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Abstract

This project was requested by the Air Force Institute of Environment Safety and Health Risk Analysis to evaluate personal exposure to turbine engine exhaust. Quantifiable indicators of exhaust exposure were identified based on selected components of turboprop exhaust – soot-borne polycyclic aromatic hydrocarbons (PAH), elemental carbon particulate matter and carbon dioxide. Since there were no U.S. occupational exposure limits (OELs) for the first two components, working OELs were chosen by analogy to assess exposure potential. Airborne concentrations of soot-borne PAH were compared with a working OEL of 0.2 mg/m^3 and elemental carbon particulate matter with 0.05 mg/m^3, both on an 8-hour time weighted average (TWA) basis. No PAH were detected with NIOSH Analytical Method 5506. Breathing zone levels were less than 10 percent of working OELs. Estimated transient elemental carbon particulate concentrations periodically exceeded excursion limits for the working OEL (0.15 mg/m^3 for 30-min excursions and 0.25 mg/m^3 for 5-minute excursions).

The photoelectric aerosol sensor (PAS) is a quantitative instrument known to respond to particle-bound PAH. The PAS is useful for identifying turbine engine exhaust concentration gradients throughout the workplace. Its short averaging time permits correlation of work activities with exposure events and allows documenting process conditions in a near real-time and time history fashion. This instrument needs more developmental work before its response can be stated in terms of an OEL for turbine engine exhaust. TWA elemental carbon concentrations were highly correlated with computed averages of PAS output.

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A Thesis

by

PAUL S. PIRKLE III

Submitted to the Office of Graduate Studies of
Texas A & M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2000

Major Subject: Industrial Hygiene

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May 2000

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ABSTRACT

Exhaust Exposure Potential from the Combustion of
JP-8 Jet Fuel in C-130 Engines. (May 2000)
Paul S. Pirkle III, B.S., Texas A&M University
Chair of Advisory Committee: Dr. James C. Rock

This project was requested by the Air Force Institute of Environment Safety and Health Risk Analysis to evaluate personal exposure to turbine engine exhaust. Quantifiable indicators of exhaust exposure were identified based on selected components of turboprop exhaust – soot-borne polycyclic aromatic hydrocarbons (PAH), elemental carbon particulate matter and carbon dioxide. Since there were no U.S. occupational exposure limits (OELs) for the first two components, working OELs were chosen by analogy to assess exposure potential. Airborne concentrations of soot-borne PAH were compared with a working OEL of 0.2 mg/m^3, elemental carbon particulate matter with 0.05 mg/m^3 and carbon dioxide with 5,000 parts per million (volumetric) all on an 8-hour time weighted average (TWA) basis. Breathing zone levels were less than 10 percent of working OELs. Estimated transient elemental carbon particulate concentrations periodically exceeded excursion limits for the working OEL (0.15 mg/m^3 for 30-min excursions and 0.25 mg/m^3 for 5-minute excursions). The primary health hazard associated with elemental carbon particles is that they serve as a vehicle for adsorbed PAH. Since PAH are relatively harmless compounds until metabolized by the body to their potent polar derivatives and excursion limits are “rules of thumb”, bodily

repair mechanisms are believed to keep pace with damaging mechanisms from short-term PAH exposures.

The photoelectric aerosol sensor (PAS) is a quantitative instrument known to respond to particle-bound PAH. The PAS shows something is particle bound, but does not confirm that the photoactive species are exclusively PAH. Knowledge of the source being sampled reduces this uncertainty. The NIOSH Analytical Method 5506 for PAH did not detect any. I conclude that the PAS is useful for identifying turbine engine exhaust concentration gradients throughout the workplace. Its short averaging time permits correlation of work activities with exposure events and allows documenting process conditions in a near real-time and time history fashion. This instrument needs more developmental work before its response can be stated in terms of an OEL for turbine engine exhaust. TWA elemental carbon concentrations were highly correlated with computed averages of PAS output. Real-time carbon dioxide measurements with an electrochemical cell correlated poorly with PAS response.

DEDICATION

I am dedicating this work to the people who are dearest to me. Mom, I have so much to thank you for. You instilled in me humility, a sense of humor, persistence, fairness, creativity and unconditional love. Dad, you have taught me more than you know. You passed on to me an engineering mindset and the value of honor, accountability and loyalty. Thank you, Paige, for being my dear sister. We also share that common bond to Aggieland, which has brought us that much closer. Michelle, I cannot express in this small space exactly what you mean to me. We have shared it all, and the thought of growing old with you gives me great joy. Your grace, kindness, patience and warmth have allowed me to become the best version of myself. Ali and Tasha, you are truly amazing, and I am very proud of you. I love you so much, and thank you for being so special and sweet.

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I wish to extend my deepest gratitude to Dr. Jim Rock. Dr. Rock is truly an amazing individual who has inspired and instructed me so that I could become a much more complete industrial hygienist. He is the primary reason I selected A&M, and I was not disappointed. Presenting industrial hygiene from a foundation of scientific and engineering principles was thoroughly interesting and beneficial.

Dr. Don Ward has also been an influential person in my A&M and Air Force careers. I first met Dr. Ward during my undergraduate years when we had, on occasion, the opportunity to discuss wind tunnel and flight test principles and Air Force career issues. I sincerely appreciate his genuine concern for my interests and his service on my Advisory Committee. I also appreciate Dr. Bruce Freeman for serving on my Committee.

Thanks are in order for Major Les Smith from the Air Force Institute for Environment, Safety and Occupational Health Risk Analysis. He facilitated merging the goals of the Air Force and those of my thesis work, thereby leveraging critical resources toward addressing a unique technical challenge. I also wish to thank the three program managers who worked at the Air Force Institute of Technology during my tour here, Majors John Johnson, James Wooten and Robert Hill. In addition to their traditional support of AFIT students, they allotted travel funds so that I could perform the fieldwork.

Without the aid of some remarkable people at the installations I surveyed, this undertaking would not have been possible. Colonel Jimmie Simmons, the operations group commander at Pope Air Force Base (AFB) opened many doors in getting the field testing underway. Technical Sergeant John McNair, the manager of the aerospace ground equipment maintenance shop, was also helpful when working at Pope AFB.

Master Sergeant Randy Dart was my point man for the evaluations performed at Savannah Air National Guard Base. I needed to conduct sampling during a vital cargo loading operation while at Dobbins Air Reserve Base, and Senior Master Sergeant John Cowman orchestrated it to perfection. Lieutenant Michael Fea did a very professional and thorough job of setting up my visit to Little Rock AFB and accommodating all of my needs during that visit. Captain Brian Joos provided invaluable insight to and coordination with Little Rock AFB flying operations.

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The assistance I received from Dr. David Leith's group at University North Carolina, Chapel Hill was extraordinary. Al Armendariz and John Volckens deserve special recognition. Al dedicated significant time and effort to teach me what their group had done and how it might apply to my work. He and John met me at the Raleigh-Durham Airport, and John accompanied me to Pope AFB, some 80 miles away, to provide hands-on training with equipment they let me borrow.

Joachim Pleil from the Environmental Protection Agency National Environmental Research Laboratory loaned me two state of the art instruments that proved invaluable for my research. For that, I am truly grateful.

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INTRODUCTION

Problem Definition

There is on-going worldwide concern regarding personnel exposure to jet fuels and their combustion products.(1) While most studies have focused on exposures to unburned fuel, awareness of turbine engine combustion products is beginning to mature. Civilian airports have started to query National Institute for Occupational Safety and Health (NIOSH) to survey their work areas and employees for potential exposures to jet engine combustion products.(2, 3) Concerns have surfaced, in part, because International Agency for Research on Cancer (IARC) classified diesel exhaust as a probable human carcinogen(4) and the American Conference of Governmental of Industrial Hygienists (ACGIH) has tagged it as a suspected human carcinogen. Whether these classifications have any relevance to turbine engine exhaust has yet to be determined.

This investigation identified quantifiable indicators of exhaust exposure originating from the combustion of JP-8 jet fuel in modern turboshaft engines used in the C-130 aircraft. This was accomplished by examining airborne concentrations of various exhaust constituents in workplaces where U.S. Air Force personnel conduct operations involving turbine engines. Particle-bound polycyclic aromatic hydrocarbons (PAH), elemental carbon, and carbon dioxide were the exhaust constituents of interest. Evaluations of other exhaust components are suggested in Appendix 1.

This thesis follows the style and format of the *American Industrial Hygiene Association Journal.*

Combustion and Emission

Like the diesel engine, turbine engines emit a wide variety of combustion products. It is estimated that exhaust from these types of processes contains from 450(5) to 1800(6) components in gaseous, vapor and aerosol forms. Due to the automotive and industrial uses of the diesel engine, there exists substantial information on the toxicological properties,(5,6) mechanisms of formation(7,8,9) and analytical measurement of diesel engine exhaust.(8,10,11)

In the last few years, pollution generated by air breathing vehicles has been thrust into the spotlight. Numerous investigations have been conducted to characterize in-flight turbine engine emission for the purposes of determining the impact of civilian and military aviation on atmospheric air quality.(12-21) One study showed that carbon dioxide was emitted at nearly 3 percent by volume from a high-bypass turbofan engine at sea level static conditions.(21) The in-flight studies were germane as they provided insight into particulate characteristics at various conditions, including ground idle conditions, and because consistencies in data reporting from occupational and environmental health investigations should always be a goal.

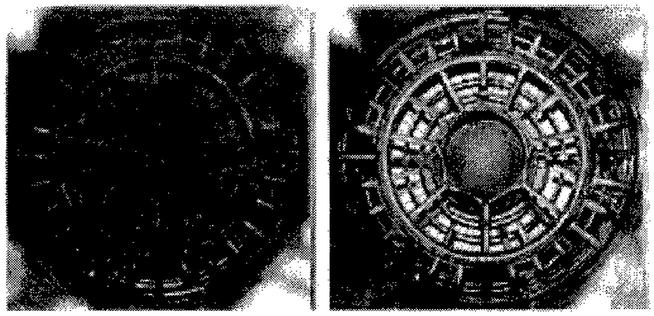
With turbine engine combustion, usable work is created by subjecting air to multistage compression on its way to the combustor. Fuel is distributed in the presence of an ignition source and combustion occurs. The expanding gas drives two aerodynamically coupled turbines, one mechanically linked to the multistage compressor and one to a rotating power output shaft. Net resultant work is converted to torque in a turboprop engine, such as the T-56 used with the C-130.

The different combustion processes likely result in varying particle size, shape, concentration and organic fraction. Although it is useful to understand the differences between diesel and turbine combustion, these differences may not provide necessary insight into particle characteristics. This is important when one considers the other process (maintenance condition and manufacturing variability of the engine, operator throttle inputs, fuel composition) and climatic (ambient temperature, barometric pressure, dew point and wind speed and direction) parameters that affect particle attributes.

