Force Base TX 78235-5123**

NOTICES

This report is published as received and has not been edited by the staff of the Institute for Environment, Safety and Occupational Health Risk Analysis (IERA).

Publication of this report does not constitute approval or disapproval of the ideas or findings. It is published in the interest of scientific and technical information (STINFO) exchange.

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The mention of trade names or commercial products in this publication is for illustration purposes and does not constitute endorsement or recommendation for use by the United State Air Force.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

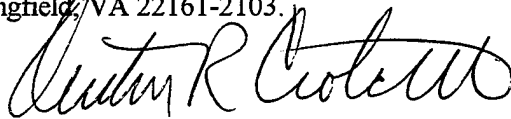
This report has been reviewed and is approved for publication.

Government agencies and their contractors registered with Defense Technical Information Center (DTIC) should direct requests for copies to: Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Ft. Belvoir, VA 22060-6218.

Non-Government agencies may purchase copies of this report from: National Technical Information Services (NTIS), 5285 Port Royal Road, Springfield, VA 22161-2103.



LESLIE B. SMITH, Maj, USAF, BSC
Industrial Hygiene Consultant



DENTON R. CROCHETT, Lt Col, USAF, BSC
Chief, Health and Safety Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

29 May 1998

3. REPORT TYPE AND DATES COVERED

Final (June 1997- May 1998)

4. TITLE AND SUBTITLE

Characterization of Aerosols from JP-8 Fuels in Jet Engine Emissions

5. FUNDING NUMBERS

6. AUTHOR(S)

Philip M. Schumacher

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Battelle Columbus Ohio
505 King Avenue
Columbus, OH 43201-2693

8. PERFORMING ORGANIZATION

IERA-RS-BR-TR-1999-0011

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Institute for Environment, Safety and Occupational Health Risk Analysis (AFMC)
Risk Analysis Directorate
Health and Safety Division
2513 Kennedy Circle
Brooks AFB, Texas 78235-5123

10. SPONSORING/MONITORING

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The emissions of the engine of a C-130E aircraft were studied under low ambient temperature (~20 °F) start-up conditions at Minneapolis AFS, MN in January 97. Samples of the engine emissions were collected using SUMMA® canisters, PS-1 medium volume samplers, and cascade impactors. The collected engine emissions were chemically analyzed by GC/MS to determine the airborne concentration of volatile organic compounds (VOC), unburned JP-8 fuel, and polynuclear aromatic hydrocarbons (PAH). The highest concentration of unburned JP-8 fuel observed directly behind the operating engine, in the loading corridor behind the aircraft, and inside the aircraft was 14.2 mg/m³, 4.7 mg/m³, and 1.5 mg/m³, respectively. Over 90 percent of the unburned JP-8 fuel was found in the vapor phase at 20 °C. The highest concentration of B2 PAH observed directly behind the operating engine, in the loading corridor behind the aircraft, and inside the aircraft was 390 ng/m³, 120 ng/m³, and 90 ng/m³, respectively. Over 86 percent of the nonvolatile B2 PAH was found in the respirable size fraction of the aerosol phase.

14. SUBJECT TERMS

C-130 JP-8 Jet Fuel Aerosols Cold Engine Starts PAH
Combustion Products Jet Engine Emissions

15. NUMBER OF PAGES

109

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT

Unclassified

20. LIMITATION OF ABSTRACT

UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89) Prescribed by ANSI Std Z-39-18
298-102 COMPUTER GENERATED

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGEMENT

The authors wish to thank Ms. Kayla Slovic, Mr. Jerry Halverson, and the personnel of the Minneapolis AFS, MN; Mr. C. Wayne Drake and the staff of the McKinley Climatic Laboratory, Eglin AFB, FL; and Maj. Les Smith, Ssgt Doug Fritts, and Ssgt Michelle Davenport of Armstrong Labs, Brooks AFB, TX for their many contributions during the field studies. The sampling efforts reported here could not have been completed without their assistance.

Contents

	Page
List of Acronyms	vii
Executive Summary	viii
Section 1.0 Objective	1-1
Section 2.0 Background	2-1
2.1 Technical Approach	2-2
Section 3.0 Test Methods	3-1
3.1 Real-Time Aerosol Monitoring Instruments	3-1
3.1.1 Aerosizer LD	3-1
3.1.2 Malvern System 2600	3-2
3.2 Sample Collection Equipment	3-4
3.2.1 Cascade Impactor	3-4
3.2.2 PS-1 Medium Volume Sampler	3-5
3.2.3 SUMMA® Canister	3-7
3.3 Chemical Analysis Methods	3-7
3.3.1 Sample Extraction Procedure	3-8
3.3.2 JP-8 Fuel Analysis	3-9
3.3.3 Polynuclear Aromatic Hydrocarbon Analysis	3-9
3.3.4 Volatile Organic Compound Analysis	3-11
Section 4.0 Climatic Chamber Tests	4-1
4.1 Chamber and Sample Location Description	4-4
4.2 Test Procedures	4-7
4.3 Tests Descriptions	4-9
4.4 Test Findings	4-15
Section 5.0 Flight Line Tests	5-1
5.1 Sampling Locations	5-1
5.2 Test Procedure	5-4
5.3 Tests Descriptions	5-4
5.4 Test Findings	5-9
Section 6.0 Conclusions and Recommendations	6-1
Section 7.0 References	7-1
Appendix A: Correction for Anisokinetic Sampling and Probe Bends in the Climatic Chamber Tests	A-1

Tables

	Page
Table 3-1. Target Polynuclear Aromatic Hydrocarbon Compounds	3-10
Table 4-1. Climatic Chamber Test Schedule	4-1
Table 4-2. Measured Concentrations of Unburned JP-8 Fuel in the PS-1 Samples of the Climatic Chamber Test	4-16
Table 4-3. Measured Concentrations of Unburned JP-8 Fuel Determined From the Impactor Filters From the Climatic Chamber Tests	4-20
Table 4-4. Estimated Original Concentrations of Unburned JP-8 Fuel Based on the Impactor Filters From the -22°F Climatic Chamber Test (Nonadecane and Icosane Only)	4-23
Table 4-5. Measured Concentrations of PAH Determined from the PS-1 Samples From the Baseline and Background Climatic Chamber Tests	4-24
Table 4-6. Exhaust Concentrations of PAH Determined from the PS-1 Samples From the Low Temperature Climatic Chamber Tests	4-25
Table 4-7. Exhaust Duct Flow Velocities in the Climatic Chamber Tests	4-33
Table 5-1. Concentration of JP-8 Fuel in Flight Line Test Samples	5-10
Table 5-2. Measured Concentration of PAH in Flight Line Test Samples (ng/m ³)	5-15
Table 5-3. Phase Distribution of B2 PAH	5-18
Table 5-4. Concentration of Volatile Organic Compounds in Flight Line Test Canister Samples	5-20

Figures

Figure 2-1. Task Structure	2-3
Figure 3-1. Aerosizer LD Instrument and Sampling Probe at the Exhaust Duct Outlet	3-3
Figure 3-2. Disassembled PS-1 Sampler (left) and Three Stage Cascade Impactor (right)	3-6
Figure 4-1a. Overall Schematic Diagram of the Climatic Chamber Test	4-2
Figure 4-1b. Photograph of the C-130J-30 Aircraft in the Climatic Test Chamber	4-3
Figure 4-2. Schematic Diagram Showing the Positions of the Sampling Locations During the Climatic Chamber Tests	4-5
Figure 4-3. Schematic Diagram of Climatic Chamber Test Sampling Location	4-6
Figure 4-4. Temperature Profiles During the 68°F Climatic Chamber Test.....	4-10
Figure 4-5. Temperature Profiles During the -9°F Climatic Chamber Test	4-11
Figure 4-6. Temperature Profile During the -22°F Climatic Chamber Test.....	4-13
Figure 4-7. Video Image of the Plume at the Exit of the Exhaust Duct at the Start of the -22°F Climatic Chamber Test	4-14
Figure 4-8. Chromatogram of the PS-Sample from Section 2 of the 68°F Climatic Chamber Test.....	4-17
Figure 4-9. Chromatogram of the PS-1 Sample from Section 2 of the -9°F Climatic Chamber Test	4-17

Figures (Continued)

	Page
Figure 4-10. Chromatogram of the PS-1 Sample from Section 2 of the -22°F Climatic Chamber Test.....	4-18
Figure 4-11. Chromatogram of the JP-8 Fuel from Eglin AFB, FL.....	4-18
Figure 4-12. Chromatogram of the Impactor Backup Filter at Section 2 of the -22°F Climatic Chamber Test.....	4-21
Figure 4-13. Chromatogram of the 1 to 10 μ m Impactor Stage Filter at Section 2 of the -22°F Climatic Chamber Test.....	4-21
Figure 4-14. Sum of the B2 PAH Concentrations in the PS-1 Samples of the Climatic Chamber Tests.....	4-26
Figure 4-15. Benzo[a]pyrene Concentrations in the PS-1 Samples of the Climatic Chamber Tests.....	4-27
Figure 4-16. Sum of the B2 PAH Concentrations in the Impactor Samples of the Climatic Chamber Tests.....	4-28
Figure 4-17. Benzo[a]pyrene Concentrations in the Impactor Samples of the Climatic Chamber Tests.....	4-29
Figure 4-18. Comparison of the Impactor Mass Distribution and the Aerosizer Volume Distributions	4-31
Figure 5-1. Positions of the Sampling Sites for the Flight Line Tests	5-2
Figure 5-2. Arrangement of the Samplers for the Head Wind Test	5-3
Figure 5-3. Wind Speed and Temperature During the Head Wind Test.....	5-5
Figure 5-4. Wind Speed and Temperature During the Tail Wind Test	5-7
Figure 5-5. Wind Speed and Temperature During the Tail Wind Background Test....	5-8
Figure 5-6. Concentration of JP-8 in the PS-1 Samples of the Flight Line Tests	5-12
Figure 5-7. Chromatogram of the PS-1 Sample Collected Behind the Engine During the Head Wind Test	5-13
Figure 5-8. Chromatogram of the JP-8 Fuel from the Minneapolis AFS MN Supply Tank	5-14
Figure 5-9. Sum of the B2 PAH Concentrations in the PS-1 Samples of the Flight Line Tests	5-16
Figure 5-10. Benzo[a]pyrene Concentrations in the PS-1 Samples of the Flight Line Tests	5-17
Figure 5-11. Benzene Concentrations in the Canister Samples of the Flight Line Tests	5-21
Figure 5-12. Toluene Concentrations in the Canister Samples of the Flight Line Tests	5-22
Figure 5-13. o-Xylene Concentrations in the Canister Samples of the Flight Line Tests	5-23
Figure 5-14. m,p-Xylene Concentrations in the Canister Samples of the Flight Line Test	5-24

List of Acronyms

APU	Auxiliary power unit
BAP	Benzo[a]pyrene
DCM	Dichloromethane
DFM	Diesel fuel marine
GC	Gas chromatograph
GC/FID	Flame ionization detector
GC/MS	Gas chromatograph/mas spectrometer
K-D	Kuderna-Danish
NIOSH	National Institute of Safety and Health
NIST	National Institute of Standards and Technology
PAH	Polynuclear aromatic hydrocarbons
PEL	Permissible exposure levels
STEL	Short-term exposure limit
TWA	time weighted average
VOC	Volatile organic compounds

EXECUTIVE SUMMARY

Aerosol characterization of JP-8 fuel jet engine emissions using both controlled-environment climatic chamber and actual flight line conditions were conducted to define the occupational exposure of air and ground crew personnel to these emissions. The experimental methods included real-time aerosol monitoring instruments and aerosol collection methods to obtain information on the airborne concentration, droplet size distribution, and chemical composition of the aerosol emitted by the engine during cold start. Chemical analyses included the determination of the quantity of unburned JP-8 fuel and polynuclear aromatic hydrocarbons (PAH) in the engine emissions. This report covers the work performed in the experimental portion of the project. The climatic chamber tests were conducted at the McKinley Climatic Laboratory at Eglin AFB, FL in June and July, 1997. The test aircraft was a new C-130J-30 undergoing tests for the aircraft manufacturer. Flight line tests were conducted at the Minneapolis AFS, MN in January, 1997.

The aerosol plume from a cold engine start has been noted as having a high level of particulate emissions (based on visible opacity of the plume). Older engines, e.g., C-130 or KC-135 aircraft, emit more aerosol during cold start than newer engines, e.g., F-15 or F-16 aircraft.

JP-8 fuel will be the standard jet fuel for the next generation of military aircraft. There have been no health studies completed on the aerosols emitted by jet engines fueled with JP-8. However, reports from units completing the conversion indicate an increase in the number of complaints from ground support crews about raw fuel odor, skin irritation, headaches, and dizziness when using JP-8 fuel. The first step in determining the permissible exposure levels (PEL) for JP-8 fuel vapors and aerosols is to characterize the vapor and aerosols emitted during jet engine cold start and warm-up at several ambient temperatures. For this program we define a cold start as the normal start-up of a jet engine that has not been operated since the previous day.

A recent report by the Subcommittee on Permissible Exposure Levels for Military Fuels recommended that the Navy's PEL (interim 8-hr time-weighted-average [TWA] PEL of 350 mg/m^3) be considered interim until additional studies are completed. The subcommittee also recommended that the Navy's 15-min short-term exposure limit (STEL) be reduced from

1,800 mg/m³ to 1,000 mg/m³ because of effects on the central nervous systems of laboratory animals and jet aircraft factory workers in Sweden.

During the climatic chamber tests aerosol samples of the engine emissions were collected at a baseline chamber temperature of 68°F, and at chamber temperatures of -9°F and -22°F. The engine produced a visible plume during the -9°F and -22°F tests that was not detected during the baseline test. The visible plume lasted approximately 5 seconds after the start of Engine 4 before it dissipated.

The samplers collected significant quantities of unburned JP-8 fuel vapors from the exhaust duct during all of the climatic chamber tests. The greatest amount of unburned JP-8 was collected at the lowest climatic chamber temperature. The highest unburned JP-8 concentration measured during the climatic chamber tests was 81 mg/m³, which was below the NIOSH recommended 10 hr TWA for kerosene of 100mg/m³. The estimated fraction of the supplied JP-8 fuel that was emitted by the engine as unburned JP-8 is 1.0, 1.4, and 2.1 percent for the 68°F, -9°F, and -22°F climatic chamber test, respectively. The new turboprop engine of the C-130J-30 appears to emit much less unburned JP-8 fuel than the engines used on the older C-130E aircraft, suggesting that ground crew exposures to unburned JP-8 will be reduced by deployment of the new aircraft.

The -22°F test was the only test that showed the presence of unburned JP-8 fuel aerosol and the unburned JP-8 aerosol was detected only in the respirable size fraction of the aerosol.

Unfortunately, partial evaporation of the fuel aerosol due to high temperatures within the exhaust duct during the climatic chamber tests prevent an accurate assessment of the unburned JP-8 fuel aerosol concentration. The estimated unburned JP-8 aerosol concentration within the exhaust duct ranges from 1.0 mg/m³ to 74 mg/m³ for the -22°F test.

The -22°F test produced the highest measured concentration of B2 PAH, 1.0 µg/m³, in the exhaust duct. Over 90 percent of the B2 PAH was in the aerosol phase. All of the B2 PAH measured in the climatic chamber tests was found in the respirable size fraction of the aerosol.

The climatic chamber tests do not provide a good approximation of actual personnel exposures due to the high exhaust duct temperatures; however, they do provide an assessment of the amount

of unburned JP-8 fuel and PAH emitted by a turboprop engine on the C-130J-30 aircraft. Most of the collected aerosol mass was extraneous material, such as rust particles or water droplets, and not material of interest for this study.

The flight line test sampling sites were chosen to allow sampling of the aerosol in the propeller wash and in locations where ground crew could be exposed to the aerosol plume during loading of the aircraft. Each site contained a cascade impactor, a PS-1 medium volume sampler, and a 6-liter SUMMA® canister (U.S. Air Force personnel collected samples at the same locations using personal samplers). Attempts to record real-time aerosol measurements using the API Aerosizer LD and the Malvern System 2600 were unsuccessful due to field operational problems.

The highest concentration of unburned JP-8 observed in the flight line tests, 14.2 mg/m^3 , was found directly behind the operating engine. The highest concentration of unburned JP-8 in the loading corridor behind the aircraft was 4.7 mg/m^3 . The highest concentration of unburned JP-8 observed inside the aircraft (1.5 mg/m^3) occurred when the prevailing wind blew from the tail toward the nose of the aircraft. Test personnel inside the aircraft during the tail wind test experienced burning eyes and noted a strong fuel odor while the engines were operating. The highest concentration of B2 PAH observed in the flight line tests was $0.4 \text{ } \mu\text{g/m}^3$. The B2 PAH was found primarily (>86 percent) in the respirable aerosol size fraction.

Future tests to measure the concentrations of unburned JP-8 fuel aerosol and PAH produced by turboprop engines should be conducted at ambient temperatures below -10°F to increase the fraction of the engine emissions in the condensed phase. Sampling during calm wind conditions with high volume sampling equipment will also allow collection of larger quantities of the aerosol for chemical analysis.

SECTION 1.0 — Objective

The overall scope of this program was to complete the characterization of JP-8 fuel jet engine aerosol emissions using both controlled-environment climatic chamber and actual flight line conditions. The aerosol data was used to define the occupational exposure of air and ground crew personnel to JP-8 fuel.

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 2.0 — Background

HQ USAF/SG has tasked AL/OEMI to determine personnel exposure levels and toxicological hazards of aerosols associated with jet engine emissions. The aerosol plume from a cold engine start has been noted as having a high level of particulate emissions (based on visible opacity of the plume). Older engines, e.g., C-130 or KC-135 aircraft, emit more aerosols during cold start than newer engines, e.g., F-15 or F-16 aircraft. Multi-engine aircraft, especially those having four or more engines started individually, have a longer period of high density plume than single or dual engine aircraft.

The U.S. Air Force completed the conversion of the standard jet fuel used in most military aircraft from JP-4 to JP-8 in October, 1995. JP-8 is similar to the kerosene type international jet fuel type Jet A-1 with the corrosion inhibitor/lubricity improver and fuel system icing inhibitor additives (MIL-T-83133D, 29 January, 1992). This fuel will be the standard jet fuel for the next generation of military aircraft.

There have been no health studies completed on the aerosols emitted by jet engines fueled with JP-8. However, reports from units completing the conversion indicate an increase in the number of complaints from ground support crews about raw fuel odor, skin irritation, headaches, and dizziness when using JP-8 fuel. The first step in determining the permissible exposure levels (PEL) for JP-8 fuel vapors and aerosols is to characterize the vapor and aerosols emitted during jet engine cold start and warm-up at several ambient temperatures. For this program we define a cold start as the normal start-up of a jet engine that has not been operated since the previous day.

As part of the design of a strategic sealift ship used to transport already-fueled military vehicles, the Navy's Occupational Safety and Health Standards Board recommended an interim 8-hr time-weighted-average (TWA) PEL of 350 mg/m^3 and a 15-min short-term exposure limit (STEL) of $1,800 \text{ mg/m}^3$ for vapors from JP-5, JP-8, and diesel fuel marine (DFM) fuels (NRC, 1996). The vehicles transported by the ships use the JP-5 and JP-8 fuels, while the DFM is used to fuel the ships. For comparison, the National Institute of Safety and Health (NIOSH) recommended 10 hr TWA for kerosene (Fuel Oil No. 1) is 100 mg/m^3 (14 ppm) (MDL, 1995). A recent report by the

Subcommittee on Permissible Exposure Levels for Military Fuels recommended that the Navy's PEL be considered interim until additional studies are completed. The subcommittee also recommended that the STEL be reduced from 1,800 mg/m³ to 1,000 mg/m³ because of effects on the central nervous systems of laboratory animals and jet aircraft factory workers in Sweden. In their report the subcommittee recommended further work to determine exposures during operational procedures, including exposures to respirable aerosols of unburned fuels (NRC, 1996).

2.1 Technical Approach

Previous chemical analyses have shown that JP-8 fuel is primarily a mixture of more than 100 straight chain and branched hydrocarbons containing from 9 to 18 carbon atoms (Mayfield, 1996) similar to kerosene. Since the exact composition of JP-8 varies from one lot of fuel to another, we did not attempt to quantify the individual components of the emitted fuel to determine the quantity of unburned JP-8 emitted by the engine. Rather, we prepared calibration standards from a sample of the fuel from each bases' JP-8 fuel supply.

Figure 2-1 shows the overall task structure for this project. The project was divided into seven tasks as described in the Statement of Work. Tasks 2, 3, and 4 are the experimental portion of the project and the remaining tasks comprise the management and reporting portions of the project. This report is the Task 5 Test Report, which covers the work performed in the experimental portion of the project. The test methods are described in Section 3, while Sections 4 and 5 present the results of the climatic chamber and flight line tests, respectively. Conclusions and recommendations are presented in Section 6.

The climatic chamber tests were conducted at the McKinley Climatic Laboratory at Eglin AFB, FL in June and July, 1997. The test aircraft was a new C-130J-30 undergoing tests for the aircraft manufacturer. Flight line tests were conducted at the Minneapolis AFS, MN, in January, 1997. The Minneapolis AFS, MN, was chosen as the location for the flight line tests on this program because C-130 aircraft are stationed at the base and the winter temperatures in Minneapolis were expected to cause the desired aerosol plume during cold engine starts.

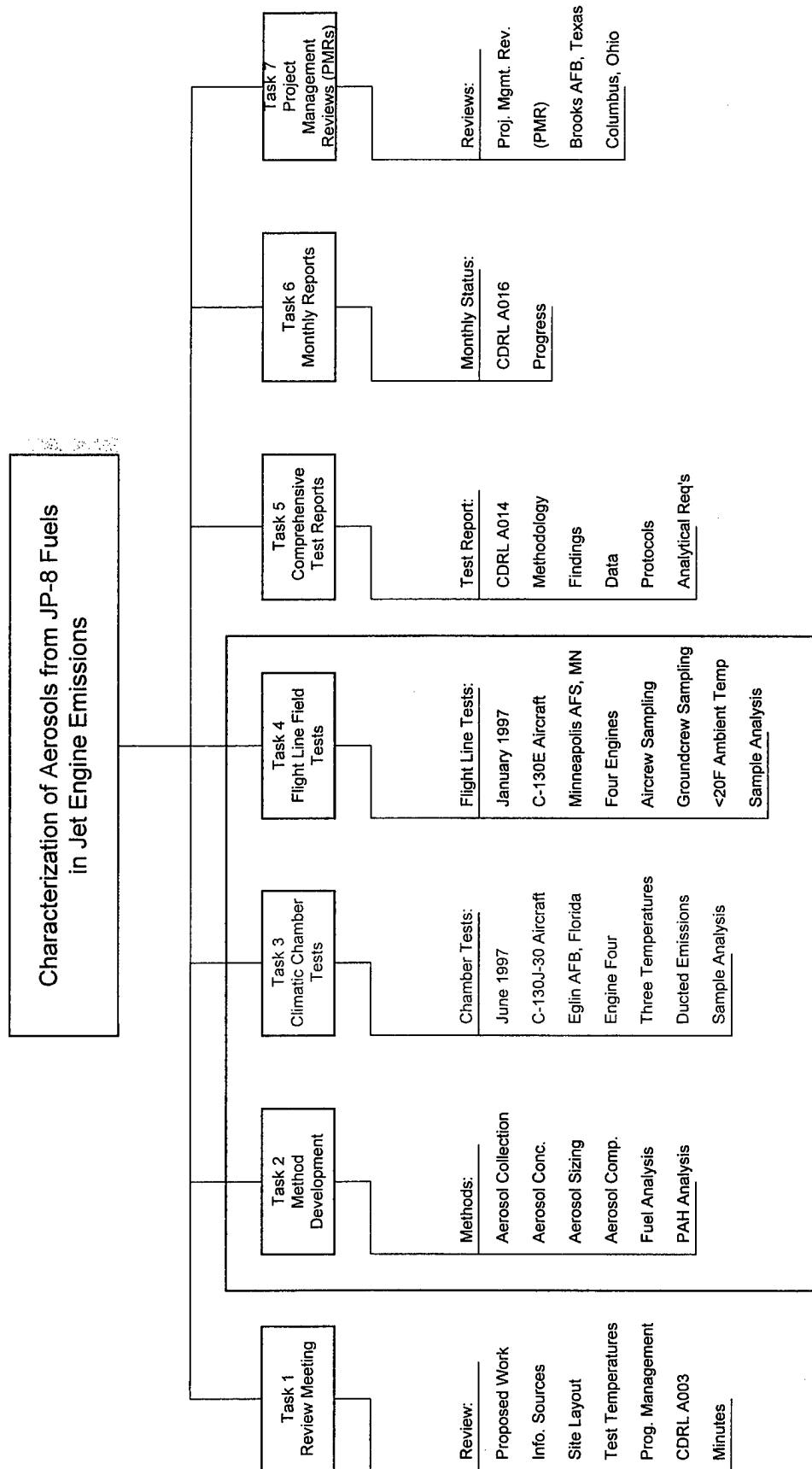


Figure 2-1. Task Structure

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 3.0 — Test Methods

The experimental methods employed for the JP-8 aerosol characterization included real-time aerosol monitoring instruments and aerosol collection methods. The real-time instruments were used to obtain rapid measurements of the aerosol concentration and size distribution. The collection methods were used to obtain samples of the jet engine emissions for chemical analysis in the laboratory. The goals of the methods were to provide information on the airborne concentration, droplet size distribution, and chemical composition of the aerosol emitted by the engine during a cold start. Chemical analyses included the determination of the quantity of unburned JP-8 fuel and polynuclear aromatic hydrocarbons (PAH) in the engine emissions. The concentration, size distribution, and composition of the aerosol are also required to assess the effects of personnel exposure to the JP-8 fuel aerosol.

Sampling under cold start conditions introduced some complications into the test procedures. Since the duration of the cold start condition was short, high sampling rate methods were used to obtain sufficient material for chemical analyses. The sampling and analysis methods are described below.

3.1 Real-Time Aerosol Monitoring Instruments

Two real-time aerosol monitoring instruments were used in this project: (1) an Aerosizer LD (API, Inc., Hadley, MA) and (2) a Malvern System 2600 (Malvern Instruments, Ltd., Worcestershire, U.K.). Both instruments presented operational problems on the flight line at subfreezing temperatures. We used the Aerosizer LD successfully during the climatic chamber tests; however, it was necessary to operate the instrument at the outlet of the exhaust duct outside the low temperature environment.

3.1.1 Aerosizer LD

The Aerosizer particle measuring system uses an aerodynamic time of flight measurement technique, and is capable of individually measuring the size of particles in the 0.2 to 700 μm

range. The Aerosizer measures particle size by expanding the air-particle suspension through a nozzle into a partial vacuum. The air leaves the nozzle at near sonic velocity and continues to accelerate through the measurement region. Particles are accelerated by the drag forces generated by the accelerating air stream. Very small particles are accelerated to nearly the air velocity by the drag force between the air and the particles. Larger particles experience lower acceleration because of their greater mass. The time of flight of a single particle is measured by generating two beams of laser light through the instrument's measurement region. As particles pass through the laser beams, they scatter light that is detected and converted into electrical signals by two photomultiplier tubes. The first photomultiplier detects scattered light as a particle passes through the first beam. The second photomultiplier detects scattered light as the particle passes through the second beam. The time between these two events (the time of flight) is measured with a precision of 25 nanoseconds. The relationship between the particle size and time of flight depends on the density of the particle. The relationship has been carefully determined using a combination of theoretical concepts and experimental measurements of particles with accurately known diameters and densities. These results are entered into the computer program and are used to convert measurements of the time of flight into particle size. Only the density of the particles must be known to complete this conversion. Figure 3-1 shows the Aerosizer at the outlet of the exhaust duct during the climatic chamber tests.