Fuel Considerations

Jet engines typically burn kerosene-type fuels, which are similar in composition and performance to diesel fuel. Civilian aircraft use Jet A-1 fuel, and the military now uses JP-8 jet fuel worldwide. JP-8 is formulated by blending Jet A-1 with three additives that inhibit icing (diethylene glycol monomethyl ether), corrosion (based on linoleic acid), and static discharge. JP-8 is a single battlefield fuel, since diesel-powered ground mobile equipment and all aircraft can use it.(22)

Jet fuel is used as a primary coolant for propulsion and non-propulsion subsystems in modern aircraft. As advanced aircraft engines have operated at higher temperatures, they have stressed the fuel to temperatures above its thermal stability limit. This causes the fuel to degrade and form varnishes, gums (oxidative instability products) and coke (thermal instability products). These instability products can lead to fuel fouling, which is an expensive maintenance problem. Fouling distorts fuel nozzle spray pattern, which can cause gas turbine combustor hot spots, adverse three-dimensional temperature distribution (called combustor pattern factor) and excessive temperatures in first-stage turbine blades. In 1989, the U.S. Air Force initiated a research program to increase thermal stability of JP-8 while maintaining performance requirements, fuel cost and fuel availability. The result of that research became known as JP-8+100. This fuel offers a 100 degree Fahrenheit increase in the bulk maximum temperature (from 325 to 425°F) and a 50 percent improvement in heat sink capability over stock JP-8. It contains an antioxidant that inhibits formation of insolubles, dispersant that keeps degrading products in solution, detergent that scrubs degraded products from engine surfaces and chelating agent to remove trace metals that speed up chemical processes of degrading products. A new JP-900 fuel is currently under development that has a thermal stability threshold of 900°F.(22) Figure 1 shows a combustor that had operated 200+ hours with JP-8 and the same combustor that had operated an additional 56 hours with JP-8+100.



(USAF photo)

200+ hours with JP-8 Next 56 hours with JP-8+100

Figure 1. Reduced Coking with JP-8+100 Fuel

Tests were conducted by burning JP-8+100 fuel in the F100-PW-200 engine mounted on the F-16A. JP-8+100 increased the mean time between fuel related augmentor anomalies by 340 percent. Fuel system maintenance costs have been reduced from $374 per flight hour with JP-8 to $106 per flight hour with JP-8+100. Maintenance man-hours have been reduced from 45 minutes per flight hour with JP-8 to 12 minutes per flight hour with JP-8+100. The F-16 Air National Guard unit at Kingsley Field, Oregon documented maintenance savings in excess of $825,000 in fiscal year 1995.

Smoke/soot reduction was also reported, but it is not clear whether this reduction was based on visible observations or quantitative analysis. Subsequent tests with other aircraft/engine permutations, including the C-130H configured with T-56-A-15 engines, have yielded similar results.(22) Based on extrapolation of the data obtained, the Air Force could have a cost avoidance of as much as $80 million per year in maintenance. The primary drawbacks to implementation of this fuel are logistical in nature. The +100 additives must be injected in the field, and they disarm the fuel filter and coalescers. If operation with JP-8+100 fuel also reduces particle emission without increasing hazardous gases and vapors, then the Air Force may realize a benefit to the health of its employees as well as a logistical advantage.

Particle Formation

When liquid fuels like diesel and JP-8 are burned under near stoichiometric conditions, the first-generation particles mainly consist of elemental carbon, a large variety of hydrocarbons and some inorganic species. Combustion particles are agglomerates of primary particles, having a chain- or grape cluster-like structure.(8) More than 95 percent of the particles are less than 1 micrometer in size.(6) Semivolatile organic compounds, such as polycyclic aromatic hydrocarbons (PAH) with four or more rings, partition into gas and particle phases and adsorb to surfaces of carbonaceous cores, when the gas cools down.(8) This partitioning is a function of the compound's vapor pressure, amount of available surface area and ambient temperature.(9) Studies with n-hexadecane as a test fuel burned in a diesel engine have shown that the magnitude and composition of these emitted particles is dominated by the air to fuel equivalence ratio (λ). With decreasing λ the emission of particles increases approximately exponentially. It is hypothesized that, at the moment of ignition, the mixing of fuel and air is not fully complete and zones with an oxygen deficiency are heated to temperatures at which organic compounds thermally decompose.(7)

Constituents of Engine Exhaust Surveyed

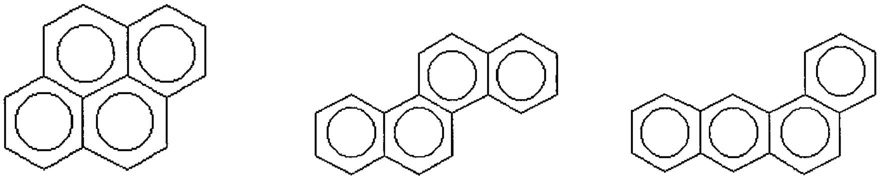
Certain species of particle-bound PAH have been identified as presenting elevated carcinogenic risk. Polycyclic aromatic hydrocarbons (PAH), particulate polycyclic organic material (PPOM) and polynuclear aromatic hydrocarbons (PNA) are synonyms frequently used to describe petroleum-based substances that NIOSH considers to be potential occupational carcinogens. One of the more commonly observed PAH is benzo[a]pyrene, which IARC has identified as a Group 2A carcinogen. This designation means that a substance is "probably carcinogenic to humans" based on limited evidence of carcinogenicity in humans and sufficient evidence of carcinogenicity in experimental animals. Similarities of metabolism of benzo[a]pyrene in human and mouse cells cultured in vitro have been reported. The relevance of this finding for evaluating the risk for man cannot yet be assessed.(4)

PAH are relatively harmless compounds. They are retained in the body because the kidney can not filter them out of the blood due to their nonpolar structure. Oxidation by metabolic enzymes converts PAH into products that are more polar. These polar products are potent carcinogens.(23) Acute exposure symptoms from benzo[a]pyrene exposure could include dermatitis and bronchitis.(24)

The extent of particle-bound PAH is available for interaction with DNA in lung, gastrointestinal tract and other human body cells is only partially understood. Early investigations indicated that little mutagenic activity would be released from soot in biological fluids. However, more recent studies suggest that substantial portions of metabolites of inhaled soot-borne benzo[a]pyrene and nitropyrene are released from the soot, metabolized and either bind to pulmonary tissues or are excreted. The information at present, therefore, indicates that at least a portion of the soot-borne organic material is released in the lung and is available to exert genotoxicity.(5)

PAH make their way into the exhaust stream in two ways, PAH in fuel that survive the combustion process and PAH formed by the combustion process itself.(25) Oxidation-generated PAH evolve when non-ideal temperatures, pressures, fuel spray patterns and fuel constituents are present. Those PAH with sufficiently low vapor pressure (typically those with four or more aromatic rings) adsorb to surfaces of carbonaceous particles, which are also generated under non-ideal conditions, as the exhaust gases cool. Examples of particle-bound PAH are presented in Figure 2.

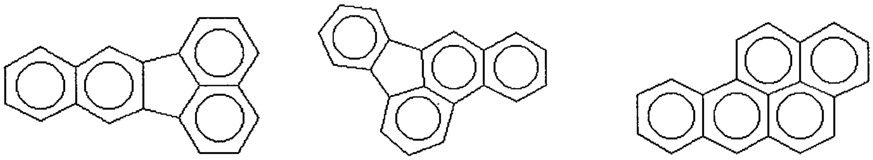
Pure elemental carbon is not a primary health concern; it is what the carbon carries on its surface that generates its toxicological interest. The elemental carbon core has a high specific surface area (30-50 m^2/g) and serves as a nucleus for condensation of organic compounds, such as semivolatile PAH, formed and volatilized by combustion.(5) Elemental carbon is the superior measure of exposure to particulate diesel exhaust because elemental carbon constitutes a large portion of the particulate mass, can be quantified at low levels and primarily originates from the diesel engine in most work environments.(10) Health risks lie in the small (0.1 to 0.5 μm diameter), poorly visible particles because it is expected that they deposit in human lungs and airways. The larger soot "flakes" visible in puffs of concentrated exhaust are less respirable and few would be expected to enter the lung.(5)



Pyrene
($C_{16}H_{10}$)

Chrysene
($C_{18}H_{12}$)

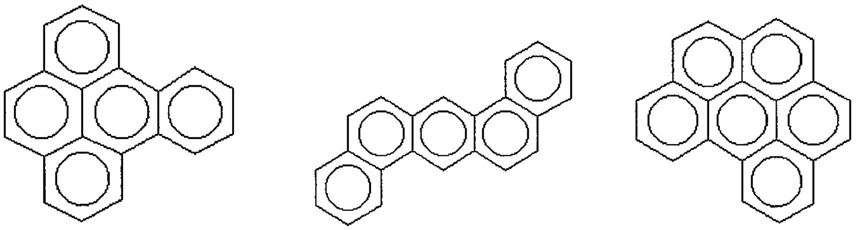
Benz[a]anthracene
($C_{18}H_{12}$)



Benzo[k]fluoranthene
($C_{20}H_{12}$)

Benzo[b]fluoranthene
($C_{20}H_{12}$)

Benzo[a]pyrene
($C_{20}H_{12}$)



Benzo[e]pyrene
($C_{20}H_{12}$)

Dibenzo[ah]anthracene
($C_{22}H_{14}$)

Benzo[ghi]perylene
($C_{22}H_{12}$)

(Source: NIST)

Figure 2. Examples of Particle-Bound PAH

Carbon dioxide is found in ambient air at volumetric concentrations of approximately 360 parts per million in the United States(26) and commonly found at concentrations 100 times higher than that at the turbine engine exhaust outlet.(21) At elevated concentrations, headache, dizziness and restlessness may occur. At concentrations of 3 to 4 percent by volume and higher, short-term exposure can lead to metabolic changes and increased respiratory rate. Coma and asphyxiation could occur at much higher concentrations.(24)

Exposure Limits

Due to its highly complex composition, exposure limits for exhaust particulate are difficult to establish. However, there are on-going efforts to develop such standards for diesel engine exhaust particulate. For this study, the most closely related occupational exposure levels (OELs) were chosen for comparison with results. See Table I below.

The American Conference of Governmental Industrial Hygienists (ACGIH) publishes Threshold Limit Values (TLVs) for a number of chemical substances. In the 1999 TLV book there is a TLV in the "Notice of Intended Changes" section for diesel exhaust (represented by submicrometer diameter total particulate concentrations) of 0.05 mg/m^3.(27) Airborne concentrations of elemental carbon could be assessed in terms of the proposed TLV by estimating the elemental carbon fraction of exhaust particulate. Birch and Carey suggest multiple ways to do this.(10) Elemental carbon fractions of 0.44 (from Volkswagen tests), 0.79 (characterization of exhaust used in animal toxicity tests) and 0.6 to 0.7 (nonextractable EC fraction of particulate in locomotive repair shop survey) are proposed. An elemental carbon fraction of 0.8 was chosen for this paper because it seems to offer the best balance between integrity of reported results and worker protection. In other words, estimations could be avoided if it was assumed that all particulate is elemental carbon, yet we have experimental evidence that EC is some fraction of the total particulate in exhaust. A lower fraction could be chosen to be even more protective, but it is believed that sufficient safety factor is built into the TLV. The same rationale describing the relationship between diesel and turbine combustion emissions applies here and may also explain whether the TLV or the discussion on EC fraction of total exhaust particulate has any relevance to turbine engine exhaust.

TABLE I.

Most Applicable Occupational Exposure Limits (OELs) for this Study

Substance	Agency	OEL	TWA Duration	Extraction Solvent	Analyte(s)
Coal tar pitch	OSHA, ACGIH	0.2 mg/m^3	8 hr	Benzene	Benzo[a]pyrene^A, chrysene^A, pyrene^A anthracene, acridine and phenanthrene
	NIOSH	0.1 mg/m^3	10 hr	Cyclohexane	Benzo[a]pyrene^A, chrysene^A, pyrene^A anthracene, acridine and phenanthrene
Diesel exhaust particulate (diameter < 1 μm)	ACGIH	0.05 mg/m^3 (proposed)	8 hr		Elemental carbon
Carbon dioxide	OSHA, NIOSH, ACGIH	5,000 ppm	8 hr		
	NIOSH, ACGIH	30,000 ppm	15 min		
	NIOSH	40,000 ppm	IDLH^B		

^{A} PAH with 4 or more rings
^{B} Immediately Dangerous to Life and Health

The Occupational Health and Safety Administration (OSHA) groups benzo[a]pyrene, chrysene, pyrene, potentially soot-borne PAH in combustion processes, with anthracene, phenanthrene and acridine as benzene soluble coal tar pitch volatiles and assigns this group a permissible exposure limit of 0.2 mg/m^3. Anthracene and phenanthrene contain three aromatic rings, and acridine is a three-ringed PAH with nitrogen bound in the middle aromatic ring. The NIOSH 10-hour time weighted average Recommended Exposure Limit for cyclohexane-extractable coal tar pitch volatiles is 0.1 mg/m^3. Although the OSHA and NIOSH exposure limits are designed to be protective for workers typically involved in the manufacturing or handling of coal tar products like creosote, they do provide a basis for exhaust exposure assessment because they include PAH assessed during this research.(24)

The ACGIH TLV for benzene-soluble coal tar pitch volatiles is also 0.2 mg/m^3, and there is a "known human carcinogen" label for this group of compounds. There exists no OSHA PEL or ACGIH TLV for individual PAH, but there are some listings for individual PAH that carry the ACGIH "suspected human carcinogen" designation.(27)

There are currently no public or occupational exposure limits for total particulate from turbine engine exhaust or elemental carbon-based limits for diesel or turbine combustion processes in the United States. The U.S. Environmental Protection Agency intends to promulgate diesel particulate emission limits in 2004.

Hazard-Generating Processes

Field studies were conducted at U.S. Air Force Bases where C-130 operations predominate. Procedures where workers are exposed to JP-8 exhaust emissions include engine running on-load/off-load (ERO), combat offload and aerospace ground equipment (AGE) operations. Personnel are also incidentally exposed when performing various duties on the flightline.

The intensity and frequency of the ERO make it the operation with the highest potential for personal exposure to exhaust. Officials at Savannah Air National Guard Base were so concerned about exhaust exposure that they implemented a policy prohibiting EROs for training; they trained with engines off. Three examples of the ERO were evaluated. C-130s are used to carry troops to established drop zones at Pope Air Force Base (AFB). After the drop, the C-130 lands and an ERO is employed to reload the troops. The ERO is also a common technique to move equipment and supplies into and out of deployed environments where exposure of a C-130 to unfriendly fire near the runway is kept to a minimum (see Figure 3). Finally, EROs conducted during the loadmaster training program were surveyed.

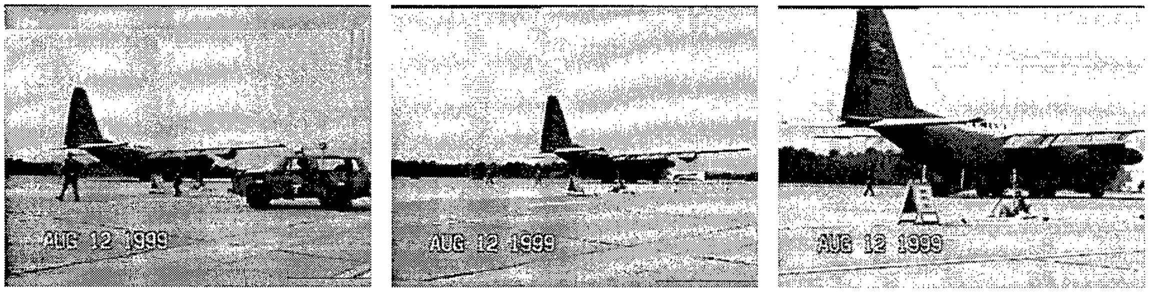
(USAF photo by Staff Sergeant David Wilcoxson)

Figure 3. C-130 from Dyess AFB Unloads Army Vehicle during Air Assault Phase of Exercise at Fort Bragg, NC

For this research, a mock ERO was performed to load and unload a diesel truck. Members of the load crew, the truck driver and his two spotters, and the loadmaster are presented with the highest degree of exposure risk. After the aircraft parks, the load crew approaches it from the rear. As the truck backs into the cargo area, one spotter is positioned inside and one out. The loadmaster also remains in the cargo area. After securing the truck, the load team departs the aircraft while the loadmaster prepares the cargo ramp for closure. See Figure 4 for a pictorial description of the process. The unload portion of the mock ERO was a mirror of the load portion.

The combat offload/ERO procedure is routinely performed at Little Rock AFB as part of the loadmaster training regimen. The combat offload is used sparingly at deployed locations. It entails depositing a payload by accelerating the aircraft so that inertia rolls the cargo off the mounting rails. This procedure starts with a reverse taxi maneuver at the end of runway. The loadmaster moves to the rear of the cargo area and, with cargo door and ramp open, aids the pilot in backing up the aircraft. They then perform the combat offload with a simulation load (bundle of 4 inch by 4 inch wood rails) and conclude with an ERO to unload a mock payload onto a forklift. The aircraft taxis from end of runway to a parking spot on the tarmac to perform the ERO. The aircraft heading for the ERO is 180 degrees opposite of the heading during the combat offload. Present procedures are conducted with aircraft parked without regard to wind direction. Review Figure 5 for a visual description of this process. Airborne units from Fort Bragg routinely jump out of Pope AFB C-130 aircraft. After landing, the troops assemble in the drop zone and board the C-130 with engines on.

Little Rock AFB industrial hygiene professionals interviewed twelve loadmasters to get a better understanding of their work environment and symptoms encountered after performing an ERO. Table II summarizes the information learned from the interviews.



Prepare for ERO

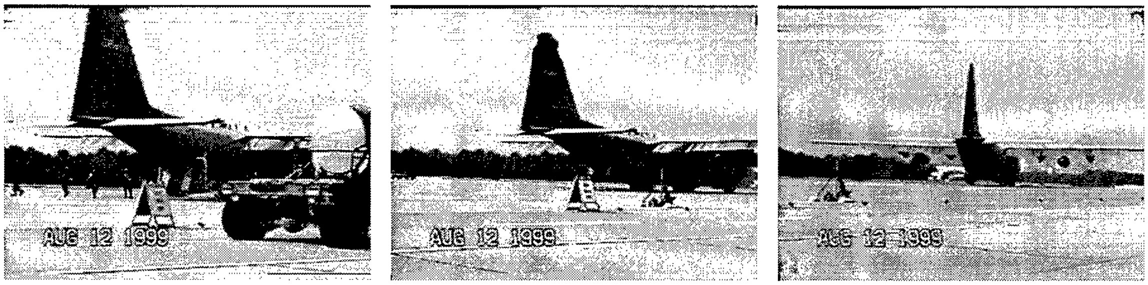
Load crew approaches C-130

Start directing truck
(out of picture)

Align truck for load

Truck nearly loaded

Loadmaster secures ramp extensions

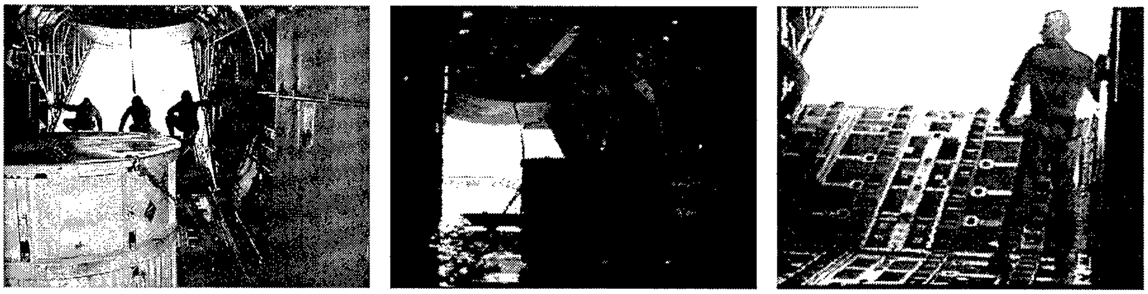


Load crew departs aircraft

Cargo ramp closing

Aircraft departs

Figure 4. Storyboard for Mock ERO at Dobbins Air Reserve Base



Reverse taxi maneuver

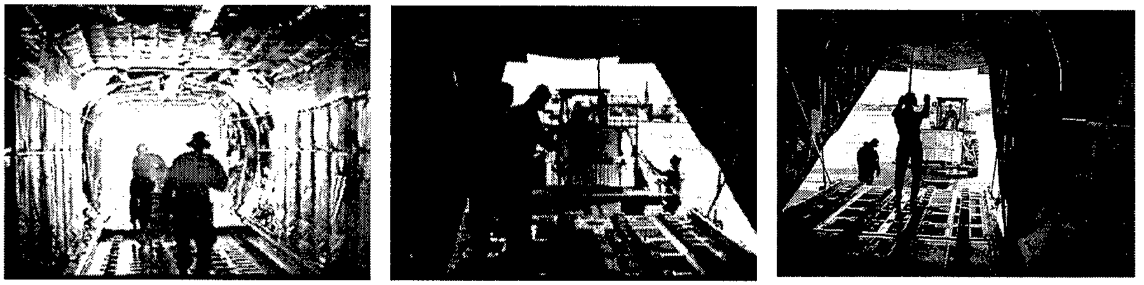
Payload released during combat offload

Cargo door open, ramp closed after combat offload

Taxiing to ERO spot

Direct forklift into position

Release tension in rails to allow cargo to move



Loadmaster rolls cargo onto forklift

Load crew secures cargo to forklift

Direct forklift away from aircraft

Figure 5. Storyboard for Combat Offload/ERO at Little Rock Air Force Base

All twelve loadmasters commented on the poor air quality in the cargo area after conducting an ERO. Air quality descriptions included "…(like) leaving a car running in a garage", "…(like) being in a room with a lot of chain smokers" and "cargo area quickly fills and become saturated with the exhaust air." One loadmaster with 3 years of experience indicated that the environmental control (ventilation) system in the C-130-H3 model was superior for controlling exhaust concentrations in the cargo area compared to the system found in the C-130-E. Another loadmaster with 20 years of experience stated that exhaust ventilation rate is dependent on the environmental control system whose capabilities vary from aircraft to aircraft. This loadmaster also mentioned that younger loadmasters are more likely to be selected for a mission that would include an ERO. Some indicated that conducting EROs in a hot environment exacerbated their discomfort.

TABLE II.

ERO Frequency, Duration and Symptoms Encountered

	Loadmaster Experience (years) [no. in group]		
	0-5 [5]	6-10 [3]	11+ [4]
Symptoms			
Difficulty breathing	2	3	1
Watery eyes	5	3	2
Scratchy throat	3	3	3
Runny nose	0	1	0
Mean no. of EROs performed per year during career	20-100	9-100	7-80
No. of EROs performed in last 12 months	12-100	2-20	6-100
Largest no. of EROs performed in 5-day period	5-20	8-15	3-40
Time of a typical ERO (minutes)	4-15	3-20	5-20
Longest ERO experienced (minutes)	35-90	20-45	20-120

Two field studies conducted for the Air Force investigating ground emissions from the C-130 aircraft fitted with T-56 engines will be useful in some respects. Some of the experiments will be repeated for comparison.(28,29) There exist at least two studies where logged PAS output was compared to laboratory analysis of time-weighted PAH air samples(28,30) that were contrasted with results from this paper.