3.1.2 Malvern System 2600

The Malvern System 2600 (Malvern Instruments Ltd., Malvern, U.K.) provides a measure of the particle size distribution and concentration based on the light scattering properties of the aerosol. It is capable of classifying particles from 1.0 to 1800 μm in diameter. The Malvern is composed of three main components: (1) a low power He-Ne laser source, (2) a receiving optic, and (3) a computer. The aerosol is introduced directly into the Malvern by spraying the sample through the measuring area. The Malvern is ideal for measuring large diameter particles since it does not require an inlet probe. The particles introduced into the measuring area scatter the light from the He-Ne laser, which is then collected by a receiving optic. The scattering angle is dependent on

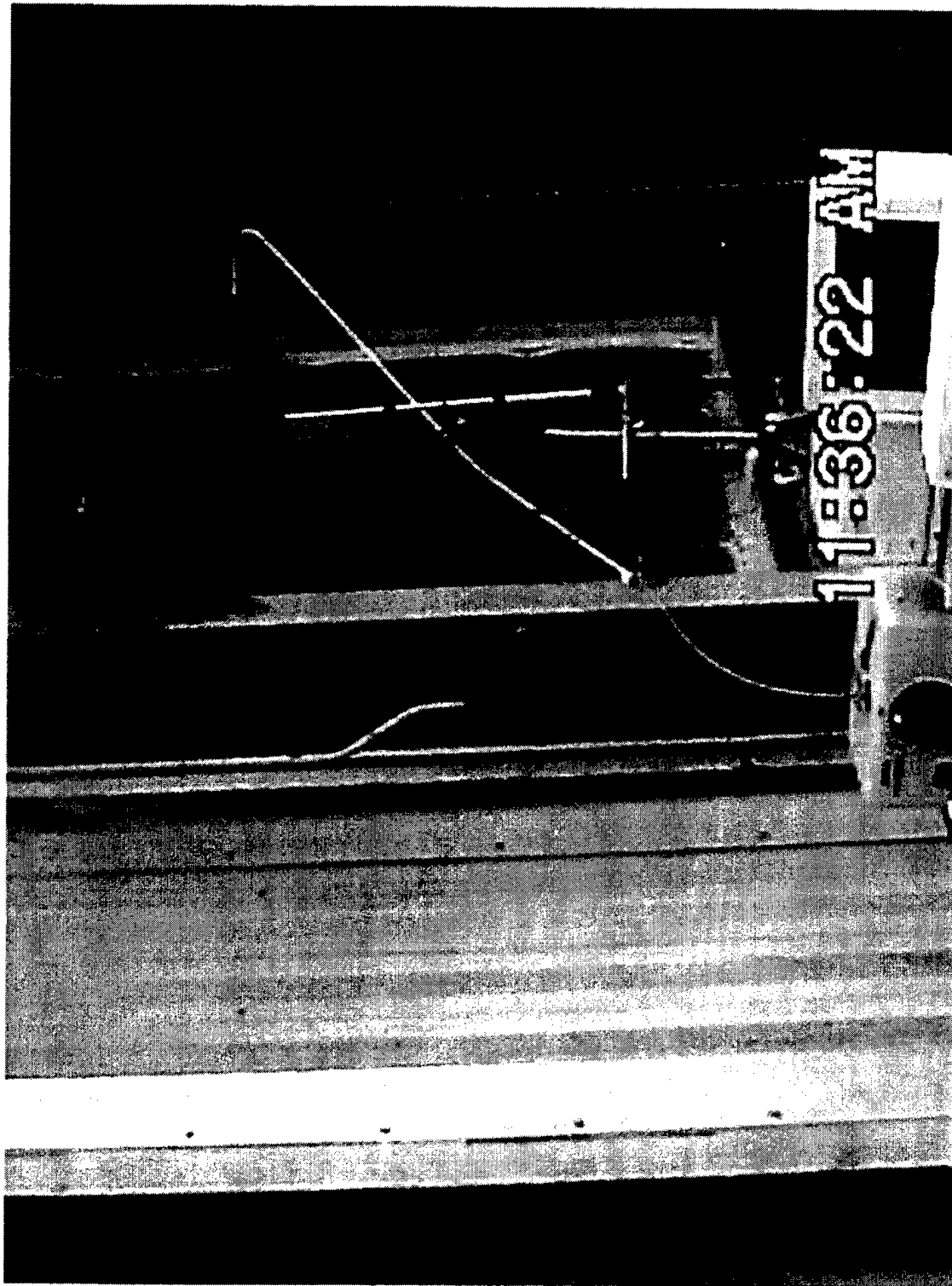


Figure 3-1. Aerosizer LD Instrument and Sampling Probe at the Exhaust Duct Outlet

the particle size. The receiving optic consists of 31 concentric annular sections, each of which corresponds to a specific scattering for a known particle size range. Each annular detector then sends an electrical output signal, which is proportional to the light intensity captured, to the computer. The computer software then translates this signal into a volume distribution curve. The particle concentration is determined based on the amount of non-scattered light which passes through the center of the detector.

Although the System 2600 appeared to be the ideal instrument for measurement of the engine emission aerosol, its need for alignment of the optics on the flight line before each test proved to be unworkable. We did not attempt to use the System 2600 during the climatic chamber tests because of the difficulties associated with instrument alignment and the need to access the aerosol plume in the exhaust duct.

3.2 Sample Collection Equipment

Several types of sampling equipment were used to collect the samples for chemical analysis in the laboratory. We collected both vapor and particulate phase samples in this program. Vapor samples were collected using 6 liter evacuated SUMMA® canisters. Samples of the fuel aerosol were collected using cascade impactors (Battelle, Columbus, OH). To sample a larger air volume for improved sensitivity, we used PS-1 medium volume samplers (General Metal Works, Cleves, OH). The PS-1 samplers collected both particulate and vapor components of the engine emissions during the start-up period. See Section 3.3 for a description of the analytical methods used to determine the chemical composition of the JP-8 emissions during this period.

3.2.1 Cascade Impactor

Cascade impactors collected the size fractionated aerosol samples for this project. Cascade impactors were selected because they are rugged and collect a sample of aerosol in known size ranges. In a cascade impactor the sample air flows through a series of nozzles directed at a sample collecting surface. Large particles entrained in the airflow separate from the air due to

inertial forces near the nozzle and strike the collecting surface. Smaller particles remain entrained in the airflow and proceed to the next stages in the impactor where they are also separated from the airflow. The inertial forces are increased at each stage of the impactor by using successively smaller nozzle diameters in each stage. The largest particles are thus collected in the first stage, while successively smaller particles are collected on the successive stages. A backup filter collects any particles too small to be caught in the impaction stages. The impactors operated at a flow rate of 12.5 liter/min.

Glass slides that have been coated with an organic grease, such as vacuum grease, are commonly used as the impaction surface in cascade impactors, because the grease improves retention of the aerosol particles on the slide. Grease-coated glass slides could not be used in these tests, because organic compounds in the grease coating interfere with the analysis of small quantities of JP-8 fuel and PAH in the collected aerosol particles. We used glass fiber filters as the impaction surface in the cascade impactors because the filter material possesses a better retention efficiency for impacted aerosol particles than uncoated glass slides. The filters were precleaned by heating them overnight in a muffle furnace at 450°C. Figure 3-2 shows a three-stage cascade impactor with the top stage removed to show the nozzle. A 6-inch ruler is included for scale. A disassembled PS-1 sampler is shown to the left of the impactor.

3.2.2 PS-1 Medium Volume Sampler

PS-1 samplers (General Metal Works, Cleves, OH) were used to collect the jet engine emissions at a greater sampling rate than was possible using the cascade impactors. The PS-1 samplers combine a filter to collect particulate material and an absorbent trap to collect vapor-phase materials. We used XAD-2 resin as the absorbent in this project. XAD-2 resin is commonly used as an adsorbent material for organic vapors in environmental sampling programs. The sampling flow rate of the PS-1 samplers was more than nine times the flow rate of the impactors so the amount of emissions collected using the PS-1 samplers was correspondingly greater than the amount of emissions collected using the impactors. The PS-1 samplers were used to measure the total amount of JP-8 fuel related materials emitted during cold engine start-up, since they collected both the aerosol and vapor. The left side of Figure 3-2 shows a disassembled PS-1

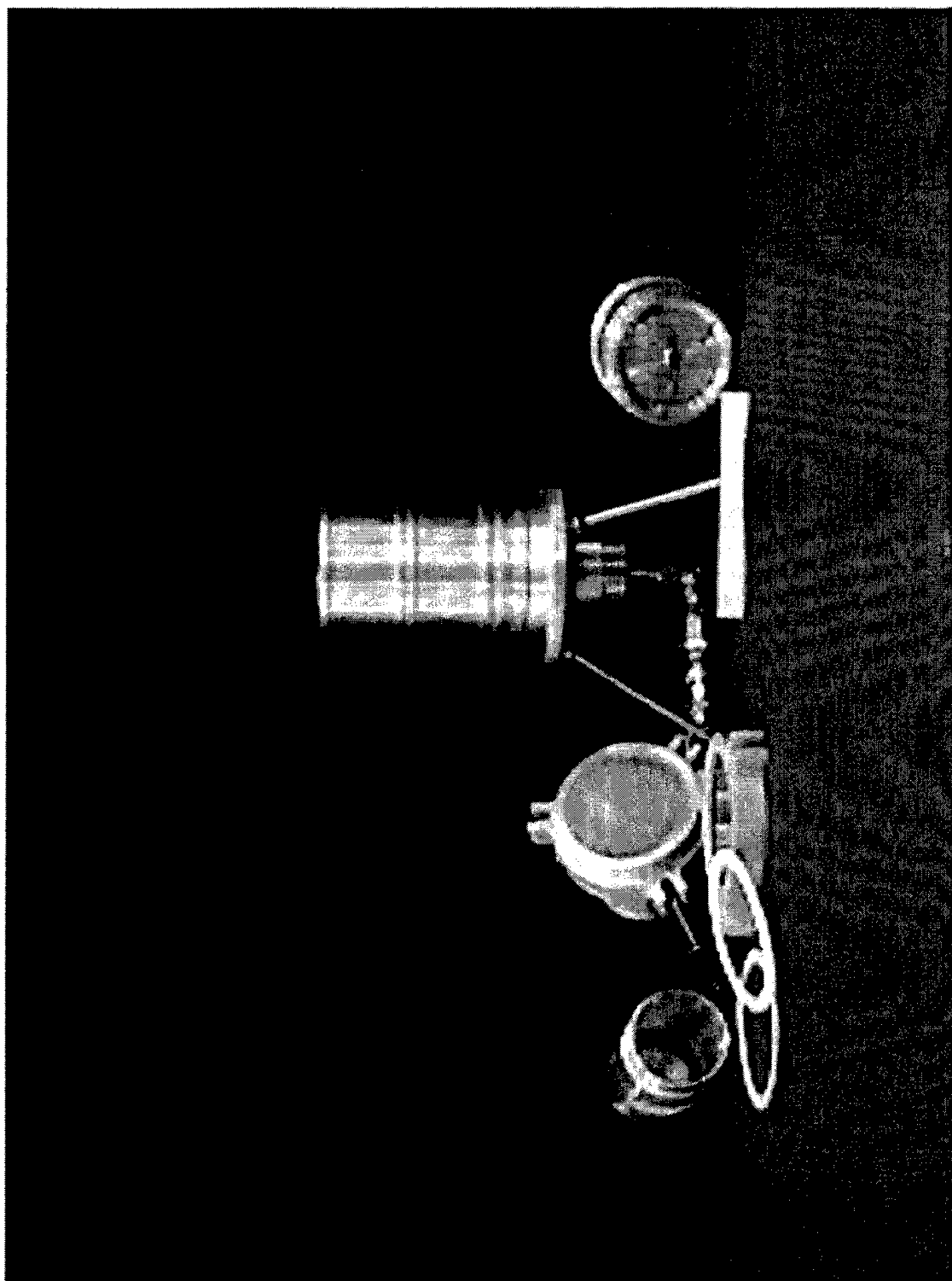


Figure 3-2. Disassembled PS-1 Sampler (left) and Three Stage Cascade Impactor (right)

sampler. The particulate filter is placed on the screen at the top of the PS-1 while the XAD-2 resin cartridge is placed into the cylindrical trap holder at the left of the figure. To assemble the sampler, the resin trap holder is screwed into the filter holder, then the sampler assembly is mounted in the PS-1 housing

The PS-1 sampler housings supplied by General Metal Works were used to mount the PS-1 samplers during the flight line tests. Since the same metal housings were unsuitable for use during the climatic chamber tests, the PS-1 samplers were removed from the metal housings and attached to the underside of the exhaust duct using special flanges fabricated at Battelle before the tests. See Section 4.1 for a description of the way the samplers were attached to the exhaust duct.

3.2.3 SUMMA® Canister

SUMMA® canisters (Scientific Instrumentation Specialists, Moscow, ID) are spherical stainless steel canisters with a 6-liter capacity. For this study the canisters were fitted with a valve and a critical flow orifice. By evacuating the canisters before use, the canisters operated as passive samplers when the valve was opened manually. The critical orifice limited the airflow rate into the canister so the canister collected an air sample over a predetermined time period. Orifice sizes were chosen to allow collection of one-half of the canister volume (3 liters) in 15 or 30 min. Canisters are normally collected to the half full point to maintain critical flow through the orifice. As the absolute pressure in the canister rises above one-half atmosphere, the sampling flow into the canister decreases significantly below the flow for critical flow conditions. The final total volume of the sample can still be determined when the sample volume exceeds one-half of the canister's capacity, however.

3.3 Chemical Analysis Methods

For the chemical analysis of the cold engine emissions during the start-up period, the PS-1 filter and XAD-2 resin trap were combined into a single sample. For the flight line tests several of the impactor stage filters were also combined to increase the quantity of material available for the

analysis. In nearly all cases insufficient material was collected on the impactor filters to permit detection of the JP-8 despite the greater quantity provided by the composite samples.

The extraction procedure used for the impactor and PS-1 samples is described in the next section. The descriptions of the analytical methods used to determine the amount of unburned JP-8 and the PAH in the impactor and PS-1 samples and the volatile organic compounds (VOC) in the SUMMA® canisters follow the description of the extraction procedure.

3.3.1. Sample Extraction Procedure

Precleaned XAD-2 resin was purchased from Supelco (Bellefonte, PA). The XAD-2 resin was cleaned again just prior to the field testing. The XAD-2 resin was extracted with dichloromethane (DCM) for 16 hr using the Soxhlet technique. After extraction, the cleaned XAD-2 was placed in a Pyrex column (9 cm x 30 cm). The drying column had sufficient space for fluidizing the XAD-2 bed while generating a minimum resin load at the exit of the column. The resin was dried by passing high-purity nitrogen through the bed. The nitrogen was purified by passing it through a charcoal trap that was positioned between the nitrogen cylinder (size 1A) and the column. The rate of nitrogen flow through the column was set to agitate the bed gently to remove the residual DCM. After drying, about 50 g of XAD-2 was packed in a PS-1 glass cartridge to a bed depth of about 2 in. The XAD-2 cartridge assembly was wrapped with cleaned aluminum foil and placed in a clean jar and sealed with Teflon® tape. It should be noted that additional cleaned aluminum foil was placed on the top of the PS-1 glass cartridge, so that the glass cartridge could be tightly placed in the jar to prevent breakage of the cartridge during shipping.

The quartz fiber filters were purchased from Pallflex (Putnam, CT). The filters were cut into the required diameter (104 mm ID) to fit the PS-1 sampling module. The cut filters were placed in an oven at 450°C overnight to remove any trace amount of organic impurity. A group of about 50 clean quartz fiber filters were placed in one set of clean petri dishes, sealed with Teflon® tape. The glass fiber filters used for the impactor were also cut into two different sizes (37 mm ID and 80 mm ID). The glass fiber filters were cleaned the same way as the quartz fiber filters. Each clean glass fiber filter was placed individually in a petri dish.

The collected PS-1 samples (filter and XAD-2) were extracted with DCM for 16 hr. Selected impactor filter samples were also extracted with DCM. The extracts were concentrated by Kuderna-Danish (K-D) evaporation to a final volume of 1 mL. The concentrated extracts were split, one portion was analyzed by a gas chromatograph equipped with a mass selective detector (GC/MS) to determine PAH, and the other portion was analyzed by a gas chromatograph equipped with a flame ionization detector (GC/FID) to determine aliphatic hydrocarbons (JP-8 fuel components).

3.3.2. JP-8 Fuel Analysis

For JP-8 fuel analysis, a Hewlett-Packard Model 5890 gas chromatograph (Hewlett-Packard Co., Analytical Products Group, Palo Alto, CA) equipped with a flame ionization detector and a Hewlett Packard 7673A auto sampler was used. A fused silica capillary DB-5 column, 60 m x 0.25 mm ID (0.25 μ m thickness), was used for analyte separation. The GC/FID calibration solutions were prepared by the dilution of JP-8 fuel obtained from the fuel source used to fuel the test aircraft. The JP-8 fuel calibration solution concentrations ranged from 216 ng/ μ l to 1730 ng/ μ l. The GC temperature program used was: 70°C for 2 min, then programmed to 290°C at 6°C/min with a 12-min hold at 290°C. Some of the PS-1 sample extracts generated GC response signals outside the calibration range, and these sample extracts were diluted and reanalyzed by GC/FID. The results obtained for the diluted samples showed that GC/FID responses were linear beyond the calibration range. The results of diluted and non-diluted sample extracts were very similar.

3.3.3. Polynuclear Aromatic Hydrocarbon Analysis

For PAH analysis, a Hewlett Packard Model 6890 gas chromatograph equipped with a mass selective detector (GC/MS), or a Finnigan TSQ-45 GC/MS (Finnigan MAT, San Jose, CA) operated in the electron impact mode, was used. Sample extracts were analyzed by GC/MS in the selected ion monitoring mode to determine PAH. A fused silica capillary DB-5 column, 60 m x 0.32 mm ID (0.25 μ m film thickness), was used for analyte resolution. The initial GC column temperature was 70°C, and the temperature was programmed to 290°C at 8°C/min.

Helium was used as the GC carrier gas. The outlet of the GC column was directly connected to the inlet of the mass spectrometer ion source. Data acquisition and processing were controlled by a Hewlett Packard chemical station. Calibration mixtures of PAH ranged from 0.001 ng/μl to 0.1 ng/μl.

Table 3-1 shows the target PAH compounds that were quantified in this study. Target compounds ranged from the volatile two-ring compounds naphthalene and biphenyl to the non-volatile seven-ring compound coronene. The B2 compounds ranked as probable human carcinogens by the U. S. EPA's Integrated Risk Information System are starred in the table. Most of the B2 compounds are non-volatile and thus are expected to concentrate in the aerosol fraction of the engine emissions.

Table 3-1. Target Polynuclear Aromatic Hydrocarbon Compounds

Volatile	Semi-Volatile	Non-Volatile
<u>2-ring</u>	<u>4-ring</u>	<u>5-ring</u>
Naphthalene	Fluoranthene	Benzo[b]fluoranthene*
Biphenyl	Pyrene	Benzo[k]fluoranthene*
	Benz[a]anthracene*	Benzo[e]pyrene
<u>3-ring</u>	Chrysene*	Benzo[a]pyrene*
Acenaphthylene		Dibenz[a,h]anthracene*
Acenaphthene	<u>5-ring</u>	
Fluorene	Cyclopenta[c,d]pyrene	<u>6-ring</u>
Phenanthrene		Indeno[1,2,3,-c,d]pyrene*
Anthracene		Benzo[g,h,i]perylene
		<u>7-ring</u>
		Coronene

*These PAH are ranked as probable human carcinogens (B2) by the U.S. EPA's Integrated Risk Information System.

3.3.4. Volatile Organic Compound Analysis

SUMMA® canisters containing samples for GC/MS analysis were pressurized with high purity air to 5 psig. The canister pressure before and after pressurization was used to calculate a sample dilution factor with the following formula:

$$\text{Dilution Factor} = \frac{\text{Final Pressure}}{29.92 \text{ in. Hg} - \text{Initial Pressure}}$$

where the initial and final pressures are expressed in absolute units (in. Hg). For example, 5 psig is equal to 40.1 in. Hg and 1 atmosphere is equal to 29.92 in. Hg. The initial canister pressure was measured when the canister was connected to the canister pressurizing system.

A Fisons MD 800 gas chromatograph (Fisons, Instruments, Beverly, MA) equipped with mass spectrometer and flame ionization detectors was used for the analyses of the volatile organics present in the canister samples. The GC contained a cryogenic preconcentration trap and the sampled air volume was 60 cc. The GC was equipped with a cryofocusing trap to refocus the collected organics onto the head of the analytical column. Analytes were chromatographically resolved on a Restek RTX-1, 60 m x 0.50 mm ID fused silica capillary column (1 µm film thickness). Optimal analytical results were achieved by temperature programming the GC oven from -50°C to 220°C at 8°/min. The column exit flow was split to direct one-third of the flow to the mass spectrometer and the remaining flow to the flame ionization detector. The mass spectrometer was operated in the total ionization mode so that all masses were scanned between 35 and 300 daltons at a rate of 1 scan per 0.5 seconds. Identifications of major components were performed by matching the mass spectra acquired from the samples to the mass spectral library from the National Institute of Standards and Technology (NIST, Gaithersburg, MD).

Quantitation was based upon comparing the flame ionization detector response of the compounds of interest to a known concentration of a dilute benzene calibration gas (traceable to NIST calibration cylinders). The following formula was used to convert the peak areas to concentration units:

$$\text{ppbC}_{(\text{compound})} = \frac{\text{ppbC}_{(\text{benzene})} * \text{Area}_{(\text{compound})}}{\text{Area}_{(\text{benzene})}}$$

The conversion from ppbC to ppb compound is carried out by dividing the ppbC value by the number of carbon atoms per compound.

SECTION 4.0 — Climatic Chamber Tests

The climatic chamber tests were conducted at the McKinley Climatic Laboratory at Eglin AFB, FL between 20 June and 3 July, 1997. Table 4-1 shows the test schedule for the climatic chamber tests. Figure 4-1a shows the overall layout of the climatic chamber and the test aircraft for these tests. Figure 4-1b is a photograph showing the test aircraft in the climatic chamber. Since the climatic chamber tests were being conducted for the aircraft manufacturer, the manufacturer's personnel controlled the timing, duration, and engine power settings. We expected the aerosol plume produced during cold start to exist for a short time, especially with the engine exhaust confined within an exhaust duct rather than emitted into the cold air surrounding the test aircraft. We also expected that the temperature within the duct could approach the engine's exhaust temperature. The climatic chamber test apparatus was designed to monitor the temperature of the XAD-2 adsorbent resin in the PS-1 samplers, which was the most temperature sensitive component of the sampling equipment, and to permit a shutdown of the samplers if the safe operating temperature of the XAD-2 was approached.

Table 4-1. Climatic Chamber Test Schedule

Test Day	Test Activity	Aircraft Requirements	Comments
Friday 20 June	Battelle staff orientation. Preliminary equipment checkout. Install test equipment on Engine 4 exhaust duct.	None	Acquaint Battelle staff with climatic chamber safety regulations. Verify equipment operation and sampling parameters.
Saturday 21 June	Background test.	None	Collect background samples from the exhaust duct.
Monday 23 June	Baseline test ~68°F	Test aircraft Engine 4	Shakedown test. Monitor exhaust temperatures and flow rates. Collect aerosol samples.
Wednesday 25 June	Low temperature engine start -9°F.	Test aircraft Engine 4	Monitor exhaust temperatures and flow rates. Collect aerosol samples.
Monday 30 June	Low temperature engine start -22°F.	Test aircraft Engine 4	Monitor exhaust temperatures and flow rates. Collect aerosol samples.
Thursday 3 July	Low temperature engine start -40°F.	Test aircraft Engine 4	Monitor exhaust temperatures and flow rates. Collect aerosol samples.

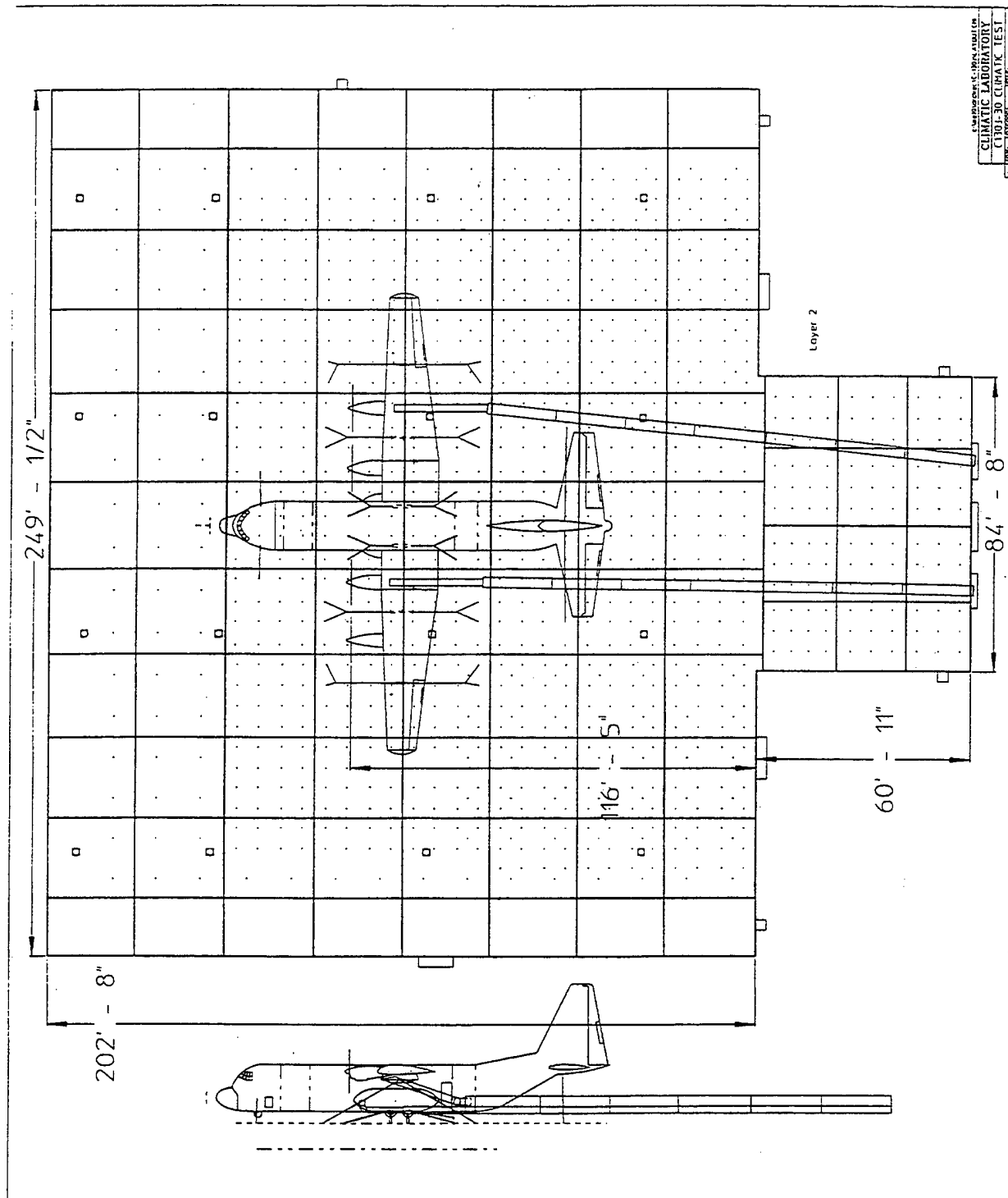


Figure 4-1a. Overall Schematic Diagram of the Climatic Test Chamber



Figure 4-1b. Photograph of the C-130J-30 Aircraft in the Climatic Test Chamber

4.1 Description of Chamber and Sampling Location

Aerosol samples were obtained from the exhaust of the outboard right engine (Engine 4) of the C-130J-30 test aircraft during cold start. The exhaust exited the climatic chamber through a circular duct. The jet engine exhaust outlet and duct inlet were separated by approximately a 2- to 4-inch gap so that some cold chamber air was entrained with the engine exhaust flow. The total duct length was 160 feet. It consisted of eight sections: one 24-inch diameter section approximately 20 feet long, followed by seven 36-inch diameter x 20 foot long sections. Considering the 24 inch duct as the first duct section, sampling sites were located in the middle of the second, third, and eighth duct sections. Figure 4-2 shows the relative positions of the sample locations with respect to the test aircraft and the exhaust duct. Each sampling site contained a PS-1 medium volume sampler, a three-stage impactor, thermocouple, and pitot tube. The exhaust duct was 6 feet above the floor of the climatic chamber, which allowed the sampling equipment to be attached underneath the duct. All probes and thermocouples extended 18 inches into the 36 inch duct. The sampling equipment was controlled and monitored from a test booth located 30 feet from the exhaust duct. The Aerosizer was used to measure the particle size distribution at the outlet of the exhaust duct outside the climatic chamber.