The electrostatic precipitation (ESP) sample collection method the group at UNC-Chapel Hill is developing was used to measure oil mist concentrations(31,32) and JP-8 aerosol plumes generated during cold engine starts. The proposed research in support of this thesis will explore whether the ESP technology is useful for JP-8 exhaust particulate-bound PAH sample collection.

MATERIALS AND METHODS

Carbonaceous composition of turbine engine exhaust in the loadmaster's breathing zone was determined. Airborne concentrations of elemental and total carbon, carbon dioxide and soot-bound polycyclic aromatic hydrocarbon (PAH) were matched with process and climatic parameters. Process parameters include aircraft heading, turbine inlet temperature, fuel flow and fuel type. Climatic variables include ambient temperature, dew point and wind speed and direction. The intent is to collect sufficient data to be able to describe the potential exposure in terms of process parameters and possibly suggest engineering solutions to exposure mitigation.

A variety of technologies are available for the collection, analysis and measurement of the parameters of interest. Those used during this study include:

- Near real-time, data-logging, photoionization aerosol sensor (PAS) for PAH,
- National Institute of Occupational Safety and Health (NIOSH) Analytical Method 5506 for PAH collected on a Teflon™ filter,
- Electrostatic precipitation sample collection combined with gas chromatography and mass spectroscopy detection (ESP/GC-MS) for PAH,

- NIOSH Analytical Method 5040 for elemental and organic carbon collected on a quartz filter and

- Near real-time, data-logging carbon dioxide analyzer.

Commercially available industrial hygiene air sampling pumps were utilized. They were calibrated before and after each sample collection episode with a primary calibration device that was configured with a near-frictionless piston and photo optic sensors to obtain volumetric flow readings. The typical apparatus setup for ERO sampling is shown in Figure 6. The picture on the right is the setup for sampling at the loadmaster's seat position when it was impractical and unsafe to place sampling equipment on the loadmaster himself, such as the troop drop with ERO pickup, yet acquire air quality data very nearly representative of personal exposures.

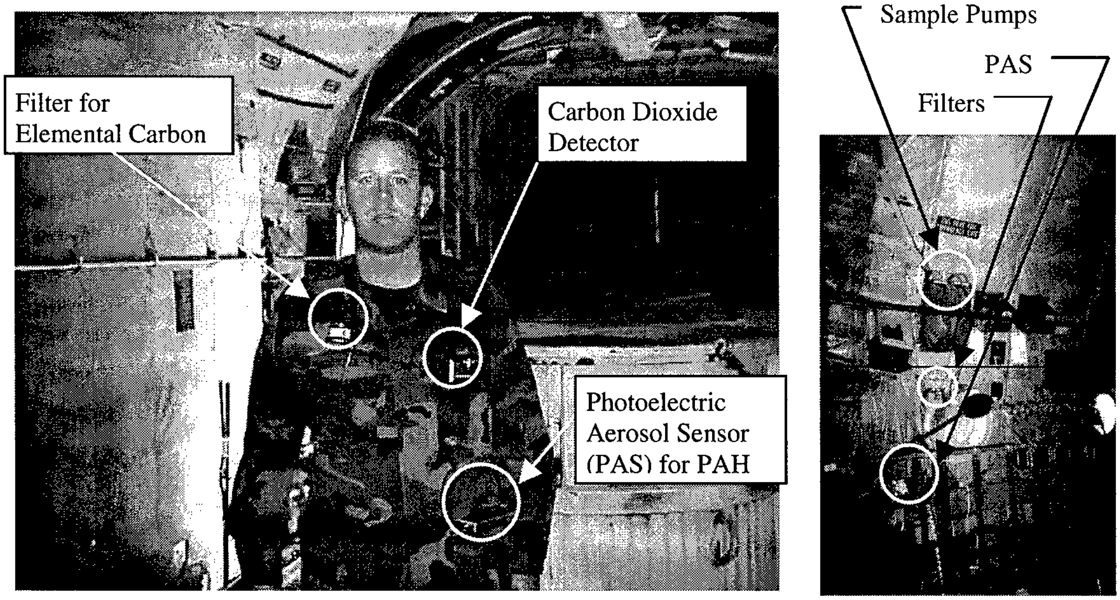


Figure 6. Typical Apparatus Setup for ERO Sampling

NIOSH Analytical Method 5506 employs high performance liquid chromatography with ultraviolet light detection (HPLC/UV). A polytetrafluoroethylene (PTFE) filter and XAD sorbent are used to collect particulate and vapor phase PAH, respectively. Since the research focus was on larger PAH molecules (4+ rings), only the PTFE filter was utilized for quantitative analysis. Each PTFE filter was shielded and immediately stored on ice and shipped cold to avoid sample loss. The laboratory then extracted the sample with acetonitrile and a 30-60 minute ultrasonic bath.(33) Clayton Group Services chain of custody procedures were used for all laboratory analyzed samples to insure sample integrity.

Sample collection using an electrostatic precipitation (ESP) device demonstrated reduced sample loss compared to filter collection methods when sampling for airborne oil mist, a substance not traditionally thought of as volatile.(31,32) The electrostatic precipitation (ESP) unit used for this research had a battery-powered, high-voltage power supply. It operated at a voltage of 5 kilovolts and a current of 15 microamps. Corona, characterized by a glow region containing positive and negative ions, established around the positively charged center wire. The space between the wire and electrode was composed of positive ions. Particles entering the charged region were imparted with a positive charge. The collection electrode was negatively charged, thus creating a Coulomb force that accelerated the charged particle to collection surface. The attraction of charged particles toward the collection electrode was a function of the number of charges acquired, electric field strength and viscous drag of the air.(34) Review Figure 7 for an axial view of the ESP collector. The ESP unit was connected in series with a traditional industrial hygiene pump to collect air samples. Although it is slightly larger and heavier than the pump, it fit adequately on a web belt.

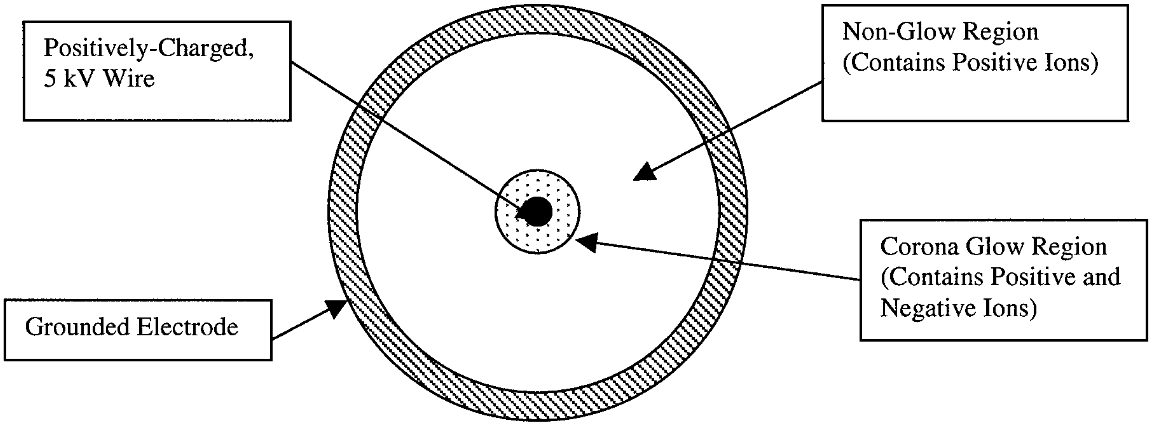
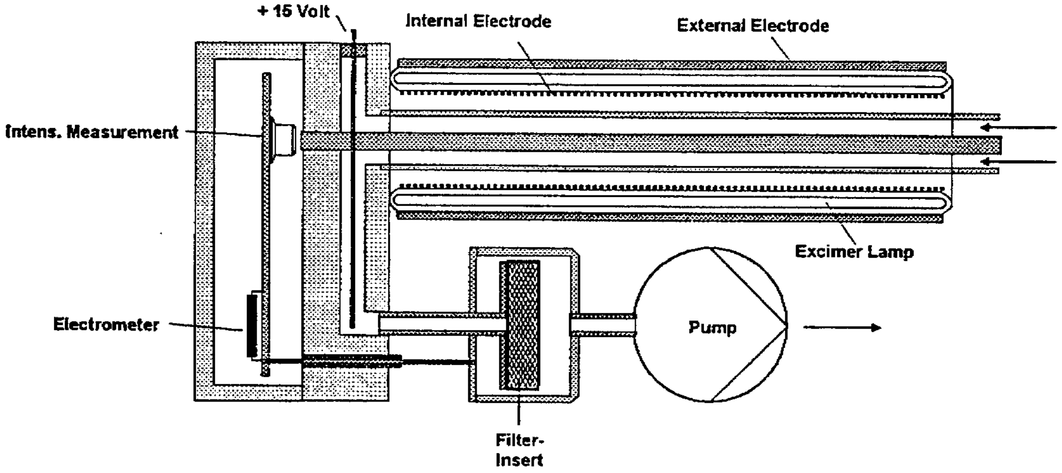


Figure 7. Axial View of High Voltage, Corona Discharge Electrostatic Precipitation (ESP) Chamber

The tube wall (grounded electrode) was lined with aluminum foil, which served as the sample media. Immediately following sampling, the foil was removed from the ESP device and placed in a vial containing n-heptane. The vial was sealed, shielded from solar radiation with aluminum foil and placed on ice to avoid sample loss. Upon receipt, the laboratory subjected the extract to gas chromatograph and mass spectroscopy to detect and quantify particle-bound PAH. The 99.5 percent pure n-heptane solvent extract was spiked with octodecane (C18) as an internal standard. There was an internal standard mass of 69.03 nanograms per 5 microliter injection of n-heptane.

Elemental and organic fractions of carbon were collected and measured using NIOSH Analytical Method 5040, which specifies collection of air samples with a 37-millimeter quartz fiber filter. A section of the filter is punched out at the lab and undergoes a two-stage thermal-optical analytical procedure.(35) First, organic and carbonate carbon (if present) are volatilized from the sample in a pure helium atmosphere as the temperature is incremented to about 820°C. Evolved carbon is catalytically oxidized to carbon dioxide (CO_2) in a bed of granular manganese dioxide (MnO_2) (held at about 900°C), reduced to methane (CH_4) in a nickel/firebrick methanator (at 450°C) and quantified as CH_4 by a flame ionization detector. The second stage involves pyrolysis correction and elemental carbon measurement. There are no reference standards for speciation of different carbon types in complex carbonaceous aerosols. Therefore, methods that speciate EC and OC are considered "operational" in the sense that the method itself defines the analyte. Results of laboratories performing such analyses can be compared on a relative basis, but it is not possible to assess the accuracy of the results.(10) This analytical method was very similar to the one used during airborne emission tests.(11,12,14) The primary difference was that the method used during airborne tests quantified evolved carbon using CO_2 instead of CH_4.

The photoelectric aerosol sensor (EcoChem PAS2000CE, or PAS) is a photoionization detector that employs an excimer lamp emitting photons with a wavelength of 208 nanometers as its excitation source. This corresponds to an ionization energy of 5.96 electron volts. The excimer lamp is a hollow, double-walled quartz tube with krypton and trace amounts of bromine sandwiched between the concentric walls. Air is pumped into the device at 1 liter per minute, through the excitation chamber (creating a positively charged particle and an electron), then past a +15-volt electrostatic filter to remove negatively charged particles. The positively charged particles are subsequently collected on a filter element (mounted in a Faraday cage) and an electrometer measures current.(36) No field calibration routine for this device exists yet. See Figure 8 for a schematic of the PAS.



(Graphic by EcoChem Analytics)

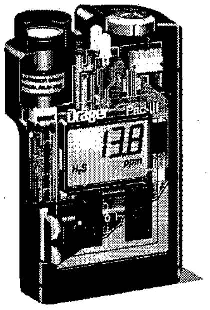
Figure 8. Schematic of Photoelectric Aerosol Sensor (PAS)

The ionization energy imparted by the excimer lamp is relatively low (5.96 eV), which means a select few compounds will ionize at this energy level. Most of the more common interfering compounds are the heavier metals. This, coupled with knowledge of the source of the ionizable compounds (e.g., turbine engine combustion), supports the claim that the PAS is fairly nonresponsive to compounds other than carbon-bound PAH typically constructed of four or more aromatic rings. Several studies address this feature.(37,38,39) However, Wilson and Barbour(39) report that the term "PAH" included substituted (e.g., alkylated) PAH and that the substituted PAH can be expected to elicit a response from the PAS as well. Interestingly, the PAS quantifies the aerosol phase PAH, which have lower ionization energies than their vapor phase counterparts.

The PAS reports values in nanograms per cubic meter (ng/m^3) by multiplying the current on the Faraday cage by a calibration constant derived from field tests. The user may choose the time averaging constant, ranging from 10 to 120 seconds. The 10-second value was chosen for this study to achieve maximum data resolution. The processor simultaneously scans and sums the electrometer and zero signals. The difference between these two sums is the background corrected instrument reading. The calibration constant is then applied. The displayed and stored value is the average value of the previous six measurements with each measurement lasting about 1 second. The advertised linear range of the PAS response is 0 to 1000 ng/m^3. Reported concentrations greater than this level could lead to recombination (free electron recombining with a charged particle), causing underestimation of actual concentrations. Since the PAS manual allows the operator to use up to 1 meter of silicon tubing attached to the inlet, one was used in order to collect breathing zone samples in parallel with other industrial hygiene samples.(36)

Recently, additional compounds, other than the well known PAH, have been detected in combustion experiments. These compounds have aromatic character and behave spectroscopically like PAH even though they have high molecular mass. In addition, these high molecular mass structures account for the largest fraction of sampled material with mass concentrations that are three to four-times higher than those of the chromatographable PAH.(40) It is not yet known whether the PAS responds to these compounds.

The pocket-sized CO_2 analyzer contains an electrochemical sensor with a lower detection limit of 0.1 percent by volume, a resolution of 0.1 percent and a range that extended to 5 percent. A schematic of the CO_2 detector is displayed in Figure 9. This device was only available for the two combat offload/ERO procedures and was used in order to correspond CO_2 values with PAS output in a time history fashion as opposed to strictly being used to assess CO_2 exposure. Prior to use, this device underwent zero calibration and span calibration with 2.5 percent CO_2 test gas. The time averaging constant was user-selectable, and the one-second data reporting interval was chosen for maximum resolution. Data could be downloaded to a computer for further analysis.



(Graphic by Dräger Safety Inc.)

Figure 9. Cutaway View of CO_2 Monitor

RESULTS

Process and Climatic Parameters

When considering the results, it will be important to keep in mind the process and climatic variables that accompany them. Review Table III and Figure 10 for this purpose. The length of the arrows in Figure 10 represents its relative wind speed, and their directions are relative to the aircraft heading. Parameter data were not obtained for the troop drop and ERO pickup operation.

Particle-Bound Polycyclic Aromatic Hydrocarbons

National Institute for Occupational Safety and Health (NIOSH) Analytical Method 5506 and an electrostatic precipitation (ESP) collection method combined with gas chromatograph and mass spectroscopy were used to detect and quantify airborne concentrations of particle-bound polycyclic aromatic hydrocarbons (PAH).

TABLE III.

Process and Climatic Parameters for Sampled Operations

	Mock ERO (load and unload)	Combat offload followed by ERO #1	Combat offload followed by ERO #2
Average turbine inlet temperature (°C)	695	650	650
Average fuel flow (lb_m/hour)	-	600	630
Flap angle (degrees)	-	0	50
Fuel type	JP-8	JP-8	JP-8
Ambient temperature (°C)	27	24	23
Wind speed (knots)	5	12	7
Wind direction (degrees)	290	170	190
Aircraft heading, COL/ERO (degrees)	/250	067/247	067/247

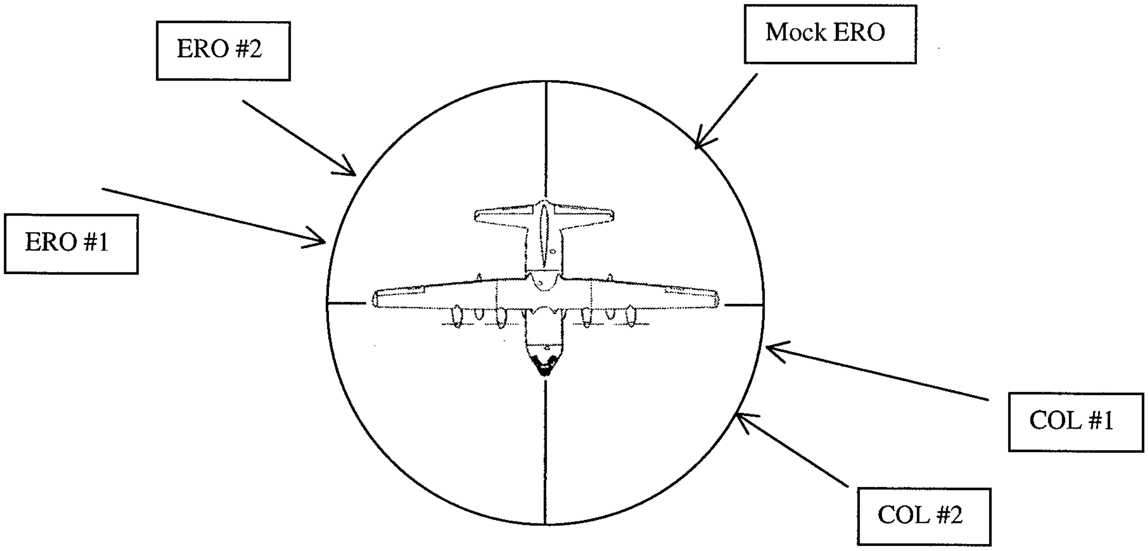


Figure 10. Relative Wind Direction and Speed (Represented by Arrow Direction and Length) for Sampled Activities

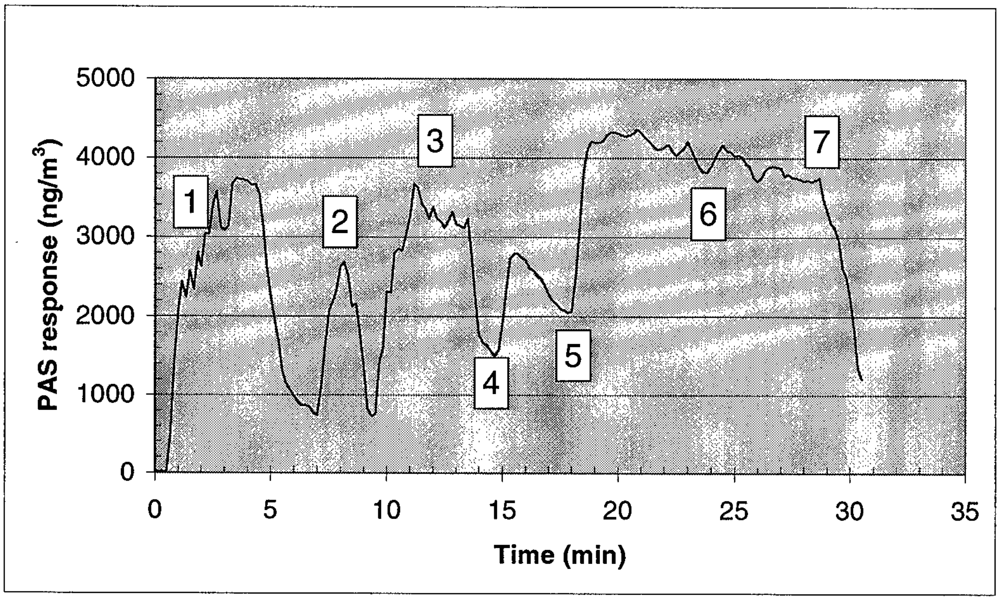
All integrated samples collected for PAH resulted in concentrations less than the detection limit for the NIOSH 5506 and ESP methods. This is true for all operations sampled (those tabulated plus flightline maintenance and aircraft maintenance inside hangar during a C-130 launch). Results are summarized in Table IV. The ratio of integrated sample result to average PAS is also tabulated. During the combat offload/ERO operation, only PAS data was acquired. Raw data collected for all contaminants during all scenarios and plots not mentioned in this section was placed in Appendix 2.

TABLE IV.

PAH Method Detection Levels and Time-Weighted Average PAS Response

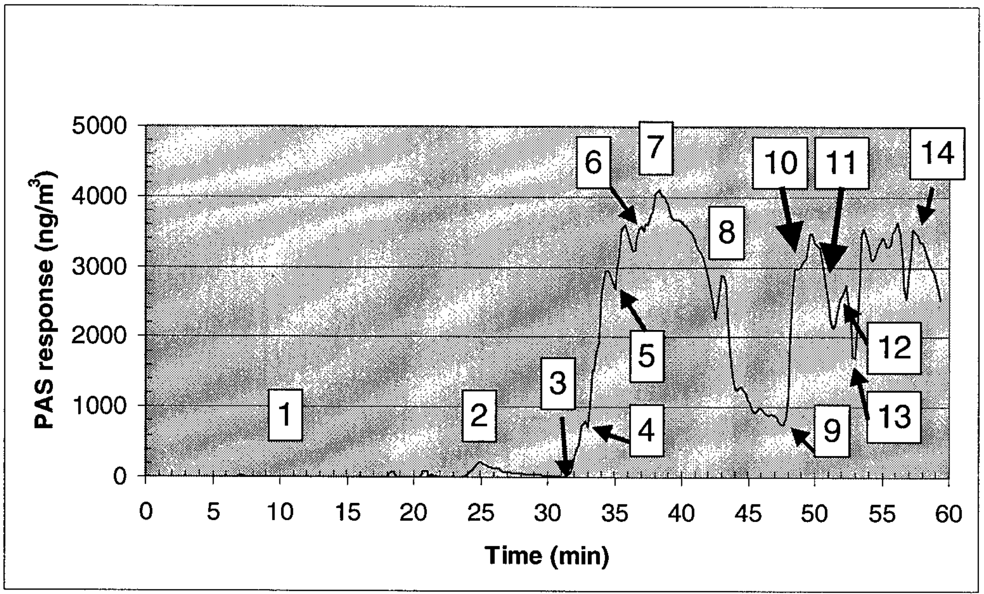
Operation	Fuel Type	Sampling/ Analytical Method	PAH Method Detection Level (mg/m^3)	Task TWA PAS Response (mg/m^3)	MDL/ PAS
Aerospace ground equipment diagnostic testing	JP-8	NIOSH ESP/GC-MS	9.E-04 2.E-03	5.E-05	16.98 37.74
Troop drop with ERO pick up	JP-8	ESP/GC-MS	1.E-04	3.E-04	0.33
C-130 launch inside hangar, 90 ft from door	JP-8+100	ESP/GC-MS	7.E-04	9.E-05	7.78
C-130 cargo drop, loadmaster seat position	JP-8+100	NIOSH	1.E-04	9.E-05	1.11
Mock ERO (shadow loadmaster)	JP-8	NIOSH	1.E-04	8.E-04	0.13
Combat offload followed by ERO #1	JP-8			3.E-03	
Combat offload followed by ERO #2	JP-8			1.E-03	

For some processes, photoelectric aerosol sensor (PAS) response data were obtained. The time histories of PAS output from the both combat offload/ERO maneuvers are provided in Figures 11 and 12.