Figure 4-3 illustrates the setup of a typical sampling location. The PS-1 provided a medium volume sample for identification of organic compounds in the aerosol and vapor state. PS-1 samples were collected on 104 mm quartz fiber filters and an XAD-2 resin cartridge. The PS-1 sampled at a flow rate of 4.6 scfm. The sampling probe attached to the PS-1 consisted of a single 90° bend. The probe extended 18 inches into the duct. The probe diameter was 0.5 inches to provide isokinetic sampling from within the duct at a sampling flow rate of 4 scfm and a duct velocity of 12 m/sec. The flow velocity measured in the exhaust duct ranged from 21 m/sec to 26 m/sec. The aerosol concentrations were corrected for the effect of the anisokinetic sampling and losses in the probe bend. See Appendix A for a description of the correction method.

The cascade impactors provided size fractionated samples of the aerosol. The impactor cut sizes were 1, 10, and 20 μm . Aerosol samples were collected on 37 mm glass fiber filters. The

Diagram of the Climatic Chamber Test Setup Eglin AFB, Florida

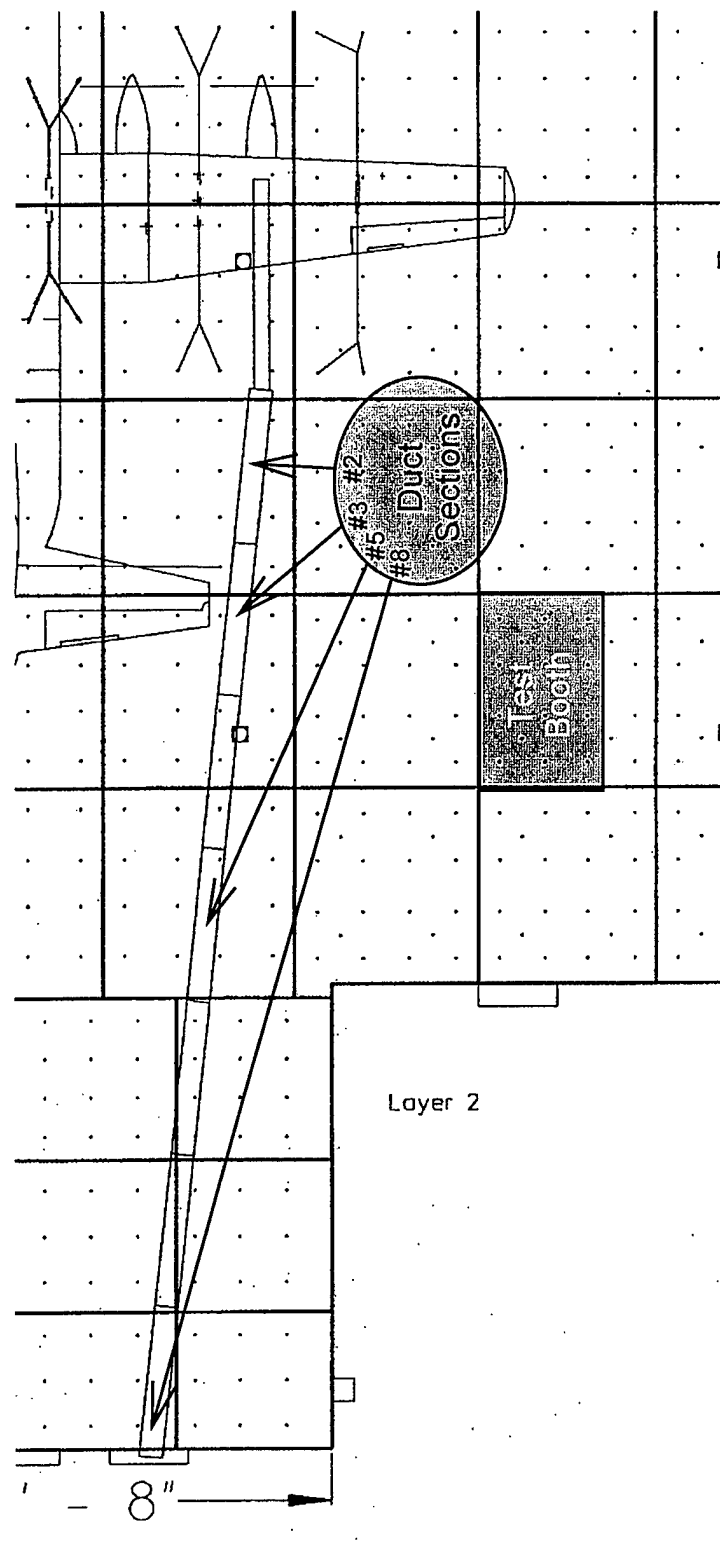


Figure 4-2. Schematic Diagram Showing the Positions of the Sampling Locations During the Climatic Chamber Tests

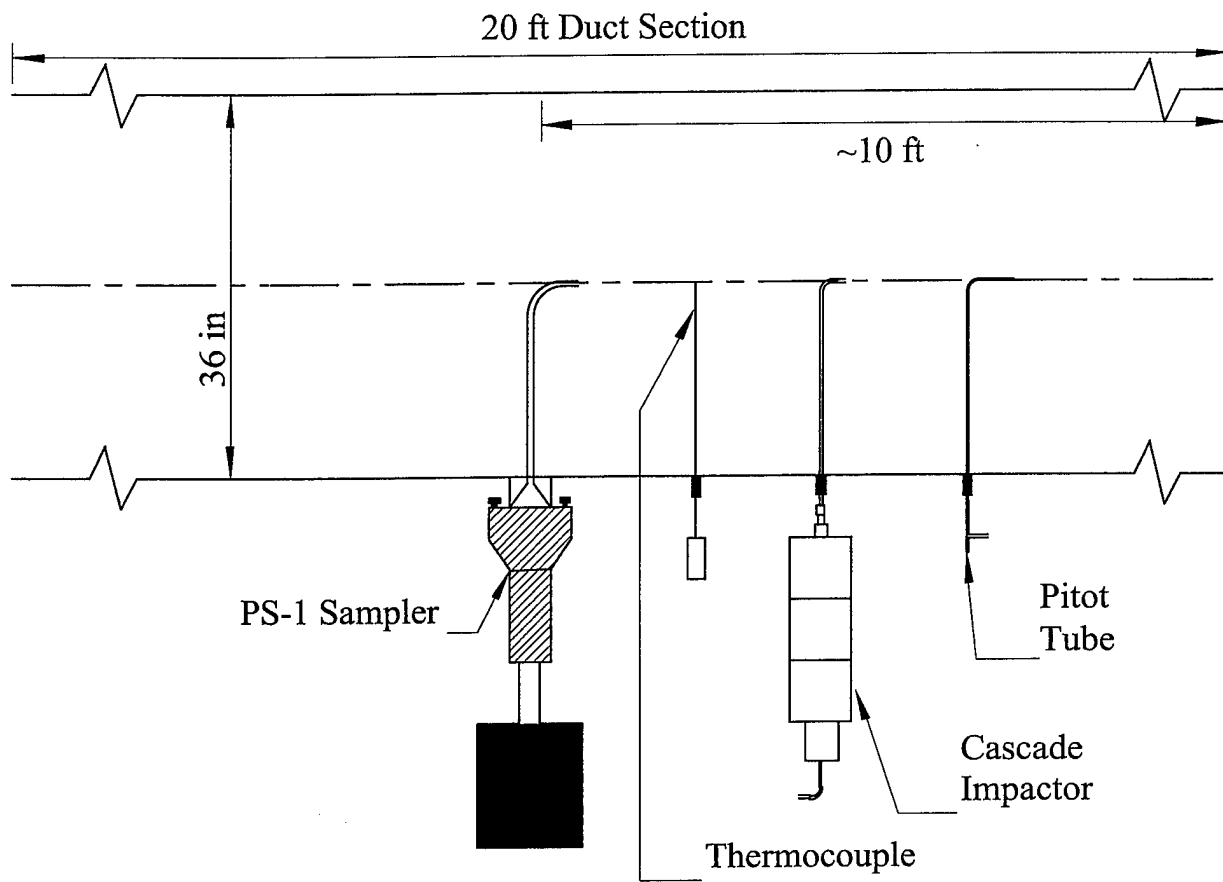


Figure 4-3. Schematic Diagram of a Climatic Test Chamber Sampling Location

aerosol mass on each stage was determined by weighing the impactor filters before and after collecting samples. The filters were weighed with a Mettler PE 160 balance. The impactors sampled at a flow rate of 12.5 liter/min. The sampling probe had a single 90° bend and was constructed of 1/4 inch O.D. stainless steel. The probe extended 18 inches into the exhaust duct.

Thermocouples (Type K) and pitot tubes (Dwyer Instruments, Inc., Michigan City, IN) were used to monitor the exhaust gas temperature and flow rate during the test. Eight thermocouples were interfaced with a software package (Omega Engineering, Inc., Stamford, CT) and temperatures were recorded electronically. Four thermocouples were used to monitor the exhaust gas temperature along the length of the duct. Thermocouples were located at the sampling sites (Sections 2, 3, and 8) and at Section 5. The thermocouples extended 18 inches into the duct. Three thermocouples were used to monitor the temperature of the gas leaving the resin cartridge in the PS-1 sampler. The PS-1 sampler was to be shut down if the temperature reached 100°C to protect the XAD-2 resin which degrades at 150°C. A final thermocouple was used to monitor the ambient temperature in the climatic chamber. This thermocouple was attached to the outside of the test booth. The pitot tubes were located at Sections 2, 3, and 8. Plastic tubing (1/4 inch) connected the pitot tubes to oil and magnehelic manometers in the test booth for monitoring during tests.

4.2. Test Procedures

The impactor filters and slides were stored in an air conditioned room with nearly constant temperature and humidity (after the test the filters were equilibrated at the same conditions). Prior to weighing the filters, the impactors were decontaminated with an ethanol rinse. The filters were weighed and loaded into the impactors approximately 24 hr prior to the test due to time restrictions on test days. The loaded impactors were sealed with Teflon® tape and stored in the controlled environment until needed for testing. The PS-1 traps and filters were also stored and loaded in the controlled environment. PS-1 samplers were loaded approximately 2 hr prior to the test. Cotton gloves were used when handling all sample media to minimize contamination.

Approximately 1 hr prior to test start, the loaded impactors and PS-1's were transported into the test chamber and attached to the exhaust duct. A check was then performed to ensure the sampling equipment was operating properly. Each PS-1 and impactor was started individually to verify the appropriate flow. The impactors sampled at a flow rate of 12.5 liter/min while the PS-1's sampled at approximately 4.6 scfm.

The impactor pumps and PS-1 samplers were controlled remotely from the test booth. Prior to engine start-up, chamber temperature, relative humidity, barometric pressure, and test descriptor were recorded on data sheets. Testing commenced when Engine 4 was cold started using the normal start-up procedures. The aircraft had been cold soaked for a minimum of 24 hr at each test temperature prior to engine start-up. The sampling equipment was started simultaneously with Engine 4 start-up based on the countdown given by test aircraft's pilot. Samples were obtained while the engine was operating at a "low speed ground idle" engine throttle setting used for start-up. The start time was recorded on the data sheet. Sampling duration varied from 2 to 3 min. The temperature profiles of the exhaust duct and the PS-1 outlets were monitored throughout the sampling period and captured electronically. The temperature profiles provided another system check to ensure samplers were operating. If the temperature at the outlet of a PS-1 reached 100°C, then the PS-1 sampler at that site would be shut down to avoid damaging the resin trap. Pressure differentials from the pitot tubes were measured with oil manometers. Pressures were recorded for each section at approximately 1-min intervals. The static pressure from Section 3 of the exhaust duct was measured with a magnehelic gauge and recorded at 1-min intervals.

After shutting down the sampling equipment, engine testing continued for another 60 to 90 min during which access to the samplers was not permitted for safety reasons. When access to the exhaust duct was granted, the samplers were removed from the exhaust duct, the impactor inlets were sealed with Teflon® tape, and the samplers were transported back to the room where the filters and resin cartridges had been stored and loaded. The resin cartridge from the PS-1 was immediately unloaded and packed in dry ice to minimize vapor losses. The impactors were given approximately 1 hr to equilibrate prior to weighing of the filters under the same conditions used for the initial weighing. The filters were then weighed, sealed into a Petri dish, and packed

in dry ice. Lastly, an aliquot of deuterium labeled chrysene- d_{12} was added to an unused XAD-2 resin cartridge as a combined field spike and field blank.

4.3. Tests Descriptions

A background sample was obtained on 21 June 97 at 20:07 EDT. The chamber temperature was 27.7°C. The jet engine was not operating during the background test so flow through the duct was negligible. The outlet of the exhaust duct was open to the outside environment. The duct had been exposed to jet exhaust from previous high temperature tests conducted on the jet engine. Sampling duration for the background test was 30.3 min. The Aerosizer was not used in this test. The thermocouples monitoring the exhaust gas and PS-1 outlet were also not in operation during the background test. Impactor slides showed negligible mass increases after the background test.

A baseline test was performed on 23 June 97 at 13:44 EDT. The chamber temperature was 14.4°C. Engine 4 was started following normal start-up procedures and operated at “low speed ground idle” for approximately 4 min. The PS-1 samplers and impactors were controlled remotely and started when the pilot started the engine. The duration of sampling for the impactors and PS-1’s was 2 min. The maximum temperature recorded at the outlet of a PS-1 was 72°C at Section 2. This temperature was well below the 100°C limit and indicated the sampling duration could be increased to 3 min in future tests. Figure 4-4 shows the temperature log obtained during the baseline test. The temperature of the chamber recorded in the log is several degrees colder than the temperature recorded by climatic chamber instruments and our hand-held temperature probe (Catalog No. 22-174B, Radio Shack, Fort Worth, TX). The temperature difference may be due to the position of the ambient temperature probe beneath a cold air inlet duct to the climatic chamber. Large amounts of rust were collected on impactor and PS-1 filters.

The first cold temperature test was performed on 25 June 97 at 11:48 EDT. The chamber temperature was -23°C (-9°F). Engine 4 was cold and started and operated at “low speed ground idle” throttle setting for approximately 4 min before Engine 2 was started. The PS-1 samplers and impactors were controlled remotely and started when the pilot started Engine 4. The

Engine 4 Exhaust Duct Temperature Profile
Climatic Chamber
Baseline Test (68°F)
23 June 1997

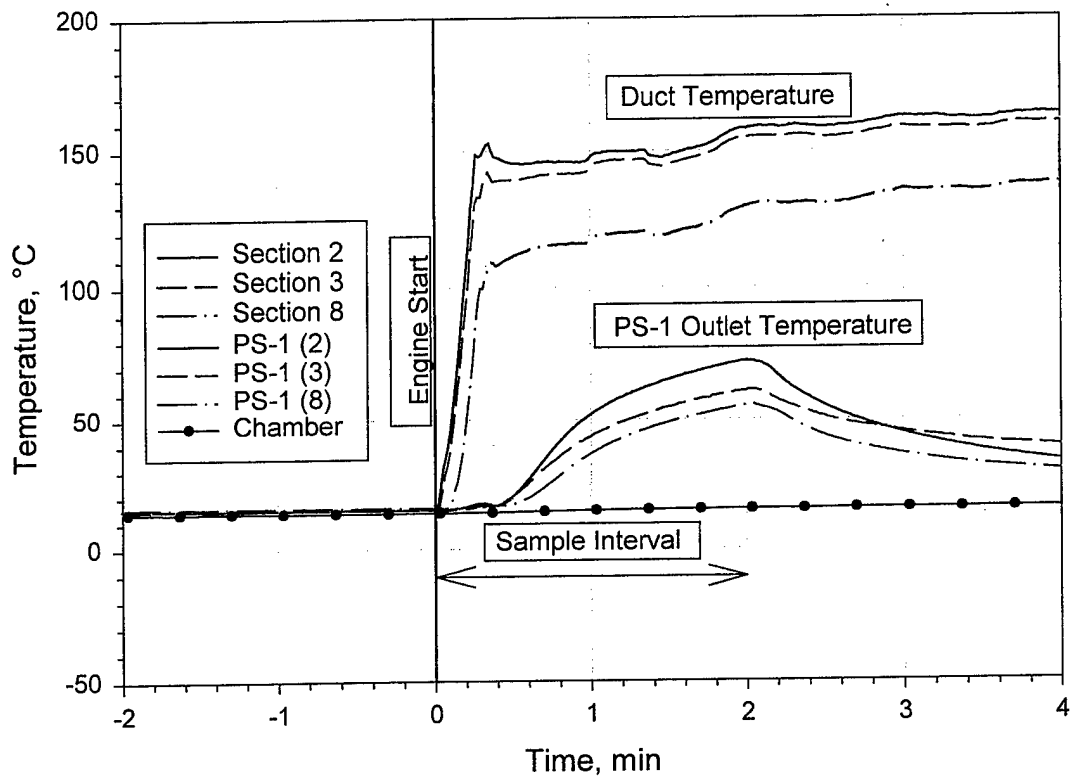


Figure 4-4. Temperature Profiles During the 68°F Climatic Chamber Test

sampling equipment was operated for 3 min. Figure 4-5 shows the temperature log obtained during the -9°F test. The aircraft manufacturer's test personnel provided six readings of the fuel flow to Engine 4 during the 3-min sampling period. The average fuel flow was 360 lb/hr, thus Engine 4 consumed approximately 8.2 kg of JP-8 during the 3-min sampling period. Impactor and PS-1 filters collected considerably less rust than the previous baseline test. A strong jet fuel odor was detected on several of the impactor filters upon their removal from the impactor.

The second cold temperature test was performed on 30 June 97 at 11:33 EDT after a 30-min delay caused by an auxiliary power unit's (APU) failure to start. The chamber temperature was -30°C (-22°F). Engine 4 was cold started following normal start-up procedures and operated at "low speed ground idle" for approximately 4 min. The PS-1 samplers and impactors were controlled remotely and started simultaneously with the engine. The sampling equipment was operated for 3 min after engine start-up. Figure 4-6 shows the temperature log obtained during the -22°F test. The aircraft manufacturer's test personnel provided three readings of the fuel flow to Engine 4 during the 3-min sampling period. The average fuel flow was 407 lb/hr, thus Engine 4 consumed approximately 9.2 kg of JP-8 during the 3-min sampling period. Again, a strong jet fuel odor was noted on the impactor filters upon removal from the impactors. Several filters were also noted to have a considerable amount of moisture on them.

The engine produced a visible plume during the -9°F and -22°F tests that was not detected during the baseline test. The visible plume lasted approximately 5 seconds after the start of Engine 4. Figure 4-7 shows the plume at the exit of the exhaust duct. The duration of the visible plume was not recorded during the -9°F test.

The final cold temperature test was performed on 03 July 97 at 11:50 EDT. The chamber temperature was -40°C (-40°F). The test was halted when Engine 4 failed to start. No samples were obtained at this temperature due to engine problems and time constraints. The sampling system was removed from the exhaust duct and the climatic chamber testing was completed. A 100 mL sample of JP-8 was removed from the same JP-8 supply as that used to fuel the aircraft. The fuel sample was used to characterize the compounds in the JP-8 fuel.

Engine 4 Exhaust Duct Temperature Profile
Climatic Chamber
Minus Nine Degree Test (-9°F)
25 June 1997

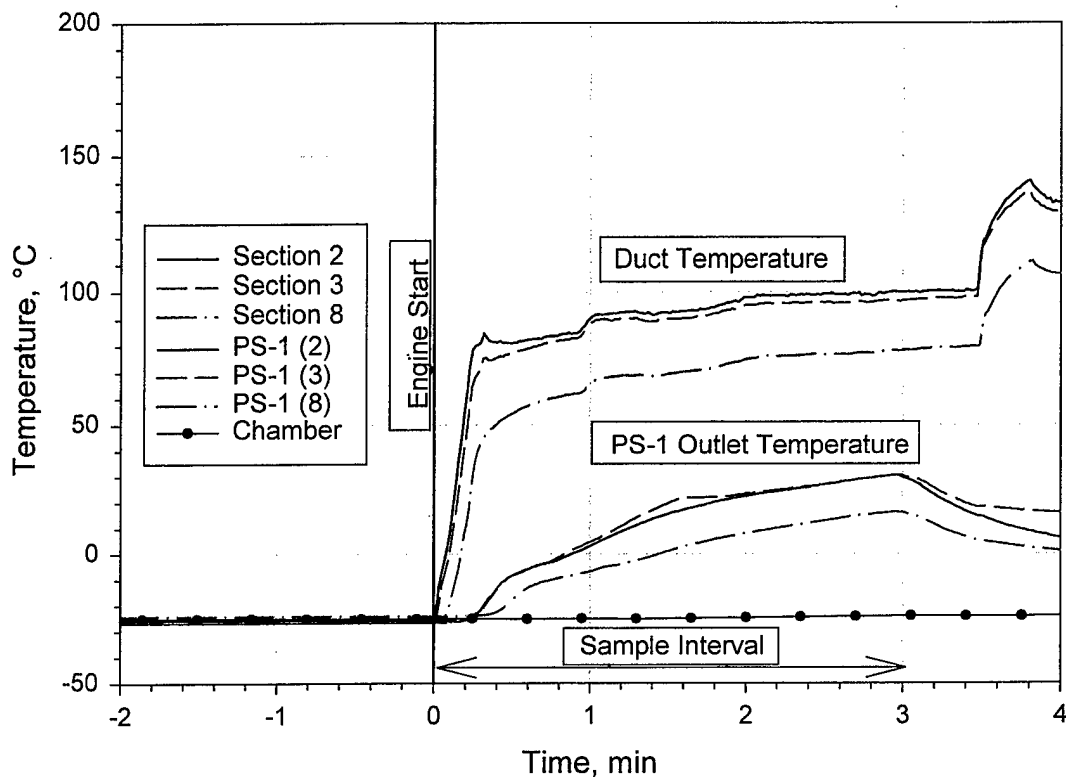


Figure 4-5. Temperature Profiles During the -9°F Climatic Chamber Test

Engine 4 Exhaust Duct Temperature Profile
Climatic Chamber
Minus Twenty Two Test (-22°F)
30 June 1997

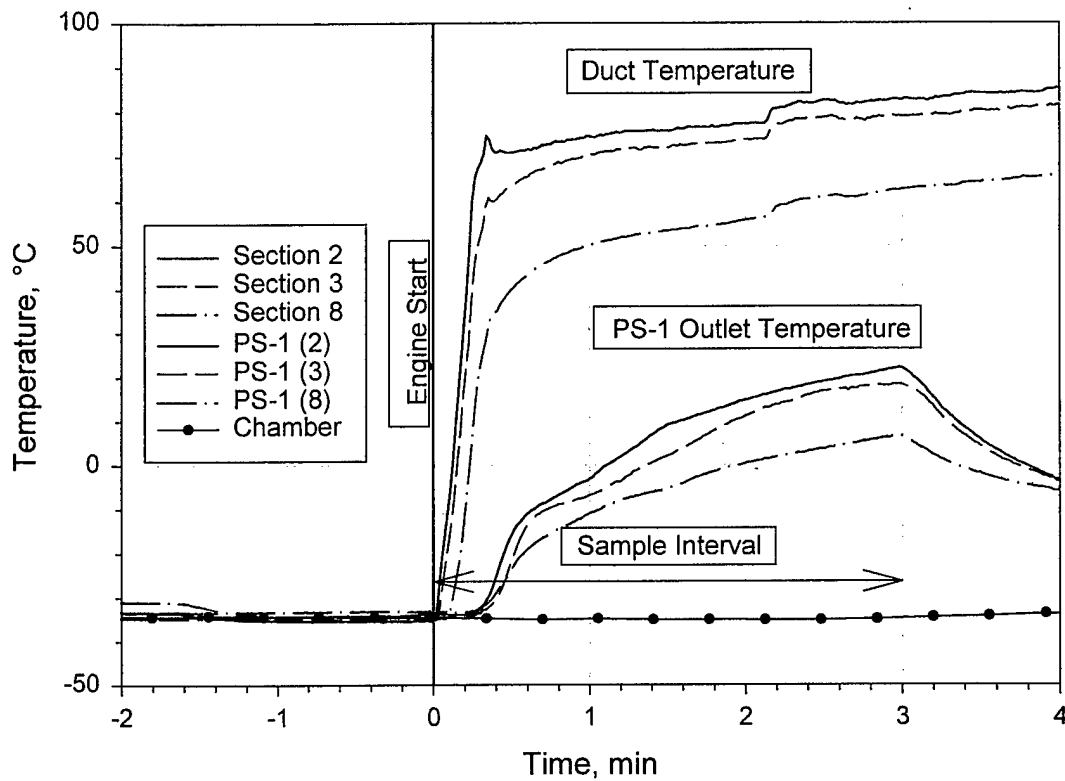


Figure 4-6. Temperature Profile During the -22°F Climatic Chamber Test



Figure 4-7. Video Image of the Plume at the Exit of the Exhaust Duct at the Start of the -22°F Climatic Chamber Test

4.4 Test Findings

The environment of the engine exhaust during the tests conducted in the climatic chamber was very different from that during the flight line tests. In the climatic chamber tests the exhaust was confined inside the duct so the dilution and cooling of the exhaust gases by the cold air in the chamber was limited to the cold air entrained from the chamber at the gap between the engine exhaust outlet and the 24-inch diameter exhaust duct section. Therefore, we anticipated a higher concentration of engine exhaust gases inside the exhaust duct during the climatic chamber tests. High exhaust duct temperatures increased the probability that any unburned JP-8 fuel aerosol emitted by the engine would evaporate in the duct, while the high concentration of engine exhaust gases increased the probability that unburned fuel would be collected on the impactor filters. Therefore, it was not clear whether the phase distribution of the unburned fuel would shift toward the condensed or vapor state.

As the temperature logs of the previous section show, the temperatures inside the exhaust duct rapidly exceeded values for which an aerosol plume was expected to occur. Visual observations at the exit of the exhaust duct confirmed that a visible aerosol plume only occurred during the initial few seconds of the -9°F and the -22°F tests. The odor of JP-8 detected on the impactor filters after the low temperature tests suggested that unburned JP-8 fuel was present; however, the decrease in the weight of the filters while they were being weighed after the low temperature tests indicated that water or other volatile materials were evaporating from the filters. The odor of JP-8 also indicated that the JP-8 aerosol was evaporating from the impactor filters during the weighing process. Since filters in the PS-1 samplers were not weighed, they were stored more quickly than the impactor filters and were less subject to evaporation of any JP-8 aerosol collected on the filters. Loss from the XAD-2 resin is not significant at normal ambient temperatures; however, at the elevated temperatures in the exhaust duct some loss of the most volatile components of the JP-8 fuel may occur during sampling.

The PS-1 samplers collected significant quantities of unburned JP-8 fuel from the exhaust duct during all of the climatic chamber tests. In the background test a small quantity of JP-8 was detected at the sample site in Section 2 closest to Engine 4. The JP-8 in the background sample

corresponded to an airborne JP-8 concentration of 0.075 mg/m³ with a blank concentration of just 0.055 mg/m³. The low concentration of JP-8 in the background sample indicated that there was little carryover of JP-8 fuel in the exhaust duct from the prior high temperature tests conducted on the aircraft. The samples collected at Sections 3 and 8 during the background test were not analyzed, because the low JP-8 concentration in the sample nearest to the engine confirmed that the JP-8 contamination on the interior surfaces of the exhaust duct was not significant when compared to the quantities of JP-8 collected during the baseline and the low temperature tests.

Table 4-2 shows the concentrations of unburned JP-8 fuel detected in the PS-1 samples from the climatic chamber tests. The JP-8 concentrations decrease from the engine toward the outlet of the exhaust duct. As expected, the amount of unburned JP-8 increased at the lower climatic chamber temperatures. The JP-8 concentrations in Table 4-2 are the sum of the vapor and the aerosol portions of the engine emissions because each PS-1's filter and adsorbent pair was combined for the extraction and analysis.

Table 4-2. Measured Concentrations of Unburned JP-8 Fuel in the PS-1 Samples of the Climatic Chamber Tests

Test ID	Behind Engine (Duct Section 2) (mg/m ³)	Near Tail (Duct Section 3) (mg/m ³)	Duct Outlet (Duct Section 8) (mg/m ³)	Field Blank (mg/m ³)
68°F (Baseline)	33.9	NA ^(a)	21.2	0.8
-9°F	49.7	44.3	32.1	0.5
-22°F	81.0 ^(b)	72.9	64.1	0.4

(a) Sample was not analyzed.

(b) Corrected for aerosol probe collection efficiency.

Figures 4-8 through 4-10 show the chromatograms of the extracts from the PS-1 samples collected at the first sample site (duct Section 2) for the baseline, -9°F, and -22°F tests, respectively. Each of the PS-1 samples shown in Figures 4-8 through 4-10 was diluted with DCM prior to the analysis to keep the Gas Chromatograph/Flame Ionization (GC/FID) peaks within the range of the calibration curve of the instrument. Figure 4-11 shows the chromatogram

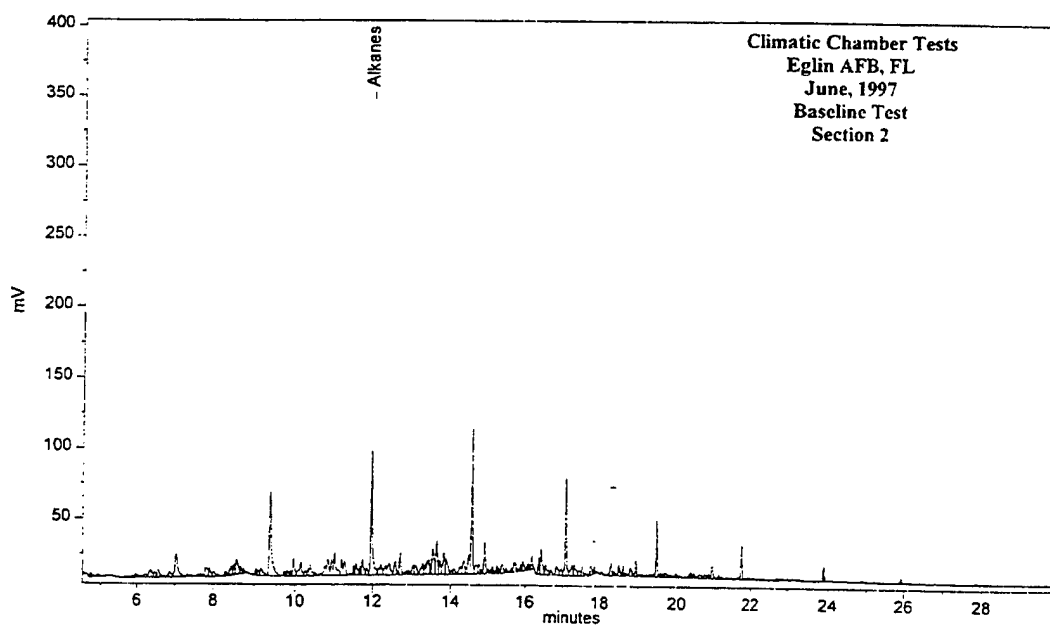


Figure 4-8. Chromatogram of the PS-1 Sample from Section 2 of the 68°F Climatic Chamber Test

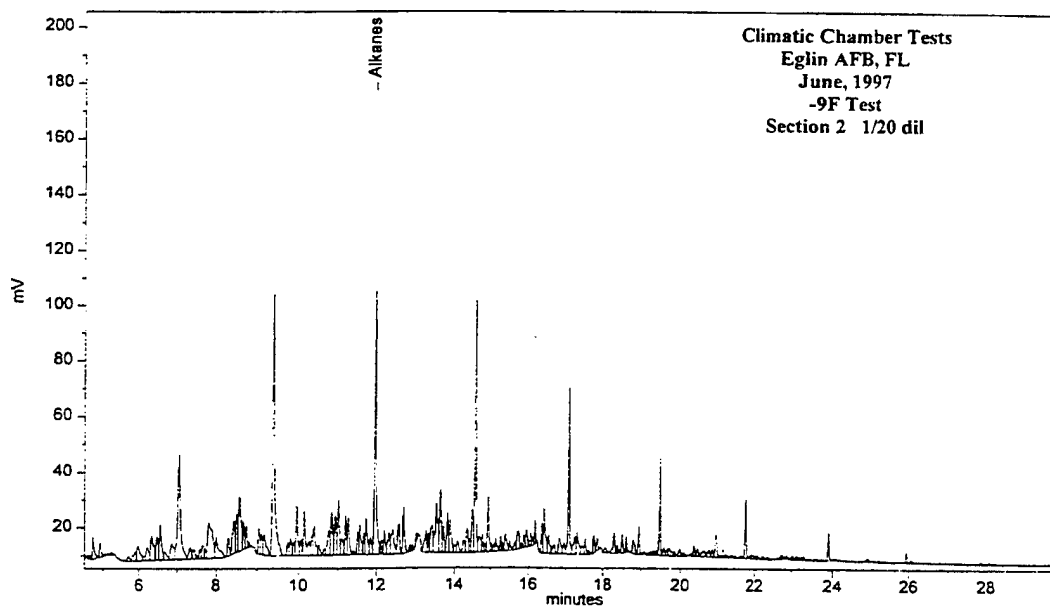


Figure 4-9. Chromatogram of the PS-1 Sample from Section 2 of the -9°F Climatic Chamber Test

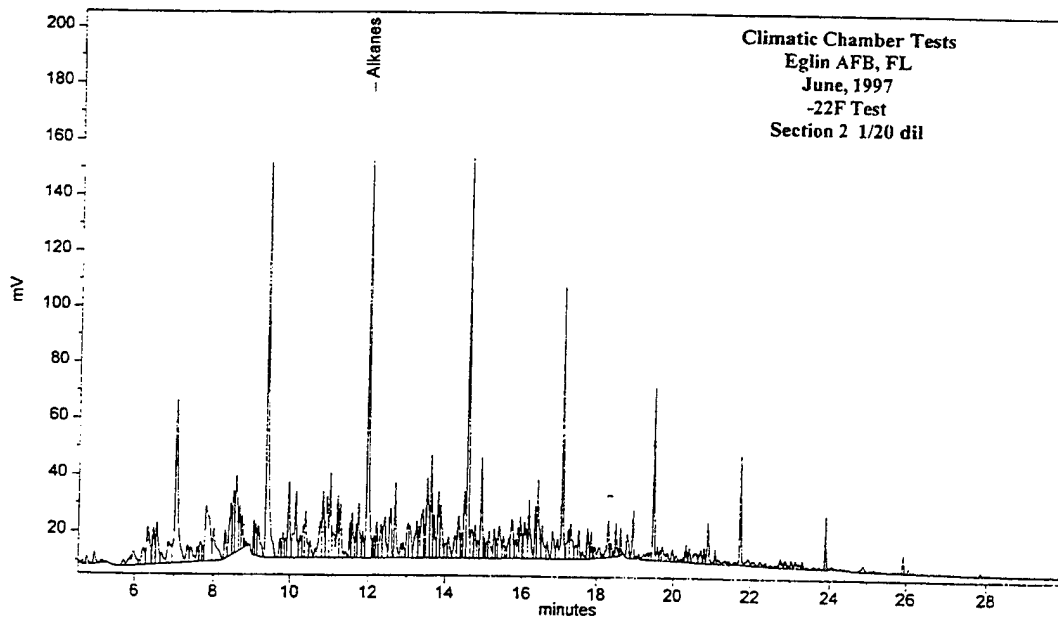


Figure 4-10. Chromatogram of the PS-1 Sample from Section 2 of the -22°F Climatic Chamber Test

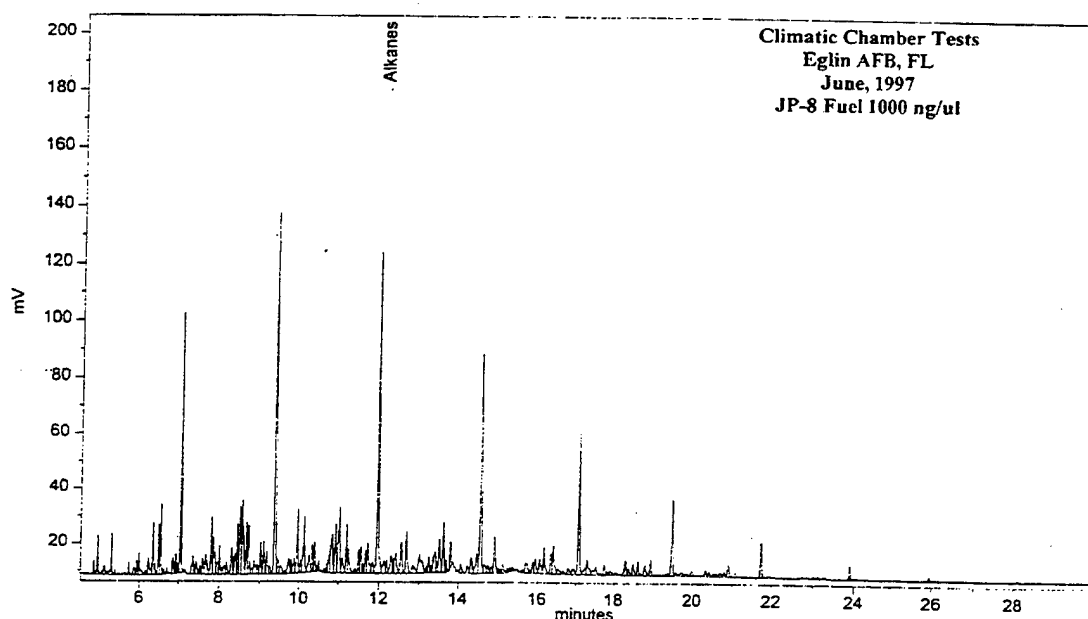


Figure 4-11. Chromatogram of the JP-8 Fuel from Eglin AFB, FL

of the raw JP-8 fuel for comparison. The largest peaks in the chromatograms are due to the straight-chain alkanes C₁₁ (undecane at ~7 min) through C₂₀ (icosane at ~28 min).

The chromatograms clearly show that the most volatile JP-8 components (the components with the shortest retention times on the GC column) are present in lower concentrations in the PS-1 samples taken from the exhaust duct rather than in the raw JP-8 fuel. As expected, lower concentrations of the volatile JP-8 components were found in the PS-1 sample taken during the baseline test than during the two low temperature tests. The reduced JP-8 concentrations shown in Table 4-2 for the baseline test were not caused primarily by preferential losses of the volatile straight-chain alkanes because the straight-chain alkanes comprise only a small percentage of the total peak area in the chromatograms.

Table 4-3 shows the concentrations of unburned JP-8 fuel detected on the impactor filters from the climatic chamber tests. The JP-8 concentrations on the impactor filters were near the JP-8 concentrations found in the field blanks in almost all cases. The -22°F test was the only test that showed the presence of unburned JP-8 fuel on the impactor filters, and the unburned JP-8 aerosol was detected only in the respirable size fraction of the aerosol. The JP-8 concentrations in Table 4-3 are based on the total peak area of the chromatogram of JP-8, as described in Section 2.1.

Figures 4-12 and 4-13 show the gas chromatograms of the extracts of the backup and the 1 to 10 µm stage filters, respectively, from the impactor at Section 2 for the -22°F test. The loss of the volatile components from the samples is evident from the chromatograms. There are several possible explanations for the observed loss of the volatile compounds in the unburned JP-8 from the impactor filters from the -22°F test. Reasons for the loss include, but are not limited to, combustion of the volatile components in the engine, evaporation of the volatile components from the JP-8 aerosol, condensation of the nonvolatile JP-8 components in the cold impactors, or a combination of these reasons. If evaporation of the volatile components is the reason for the loss of the volatile JP-8 components, the evaporation may have occurred inside the duct or after

Table 4-3. Measured Concentrations of Unburned JP-8 Fuel Determined from the Impactor Filters from the Climatic Chamber Tests

Test	Sample Location	JP-8 Aerosol Concentration (mg/m ³)			
		Impactor >20 µm	Impactor 10-20 µm	Impactor 1-10 µm	Impactor <1 µm
68°F (Baseline)	Section 2	3.5	3.5	3.5	3.5
68°F (Baseline)	Section 3	3.5	NA ^(a)	NA	NA
68°F (Baseline)	Section 8	3.4	3.5	3.5	3.7
68°F (Baseline)	Field Blank	3.5			3.6
-9°F	Section 2	NA	NA	2.3	2.5
-9°F	Section 3	NA	NA	NA	NA
-9°F	Section 8	NA	NA	NA	NA
-9°F	Field Blank	2.3			2.4
-22°F	Section 2	2.3	2.3	2.9	2.9
-22°F	Section 3	2.3	2.3	2.3	2.5
-22°F	Section 8	2.3	2.3	2.6	2.6
-22°F	Field Blank	2.3			2.4

(a) Sample was not analyzed.

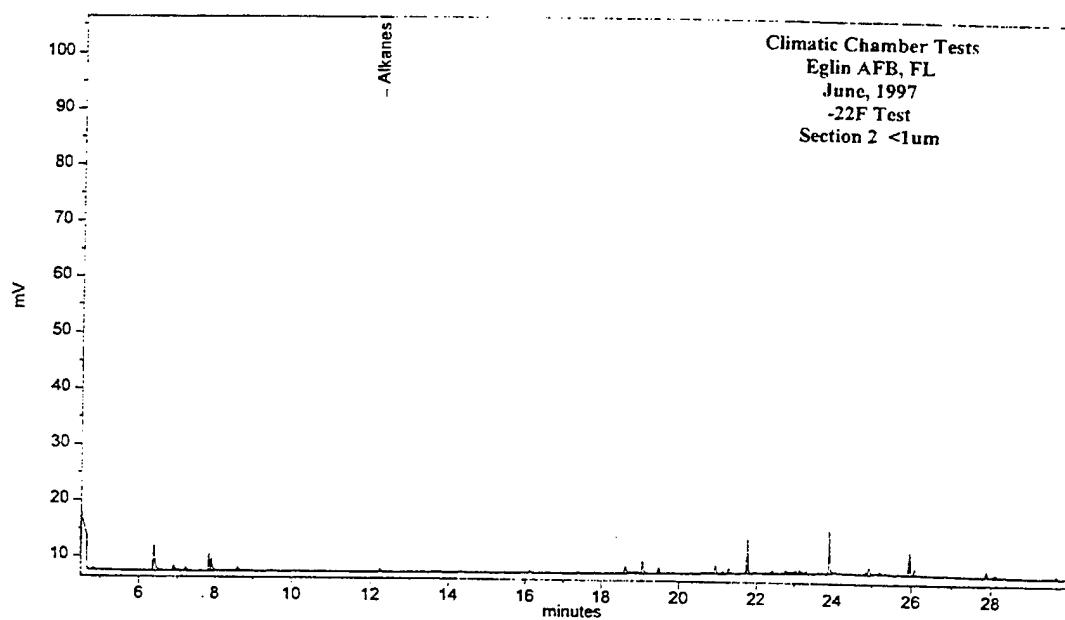


Figure 4-12. Chromatogram of the Impactor Backup Filter at Section 2 of the -22°F Climatic Chamber Test

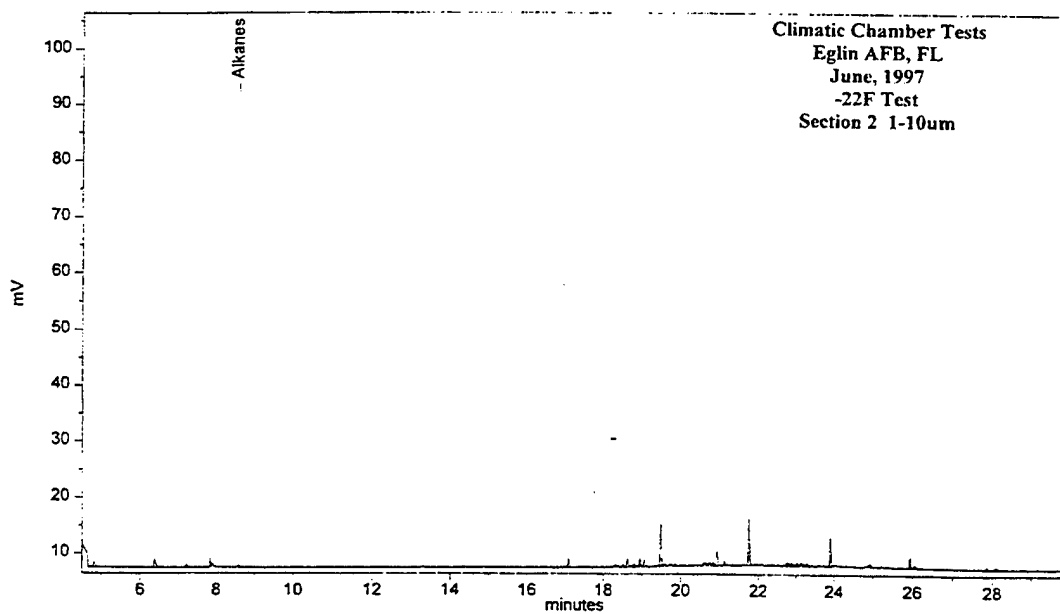


Figure 4-13. Chromatogram of the 1 to 10 μm Impactor Stage Filter at Section 2 of the -22°F Climatic Chamber Test

the samples were collected. Since the volatile JP-8 components remained in the PS-1 samples, the volatile components were not removed by combustion in the engine. The lack of volatile JP-8 aerosol at Section 3 suggests that both evaporation in the duct and condensation in the impactors occurred during the -22°F test because the aerosol collected by the impactor at Section 2 was not found at Section 3 and reappeared in the impactor sample at Section 8 where the duct temperature was lower. The odor of JP-8 observed during the weighing of the impactor filters indicates that evaporation also occurred after the samples were collected, but before the samples were packed in dry ice. Given the probability of multiple causes for the loss of the volatile JP-8 fuel components, an accurate assessment of the total quantity of unburned JP-8 aerosol emitted by the engine would appear unlikely.

Fortunately, the nonadecane and icosane peaks in Figures 4-12 and 4-13 are present in the same relative abundance on the impactor filters and in the raw JP-8 fuel, which indicates that the heavy hydrocarbon compounds can be used to estimate the quantity of unburned JP-8 aerosol emitted by the engine. To estimate the original quantity of JP-8 aerosol emitted by the engine during the -22°F test, we prepared a second GC calibration curve using only the nonadecane and icosane GC peak areas in the standard solutions. The impactor filter samples that contained JP-8 aerosol were reanalyzed based on the nonadecane and icosane concentrations in the samples. Table 4-4 shows the estimated original unburned JP-8 concentrations in the reanalyzed impactor filter samples. The estimated total original JP-8 aerosol concentrations given in Table 4-4 are in excellent agreement with the total JP-8 concentrations determined from the analyses of the corresponding PS-1 samples shown in Table 4-2 above. The unburned JP-8 aerosol collected at Section 2 was probably emitted by the engine as aerosol, which then evaporated in the duct before reaching the samplers at Section 3. The JP-8 aerosol collected at Section 8 was probably formed by recondensation of JP-8 vapors within the duct or cold impactor. No unburned JP-8 aerosol was detected on the 10 to 20 μm or $> 20 \mu\text{m}$ impactor stage filters from the climatic chamber tests.

Table 4-4. Estimated Original Concentrations of Unburned JP-8 Fuel Based on the Impactor Filters from the -22°F Climatic Chamber Test (Nonadecane and Icosane Only)

Sample Location	JP-8 Concentration (mg/m ³)		
	Impactor 1-10 µm	Impactor <1 µm	Total
Section 2	24.0 ^(a)	49.8 ^(a)	73.8
Section 3	ND ^(b)	ND	ND
Section 8	22.2 ^(a)	25.0 ^(a)	47.2 ^(a)

(a) Corrected for aerosol probe collection efficiency.

(b) Nonadecane and icosane peaks were not detected.

Table 4-5 shows the results of the PAH analyses of the samples collected by the PS-1 samplers during the background and the baseline tests. The PAH concentrations detected in the exhaust duct during the background test, while clearly above the equivalent concentrations derived for the field blank, are negligible when compared with the PAH concentrations found in the baseline test. Table 4-6 shows the results of the PAH analyses of the samples collected by the PS-1 samplers during the low temperature climatic chamber tests. The semi-volatile and nonvolatile PAH concentrations shown in Tables 4-5 and 4-6 have been corrected for the effects of an isokinetic sampling by dividing the measured PAH concentration by the correction factor 0.99. The volatile PAH naphthalene, biphenyl, and acenaphthylene comprise the bulk of the PAH collected in the PS-1 samplers. Figures 4-14 and 4-15 show the measured concentrations of the B2 PAH and BAP, respectively, in the samples collected by the PS-1 samplers. The PAH concentrations are reported as µg/m³ to ease reading of the tables, but are plotted as ng/m³ to aid comparison with the results of the flight line tests to be presented in Section 5.4.

Figures 4-16 and 4-17 show the measured concentrations of the B2 PAH and BAP determined from the aerosol collected on the impactor filters during the climatic chamber tests. Tables

Table 4-5. Measured Concentrations of PAH Determined from the PS-1 Samples
from the Baseline and Background Climatic Chamber Tests

Compound	PAH Concentration ($\mu\text{g}/\text{m}^3$)									
	Baseline Test					Background Test				
	Section 2	Section 3	Section 8	Field Blank	Section 2	Section 3	Section 8	Field Blank	Section 2	Field Blank
Naphthalene	33.59	NA ^(a)	27.49	0.43	0.067	NA	NA	0.026	NA	0.026
Biphenyl	8.63	NA	5.71	0.01	0.011	NA	NA	0.001	NA	0.001
Acenaphthylene	4.94	NA	2.94	0.004	0.001	NA	NA	0.000	NA	0.000
Acenaphthene	0.78	NA	0.50	0.02	0.005	NA	NA	0.001	NA	0.001
Fluorene	2.36	NA	1.36	0.01	0.004	NA	NA	0.001	NA	0.001
Phenanthrene	2.00	NA	1.25	0.11	0.014	NA	NA	0.004	NA	0.004
Anthracene	0.37	NA	0.16	0.01	0.001	NA	NA	0.001	NA	0.001
Flouranthene	0.52	NA	0.30	0.03	0.005	NA	NA	0.002	NA	0.002
Pyrene	0.64	NA	0.32	0.01	0.002	NA	NA	0.001	NA	0.001
Cyclopenta[c,d]pyrene	0.14	NA	0.03	0.01	0.001	NA	NA	0.001	NA	0.001
Benz[a]anthracene ^(b)	0.07	NA	0.04	0.01	0.001	NA	NA	0.001	NA	0.001
Chrysene	0.07	NA	0.04	0.01	0.001	NA	NA	0.001	NA	0.001
Benzo[b]fluoranthene ^(b)	0.09	NA	0.04	0.01	0.001	NA	NA	0.001	NA	0.001
Benzo[k]fluoranthene ^(b)	0.04	NA	0.02	<0.004	0.001	NA	NA	0.001	NA	0.001
Benzo[e]pyrene	0.04	NA	0.02	<0.004	0.0003	NA	NA	<0.0003	NA	<0.0003
Benzo[a]pyrene ^(b)	0.05	NA	0.01	<0.004	<0.0003	NA	NA	<0.0003	NA	<0.0003
Indeno[1,2,3-c,d]pyrene ^(b)	0.09	NA	0.03	<0.004	<0.0003	NA	NA	<0.0003	NA	<0.0003
Dibenz[a,h]anthracene ^(b)	0.01	NA	0.01	<0.004	<0.0003	NA	NA	<0.0003	NA	<0.0003
Benzo[g,h,i]perylene	0.11	NA	0.03	<0.004	<0.0003	NA	NA	<0.0003	NA	<0.0003
Coronene	0.06	NA	0.02	<0.004	<0.0003	NA	NA	<0.0003	NA	<0.0003
Sum of B2 PAH	0.42	NA	0.19	0.03	0.003	NA	NA	0.003	NA	0.003
Sum of Target PAH	54.6	NA	40.3	0.68	0.116	NA	NA	0.041	NA	0.041

(a) Sample was not analyzed.

(b) B2 PAH Compounds

Table 4-6. Exhaust Concentrations of PAH Determined from the PS-1 Samples
from the Low Temperature Climatic Chamber Tests

Compound	PAH Concentration ($\mu\text{g}/\text{m}^3$)									
	-9°F Test					-22°F Test				
	Section 2	Section 3	Section 8	Field Blank	Section 2	Section 3	Section 8	Field Blank	Section 2	Field Blank
Naphthalene	42.97	39.38	36.98	0.338	45.28	48.66	39.07	0.261		
Biphenyl	9.44	8.64	7.42	0.006	12.16	12.97	10.08	0.006		
Acenaphthylene	5.40	4.77	3.69	<0.003	8.05	7.08	5.38	0.003		
Acenaphthene	0.55	0.50	0.44	0.013	0.83	0.97	0.67	0.009		
Fluorene	2.62	2.33	1.76	0.009	3.96	3.71	2.74	0.006		
Phenanthrene	2.41	2.23	1.76	0.034	3.77	4.02	2.98	0.026		
Anthracene	0.26	0.23	0.11	0.006	0.42	0.41	0.31	0.005		
Flouranthene	0.68	0.56	0.46	0.026	1.09	1.20	0.82	0.020		
Pyrene	0.80	0.66	0.50	0.009	1.32	1.41	0.93	0.007		
Cyclopenta[c,d]pyrene	0.05	0.04	0.02	0.008	0.08	0.07	0.04	0.009		
Benz[a]anthracene ^(a)	0.07	0.05	0.03	0.010	0.10	0.11	0.08	0.009		
Chrysene ^(a)	0.08	0.05	0.05	0.007	0.12	0.14	0.11	0.006		
Benzo[b]flouranthene ^(a)	0.11	0.09	0.08	0.007	0.19	0.21	0.17	0.008		
Benzo[k]flouranthene ^(a)	0.04	0.03	0.03	0.007	0.06	0.07	0.06	0.007		
Benzo[e]pyrene	0.05	0.04	0.04	<0.003	0.09	0.10	0.08	<0.003		
Benzo[a]pyrene ^(a)	0.02	0.02	0.02	<0.003	0.05	0.05	0.04	<0.003		
Indeno[1,2,3-c,d]pyrene ^(a)	0.19	0.19	0.15	<0.003	0.37	0.45	0.36	<0.003		
Dibenz[a,h]anthracene ^(a)	0.02	0.02	0.02	<0.003	0.03	0.03	0.03	<0.003		
Benzo[g,h,i]perylene	0.18	0.18	0.14	<0.003	0.38	0.44	0.35	<0.003		
Coronene	0.10	0.12	0.11	<0.003	0.23	0.31	0.26	<0.003		
Sum of B2 PAH	0.52	0.45	0.37	0.031	0.93	1.06	0.86	0.031		
Sum of Target PAH	66.04	60.13	53.79	0.480	78.58	82.41	64.58	0.382		

(a) B2 PAH Compounds

Sum of B2 PAH Concentrations
Climatic Chamber Tests
McKinley Climatic Laboratory, Eglin AFB
June, 1997

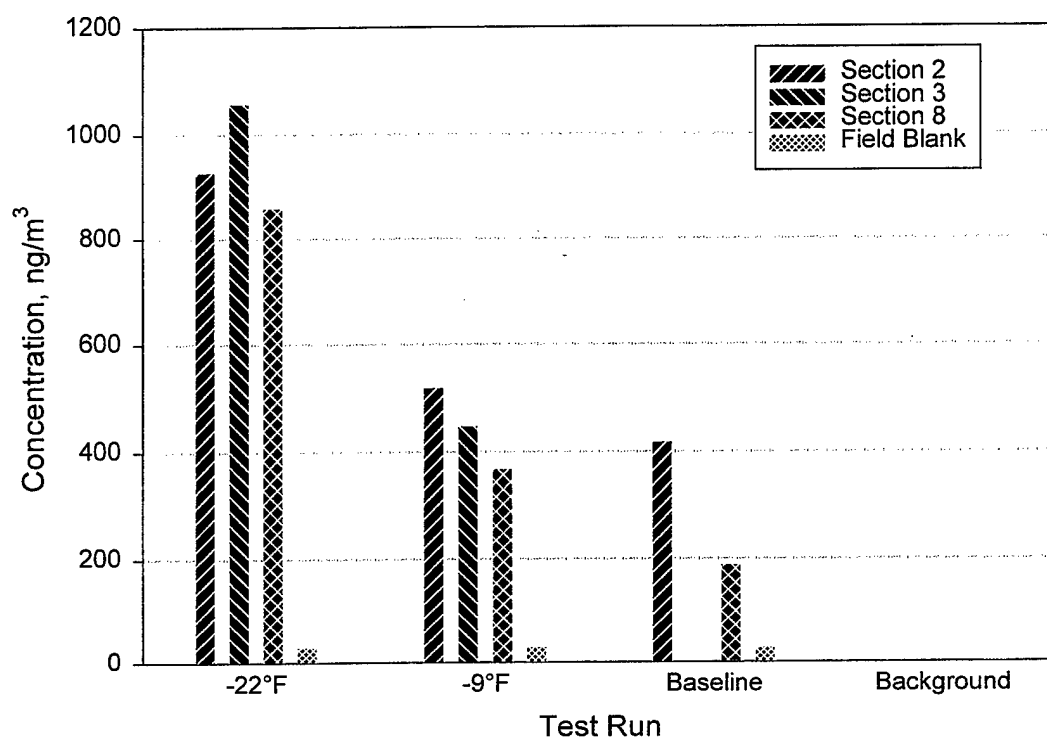


Figure 4-14. Sum of the B2 PAH Concentrations in the PS-1
Samples of the Climatic Chamber Tests