1	1st reverse taxi maneuver
2	2nd reverse taxi maneuver; combat offload
3	Close cargo ramp and door; taxi to ERO location; walk from rear to front of cargo area
4	Walk from front to rear of cargo area to perform ERO
5	Open cargo ramp and door for ERO; waiting for load crew
6	Forklift in place for cargo extraction
7	Both rear crew doors (adjacent to cargo ramp and door) open; noticeable cross breeze

Figure 11. Photoelectric Aerosol Sensor Response Time History for the Combat Offload/Engine Running Offload at Little Rock AFB on 23 Feb 00



1	Pre-flight procedures in front of aircraft
2	Board aircraft and close left front crew door
3	Open cargo door; move to rear of cargo area
4	Aircraft turned 180° to position for combat offload
5	Engine speed noticeably increased
6	Begin reverse taxi maneuver
7	End reverse taxi maneuver
8	Combat offload then cargo and ramp closed; move to front of cargo area; taxi to parking spot for ERO
9	Cargo door open; move to rear of cargo area
10	Begin first 90° turn to park for ERO; then another 90° turn
11	Parked for ERO (180° from combat offload heading)
12	Cargo ramp down; move to front of cargo area
13	Move to rear of cargo area; wait for load crew; then moving back and forth from front to rear of cargo area for ERO
14	Forklift backs away from aircraft with payload then close door and ramp

Figure 12. Photoelectric Aerosol Sensor Response Time History for the Combat Offload/Engine Running Offload at Little Rock AFB on 24 Feb 00

Exhaust Particulate Matter

Total particulate matter was not quantified in this study. It is assumed that elemental carbon comprised an estimated 80 percent of the total exhaust particulate. Results are reported in terms of this estimated elemental carbon fraction of exhaust particulate and simply in terms of elemental carbon in Table V.

TABLE V.

Exhaust Particulate Exposure Data in Terms of Elemental Carbon and Total Particulate

Task	EC task TWA (mg/m^3)	EC 8-hr TWA (mg/m^3)	Estimated total exhaust particulate task TWA (mg/m^3)	Estimated total exhaust particulate 8-hr TWA (mg/m^3)
-86 cart diagnostic testing	***0.009***[A]			
Airborne cargo drop #1	***0.001***[A]			
Airborne cargo drop #2	***0.003***[A]			
Flightline maintenance during launch	0.003	<<0.001	0.004	<<0.001
Mock ERO (driver)	0.050	0.005	0.063	0.006
Mock ERO (spotter #1)	0.010	<0.001	0.013	0.001
Mock ERO (spotter #2)	0.077	0.007	0.096	0.008
Mock ERO (static at loadmaster seat)	0.041	0.004	0.051	0.005
Troop drop with ERO pick up	0.014	0.007	0.018	0.009
Combat offload followed by ERO #1	0.220	0.014	0.275	0.111
Combat offload followed by ERO #2	0.089	0.011	0.111	0.014

[A] Below Reported Detection Limit (in bold italic)

A common parameter reported in airborne jet exhaust emission studies is the elemental carbon to total carbon ratio (EC/TC). This parameter helps describe the nature of the carbon content in exhaust emissions. Descriptive statistics for EC/TC observations during the troop drop with ERO pick up, mock ERO with load and unload and the two combat offload/ERO maneuvers are presented in Table VI.

TABLE VI.

Descriptive Statistics for Elemental Carbon to Total Carbon Ratio

Mean	0.385
Standard Error	0.042
Median	0.391
Standard Deviation	0.126
Range	0.424
Count	9
95% Confidence Interval	±0.096

Carbon Dioxide Concentrations

Carbon dioxide measurements were collected during the two combat offload/ERO data runs. Maximum instantaneous CO_2 concentrations did not exceed 9,000 part per million by volume and the applicable OELs were not approached. Figure 13 represents the time history of carbon dioxide concentration for the first maneuver plotted with PAS response for comparison. During the second combat offload/ERO, the CO_2 detector only responded in the 0.2 to 0.3 percent range for 18 seconds during the reverse taxi procedure. For comparison, review the PAS response for this maneuver in Figure 12.

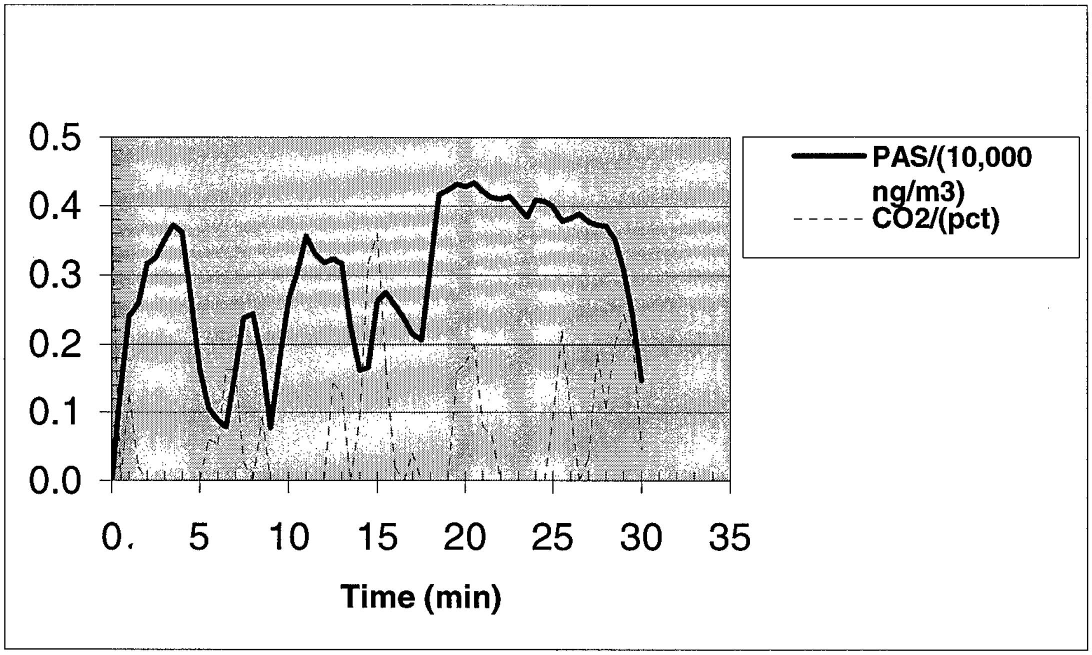


Figure 13. Comparison of CO_2 and PAS Response during Combat Offload/ERO at Little Rock AFB on 23 Feb 00

DISCUSSION

Particle-Bound Polycyclic Aromatic Hydrocarbons

As stated, results from integrated particle-bound PAH sampling were below detection limits for all operations surveyed. This agreed with sampling performed during very similar ERO operations.(28) This meant that breathing zone soot-borne PAH levels were less than 10 percent of the most appropriate OEL, the OSHA permissible exposure limit for benzene-extractable coal tar pitch volatiles.

Time-weighted average (TWA) PAS response ranged from 7.5 times less than to 37 times greater than detection limits for the NIOSH and ESP/GC-MS methods. The fact that the average PAS response occasionally exceeded the detection limit could be explained by sample evaporative loss with the NIOSH and ESP/GC-MS methods and the PAS responding to particles covered with substances that ionize at energies below 5.96 eV other than PAH.

Exhaust Particulate Matter

There were no instances of exceeding the ACGIH proposed 8-hour TLV for diesel exhaust particulate (0.05 mg/m^3). This was true when assuming elemental carbon was 80 or 100 percent of total exhaust particulate. For transient carbon concentrations, a novel approach was taken. Peak-to-average ratios for the PAS response were applied to integrated carbon loadings. The assumption that PAS response is a good measure of transient engine exhaust was based in part on the strong correlation between integrated elemental carbon concentrations and average response from the PAS over identical time periods (see next section). Although this is weak evidence for real-time correlation, this allowed duration above 30-minute and 5-minute excursion limits (ELs) to be computed. The proposed ACGIH TLV for diesel exhaust (submicron total particulate) was used to calculate times in excess of the 30-minute and 5-minute ELs, defined as 3X and 5X the 8-hour TLV, respectively.

This assessment is limited by the variability in differing combustion processes, process and climatic parameters and other sources of randomness that result in highly complex exhaust composition and exposure time series. Task (length of sample period) and 8-hour time-weighted average concentrations and the duration above the 30-minute EL (using a 30-minute moving mean) and the 5-minute ELs (using a 5-minute moving mean) are reported in Table VII. The plots of the estimated total particulate moving means are presented in Figures 14 and 15.

TABLE VII.