Benzo[a]pyrene PAH Concentrations
Climatic Chamber Tests
McKinley Climatic Laboratory, Eglin AFB
June, 1997

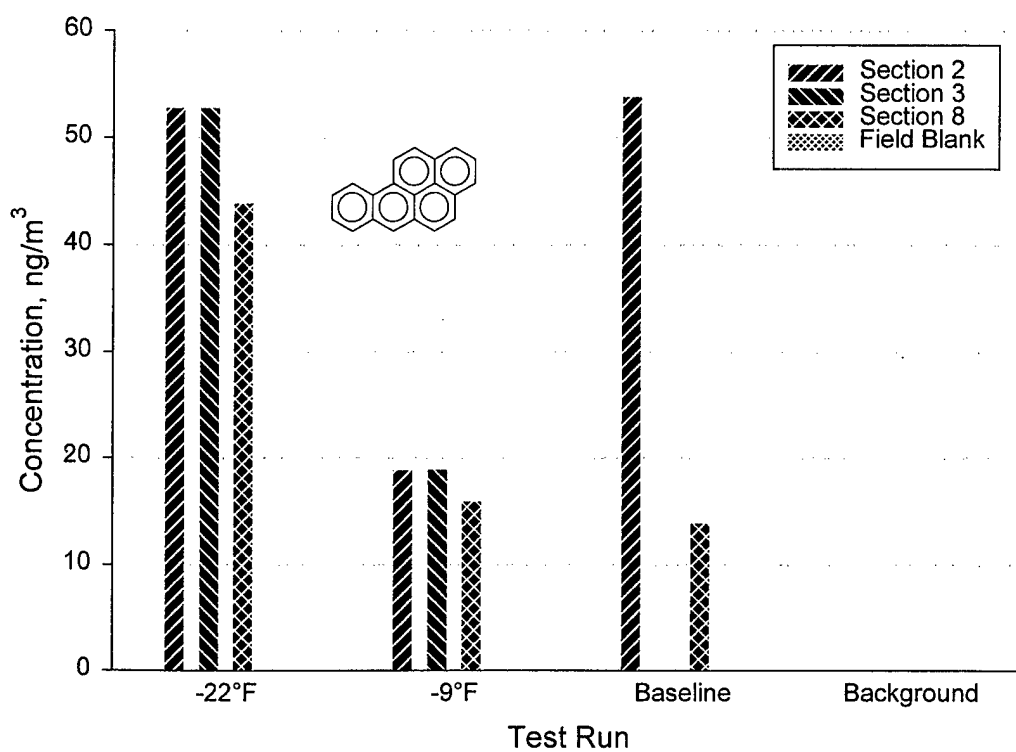


Figure 4-15. Benzo[a]pyrene Concentrations in the PS-1 Samples of the Climatic Chamber Tests

Sum of B2 PAH Concentrations
Climatic Chamber Tests
McKinley Climatic Laboratory, Eglin AFB
June, 1997

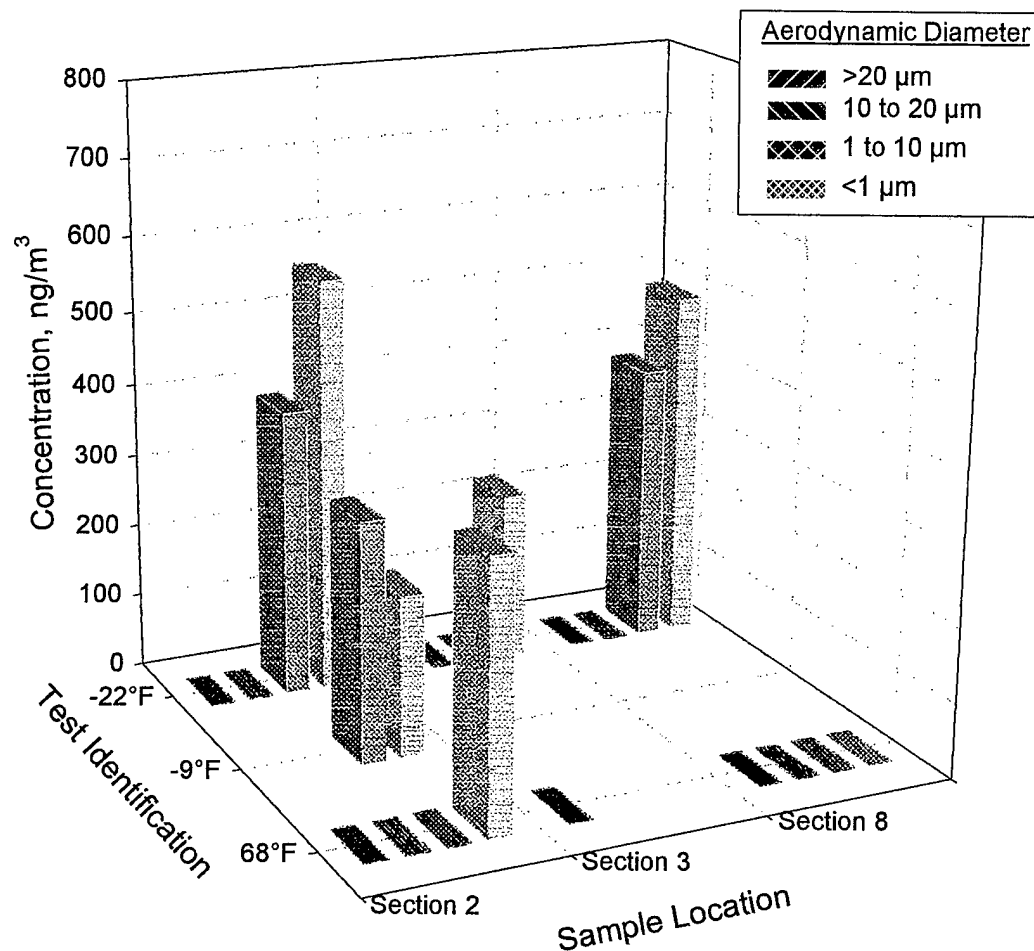


Figure 4-16. Sum of the B2 PAH Concentrations in the Impactor Samples of the Climatic Chamber Tests

Benzo[a]pyrene PAH Concentrations
Climatic Chamber Tests
McKinley Climatic Laboratory, Eglin AFB
June, 1997

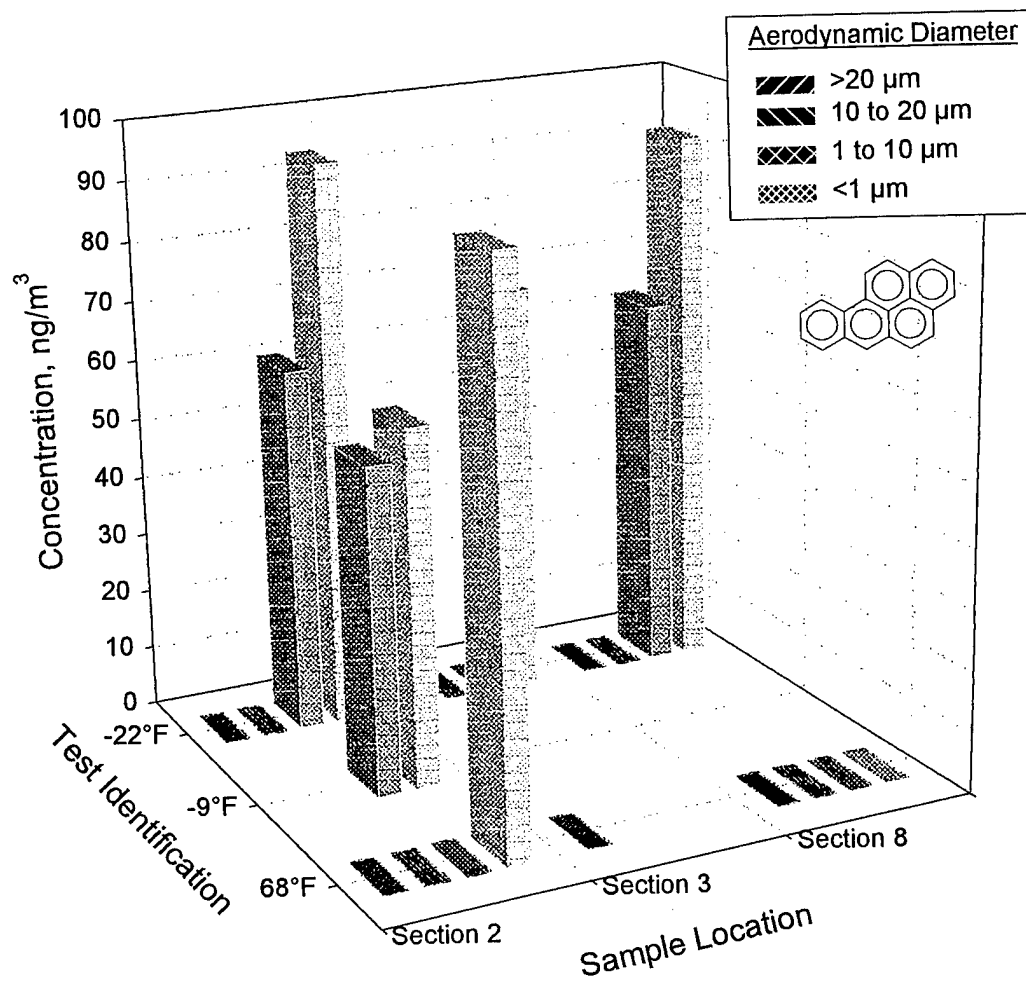


Figure 4-17. Benzo[a]pyrene Concentrations in the Impactor Samples of the Climatic Chamber Tests

showing the PAH concentrations determined from the impactor samples are included in Appendix B. The concentration profiles in the impactor samples are similar to the concentration profiles in the PS-1 samples for most of the PAH compounds measured; however, the impactor samples contain low concentrations of the volatile PAH, as expected.

With a few exceptions, all of the PAH measured in the impactor samples during the climatic chamber tests was found in the respirable fraction of the collected aerosol with the majority of the PAH found in the submicrometer size fraction. The PAH compounds detected on the 10 to 20 μm and $> 20 \mu\text{m}$ impactor filters were typically observed in nearly the same concentrations on the field blank filters.

As noted above, the Aerosizer LD real-time aerosol monitor was mounted outside the climatic chamber at the exit of the exhaust duct. The Aerosizer sampled the engine emissions after the exhaust emissions left the duct but before the emissions had mixed with the hot, humid air outside the climatic chamber. Figure 4-7 above illustrated that the Aerosizer sample probe was located within the plume from the exhaust duct. Figure 4-18 compares the cumulative mass distribution measured by the impactors located at Section 8 with the cumulative volume distribution measured by the Aerosizer at engine start-up. For the baseline test, the impactors indicate that ~75 percent of the aerosol mass was smaller than 1 μm in aerodynamic diameter, while for the low temperature tests, ~50 percent of the aerosol mass was larger than 20 μm . The Aerosizer data are not in good agreement with the impactor mass distribution.

Comparing the aerosol size distributions measured by the impactors and the Aerosizer with the results of the chemical analyses for unburned JP-8 and PAH indicates that most of the aerosol collected by the impactors and the Aerosizer is extraneous material, such as rust particles or water droplets, and not material of interest for this study.

Comparison of the
Impactor and Aerosizer
Particle Size Distributions
Climatic Chamber Tests
June - July, 1997

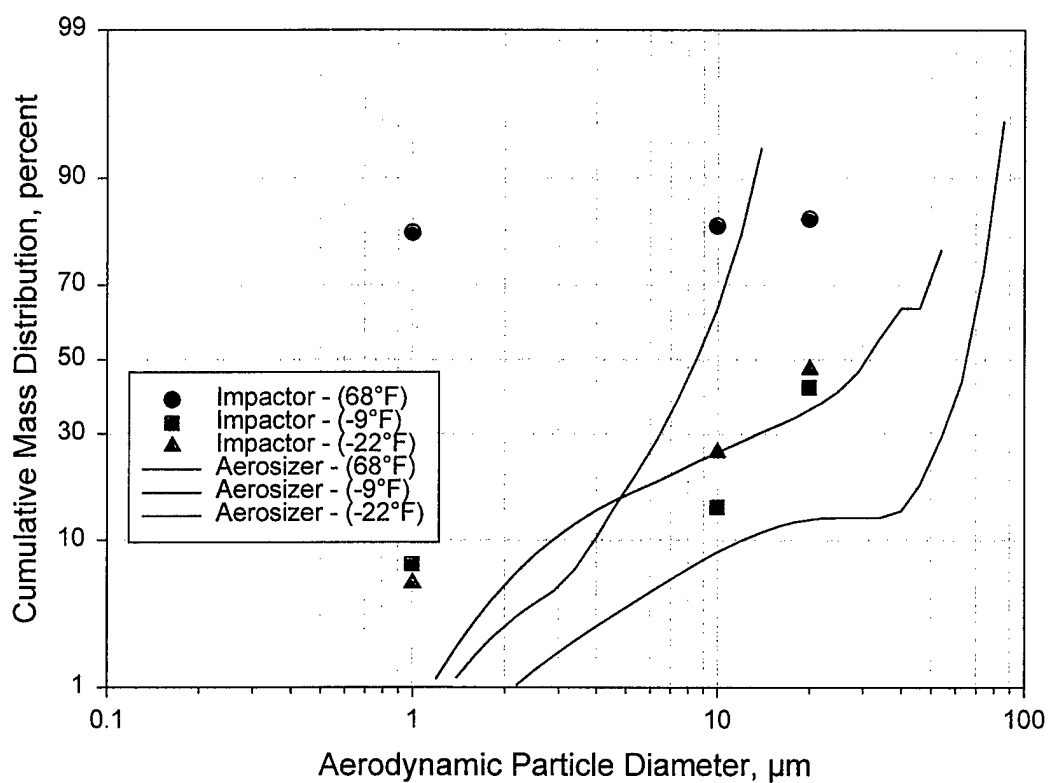


Figure 4-18. Comparison of the Impactor Mass Distribution
and the Aerosizer Volume Distributions

The pitot tubes measured the dynamic pressure developed by the exhaust flow within the duct. We calculated the flow velocity, V (ft/min), in the exhaust duct at each sampler location using the measured dynamic pressure and the following equation provided by the pitot tube manufacturer:

$$V = 1096.2 \sqrt{\frac{P_v}{D}}$$

where

P_v is the measured dynamic pressure (in. H_2O)

and D is the density of the exhaust gas (lb/ft^3).

The density of the exhaust gas was evaluated using the following formula for air (Weast, 1969):

$$D = \frac{0.001293}{1 + 0.00367t} P$$

where

D is the air density (g/ml)

t is the gas temperature ($^{\circ}C$)

and P is the gas pressure (atmospheres).

Table 4-7 shows the measured dynamic pressures and the calculated flow velocities (converted to m/sec) in the exhaust duct for each climatic chamber test. The flow velocity at Section 2 is greater than at the two downstream sample locations because the samplers at Section 2 were located approximately 3 duct diameters downstream from the transition from the 24-inch to the 36-inch diameter duct. At only 3 duct diameters from the transition in duct size, the flow profile was concentrated at the center of the duct. The flow profile at Section 3, which is approximately 10 duct diameters downstream of the size transition, appears to be more uniform. The good agreement between the duct flow velocities measured at Section 3 and Section 8 indicates that the flow was uniform at Section 3.

The duct flow velocities and the concentration of unburned JP-8 fuel collected by the PS-1 samplers were used to estimate the fraction of the fuel supplied to Engine 4 that was emitted as unburned JP-8. The flow velocity and JP-8 concentration from Section 3 were used for the estimate because the flow velocity at Section 2 was an overestimate of the flow as described above. The JP-8 concentration from Section 2 was used with the flow at Section 3 for the estimate for the baseline test because the PS-1 sample from Section 3 was not analyzed for the baseline test. The value obtained for the baseline test is an overestimate of the fraction of unburned JP-8 emitted. The estimated fraction of the supplied JP-8 fuel that was emitted by Engine 4 as unburned JP-8 is 1.0, 1.4, and 2.1 percent for the baseline, -9°F, and -22°F climatic chamber tests, respectively. As the results of the flight line tests will show, the new turboprop engine appears to be much more fuel efficient than the engines used on the older aircraft.

Table 4-7. Exhaust Duct Flow Velocities in the Climatic Chamber Tests

Test	Duct Section	Dynamic Pressure (in. H ₂ O)	Temperature (°C)	Flow Velocity (m/Sec)
Baseline	2	1.4	158	26.2
Baseline	3	1	155	22.0
Baseline	8	1	130	21.4
-9°F	2	1.55	100	25.6
-9°F	3	1.2	97	22.4
-9°F	8	1.1	78	20.9
-22°F	2	1.7	83	26.2
-22°F	3	1.3	80	22.8
-22°F	8	1.2	63	21.4

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 5.0 — Flight Line Tests

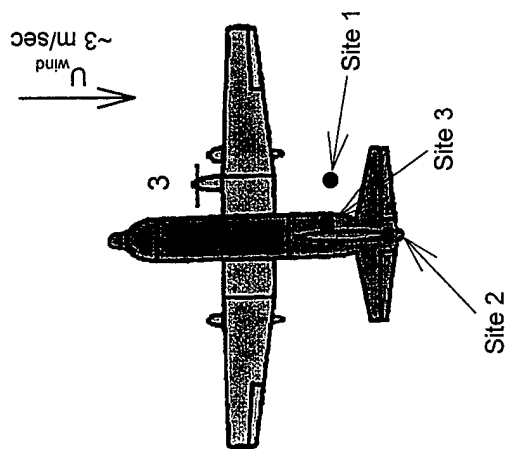
The flight line tests were conducted at the Minneapolis AFS, MN, in January, 1997. The Minneapolis AFS is adjacent to the Minneapolis-St. Paul International Airport and shares the airport runway. The airport generated heavy private and commercial airline traffic on the taxiways adjacent to the flight line where the tests occurred. We performed background tests to measure the impact of that aircraft traffic on our test results. As noted below, the background PAH concentrations observed in this study were approximately two times greater than the PAH concentrations observed in Boston, MA and Columbus, OH in prior studies. Our background PAH concentrations appear to be consistent with the PAH concentrations observed in other large metropolitan areas (Chuang, 1991, Kelly, 1992, and Chuang, 1996).

5.1 Sampling Locations

The sampling sites were chosen to allow sampling of the aerosol in the propeller wash and in locations where ground crew could be exposed to the aerosol plume during loading of the aircraft. Sampling Site 1 was located 10 feet to the side of the rear cargo door, directly behind Engine 3. Site 2 was located in the loading corridor beneath the tail of the aircraft. Site 3 was inside the cargo hold of the plane near the rear troop doors. Figure 5-1 shows the positions of the sampling sites relative to the test aircraft for the flight line tests. Each site included a cascade impactor, a PS-1 medium volume sampler, and a 6-liter SUMMA® canister (U.S. Air Force personnel collected samples at the same locations using personal samplers). Figure 5-2 shows the arrangement of the samplers for the head wind test. Attempts to record real-time aerosol measurements using the API Aerosizer LD and the Malvern System 2600 were unsuccessful due to field operational problems. Aerosol samples in the cascade impactors were collected on glass fiber filters. These filters were weighed on site before and after sampling. After testing, all samples were packed in dry ice to be analyzed upon return to Battelle Columbus Laboratories.

Flight Line Tests Minneapolis AFS, MN January, 1997

Head Wind Test



Tail Wind Test

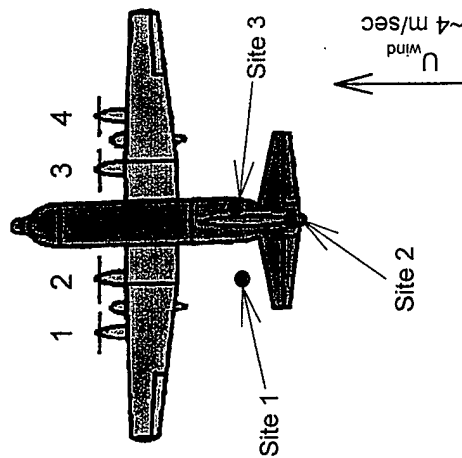


Figure 5-1. Positions of the Sampling Sites for the Flight Line Tests



Figure 5-2. Arrangement of the Samplers for the Head Wind Test

5.2 Test Procedure

Test procedures for the flight line tests were similar to the test procedures used for the climatic chamber test. Six-stage impactors were used during the flight line tests and the PS-1 samples were mounted in their standard metal housings. The impactor filters and PS-1 samplers were handled in the same manner as at the climatic chamber.

5.3 Tests Descriptions

The head wind test, in which a single engine was operated, was conducted on 22 January 97 at 1500 EST. The C130E aircraft 1835, located on Spot 2 of the flight line and powered by T56-7 engines was used for this test. Time constraints did not allow a background test to be performed. The temperature was -6°C (21°F) with a 3 to 4 m/sec headwind. A strong kerosene odor existed inside the plane from the space heaters used by the maintenance crew for their comfort. Prior to sampling, the heaters were removed and the cargo and troop doors were opened for 10 min to flush out the kerosene vapors. The cargo door was closed during testing. The troop doors were opened approximately 2 inches during testing to allow for passage of electrical power cords. Engine 3 was started by the ground crew chief following the normal procedure and operated at the "low speed ground idle" throttle setting. A small plume of mist was exhausted from the engine for several seconds after start-up, but the expected dense plume was not observed. Site 1 was located to the right of the rear cargo door for this test (behind Engine 3). The meteorological station at Site 1 measured a wind velocity of 10.5 to 12.5 m/sec at Site 1 while the engine was operating. The meteorological station's outside temperature sensor was not deployed for the head wind test. Figure 5-3 shows the wind speed and cargo compartment temperatures measured during the head wind test. The sampling duration was 15 min from the time of engine start-up. The aircraft used 200 lbs of fuel during the test (800 lbs per hr). The impactors and PS-1's were controlled remotely from the cargo compartment of the test aircraft and started simultaneously with the engine. The PS-1's sampled at a flow rate of 4 scfm while the impactors operated at 12.5 liters/min. The SUMMA® canisters could not be controlled remotely and were opened 5 min prior to engine start-up and closed 5 min after engine shutdown. The flow into the

Head Wind Flight Line Test
Minneapolis AFS, MN
22 January, 1997

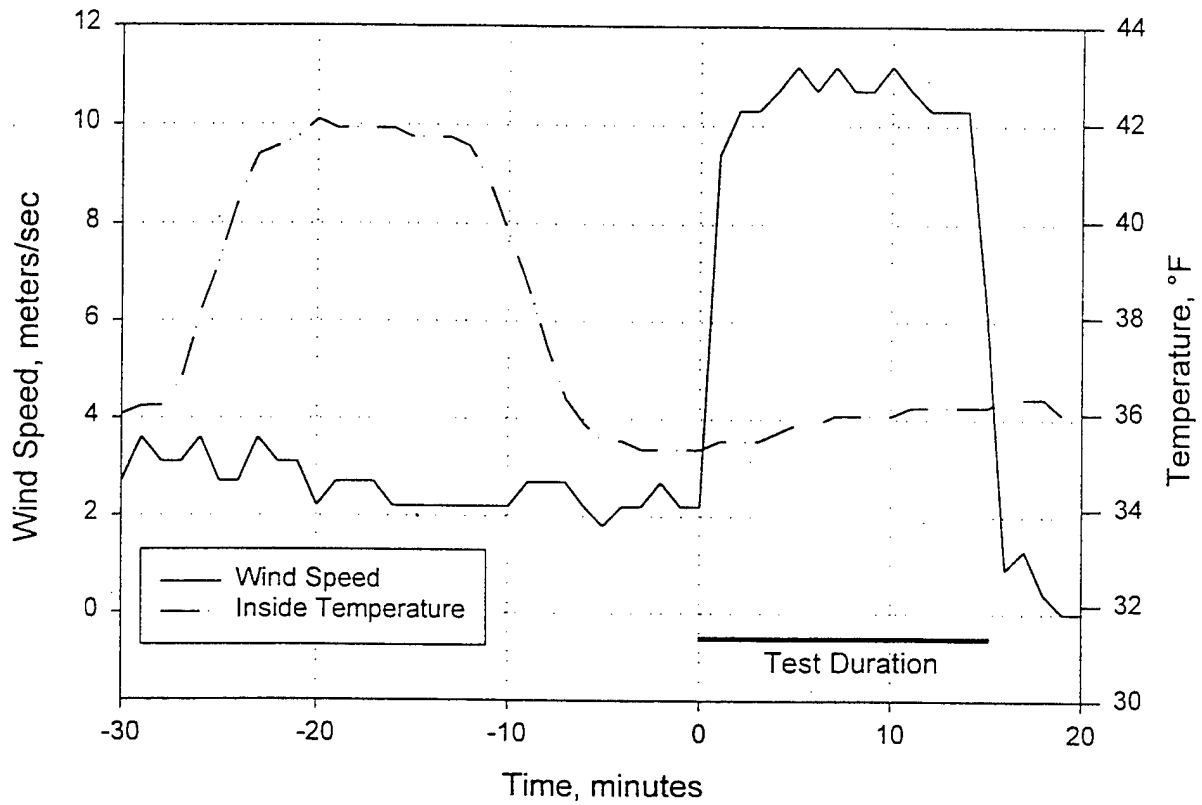


Figure 5-3. Wind Speed and Temperature During the Head Wind Test

canisters was approximately 170 cc/min. Visual inspection of the filters after test completion indicated aerosol was collected at Sites 1 and 2. Filters at Site 3 appeared clean.

A background sample prior to the tail wind test was obtained on 23 January 97 at 1230 EST. Site locations were the same as the previous day, except Site 1 was on the left side of the plane (behind Engine 2). Site 1 was relocated behind Engine 2 so that the AC generator could be located to the right of the test aircraft and away from an active taxiway and a large snow bank near the left wingtip of the C-130E on Spot 1. The temperature was -10°C with a wind of 3 to 4 m/sec from the east. This wind direction was opposite from the previous day. The test was operated following the same procedure used in the single engine test. Sample duration was 31 min. Sites 2 and 3 did not have canisters.

The tail wind test, in which all four engines were operated, was performed on 23 January 97 at 1600 EST. The C-130E aircraft 1806, located on Spot 1 and powered by T56-7 engines, was used for the tail wind test. Procedures and sampling equipment were the same as those used for the previous two tests. Site 1 remained behind Engine 2. The canister flow rates were reduced to 70 cc/min. Engine start-up sequence was 4, 3, 2, engine, and 1. Normal start-up sequence was 3, 4, 2, and 1. The sampling duration was 20 min after start-up of the first engine. Figures 5-4 and 5-5 show the wind speed and the inside and outside temperatures during the tail wind test and the tail wind background test, respectively. The total fuel consumption was not reported. It was noted that the visible plume from the engines stopped approximately 10 min after the engines started. The plume was not detected by the observer outside the aircraft; however, snow on the top of the wings was blown from the trailing edge of the right wing. A large diffuse cloud, believed to be blowing snow, was visible in front of the test aircraft for the duration of engine operation. The propeller wash did not reach Site 2 because of the wind moving from the tail to the nose of the aircraft. Engine exhaust entered the plane through the slightly opened troop doors. The cargo door was closed. Several people in the cargo hold experienced eye irritation from the exhaust fumes. Inspection of the PS-1 filters after shutdown showed discolored filters at Sites 1 and 3 while Site 2 appeared clean. Impactor filters showed similar results.

Tail Wind Flight Line Test
Minneapolis AFS, MN
23 January, 1997

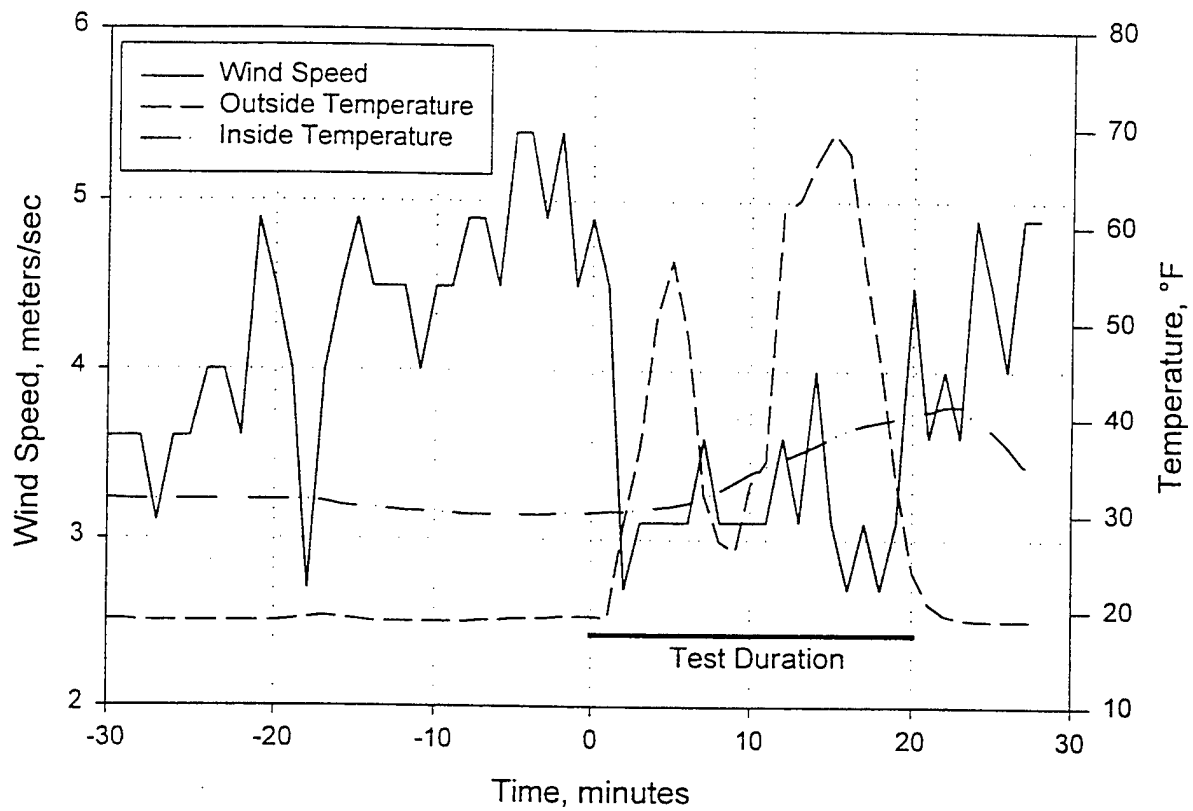


Figure 5-4. Wind Speed and Temperature During the Tail Wind Test

Tail Wind Flight Line Test Background
Minneapolis AFS, MN
23 January, 1997

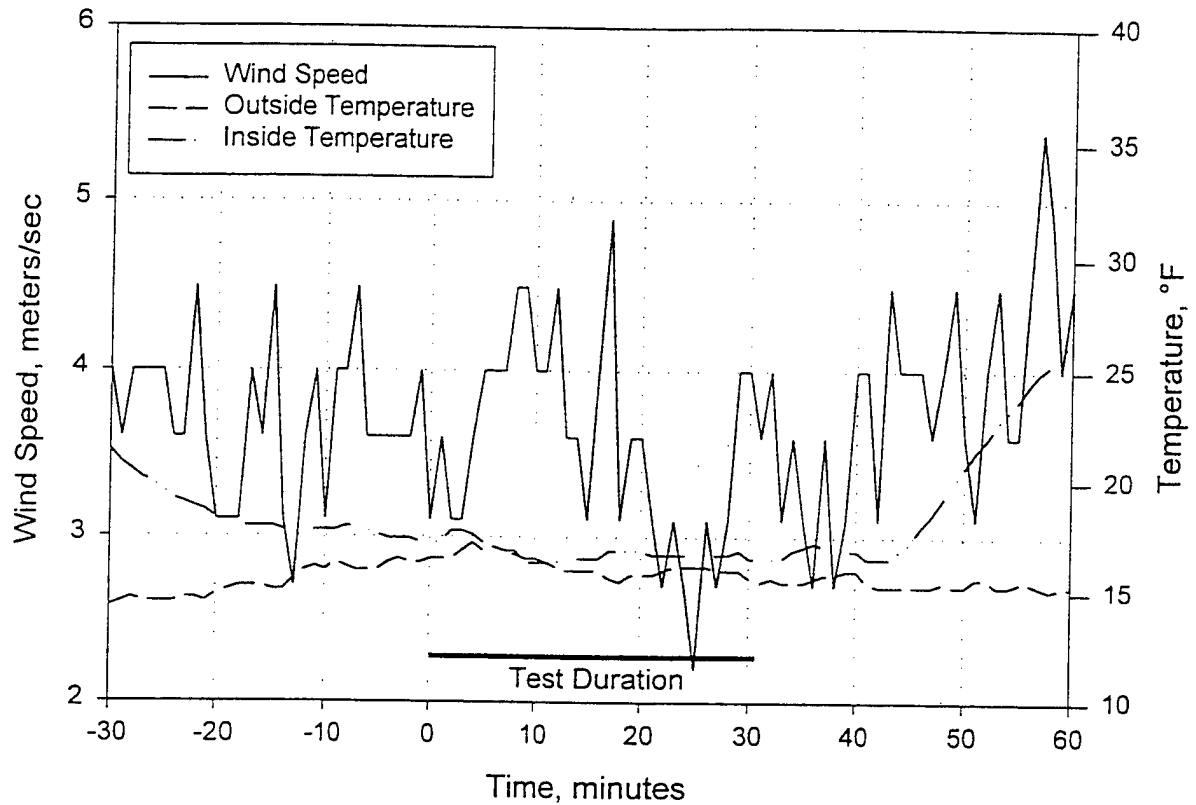


Figure 5-5. Wind Speed and Temperature During the Tail Wind Background Test

5.4 Test Findings

A major finding of the flight line tests was the importance of the prevailing wind direction on the measured concentrations and distribution of the engine emissions. We observed higher concentrations of unburned JP-8 fuel, PAH, and VOC when a single engine was operated during the head wind test than when all four engines were running during the tail wind test. The concentrations of the engine emissions inside the cargo compartment were much higher in the tail wind test than in the head wind test, however. Air crew exposure to the engine emissions may, therefore, be quite different from the exposure of the ground crew personnel under differing prevailing wind conditions.

During the head wind test the prevailing wind and the propeller wash reinforced one another so that the emissions from the operating engine were directed past the cargo compartment and toward the sampling sites behind the test aircraft. During the tail wind test, the opposing wind and the propeller wash caused a net reduction in the wind speed measured at Site 1. The opposing wind and propeller wash trapped some of the engine emissions behind the wings and forced engine emissions into the aircraft's cargo compartment. Table 5-1 presents the concentrations of unburned JP-8 fuel measured during the flight line tests. The JP-8 fuel concentrations observed with the PS-1 samplers and the impactors at each sample site are reported as $\mu\text{g}/\text{m}^3$. Comparing the JP-8 concentrations in the PS-1 samples with the JP-8 concentrations in the impactor samples in Table 5-1 shows that over 90 percent of the unburned JP-8 collected in the flight line tests was in the vapor phase rather than in the aerosol phase. All of the JP-8 aerosol was detected in the respirable particle size range. We did not detect JP-8 aerosol in the filters of the impactor stages that collected particles larger than $8\ \mu\text{m}$. The field blank values were converted to equivalent concentration values for comparison with the JP-8 concentrations observed at the sampling sites. Blank concentration values are insignificant for all of the PS-1 samples except the background samples and the sample from the loading corridor in the tail wind test.

The greatest concentrations of unburned JP-8 emissions were found in samples taken directly behind the operating engine, or engines, in both tests, as expected. The highest concentration

Table 5-1. Concentration of JP-8 Fuel in Flight Line Test Samples

Test	Sample Site	Sample Location	JP-8 Concentration ($\mu\text{g}/\text{m}^3$)		
			PS-1 Sample	Impactor <1 μm	Impactor 1 - 8 μm
Head Wind (No. 3)	1	Behind Engine	14150	720	440
Head Wind (No. 3)	2	Loading Corridor	4658	380	460
Head Wind (No. 3)	3	Load Master	477	NA ^(a)	410
Head Wind (No. 3)	--	Field Blank	49		370
Tail Wind	1	Behind Engine	3486	250	290
Tail Wind	2	Loading Corridor	71	NA	240
Tail Wind	3	Load Master	1520	260	260
Tail Wind	--	Field Blank	24		270
Tail Wind (Background)	1	Behind Engine	41	160	170
Tail Wind (Background)	2	Loading Corridor	30	NA	NA
Tail Wind (Background)	3	Load Master	42	NA	NA
Tail Wind (Background)	--	Field Blank	37		180

(a) NA = Not analyzed

occurred behind Engine 3 in the head wind test because the prevailing wind blew the engine emissions toward the sampling site. In the tail wind test the prevailing wind partially protected the sampling sites from the engine emissions. Figure 5-6 shows the pattern of the JP-8 concentrations in the flight line tests. This concentration pattern was also observed for the PAH and VOC emissions. Figure 5-7 shows the gas chromatogram recorded for the extract of the PS-1 sample collected behind the engine during the head wind test. For comparison, Figure 5-8 shows the gas chromatogram obtained for the JP-8 fuel taken from the base's JP-8 supply tank. The chromatograms are nearly identical, indicating the validity of the calibration of the unburned JP-8 concentration based on the standards prepared from the JP-8 fuel samples from the JP-8 supply tank.

The PAH concentrations exhibited a pattern that was similar to the concentration pattern of the unburned JP-8 fuel. Table 5-2 shows the measured concentrations of the target PAH compounds in the flight line test PS-1 samples. Figure 5-9 presents the concentrations of the B2 PAH collected by the PS-1 samplers during the flight line tests. Concentrations of the B2 PAH detected in Columbus, OH; Durham, NC; Boston, MA; and Houston, TX, were included for comparison of the concentrations measured in this study. As noted above, the B2 PAH concentrations found here in the background samples are slightly higher than the B2 PAH concentrations reported in the urban areas. Since these samples were collected at a major airport, the B2 PAH concentration measurements for this study appeared reasonable. Figure 5-10 shows the benzo[a]pyrene (BAP) PAH concentrations measured during the flight line tests. Concentrations of BAP measured in the urban areas were again included for comparison with our background values. The background concentrations of BAP were also similar to the BAP concentrations reported for the above cities.

Unfortunately the quantity of emitted material collected by the cascade impactors was too small to allow determination of the PAH in most of the impactor samples. Table 5-3 shows the phase distribution of the B2 PAH collected directly behind Engine 3 during the head wind test. This sample contained the highest measured concentrations of unburned JP-8 fuel, PAH, and volatile

JP-8 Fuel Concentrations
Flight Line Tests
Minneapolis AFS, MN
January, 1997

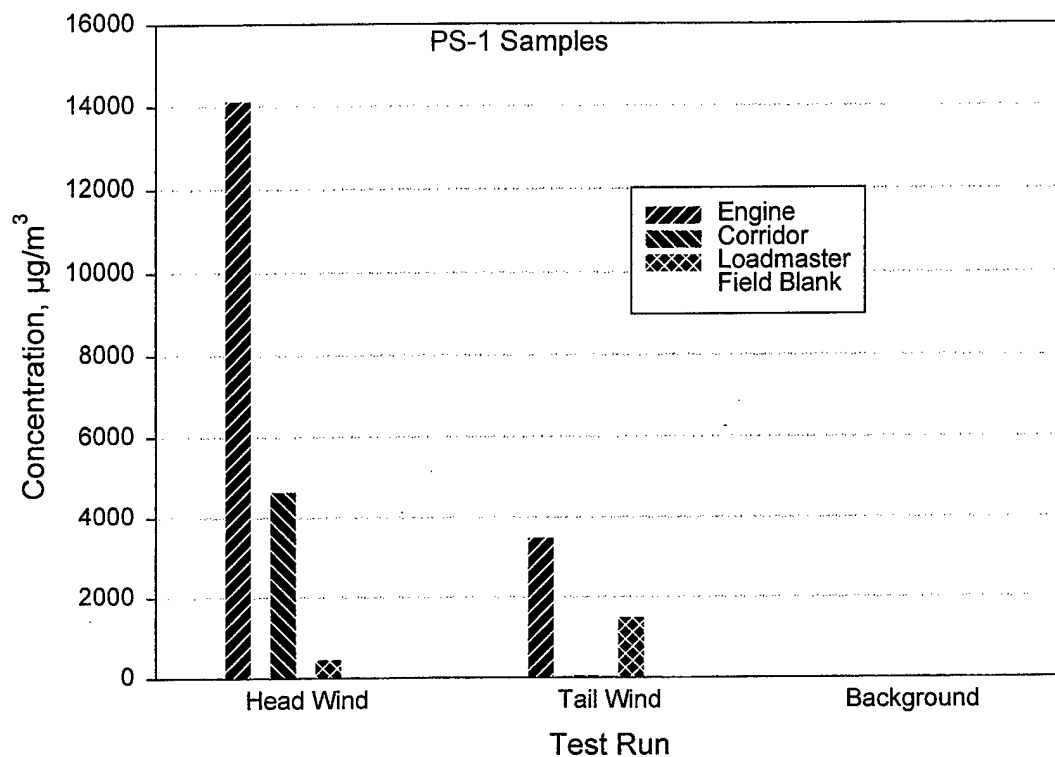


Figure 5-6. Concentration of JP-8 in the PS-1 Samples of the Flight Line Tests

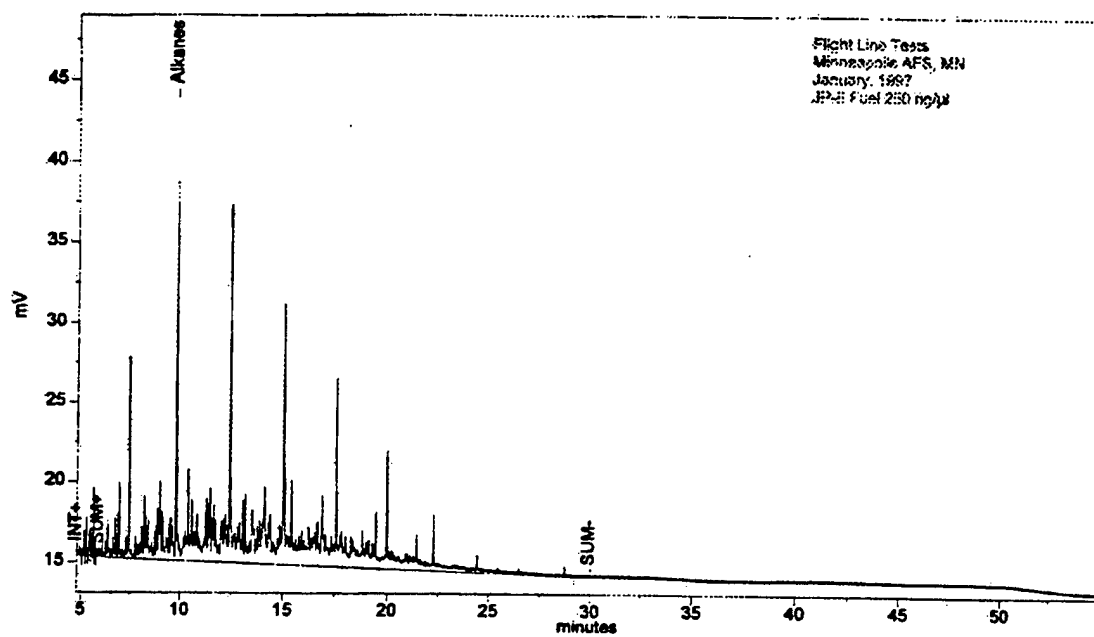


Figure 5-7. Chromatogram of the PS-1 Sample Collected Behind the Engine During the Head Wind Test

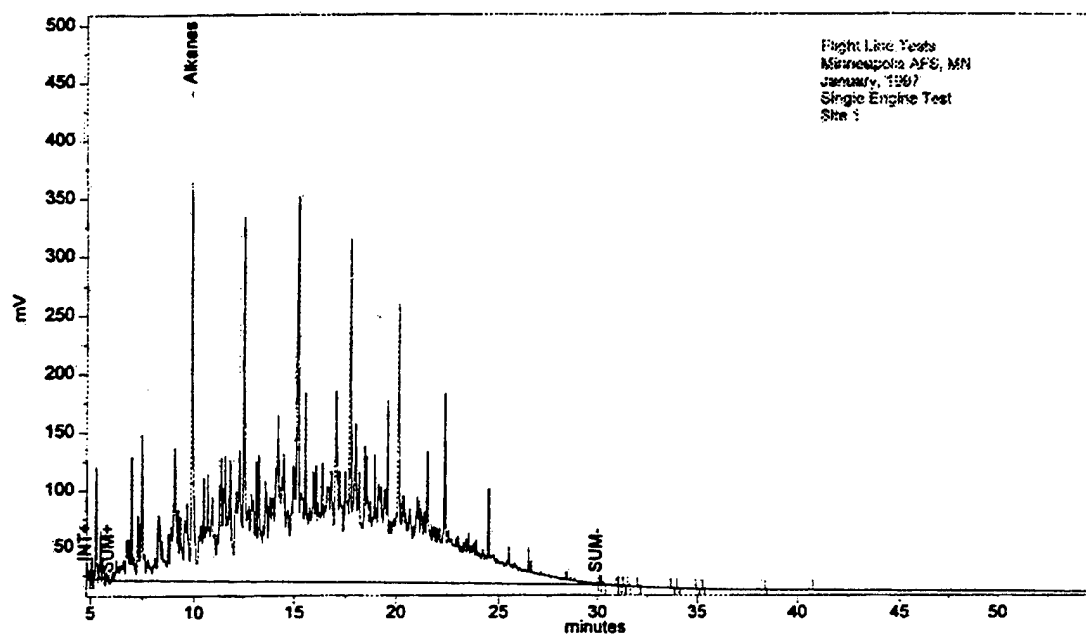


Figure 5-8. Chromatogram of the JP-8 Fuel from the Minneapolis AFS MN Supply Tank

Table 5-2. Measured Concentration of PAH in Flight Line Test Samples (ng/m³)

Compound	Head Wind Test				Tail Wind Test				Average Background
	Behind Engine	Loading Corridor	Load Master	Field Blank	Behind Engine	Loading Corridor	Load Master	Field Blank	
Naphthalene	3580	2557	598	238	2756	260	2071	178	90
Biphenyl	1560	937	104	12	1055	27	422	9	11
Acenaphthylene	1088	425	16	<1	503	6	135	<0.9	1
Acenaphthene	429	134	16	<1	152	5	47	<0.9	5
Fluorene	1180	367	26	<1	420	9	101	<0.9	5
Phenanthrene	772	270	42	68	340	26	93	51	27
Anthracene	102	31	2	<1	36	1	7	<0.9	1
Fluoranthene	264	90	13	13	118	8	44	10	6
Pyrene	358	117	11	6	158	7	61	5	4
Cyclopenta[c,d]pyrene	209	78	2	<1	82	2	60	<0.9	<0.6
Benz[a]anthracene*	68	22	4	4	29	3	17	3	2
Chrysene*	46	15	3	3	21	3	12	2	2
Benzo[b]fluoranthene*	87	27	3	<1	40	3	22	<0.9	2
Benzo[k]fluoranthene*	18	9	3	<1	12	2	7	<0.9	1
Benzo[e]pyrene	31	10	2	<1	15	2	9	<0.9	1
Benzo[a]pyrene*	67	22	3	<1	31	3	17	<0.9	2
Indeno[1,2,3-c,d]pyrene*	100	26	2	<1	39	2	20	<0.9	1
Dibenz[a,h]anthracene*	10	4	2	<1	4	2	3	<0.9	1
Benzo[g,h,i]perylene	98	27	3	<1	41	2	21	<0.9	1
Coronene	38	12	<1	<1	17	<0.9	9	<0.9	<0.6
Sum of B2 PAH	396	125	21	7	177	17	98	5	10
Sum of Target PAH	10107	5181	855	344	5869	372	3178	258	163

Sum of B2 PAH Concentrations
Flight Line Tests
Minneapolis AFS, MN
January, 1997

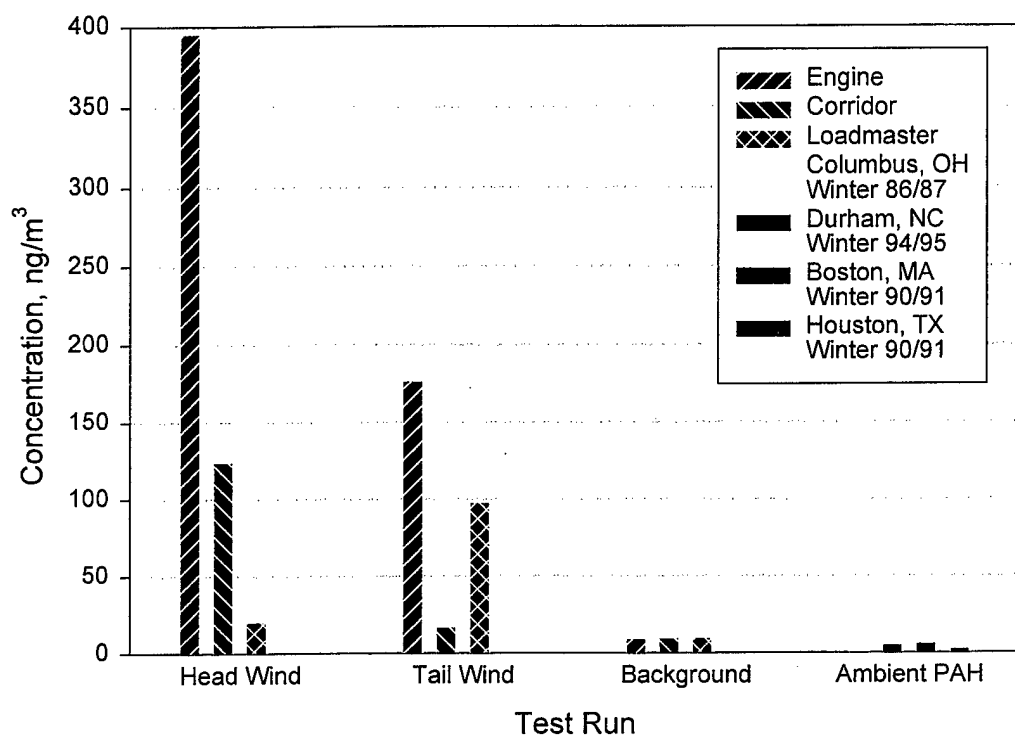


Figure 5-9. Sum of the B2 PAH Concentrations in the PS-1 Samples of the Flight Line Tests

Benzo[a]pyrene PAH Concentrations
Flight Line Tests
Minneapolis AFS, MN
January, 1997

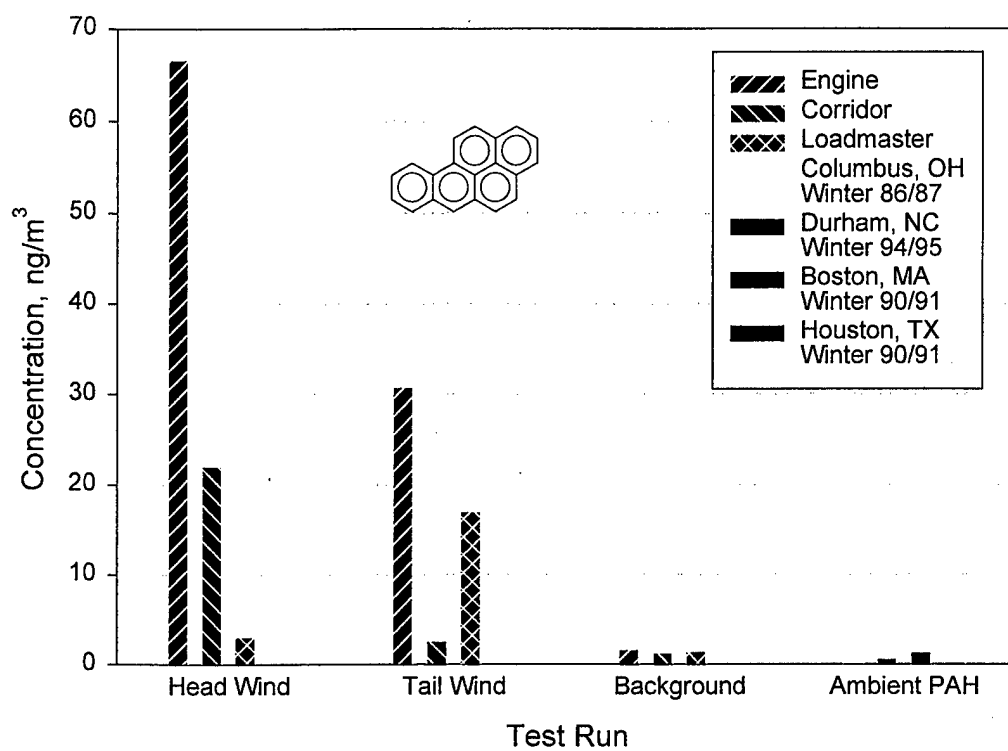


Figure 5-10. Benzo[a]pyrene Concentrations in the PS-1 Samples of the Flight Line Tests

Table 5-3. Phase Distribution of B2 PAH

	B2 PAH				
	PS-1 Sample, ng/m ³ Vapor Particulate	Impactor, ng/m ³		Impactor, % of total	
		< 1 µm	1-8 µm	< 1 µm	1-8 µm
Head Wind Test Behind Engine	400	210	130	53	33

organic compound (VOC) in our flight line tests. For the samples collected behind the engine, at least 86 percent of the B2 PAH was present in the aerosol phase. The B2 PAH in the aerosol phase was also primarily in the respirable particles.

The concentrations of the VOC detected during the flight line tests showed the same pattern as the unburned JP-8 fuel and PAH concentrations. Again, the concentration pattern was influenced strongly by the prevailing wind direction. Table 5-4 shows the concentrations of the VOC collected by the SUMMA® canisters during the flight line tests. The VOC concentrations are reported in parts per billion as carbon (ppbC). Concentrations in ppbC can be converted to ppb by dividing the ppbC value by the number of carbon atoms in the compound. For example, in Table 5-4 benzene is reported as 160 ppbC. The corresponding concentration of benzene is 26.7 ppb, which is well below the NIOSH TLV-TWA value of 0.1 ppm for benzene. The benzene concentrations found at the other sample sites of the flight line tests are also well below the NIOSH TLV-TWA for benzene. The high concentrations of isopropyl alcohol that was found were due to residual alcohol from cleaning of the critical flow orifices used with the canisters. Figures 5-11 through 5-14 show the concentrations of benzene, toluene, o-xylene, and m,p-xylene, respectively, found in the flight line tests. The vapor phase concentrations of these compounds were well below the exposure limits established for these compounds.

To compare the quantity of unburned JP-8 emitted by the new turboprop engine on the C-130J-30 aircraft, the quantity of unburned JP-8 fuel emitted by Engine 3 during the head wind test at Minneapolis AFS, MN was estimated. To make the estimate, the engine exhaust was assumed to be mixed with the propeller wash in a cylinder having a diameter equal to the length of the propeller (13.45 ft.). The propeller wash flow was estimated using the measured wind speed at the sampler (11 m/s) and the diameter of the cylinder containing the propeller wash was approximately 145 m³/s. The engine's unburned JP-8 emission rate was based on the measured JP-8 concentration (14 mg/m³) and the propeller wash flow was 2.0 g/s or 4 lb over the 15 min test interval. The unburned JP-8 emission corresponded to approximately 2 percent of the fuel (200 lb) supplied to the engine during the test.