Times Exceeding ACGIH Excursion Limits for Estimated Total Exhaust Particulate

	Troop drop with ERO pick up	Combat offload followed by ERO #1	Combat offload followed by ERO #2
Time exceeding 30-min. EL[A]/length of task (minutes)	0/241	-[B]	9/60
Time exceeding 5-min. EL[C] /length of task (minutes)	0/241	18/31	14/60

[A] Based on 30-minute moving mean
[B] Task only 31 minutes long
[C] Based on 5-minute moving mean

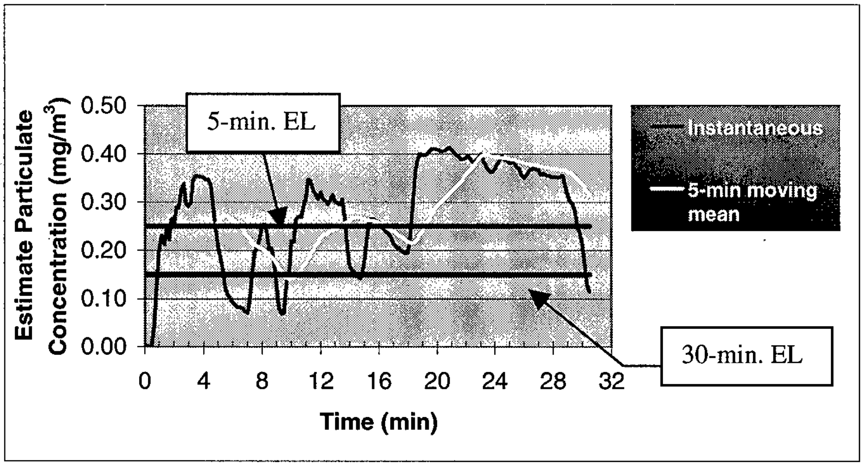


Figure 14. Estimated Total Exhaust Particulate Concentration during Combat Offload/Engine Running Offload at Little Rock AFB, 23 Feb 00

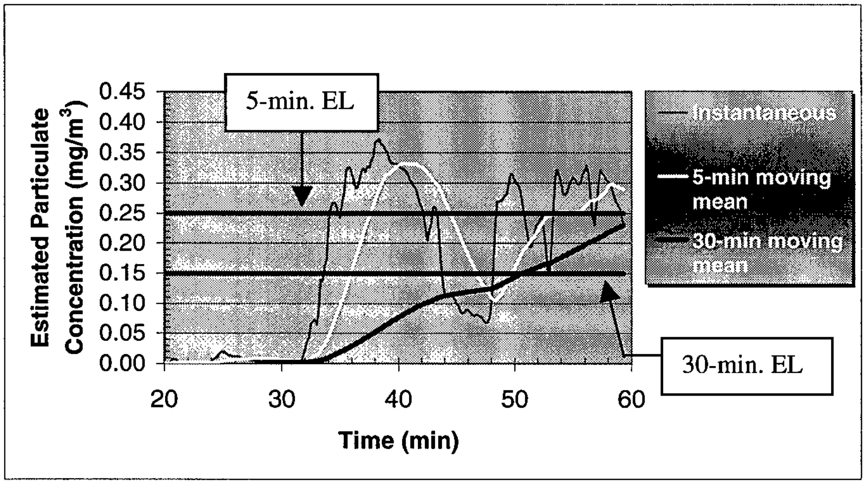


Figure 15. Estimated Total Exhaust Particulate Concentration during Combat Offload/Engine Running Offload at Little Rock AFB, 24 Feb 00

Simple Linear Regression for <EC> versus <PAS Response>

Six data pairs of average EC and PAS response were observed. These 6 data pairs represent measurements at the loadmaster position during maneuvers with the rear cargo door and ramp open and engines running. When EC is plotted versus PAS response, the linear regression model in Figure 16 was observed.

Residuals for the simple linear regression were normally distributed and well behaved. This, combined with poorer fit with square root and natural logarithmic transformations of elemental carbon data, indicated that the linear model was the most appropriate.

Simple linear regression for CO_2 output versus PAS response for the first combat offload/ERO was quite poor (adjusted $R^2 = 0.012$). The lack of correlation between the CO_2 analyzer output and the PAS response and the fact that the analyzer only recorded nonzero values during the reverse taxi procedure of the second combat offload/ERO might be explained by mixing of air and the CO_2 analyzer's relatively low resolution of 0.1 percent. By the time well-mixed air had reached the cargo area, carbon dioxide may not have been easily detected by the analyzer used.

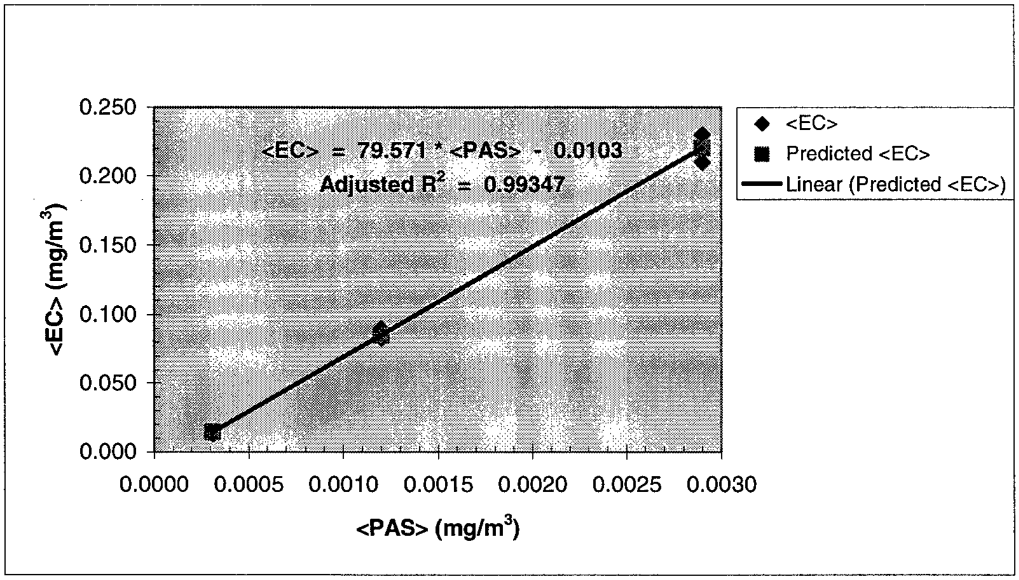


Figure 16. Simple Linear Regression Fit: Time-Weighted Averages of Elemental Carbon and Photoelectric Aerosol Sensor Response

An elemental carbon to total carbon (EC/TC) ratio of 0.10 at ground idle conditions for a research aircraft called ATTAS was observed.(12) This aircraft is powered by Rolls-Royce turbofans, and its exhaust and plume properties are "well characterized." In contrast, mean EC/TC ratios of 0.385 ± 0.042 were observed during this study of conditions in the cargo area of C-130 aircraft outfitted with four T-56 turboprop engines.

CONCLUSIONS

The increased anxiety about diesel exhaust exposure has contributed to growing concern about exhaust from other forms of combustion. The Air Force Institute of Environment Safety and Health Risk Analysis requested this project. Quantifiable indicators of exposure to turboshaft engine exhaust were identified. Breathing zone measurements of indicators of exhaust gas were conducted with NIOSH methods 5506 for PAH and 5040 for elemental carbon, with a developmental electrostatic precipitation collection method, with a direct reading electrochemical cell for carbon dioxide and with a photoionization detector that responds to particles with PAH bound to their surfaces.

There exists no U.S. occupational exposure limit (OEL) for individual polycyclic aromatic hydrocarbons (PAH). Therefore, it was assumed that the OEL for solvent-extractable PAH was a reasonable guideline for soot-borne PAH in turbine engine exhaust. Also, there are currently no public or occupational exposure limits for total particulate from turbine engine exhaust or elemental carbon-based limits for diesel or turbine combustion processes in the United States. For this study, it was assumed that elemental carbon is a useful marker for turbine engine exhaust. Working OELs were chosen by analogy to assess exposure potential. Airborne concentrations of soot-borne PAH were compared with a working OEL of 0.2 milligrams per cubic meter (mg/m^3), elemental carbon particulate matter with 0.05 mg/m^3 and carbon dioxide with 5,000 parts per million (volumetric) all on an 8-hour time weighted average (TWA) basis.

No particle-bound PAH were detected with solvent-extraction methods. The photoelectric aerosol sensor (PAS), with factory calibration and no field calibration procedure yet available, showed photoelectric currents suggesting that airborne concentrations of particle-bound PAH were less than 0.001 mg/m^3 for sampled activities. Since these breathing zone levels are less than 10 percent of the working OEL, there is no obvious indication of health hazards from these data. Keeping in mind that PAH are relatively harmless compounds until metabolized by the body to their potent polar derivatives and that excursion limits are "rules of thumb", bodily repair mechanisms are believed to keep pace with damaging mechanisms from short-term PAH exposures.

Carbon dioxide concentrations were likewise significantly below applicable OELs. Estimated airborne concentrations of total exhaust particulate did not exceed the working OEL of 0.05 mg/m^3. For transient carbon concentrations, a novel approach was taken. Peak-to-average ratios for the PAS response were applied to time-averaged carbon concentrations to estimate transient carbon concentrations. Estimated transient elemental carbon particulate concentrations in turbine engine exhaust periodically exceeded excursion limits for the working OEL (0.15 mg/m^3 for 30-min excursions and 0.25 mg/m^3 for 5-minute excursions).

The PAS is a quantitative instrument and shows something is particle bound, but does not confirm that the photoactive species are PAH. The PAS is useful for identifying turbine engine exhaust concentration gradients throughout the workplace. Its short averaging time permits correlation of work activities with exposure events and allows documenting process conditions in a near real-time and time history fashion. This instrument needs more developmental work before its response can be stated in terms of an OEL for turbine engine exhaust.

TWA elemental carbon concentrations were highly correlated with computed averages of PAS output. Real-time carbon dioxide measurements with an electrochemical cell correlated poorly with PAS response. Further independent studies are needed to confirm these relationships. There may be ways to correlate PAS output to other indices of exhaust exposure that have yet to be explored.

The electrostatic precipitation collection method being developed at the University of North Carolina at Chapel Hill was used in conjunction with gas chromatography and mass spectroscopy for PAH quantitation. No PAH were detected in these studies of turbine engine exhaust. This agrees with results using NIOSH Analytical Method 5506.

Based on reported symptoms, sampling for mucous membrane irritants, such as aldehydes and 2- and 3-ringed PAH, should be performed in the cargo area during engine running onload/offload events. Studies have indicated that there are no appreciable aldehyde concentrations in exhaust gases,(20) but this or another irritant is concentrating in the cargo area. More future work is suggested in Appendix 1.

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APPENDICES

Appendix 1
Considerations for Future Work

Ground-based studies are routinely conducted to derive emission indices for environmental pollution estimations. Future studies of this variety should include gathering elemental carbon (EC) data using NIOSH Analytical Method 5040. This method provides total carbon (TC) results as well, so that EC/TC ratios can be easily computed. This ratio is reported in airborne environmental emission studies and characterizes the carbon content of the exhaust stream. Size selective total particulate analyses would also be beneficial when assessing particle attributes of the engine exhaust.

When performing any study that involves evaluating exhaust constituency, fuel characteristics must be sampled and documented. Consult with the local fuel manager, but several American Society for Testing Materials (ASTM) fuel sampling methods are available. If polycyclic aromatic hydrocarbons (PAH) will be evaluated, PAH analysis of raw fuel needs to be accomplished as well since the majority of PAH that are distributed in exhaust are those that survive the combustion process.(25)

Also note that the U.S. Air Force is implementing JP-8+100 jet fuel, which possibly alter particle emission characteristics compared to stock JP-8. Parallel particle size and concentration analyses should be performed with JP-8+100 and JP-8 fuels to determine if there are any reductions associated with the former fuel.

The research in this thesis was limited to exhaust potential from C-130 turboprop engines during engine running onload/offload (ERO) operations. Other exposure scenarios need to be assessed, chiefly those that include exposure to personnel who work behind aircraft or inside cargo areas when engines are running. These include but are not limited to:

- Routine civilian airport operations,
- "Large Package" operation like at Pope AFB where large scale cargo movement operations are performed and personnel exposures on the ramp are reported to occur,
- C-17 and other cargo aircraft ERO operations (if applicable),
- Aeromedical evacuation with engines running (if applicable) as respiratory system repressed patients may be more prone to health impairment.

As a final note, the author hopes to suggest how technologies being developed for the detection and measurement of combustion aerosols might be applied to industrial hygiene surveillance. Instruments employing techniques such as Fourier transform infrared emission spectroscopy (A.1.) and laser-induced incandescence (A.2.,A.3.) might one day become standard tools for assessing combustion particulate exposure.