Table 5-4. Concentration of Volatile Organic Compounds in Flight Line Test Canister Samples

Compound	Head Wind Test				Tail Wind Test			
	Engine (ppbC) ^(a)	Corridor (ppbC)	Loadmaster (ppbC)	Background Engine (ppbC)	Engine (ppbC)	Corridor (ppbC)	Loadmaster (ppbC)	Background Engine (ppbC)
Propene	433.0	284.0	10.2	7.2	278.0	ND ^(b)	118.0	ND
Propane	123.0	62.5	9.2	5.6	52.0	14.1	31.9	ND
Butene ^(c)	202.0	118.0	ND	ND	8.0	ND	46.0	ND
Butene ^(c)	188.0	124.0	ND	ND	104.0	ND	43.3	ND
n-butane	12.7	ND	ND	ND	122.0	ND	6.4	ND
Isopropyl Alcohol	535.0	211.0	472.0	ND	ND	ND	ND	3400.0
Cyclopentane	98.4	48.1	ND	ND	56.2	ND	25.5	ND
n-pentane	5.0	14.7	ND	ND	13.6	ND	5.6	ND
Pentadiene/Cyclopentene	56.4	45.5	83.2	7.6	34.5	ND	16.2	ND
3-penten-1-yne	39.0	36.3	ND	ND	31.2	ND	ND	ND
C6H12	74.2	46.7	ND	ND	45.1	ND	17.7	ND
C6H10	11.5	ND	ND	ND	ND	ND	ND	ND
Benzene	160.0	104.0	15.2	12.2	113.0	10.4	46.8	16.9
Dimethyl Cyclopentane	43.6	28.2	12.3	6.2	27.2	ND	10.6	ND
Toluene	97.7	58.8	11.4	70.4	48.4	ND	21.4	ND
Ethylbenzene	23.3	ND	ND	14.6	ND	ND	ND	16.2
m,p-xylene	70.6	18.7	ND	11.0	33.4	ND	11.1	21.3
Styrene	26.5	ND	ND	10.0	15.8	ND	ND	14.7
o-xylene	22.5	14.4	ND	12.2	16.5	ND	5.0	22.0
4-ethyltoluene	28.1	ND	8.3	5.1	14.3	ND	ND	16.9
1,3,5-trimethylbenzene	29.4	ND	11.6	11.5	22.8	ND	4.8	16.2
1,2,4-trimethylbenzene	72.0	15.3	51.9	11.0	51.8	ND	9.2	26.8
C10 alkane	96.9	ND	37.7	5.4	41.1	ND	16.1	16.9

(a) ppbC = part per billion as carbon.

(b) ND = not detected.

(c) Compound may be 1-butene, *cis*-2-butene, or *trans*-2-butene

Volatile Organic Compound Concentrations
Flight Line Tests
Minneapolis AFS, MN
January, 1997

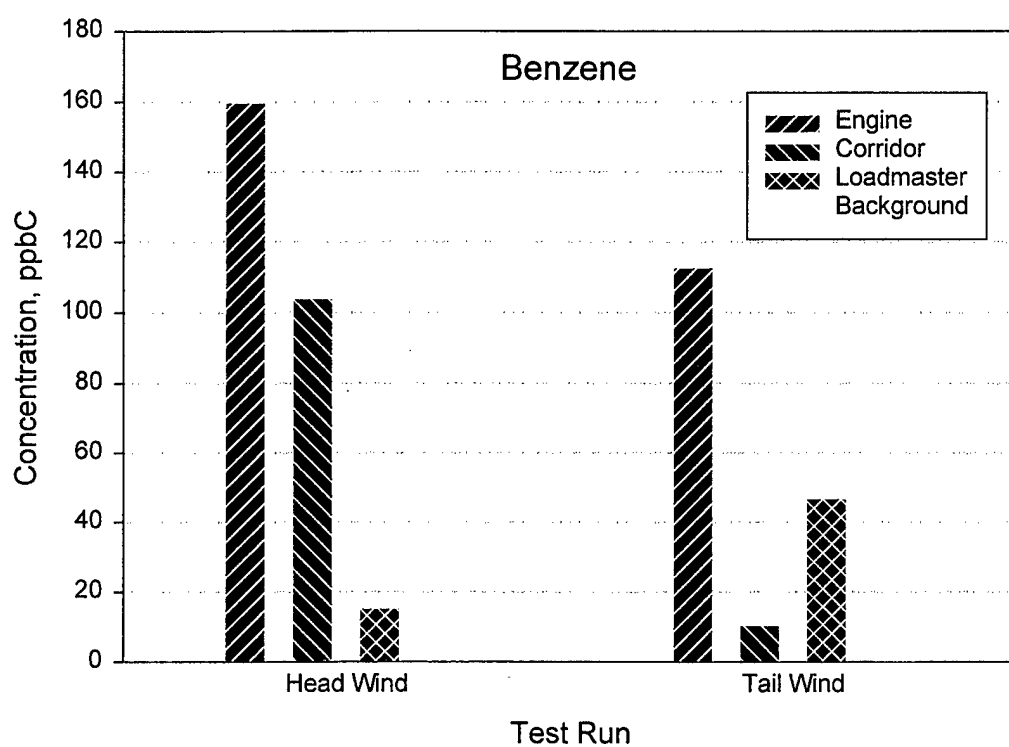


Figure 5-11. Benzene Concentrations in the Canister Samples of the Flight Line Tests

Volatile Organic Compound Concentrations
Flight Line Tests
Minneapolis AFS, MN
January, 1997

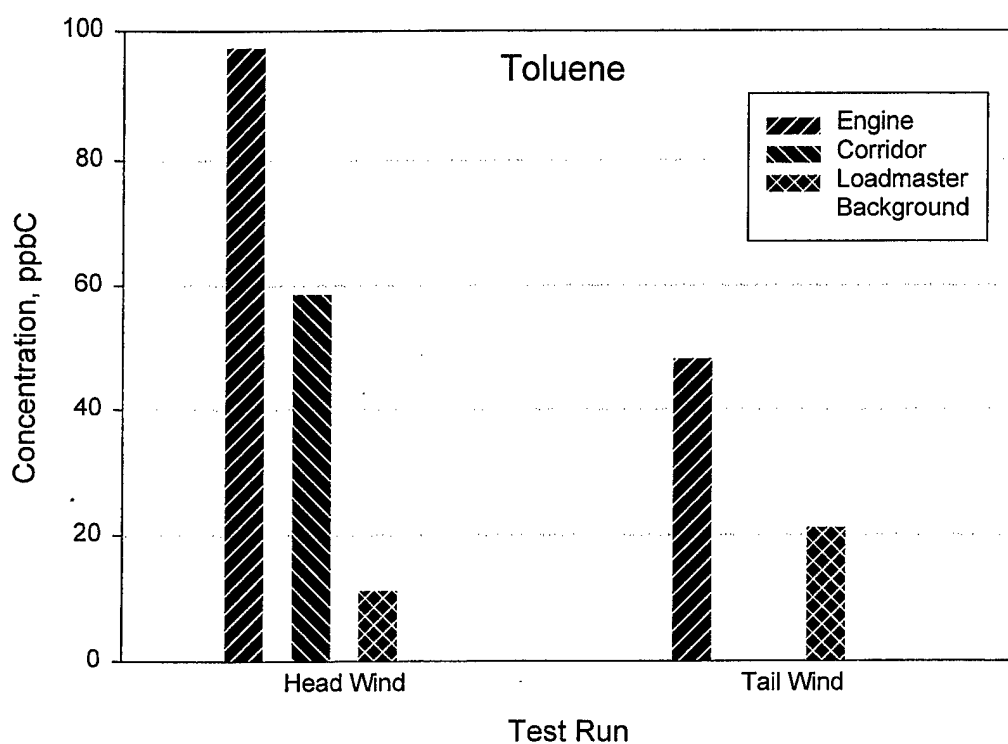


Figure 5-12. Toluene Concentrations in the Canister Samples of the Flight Line Tests

Volatile Organic Compound Concentrations
Flight Line Tests
Minneapolis AFS, MN
January, 1997

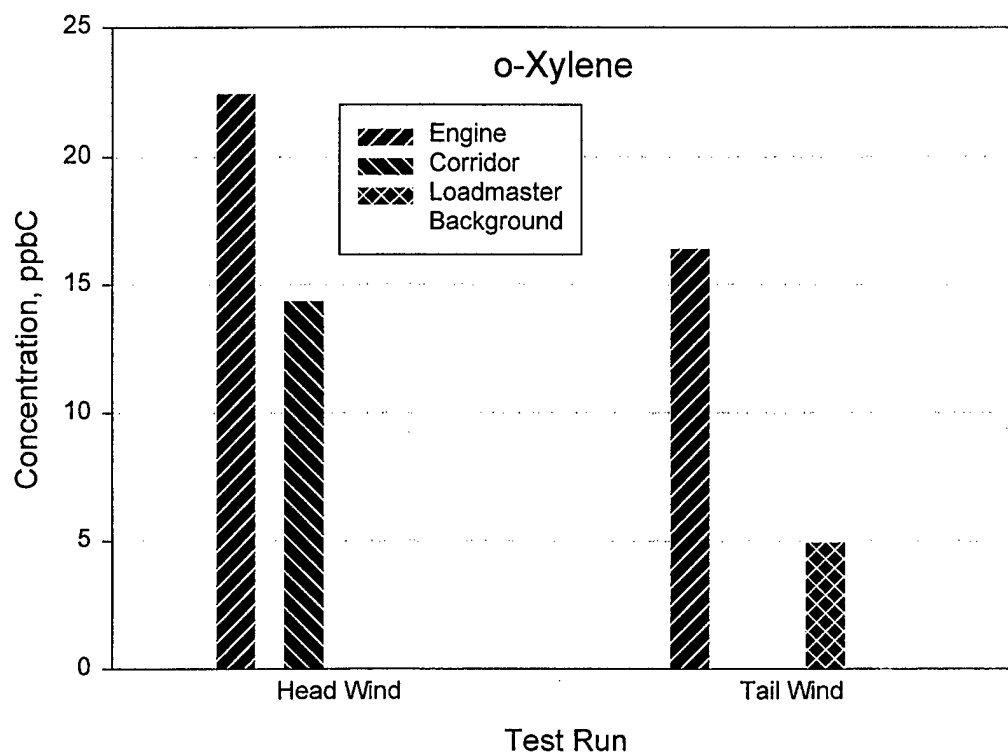


Figure 5-13. o-Xylene Concentrations in the Canister Samples of the Flight Line Tests

Volatile Organic Compound Concentrations
Flight Line Tests
Minneapolis AFS, MN
January, 1997

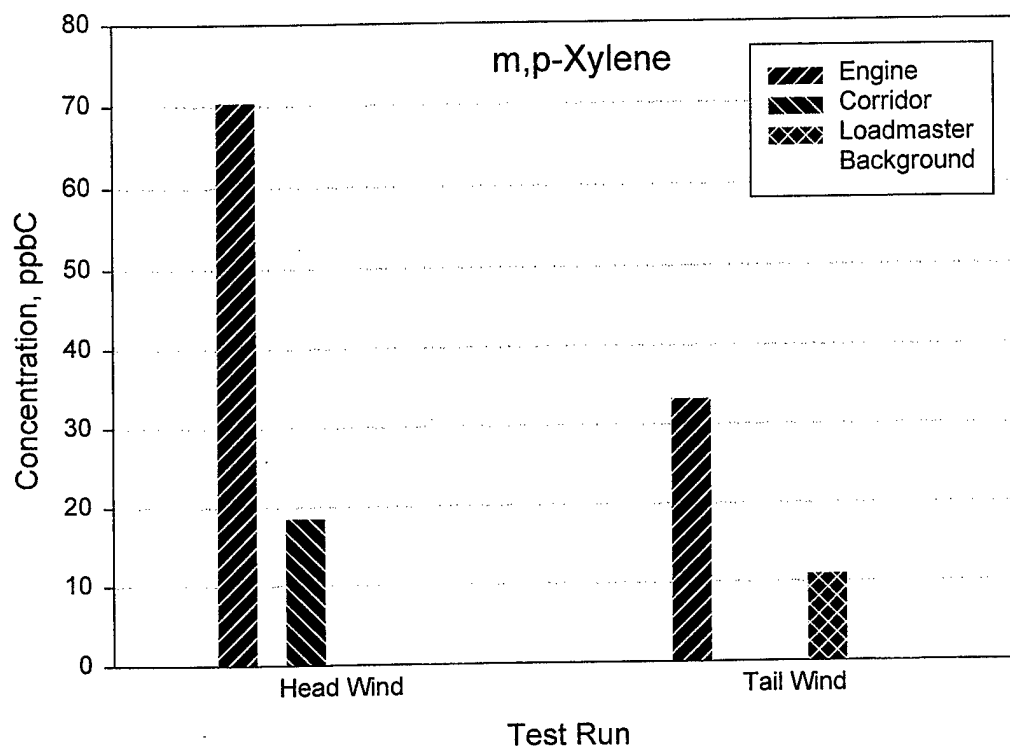


Figure 5-14. m,p-Xylene Concentrations in the Canister Samples of the Flight Line Tests

SECTION 6.0 — Conclusions and Recommendations

The amounts of unburned JP-8 fuel and PAH emitted in the engine exhaust during cold engine start up have been determined from the measurements of the exhaust emissions of the turboprop engines on both new and old C-130 aircraft (presented in Sections 4 and 5). The measurements demonstrated that unburned JP-8 fuel was emitted from both new and old C-130 engines in vapor and aerosol forms. The PAH compounds were also detected in the vapor and aerosol phases. The concentrations of the engine exhaust emissions can be used to estimate the occupational exposure of air and ground crews to the target compounds.

Difficulties were encountered during the climatic chamber and flight line tests, however. In the climatic chamber tests the engine exhaust gases were confined within a 36-inch diameter exhaust duct located between the engine exhaust outlet and the exterior of the climatic chamber. While the duct confined the exhaust flow, thereby increasing the concentrations of the exhaust gases, it also prevented the exhaust gases from mixing with the cold air in the chamber, preventing the rapid quenching or cooling of the exhaust that occurred on the flight line. The gas temperatures inside the duct were many degrees warmer than the temperature of the cold air in the climatic chamber. The measurements during the -22°F test demonstrated that the JP-8 fuel aerosol emitted by the engine evaporated within the duct then recondensed before reaching the duct outlet. The PAH exhibited the same behavior.

During the flight line tests the prevailing wind introduced a strong influence on the concentrations of the target compounds detected at the sample sites. The influence of the prevailing wind depended on whether the wind aided or interfered with the transport of the engine exhaust toward the sample site. The prevailing wind caused a greater concentration of engine exhaust emissions to be observed in the test in which a single engine was operated rather than in the test in which all four engines operated. This drastically altered the concentration of the exhaust emissions inside the test aircraft. Quenching of the engine exhaust emissions during the flight line tests more closely approximated the exposure conditions of air and ground crew personnel, however.

Based on the results of the climatic chamber tests, the following conclusions were reached:

- Unburned JP-8 fuel and PAH vapors were emitted by the engines of the C-130J-30 aircraft during all of the climatic chamber tests. The greatest detectable unburned JP-8 fuel concentrations were found during the -22°F test (maximum duct temperature 83°C). Based on the analyses of the nonadecane and icosane peaks in the JP-8 fuel aerosol, the concentration of unburned JP-8 fuel in the aerosol phase might be as high as 74 mg/m³. The concentration of unburned JP-8 fuel based on the full chromatogram (without the volatile hydrocarbons) was only 1.0 mg/m³, which appeared to be an underestimate of the true JP-8 concentration in the engine exhaust duct.
- The excellent agreement between the unburned JP-8 concentration measurements derived from the PS-1 samples (total of the vapor- and aerosol-phase JP-8) (see Table 4-2) and from the impactor filters using the nonadecane and icosane peak calibration (see Table 4-4) at Section 2 indicated that those nonvolatile hydrocarbons were initially present in the aerosol phase in the engine exhaust and were efficiently collected by the impactors. The submicrometer size fraction contained 68 percent of the collected nonvolatile unburned JP-8 aerosol.
- The greatest concentration of B2 PAH aerosol, 1.0 mg/m³, was observed during the -22°F test.
- Approximately 2.1 percent of the fuel supplied to Engine 4 during the 3-min sample collection period of the -22°F test was emitted as unburned JP-8. The estimated fraction of supplied JP-8 fuel emitted from Engine 4 was approximately 1.4 and 1.0 percent during the sample collection period of the -9°F and baseline tests, respectively.
- The measured unburned JP-8 fuel and PAH aerosol occurred in the respirable size range (<10 µm aerodynamic diameter) during the -22°F test. The target aerosol was not detected in the 10 to 20 µm or >20 µm size ranges.
- An accurate assessment of Engine 4's unburned JP-8 aerosol emissions was not possible because the emitted fuel aerosol evaporated then recondensed while in the

exhaust duct. Loss of volatile compounds in the JP-8 also occurred while weighing the impactor filters after the tests, as indicated by the odor of JP-8 observed during weighing.

- Aerosol mass distributions measured with the impactors and the real-time aerosol monitor cannot be related to the size distribution of the unburned JP-8 fuel or the PAH aerosol. Chemical analysis of the collected aerosol was required to determine the distribution of the target compounds. Interfering materials in the exhaust gases (i.e., water droplets and rust particles) obscured the mass distribution of the target compounds.

Based on the results of the flight line test, the following conclusions were reached:

- Unburned JP-8 fuel aerosol and PAH were emitted from C-130E turboprop engines during cold engine start-up. The highest concentration of unburned JP-8 fuel was found directly behind the operating engine during the head wind test (14.2 mg/m^3); however, ground crew personnel are not permitted behind an operating engine. The highest potential ground crew exposure to unburned JP-8 fuel was found in the loading corridor during the head wind test (4.7 mg/m^3). During the tail wind test a JP-8 fuel concentration of 1.5 mg/m^3 was observed at the loadmaster's station inside the aircraft. Test personnel inside the aircraft complained of burning eyes when exposed to the engine exhaust during the tail wind test.
- Based on our crude estimate of the quantity of unburned JP-8 fuel emitted by Engine 3 during the head wind test, approximately 2 percent of the JP-8 fuel supplied to the engine was emitted unburned. Over 90 percent of the unburned JP-8 was emitted in the vapor phase at the temperature of the flight line tests.
- In the head wind test, 125 ng/m^3 of the B2 PAH was detected in the loading corridor. In the tail wind test, 98 ng/m^3 of the B2 PAH was detected at the loadmaster's station. These nonvolatile PAH were present predominantly in the aerosol phase.

- Limited results suggested that the PAH partitions between the vapor and aerosol phase in accordance with the vapor pressure of the compounds. Approximately 86 percent of the B2 PAH was present in the aerosol phase. All of the detected B2 PAH in the aerosol was found in the respirable size fraction ($<8\text{ }\mu\text{m}$).
- Prevailing wind direction had a strong effect on the concentration and distribution of the engine emissions around the aircraft.
- More aerosol must be collected to measure the aerosol mass distribution and composition at the locations occupied by air and ground crew personnel. Measurable aerosol was only found behind the engines where personnel were not permitted during engine operation.
- Sample collection should be performed at temperatures below 20°F to obtain sufficient aerosol for study.
- Measured concentrations of the VOCs, benzene, toluene, and the xylenes were well below the exposure limits established for those compounds.

Following are recommendations for future work to improve the characterization of aerosols produced by the engines of aircraft fueled by JP-8 during cold engine start up:

- Conduct future flight line tests at ambient temperatures below -10°F to increase the density and duration of the plume produced at cold engine start-up.
- Conduct future flight line tests under calm wind conditions. Strong prevailing winds disperse the plume and affect the distribution of emitted aerosols and vapors.
- Do not weigh the impactor filters before and after tests. The mass collected on the impactor filters is not an accurate indication of the quantity of the target compounds present in the aerosol. Chemical analysis of the collected aerosol is required to determine the distribution of the target compounds.

- Minimize the time interval between sample collection and removal of the samplers from the exhaust duct during climatic chamber tests. Delay in storage of the collected aerosol in dry ice increases the potential for loss of the volatile compounds before they can be quantified.
- Increase the amount of chamber air aspirated with the engine exhaust during climatic chamber tests to increase the quenching of the exhaust gases. Better quenching of the exhaust gas should make the climatic chamber tests more closely resemble flight line conditions.

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 7.0 – References

Air Velocities with the Dwyer Pitot Tube, Bulletin No. H-11, Dwyer Instruments, Inc., Michigan City, IN, 1992.

Chuang, J.C., Callahan, P.J., and Lyu, C.W. Field method evaluation of total exposure of children from low-income families that include smokers to polycyclic aromatic hydrocarbons, Final Report to U.S. EPA, Contract Number 68-D4-0023, Work Assignment No. 9, July 1996.

EPA Approach for Assessing the Risks Associated with Chronic Exposures to Carcinogens, World Wide Web Page, URL:
<http://www.epa.gov/ngispgm3/iris/Carcinogenicity.html>, Last Update: 13 March, 1997.

Kelly, T.J., Chuang, J.C., and Callahan, P.J. Field measurements of atmospheric polynuclear aromatic hydrocarbon concentrations and phase distribution at TAMS sites. Proceedings of the 1992 U.S. EPA/AWMA International Symposium, Report No. EPA/600/R-92/131, pp 31-36, 1992.

Material Safety Data Sheet OHS33651, MDL Information Systems, Inc., San Leandro, CA, Aug., 1995.

Mayfield, H. T., JP-8 Composition and Variability, Report AL/EQ-TR-1996-0006, Air Force Materiel Command, Tyndall AFB, FL, May, 1996.

Smith, Maj. L., Personal Communication, 7 April, 1997.

Stephens, D. C., Review of Aspiration Coefficients of Thin-Walled Sampling Nozzles, J. Aerosol Sci., Vol. 17 No. 4, pp. 729-783, 1986.

Subcommittee on Permissible Exposure Levels for Military Fuels, "Permissible Exposure Levels for Selected Military Fuel Vapors", National Research Council, National Academy Press, Washington, D. C., 1996.

Weast, R. C., Ed., Handbook of Chemistry and Physics, 49 Edition. The Chemical Rubber Co., Cleveland, OH, 1968.

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix A

Correction for Anisokinetic Sampling and Probe Bends in the Climatic Chamber Tests

Appendix A

Correction for Anisokinetic Sampling and Probe Bends in the Climatic Chamber Tests

The aerosol aspiration efficiency, A , of a sampling nozzle oriented at 0 degrees to a wind is:

$$A = 1 + \left(\frac{w}{u} - 1 \right) \left[1 - \frac{1}{1 + \left(2 + 0.62 \frac{u}{w} \right) \left(\frac{w}{u} + s + k \right)} \right]$$

where

W is the wind velocity (m/sec),

U is the sampling velocity in the probe (m/sec),

and Stk is the particle Stokes number.

The Stokes number is:

$$Stk = \frac{c_p d_p^2 \rho_p u}{18 \mu D}$$

where

C_p is the slip correction,

d_p is the particle diameter (m)

ρ_p is the particle density (kg/m^3)

μ is the gas viscosity (Pa sec),

and D is the diameter of the probe (m) (Stephens, 1986)

The loss of aerosol particles in the 90 degree bend of the sampling probe was calculated by a turbulent deposition model in the SAMPLEF computer program.

Turbulent deposition of particles in straight pipes is treated in SAMPLEF with the assumption that the deposition surface may not be ideally smooth, and even the particles that are deposited

may cause an increase in surface roughness. Aerosol deposition from turbulent flows onto rough surfaces is modeled using correlations developed by Wood (1981). According to that approach, deposition of particles due to molecular diffusion, enhanced by turbulent eddies, and due to inertial effects are both considered.

In bends, a secondary flow promotes a more energetic hydrodynamic regime and higher pressure drop as compared to a smooth straight pipe of the same length. The turbulent flow in a bent pipe also provides favorable conditions for the diffusional and inertial deposition of aerosol particles. The turbulent bend modeling approach was validated against several large-scale experiments, which showed good agreement between experimental data and model predictions for relatively large sampling tubes (V. Kogan et al., 1987).

In addition to turbulent deposition, SAMPLEF considers gravitational settling of particles onto the horizontal surfaces of the pipes. As a first approximation, the Stokes formulation of settling velocity is used.

SAMPLEF calculates the steady-state deposition and transport of aerosols through the sampling system. It calculates fluid thermodynamic and hydrodynamic properties for an arbitrary set of sample flow rates, temperature, and air humidity, and uses these properties for evaluating the transport parameters for airborne particulate matter.

The overall aerosol transfer efficiency for the probe was calculated as the product of the aspiration efficiency and the bend transfer efficiency. Tables A-1 shows the estimated aspiration, bend, and overall transfer efficiencies of the PS-1 and impactor probes for the climatic chamber tests for 10 μm particles. As expected the overall transfer efficiency for 1 μm particles was 1.00 ± 0.03 and can be neglected.

Table A-1. Estimated Aerosol Transfer Efficiencies for the Climatic Chamber Tests (10 μ m particles)

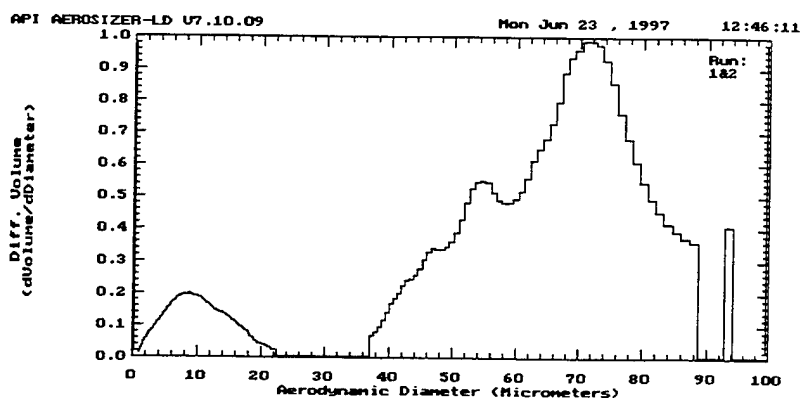
Test	Duct Section	PS-1 Transfer Efficiency			Impactor Transfer Efficiency		
		Aspiration	Bend	Overall	Aspiration	Bend	Overall
68°F	2	1.25	0.80	1.00	1.74	0.84	1.46
	3	1.13	0.80	0.90	1.50	0.84	1.25
	8	1.11	0.80	0.89	1.46	0.84	1.22
-9°F	2	1.26	0.80	1.01	1.77	0.84	1.48
	3	1.13	0.80	0.90	1.52	0.84	1.27
	8	1.11	0.80	0.89	1.46	0.84	1.22
-22°F	2	1.27	0.80	1.01	1.77	0.84	1.48
	3	1.14	0.80	0.91	1.52	0.84	1.27
	8	1.11	0.80	0.89	1.46	0.84	1.22

The sampling velocity of the Aerosizer probe was approximately 10 percent of the velocity of the exhaust gases at Section 8. Since the flow in the Aerosizer was laminar rather than turbulent, the turbulent bend deposition model was not used to estimate the particle deposition in the Aerosizer probe. The large radius of the bend in the Aerosizer probe did not cause removal of the aerosol particles in the bend. Table A-2 shows the estimated aspiration efficiency of the Aerosizer probe for 1, 10, and 25 μ m particles.

Table A-2. Aspiration Efficiency of the Aerosizer Probe in the Climatic Chamber Tests

Test	Aspiration Efficiency		
	1 μ m	10 μ m	25 μ m
68°F	1.22	7.25	9.65
-9°F	1.22	7.28	9.66
-22°F	1.23	7.34	9.68

The aerosol concentrations were corrected for transfer efficiency by dividing the measured concentrations of the target compounds by the efficiencies shown in Tables A-1 and A-2. Figures A-1 through A-6 show the uncorrected Aerosizer output for the first two measurement cycles of the climatic chamber tests.



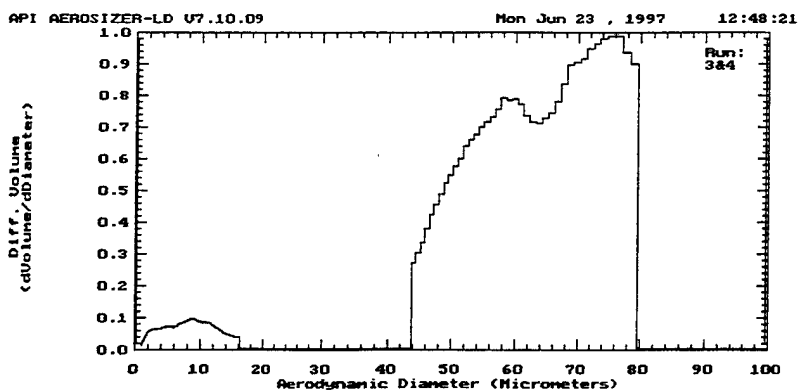
Directory: c:\egll Run 1 taken on Mon Jun 23 12:46:11 1997 Volume Distribution by Aerodynamic Diameter
Test #1 68 F 06-23-97 exhaust sample Regularization: High

Flow Rate Range: 1.96 to 2.00 l/min
Concentration : 3.79e+07 particles/cubic meter (Counting Efficiency=1.000)
Mass Loading : 1.90e+01 mg/cubic meter (Counting Efficiency=1.000)

PARAMETERS		DISPERSER CONTROL		%UNDER	SIZE	%UNDER	SIZE
Material	: ambient aerosol	Dispenser Type	: AeroSampler	5%	11.38	55%	68.79
Density	: 1.00	Heater	: OFF	10%	41.13	60%	70.36
Run Length (sec)	: 118.5	Purge	: OFF	15%	46.83	65%	71.89
PMT Voltage (volts)	: 1100.0			20%	51.09	70%	73.43
Laser Current (mA)	: 41.1			25%	54.13	75%	75.08
Clock Freq (MHz)	: 40.0			30%	56.99	80%	76.97
Sum of channels	: 151737			35%	60.12	85%	79.31
Lower Size Limit	: 0.10			40%	62.85	90%	82.25
Upper Size Limit	: 99.80			45%	65.14	95%	85.91
Nozzle Type	: 200um	SCANS 1 AND 2 COMBINED		50%	67.12		
Baseline Offset	: 0.10	BETWEEN 6.6 & 6.7 MICRONS					
Noise Filter	: 6.00						
Mean Size	: 55.82	D(4,3)	: 62.32	Mode (Linear Scale): 70.80			
Standard Deviation	: 1.822	D(3,2)	: 39.61	Spec surf area: 0.151 sq meter/g			

UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER
		100	4.8887	86.0	95.111	10.0	0.8883	8.60	3.2916	1.00	0.0063	0.86	0.0057		
		86.0	23.347	74.0	71.764	8.60	0.7700	7.40	2.5216	0.86	0.0033	0.74	0.0024		
		74.0	31.466	63.0	40.298	7.40	0.6735	6.30	1.8482	0.74	0.0016	0.63	0.0008		
		63.0	15.523	54.0	24.775	6.30	0.4924	5.40	1.3558	0.63	0.0006	0.54	0.0003		
		54.0	10.686	46.0	14.089	5.40	0.3822	4.60	0.9736	0.54	0.0002	0.46	0.0001		
		46.0	4.7551	40.0	9.3342	4.60	0.2467	4.00	0.7268	0.46	0.0001	0.40	0.0000		
		40.0	1.0714	34.0	8.2627	4.00	0.2146	3.40	0.5122	0.40	0.0000	0.34	0.0000		
		34.0	0.0000	29.0	8.2627	3.40	0.1525	2.90	0.3597	0.34	0.0000	0.29	0.0000		
		29.0	0.0000	25.0	8.2627	2.90	0.1061	2.50	0.2536	0.29	0.0000	0.25	0.0000		
		25.0	0.0148	22.0	8.2479	2.50	0.0704	2.20	0.1833	0.25	0.0000	0.22	0.0000		
		22.0	0.5499	18.0	7.6980	2.20	0.0786	1.80	0.1047	0.22	0.0000	0.18	0.0000		
180	0.0000	160	100.00	18.0	0.6001	16.0	7.0979	1.80	0.0321	1.60	0.0727	0.18	0.0000	0.16	0.0000
160	0.0000	140	100.00	16.0	0.8031	14.0	6.2948	1.60	0.0264	1.40	0.0462	0.16	0.0000	0.14	0.0000
140	0.0000	120	100.00	14.0	0.9603	12.0	5.3345	1.40	0.0202	1.20	0.0260	0.14	0.0000	0.12	0.0000
120	0.0000	100	100.00	12.0	1.1546	10.0	4.1799	1.20	0.0140	1.00	0.0120	0.12	0.0000	0.10	0.0000

Figure A-1. Aerosizer Output for the 68°F Climatic Chamber Test (Cycle 1)



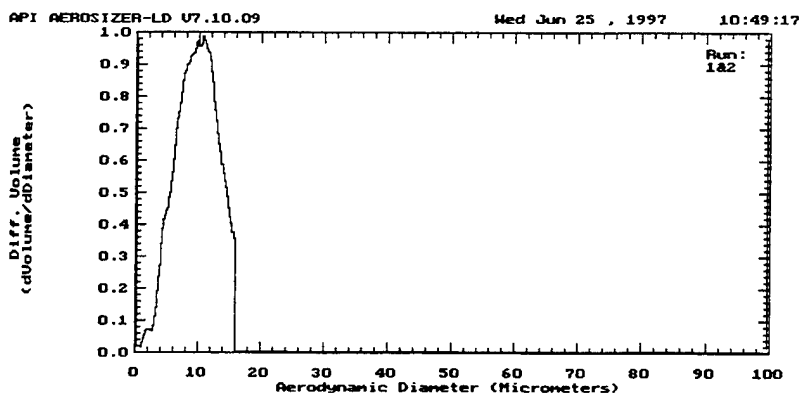
Directory: c:\egll Run 3 taken on Mon Jun 23 12:48:21 1997 Volume Distribution by Aerodynamic Diameter
 Test #1 68 F 06-23-97 exhaust sample Regularization: High

Flow Rate Range: 1.96 to 2.00 l/min
 Concentration : 1.14e+07 particles/cubic meter (Counting Efficiency=1.000)
 Mass Loading : 6.13e+00 mg/cubic meter (Counting Efficiency=1.000)

PARAMETERS		DISPERSER CONTROL		%UNDER	SIZE	%UNDER	SIZE
Material	: ambient aerosol	Disperser Type	: AeroSampler	5%	44.92	55%	66.03
Density	: 1.00	Heater	: OFF	10%	48.29	60%	67.75
Run Length (sec)	: 118.5	Purge	: OFF	15%	50.82	65%	69.30
PMT Voltage (volts)	: 1100.0			20%	53.01	70%	70.81
Laser Current (mA)	: 41.1			25%	55.02	75%	72.28
Clock Freq (MHz)	: 40.0			30%	56.90	80%	73.70
Sum of channels	: 45754			35%	58.67	85%	75.10
Lower Size Limit	: 0.10			40%	60.41	90%	76.48
Upper Size Limit	: 99.80			45%	62.25	95%	77.92
Nozzle Type	: 200um	SCANS 3 AND 4 COMBINED		50%	64.16		
Baseline Offset	: 0.10	BETWEEN 5.7 & 5.8 MICRONS					
Noise Filter	: 6.00						
Mean Size	: 58.39	D(4,3)	: 61.96	Mode (Linear Scale):		75.28	
Standard Deviation	: 1.569	D(3,2)	: 46.07	Spec surf area:		0.13 sq meter/g	

UPPER	%	LOWER	%	UPPER	%	LOWER	%	UPPER	%	LOWER	%	UPPER	%	LOWER	%
SIZE	IN	SIZE	UNDER	SIZE	IN	SIZE	UNDER	SIZE	IN	SIZE	UNDER	SIZE	IN	SIZE	UNDER
		100	0.0000	86.0	100.00	10.0	0.4610	8.60	1.8819	1.00	0.0071	0.86	0.0059		
		86.0	18.930	74.0	81.070	8.60	0.3882	7.40	1.4937	0.86	0.0036	0.74	0.0024		
		74.0	34.101	63.0	46.970	7.40	0.3167	6.30	1.1770	0.74	0.0016	0.63	0.0007		
		63.0	24.549	54.0	22.421	6.30	0.2272	5.40	0.9498	0.63	0.0005	0.54	0.0002		
		54.0	16.064	46.0	6.3568	5.40	0.2040	4.60	0.7457	0.54	0.0002	0.46	0.0001		
		46.0	2.6722	40.0	3.6846	4.60	0.1466	4.00	0.5992	0.46	0.0000	0.40	0.0000		
		40.0	0.0000	34.0	3.6846	4.00	0.1396	3.40	0.4595	0.40	0.0000	0.34	0.0000		
		34.0	0.0000	29.0	3.6846	3.40	0.1145	2.90	0.3451	0.34	0.0000	0.29	0.0000		
		29.0	0.0000	25.0	3.6846	2.90	0.0884	2.50	0.2567	0.29	0.0000	0.25	0.0000		
		25.0	0.0000	22.0	3.6846	2.50	0.0639	2.20	0.1928	0.25	0.0000	0.22	0.0000		
		22.0	0.0000	18.0	3.6846	2.20	0.0775	1.80	0.1152	0.22	0.0000	0.18	0.0000		
180	0.0000	160	100.00	18.0	0.0130	16.0	3.6717	1.80	0.0341	1.60	0.0811	0.18	0.0000	0.16	0.0000
160	0.0000	140	100.00	16.0	0.2982	14.0	3.3735	1.60	0.0290	1.40	0.0521	0.16	0.0000	0.14	0.0000
140	0.0000	120	100.00	14.0	0.4367	12.0	2.9368	1.40	0.0230	1.20	0.0292	0.14	0.0000	0.12	0.0000
120	0.0000	100	100.00	12.0	0.5939	10.0	2.3429	1.20	0.0161	1.00	0.0130	0.12	0.0000	0.10	0.0000

Figure A-2. Aerosizer Output for the 68°F Climatic Chamber Test (Cycle 2)



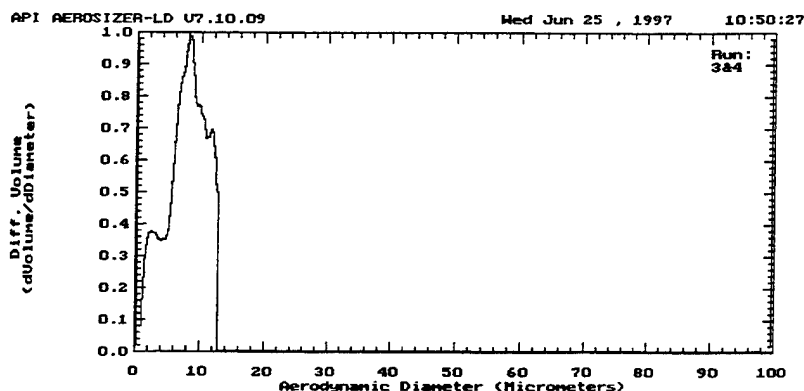
Directory: c:\eg12 Run 1 taken on Wed Jun 25 10:49:17 1997 Volume Distribution by Aerodynamic Diameter
 Test #2 0 F 06-25-97 exhaust sample Regularization: High
 G337602-21 Eglin AFB

Flow Rate Range: 2.00 to 2.00 l/min
 Concentration : 8.94e+07 particles/cubic meter (Counting Efficiency=1.000)
 Mass Loading : 6.09e+00 mg/cubic meter (Counting Efficiency=1.000)

PARAMETERS		DISPERSER CONTROL		%UNDER	SIZE	%UNDER	SIZE
Material	: ambient aerosol	Disperser Type	: AeroSampler	5%	4.253	55%	10.15
Density	: 1.00	Heater	: OFF	10%	5.257	60%	10.61
Run Length (sec)	: 59.0	Purge	: OFF	15%	6.066	65%	11.06
PMT Voltage (volts)	: 1100.0			20%	6.702	70%	11.53
Laser Current (mA)	: 38.7			25%	7.266	75%	12.01
Clock Freq (MHz)	: 40.0			30%	7.782	80%	12.55
Sum of channels	: 180903			35%	8.275	85%	13.16
Lower Size Limit	: 0.10			40%	8.757	90%	13.88
Upper Size Limit	: 99.80			45%	9.232	95%	14.74
Nozzle Type	: 200um	SCANS 1 AND 2 COMBINED		50%	9.694		
Baseline Offset	: 0.10	BETWEEN 2.6 & 2.7 MICRONS					
Noise Filter	: 6.00						
Mean Size	: 8.961	D(4,3)	: 9.600	Mode (Linear Scale): 10.72			
Standard Deviation	: 1.494	D(3,2)	: 8.113	Spec surf area: 0.74 sq meter/g			

UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER
100	0.0000	86.0	100.00	10.0	14.994	8.60	38.354	1.00	0.0356	0.86	0.0298				
86.0	0.0000	74.0	100.00	8.60	12.090	7.40	26.264	0.86	0.0170	0.74	0.0127				
74.0	0.0000	63.0	100.00	7.40	9.5445	6.30	16.720	0.74	0.0063	0.63	0.0065				
63.0	0.0000	54.0	100.00	6.30	5.9188	5.40	10.801	0.63	0.0013	0.54	0.0052				
54.0	0.0000	46.0	100.00	5.40	4.1743	4.60	6.6269	0.54	0.0005	0.46	0.0046				
46.0	0.0000	40.0	100.00	4.60	2.6755	4.00	3.9514	0.46	0.0008	0.40	0.0038				
40.0	0.0000	34.0	100.00	4.00	1.7463	3.40	2.2051	0.40	0.0015	0.34	0.0023				
34.0	0.0000	29.0	100.00	3.40	0.7763	2.90	1.4288	0.34	0.0013	0.29	0.0010				
29.0	0.0000	25.0	100.00	2.90	0.3363	2.50	1.0925	0.29	0.0006	0.25	0.0003				
25.0	0.0000	22.0	100.00	2.50	0.2267	2.20	0.8658	0.25	0.0002	0.22	0.0001				
22.0	0.0000	18.0	100.00	2.20	0.3175	1.80	0.5483	0.22	0.0001	0.18	0.0000				
18.0	0.0000	16.0	100.00	1.80	0.1534	1.60	0.3950	0.18	0.0000	0.16	0.0000				
16.0	0.0000	14.0	100.00	1.60	9.2432	14.0	90.757	1.60	0.1362	1.40	0.2588	0.16	0.0000	0.14	0.0000
14.0	0.0000	12.0	100.00	1.40	15.905	12.0	74.852	1.40	0.1124	1.20	0.1464	0.14	0.0000	0.12	0.0000
12.0	0.0000	10.0	100.00	1.20	21.503	10.0	53.349	1.20	0.0810	1.00	0.0654	0.12	0.0000	0.10	0.0000

Figure A-3. Aerosizer Output for the -9°F Climatic Chamber Test (Cycle 1)



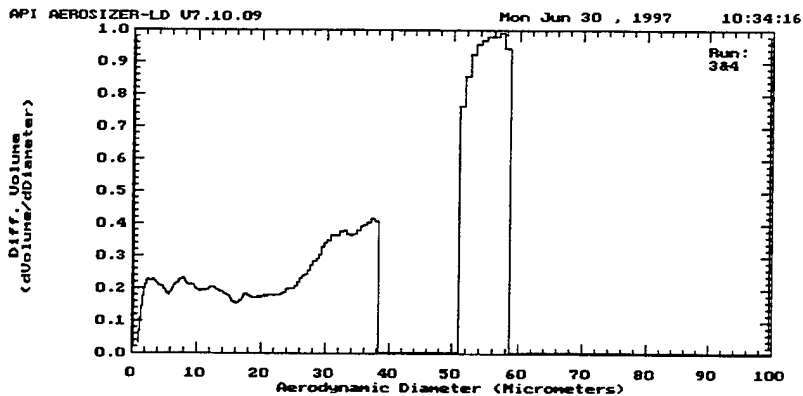
Directory: c:\eg12 Run 3 taken on Wed Jun 25 10:50:27 1997 Volume Distribution by Aerodynamic Diameter
 Test #2 0 F 06-25-97 exhaust sample Regularization: High
 G337602-21 Eglin AFB

Flow Rate Range: 1.96 to 2.00 l/min
 Concentration : 1.47e+07 particles/cubic meter (Counting Efficiency=1.000)
 Mass Loading : 2.55e-01 mg/cubic meter (Counting Efficiency=1.000)

PARAMETERS		DISPERSER CONTROL		%UNDER	SIZE	%UNDER	SIZE
Material	: ambient aerosol	Dispenser Type	: AeroSampler	5%	2.070	55%	8.305
Density	: 1.00	Heater	: OFF	10%	3.029	60%	8.682
Run Length (sec)	: 59.2	Purge	: OFF	15%	4.036	65%	9.109
PMT Voltage (volts)	: 1100.0			20%	5.037	70%	9.572
Laser Current (mA)	: 38.7			25%	5.785	75%	10.04
Clock Freq (MHz)	: 40.0			30%	6.314	80%	10.53
Sum of channels	: 29586			35%	6.757	85%	11.06
Lower Size Limit	: 0.10			40%	7.172	90%	11.58
Upper Size Limit	: 99.80			45%	7.573	95%	12.12
Nozzle Type	: 200um	SCANS 3 AND 4 COMBINED		50%	7.945		
Baseline Offset	: 0.10	BETWEEN 4.9 & 5.0 MICRONS					
Noise Filter	: 6.00						
Mean Size	: 6.859	D(4,3)	: 7.680	Mode (Linear Scale):		8.25	
Standard Deviation	: 1.713	D(3,2)	: 5.677	Spec surf area:		1.06 sq meter/g	

UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER
		100	0.0000	86.0	100.00	10.0	15.627	8.60	58.954	1.00	0.2528	0.86	0.2190		
		86.0	0.0000	74.0	100.00	8.60	16.151	7.40	42.804	0.86	0.1287	0.74	0.0903		
		74.0	0.0000	63.0	100.00	7.40	12.954	6.30	29.849	0.74	0.0598	0.63	0.0305		
		63.0	0.0000	54.0	100.00	6.30	7.6728	5.40	22.176	0.63	0.0200	0.54	0.0105		
		54.0	0.0000	46.0	100.00	5.40	4.4146	4.60	17.762	0.54	0.0068	0.46	0.0037		
		46.0	0.0000	40.0	100.00	4.60	2.9352	4.00	14.826	0.46	0.0023	0.40	0.0014		
		40.0	0.0000	34.0	100.00	4.00	2.9418	3.40	11.885	0.40	0.0010	0.34	0.0004		
		34.0	0.0000	29.0	100.00	3.40	2.5532	2.90	9.3316	0.34	0.0003	0.29	0.0001		
		29.0	0.0000	25.0	100.00	2.90	2.0794	2.50	7.2521	0.29	0.0001	0.25	0.0000		
		25.0	0.0000	22.0	100.00	2.50	1.5767	2.20	5.6754	0.25	0.0000	0.22	0.0000		
		22.0	0.0000	18.0	100.00	2.20	2.0615	1.80	3.6139	0.22	0.0000	0.18	0.0000		
180	0.0000	160	100.00	18.0	0.0000	16.0	100.00	1.80	0.9690	1.60	2.6449	0.18	0.0000	0.16	0.0000
160	0.0000	140	100.00	16.0	0.0000	14.0	100.00	1.60	0.8805	1.40	1.7644	0.16	0.0000	0.14	0.0000
140	0.0000	120	100.00	14.0	6.0328	12.0	93.967	1.40	0.7410	1.20	1.0234	0.14	0.0000	0.12	0.0000
120	0.0000	100	100.00	12.0	19.386	10.0	74.581	1.20	0.5515	1.00	0.4718	0.12	0.0000	0.10	0.0000

Figure A-4. Aerosizer Output for the -9°F Climatic Chamber Test (Cycle 2)



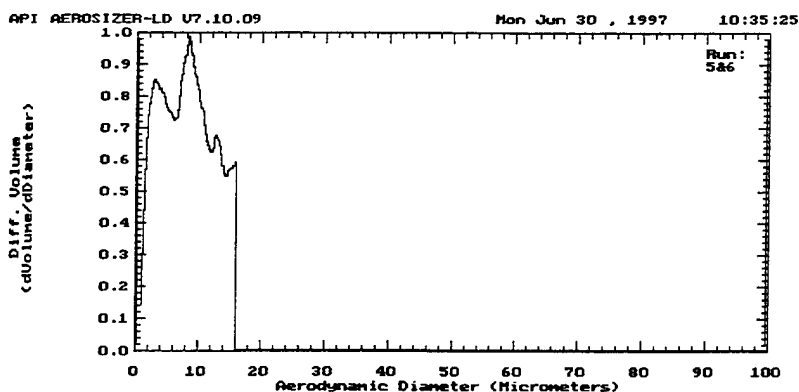
Directory: c:\egl3 Run 3 taken on Mon Jun 30 10:34:16 1997 Volume Distribution by Aerodynamic Diameter
 Test #3 -20 F 06-30-97 exhaust sample Regularization: High
 G337602-21 Eglin AFB

Flow Rate Range: 1.96 to 2.00 l/min
 Concentration : 9.85e+07 particles/cubic meter (Counting Efficiency=1.000)
 Mass Loading : 7.63e+00 mg/cubic meter (Counting Efficiency=1.000)

PARAMETERS		DISPERSER CONTROL		%UNDER	SIZE	%UNDER	SIZE
Material	: ambient aerosol	Disperser Type	: AeroSampler	5%	4.928	55%	37.63
Density	: 1.00	Heater	: OFF	10%	8.766	60%	51.73
Run Length (sec)	: 59.2	Purge	: OFF	15%	12.76	65%	52.65
PMT Voltage (volts)	: 1100.0			20%	17.32	70%	53.50
Laser Current (mA)	: 41.1			25%	21.88	75%	54.33
Clock Freq (MHz)	: 40.0			30%	25.99	80%	55.16
Sum of channels	: 197044			35%	29.03	85%	55.97
Lower Size Limit	: 0.10			40%	31.36	90%	56.78
Upper Size Limit	: 99.80			45%	33.52	95%	57.59
Nozzle Type	: 200um	SCANS 3 AND 4 COMBINED		50%	35.65		
Baseline Offset	: 0.10	BETWEEN 4.9 & 5.0 MICRONS					
Noise Filter	: 6.00						
Mean Size	: 29.19	D(4,3)	: 36.52	Mode (Linear Scale):			57.11
Standard Deviation	: 2.245	D(3,2)	: 17.90	Spec surf area:		0.335 sq meter/g	

UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER
		100	0.0000	86.0	100.00	10.0	1.8149	8.60	9.7803	1.00	0.0464	0.86	0.0391		
		86.0	0.0000	74.0	100.00	8.60	1.6827	7.40	8.0976	0.86	0.0229	0.74	0.0163		
		74.0	0.0000	63.0	100.00	7.40	1.4851	6.30	6.6125	0.74	0.0100	0.63	0.0062		
		63.0	27.022	54.0	72.978	6.30	1.0595	5.40	5.5530	0.63	0.0033	0.54	0.0029		
		54.0	16.983	46.0	55.995	5.40	0.9687	4.60	4.5843	0.54	0.0012	0.46	0.0017		
		46.0	0.0000	40.0	55.995	4.60	0.7774	4.00	3.8069	0.46	0.0005	0.40	0.0011		
		40.0	9.9012	34.0	46.094	4.00	0.8119	3.40	2.9951	0.40	0.0005	0.34	0.0007		
		34.0	11.146	29.0	34.948	3.40	0.7019	2.90	2.2932	0.34	0.0003	0.29	0.0003		
		29.0	6.2707	25.0	28.677	2.90	0.5576	2.50	1.7356	0.29	0.0002	0.25	0.0001		
		25.0	3.5411	22.0	25.136	2.50	0.4206	2.20	1.3150	0.25	0.0001	0.22	0.0001		
		22.0	4.3669	18.0	20.769	2.20	0.5272	1.80	0.7878	0.22	0.0000	0.18	0.0000		
180	0.0000	160	100.00	18.0	2.1309	16.0	18.638	1.80	0.2348	1.60	0.5530	0.18	0.0000	0.16	0.0000
160	0.0000	140	100.00	16.0	2.1352	14.0	16.503	1.60	0.2019	1.40	0.3510	0.16	0.0000	0.14	0.0000
140	0.0000	120	100.00	14.0	2.4649	12.0	14.038	1.40	0.1575	1.20	0.1935	0.14	0.0000	0.12	0.0000
120	0.0000	100	100.00	12.0	2.4429	10.0	11.595	1.20	0.1080	1.00	0.0855	0.12	0.0000	0.10	0.0000

Figure A-5. Aerosizer Output for the -22°F Climatic Chamber Test (Cycle 1)



Directory: c:\egl3 Run 5 taken on Mon Jun 30 10:35:25 1997 Volume Distribution by Aerodynamic Diameter
 Test #3 -20 F 06-30-97 exhaust sample Regularization: High
 G337602-21 Eglin AFB

Flow Rate Range: 1.96 to 2.00 l/min
 Concentration : 3.30e+07 particles/cubic meter (Counting Efficiency=1.000)
 Mass Loading : 4.61e-01 mg/cubic meter (Counting Efficiency=1.000)

PARAMETERS		DISPERSER CONTROL		%UNDER	SIZE	%UNDER	SIZE
Material	: ambient aerosol	Disperser Type	: AeroSampler	5%	1.863	55%	8.564
Density	: 1.00	Heater	: OFF	10%	2.553	60%	9.167
Run Length (sec)	: 59.2	Purge	: OFF	15%	3.203	65%	9.817
PMT Voltage (volts)	: 1100.0			20%	3.869	70%	10.53
Laser Current (mA)	: 41.1			25%	4.553	75%	11.31
Clock Freq (MHz)	: 40.0			30%	5.275	80%	12.18
Sum of channels	: 66324			35%	6.023	85%	13.01
Lower Size Limit	: 0.10			40%	6.763	90%	13.91
Upper Size Limit	: 99.80			45%	7.405	95%	14.90
Nozzle Type	: 200um	SCANS 5 AND 6 COMBINED		50%	7.998		
Baseline Offset	: 0.10	BETWEEN 6.6 & 6.7 MICRONS					
Noise Filter	: 6.00						
Mean Size	: 6.783	D(4,3)	: 8.064	Mode (Linear Scale): 8.25			
Standard Deviation	: 1.915	D(3,2)	: 5.282	Spec surf area: 1.14 sq meter/g			

UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER	UPPER SIZE	% IN	LOWER SIZE	% UNDER
		100	0.0000	86.0	100.00	10.0	11.029	8.60	55.309	1.00	0.3053	0.86	0.2574		
		86.0	0.0000	74.0	100.00	8.60	10.347	7.40	44.963	0.86	0.1546	0.74	0.1028		
		74.0	0.0000	63.0	100.00	7.40	8.1329	6.30	36.830	0.74	0.0697	0.63	0.0331		
		63.0	0.0000	54.0	100.00	6.30	5.9812	5.40	30.849	0.63	0.0222	0.54	0.0109		
		54.0	0.0000	46.0	100.00	5.40	5.5153	4.60	25.333	0.54	0.0074	0.46	0.0036		
		46.0	0.0000	40.0	100.00	4.60	4.3615	4.00	20.972	0.46	0.0023	0.40	0.0013		
		40.0	0.0000	34.0	100.00	4.00	4.4792	3.40	16.493	0.40	0.0009	0.34	0.0003		
		34.0	0.0000	29.0	100.00	3.40	3.8151	2.90	12.678	0.34	0.0003	0.29	0.0001		
		29.0	0.0000	25.0	100.00	2.90	3.0773	2.50	9.6004	0.29	0.0001	0.25	0.0000		
		25.0	0.0000	22.0	100.00	2.50	2.2209	2.20	7.3795	0.25	0.0000	0.22	0.0000		
		22.0	0.0000	18.0	100.00	2.20	2.8038	1.80	4.5757	0.22	0.0000	0.18	0.0000		
180	0.0000	160	100.00	18.0	0.0000	16.0	1.2828	1.60	3.2929	0.18	0.0000	0.16	0.0000		
160	0.0000	140	100.00	16.0	9.5327	14.0	90.467	1.60	1.1284	1.40	2.1645	0.16	0.0000	0.14	0.0000
140	0.0000	120	100.00	14.0	11.520	12.0	78.947	1.40	0.9272	1.20	1.2372	0.14	0.0000	0.12	0.0000
120	0.0000	100	100.00	12.0	12.609	10.0	66.338	1.20	0.6745	1.00	0.5627	0.12	0.0000	0.10	0.0000

Figure A-6. Aerosizer Output for the -22°F Climatic Chamber Test (Cycle 2)

References

Kogan, V. , Kuhlman, M. R., and Gieseke, J. A. (1987), "Turbulent Deposition of Aerosol Particles in Bends," presented at the 1987 Annual Meeting of the American Association for Aerosol Research, Seattle, Washington.

Stephens, D. C., Review of Aspiration Coefficients of Thin-Walled Sampling Nozzles, *J. Aerosol Sci.*, Vol. 17 No. 4, pp. 729-783, 1986.

Wood, N. B. (1981), *J. Aerosol Sci.*, Vol. 12, No. 3, pp. 275-290.