A potential technology for improved PAH sample collection is using solid cyclodextrin to decrease sample volatility during air sampling.(A.4.) Butterfield et al. reports that fluorescence intensity of their test PAH is enhanced in the presence of increasing solid cyclodextrin.

Imaging with an infrared camera may be suitable for recording the exhaust formation and migration by tracking carbon dioxide concentrations. Carbon dioxide absorbs infrared radiation at wavelengths of 2.69 micrometers (μm), 2.76 μm, 4.25 μm, 14 μm, and 15 μm (Source: Snell-Ettre, Encyclopedia of Industrial Chemical Analysis, Vol. 8). It is not believed that infrared imaging is used widely for this purpose and might offer a novel approach to visualizing plume behavior. Such real-time visualization may lead to previously untested means to prevent exhaust re-entrainment into the C-130 cargo area during ground operations.

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Appendix 2
Unreduced Data and Other PAS Time Histories

This appendix contains unreduced data in table form and PAS response time histories for events not discussed in the body of this thesis. Note that the time histories do not all have the same PAS response and time scales when attempting to make multiple event comparisons. Table A2.1. summarizes sample collection, process description and results information for all samples obtained on the first data collection trip. This first trip started at Pope Air Force Base (AFB), NC, proceeded to Savannah Air National Guard Base (ANGB), GA and concluded at Dobbins Air Reserve Base (ARB), GA. Table A2.2. presents similar information for data collection efforts at Little Rock Air Force Base, AR.

Figure A2.1. is a time history of the PAS response during a troop drop mission at Pope AFB that included an engine running onload of personnel. The PAS was statically positioned in the C-130 cargo area at the loadmaster's seat position. It was deemed that mounting sample equipment on the loadmaster for this mission might violate safety of flight principles. The investigator did not have clearance to fly on this mission and the flight log was not consulted, so process correlation to exposure can only be suggested. It appears that the engine running onload began at approximately the 110 minute mark and an engine running offload of troops at Fort Bragg started at approximately 187 minute mark.

Figure A2.2. shows the spiked PAS response inside a maintenance hangar when a C-130 taxied by a prior to takeoff. The PAS instrument was placed in a static location in the middle of the hangar approximately 90 feet from the hangar door. Figure A2.3. depicts the PAS response at the loadmaster seat position aboard a C-130 during an airborne cargo drop mission at Savannah ANGB. Again, the investigator did not have clearance to fly on this mission, but it appears that the PAS response in the first 20 minutes could be attributed to ground maneuvers (e.g., taxiing) with cargo door open.

Figure A2.4. presents a time history of a staged engine running onload and offload (ERO) at Dobbins ARB. The PAS this time was mounted on the investigator who shadowed the loadmaster during all phases of the ERO. Process information is provided to time correlate activity and exposure.

Table A2.1.
Raw Data
Pope AFB, Savannah ANGB and Dobbins ARB

Sample Number	Date	Time On	Time Off	Flow Rate [Pre] (L/min)	Flow Rate [Post] (L/min)	Analyte of Interest	NIOSH Method	Name or Position	Pump S/N	Notes	EC (mg/m^3)	OC (mg/m^3)	EC/TC	PAH [Filter] (mg/m^3)	PAH [ESP] (mg/m^3)	PAH [PAS TWA] (mg/m^3)
PZ996000	3-Aug	1016 1052	1041 1056	4030	4008	EC	5040	Green	1104	-86 cart & munitions loader	***0.009***	0.070	0.114			5.E-05
PZ996001	3-Aug	1016 1052	1041 1056	4004	4017	PAH	5506	Green	1102					***9.E-04***		5.E-05
PZ996002	3-Aug	1438	1541	4007	3993	PAH	5506m	area	1098	-86 cart run; C-130 taxied by @ 1520					***8.E-04***	2.E-03
PZ996003	3-Aug	1438	1541	4028	4013	EC	5040	area	1064	-86 cart run; C-130 taxied by @ 1520	0.400	0.320	0.556			2.E-03
PB996004	K (PAH) (PTFE)															
PZ996005	3-Aug	1438	1541	4023	3934	PAH	5506	area	1097	-86 cart run; C-130 taxied by @ 1520				***4.E-04***		2.E-03
PZ996006	BLIND BLANK (EC)															
PZ996007	BLIND BLANK (PAH) (heptane extract)															
PZ996008	2-Aug	1354	1417	4028	4013	PAH	5506m	area	1067	-86 cart run; first run using ESP sampler					***2.E-03***	2.E-04
PB996009	BLANK (EC)															
PZ996010	3-Aug	1016 1052	1041 1056	4009	3943	PAH	5506m	Pirkle/ Green	1067	-86 cart & munitions loader					***2.E-03***	5.E-05
PB996011	BLANK (PAH) (heptane extract)															

Sample Number	Date	Time On	Time Off	Flow Rate [Pre] (L/min)	Flow Rate [Post] (L/min)	Analyte of Interest	NIOSH Method	Name or Position	Pump S/N	Notes	EC (mg/m^3)	OC (mg/m^3)	EC/TC	PAH [Filter] (mg/m^3)	PAH [ESP] (mg/m^3)	PAH [PAS TWA] (mg/m^3)
PZ996012	4-Aug	1038	1630	2056	1928	PAH	5506	Verdone	1102	ERO at pick up site; samplers on board C-130; pax drop/pick up					***1.E-04***	3.E-04
PZ996013	4-Aug	1038	1627	2978	2949	EC	5040	Verdone	1104		0.013	0.029	0.310			3.E-04
PZ996014	BLIND BLANK (EC)															
PZ996015	4-Aug	1038	1630	2998	2866	EC	5040	Digsby	1097	ERO at pick up site; samplers on board C-130; pax drop/pick up	0.014	0.027	0.341			3.E-04
PZ996016	4-Aug	1038	1627	1995	1943	PAH	5506	Digsby	1098						***1.E-04***	3.E-04
PZ996017	6-Aug	1336	1440	3986	3911	EC	5040	area	1101	-86 run on diesel (Savannah)	0.072	1.200	0.057			6.E-04
PZ996018	6-Aug	1336	1440	4012	3960	EC	5040	area	1104		***0.004***	0.040	-			6.E-04
PZ996019	6-Aug	1336	1440	4016	3926	PAH	5506	area	1074					***4.E-04***		6.E-04
PZ996020	6-Aug	1336	1440	3985	3926	PAH	5506	area	1102					***4.E-04***		6.E-04
PZ996021	6-Aug	1336	1440	4023	3893	PAH	5506m	area	1097						***8.E-04***	6.E-04
PZ996022	6-Aug	1336	1440	3969	3901	PAH	5506m	area	1103						***8.E-04***	6.E-04
PZ996023	7-Aug	0753	0913	2011	1966	PAH	5506	Harris	1095	flightline maintenance during launch				***6.E-04***		
PZ996024	7-Aug	0756	1044	1960	1913	PAH	5506	Murray	1070	dock worker				***3.E-04***		
PZ996025	7-Aug	0756	1046	1993	1963	PAH	5506	Spivey	1099	during				***3.E-04***		
PZ996026	7-Aug	0759	1043	2001	1863	PAH	5506m	area	1103	hangar; 90' from door during launch					***7.E-04***	9.E-05
PZ996027	7-Aug	0753	0913	1987	1998	PAH	5506m	Harris	1097	flightline maintenance during launch					***1.E-03***	
PZ996028	7-Aug	0750	0811	3926	3975	EC	5040	McPherson	1074		0.003	0.066	0.043			
PZ996029	7-Aug	0750	0811	3926	3890	EC	5040	McPherson	1102		0.003	0.073	0.039			

Sample Number	Date	Time On	Time Off	Flow Rate [Pre] (L/min)	Flow Rate [Post] (L/min)	Analyte of Interest	NIOSH Method	Name or Position	Pump S/N	Notes	EC (mg/m^3)	OC (mg/m^3)	EC/TC	PAH [Filter] (mg/m^3)	PAH [ESP] (mg/m^3)	PAH [PAS TWA] (mg/m^3)
(cont 6028)	7-Aug	0830	1040	–	–	–	–	Crawford	1074	flightline maintenance during launch						
(cont 6029)	7-Aug	0830	1040	–	–	–	–	Crawford	1102							
PB996031	BLANK (PAH) (PTFE)															
PZ996032	7-Aug	1005	1257	3911	3945	EC	5040	loadmaster	1101	on board C-130; cargo drop	***0.001***	0.034	-			9.E-05
PZ996033	7-Aug	1005	1257	3960	4013	PAH	5506	loadmaster	1104					***1.E-04***		9.E-05
PZ996034	BLIND BLANK (EC)															
PZ996035	BLIND BLANK (PAH) (PTFE)															
PZ996036	8-Aug	1035	1300	3987	3913	PAH	5506	loadmaster	1104	on board C-130; practice drop				***3.E-04***		
PZ996037	8-Aug	1035	1300	4025	3963	EC	5040	loadmaster	1101		***0.003***	0.010	0.231			
PB996038	BLANK (EC)															
PZ996039	8-Aug	1035	1300	4013	3958	PAH	5506m	loadmaster	1097	on board C-130; practice drop					***6.E-04***	
PZ996040	8-Aug	1023 1203	1100 1313	1960	1960	PAH	5506	Perry	1070	AGE work area during launch (inside; door open)				***5.E-04***		
PZ996041	8-Aug	1031	1213	2011	1983	PAH	5506	Futch	1095					***5.E-04***		
PB996042	BLANK (PAH) (heptane extract)															
PB996043	BLANK (PAH) (PTFE)															
PB996044	BLANK (PAH) (heptane extract)															
PB996045	BLANK (EC)															
PZ996046	BLIND BLANK (PAH) (PTFE)															
PZ996047	BLIND BLANK (PAH) (heptane extract)															
PZ996048	***Delete sample number***															

Sample Number	Date	Time On	Time Off	Flow Rate [Pre] (L/min)	Flow Rate [Post] (L/min)	Analyte of Interest	NIOSH Method	Name or Position	Pump S/N	Notes	EC (mg/m^3)	OC (mg/m^3)	EC/TC	PAH [Filter] (mg/m^3)	PAH [ESP] (mg/m^3)	PAH [PAS TWA] (mg/m^3)
PZ996049	***Delete sample (due to Brooks $$ shortage)***									First samples @ Dobbins; crew chief during launch; possible interference w/previous run						
PZ996050	***Delete sample (due to Brooks $$ shortage)***															
PZ996051	11-Aug	47 min		3984	3920	PAH	5506m	area	1101	-86 run w/diesel (Dobbins)					***1.E-03***	2.E-04
PZ996052	11-Aug	59 min		4040	3947	EC	5040	area	1104		0.069	3.200	0.021			2.E-04
PZ996053	11-Aug	59 min		3987	3720	PAH	5506	area	1064					***5.E-04***		2.E-04
PZ996054	11-Aug	59 min		2013	1946	PAH	5506m	area	1097						***2.E-03***	2.E-04
PZ996055	11-Aug	59 min		2000	1987	EC	5040	area	1074		0.070	3.000	0.023			2.E-04
PZ996056	***Delete sample number***									sample contaminated						
PZ996057	12-Aug	44 min		3974	3950	PAH	5506m	driver	1103	ERO (load & unload a truck); including samples 6066-6068					***1.E-03***	
PZ996058	12-Aug	43 min		3999	3991	PAH	5506	driver	1098					***6.E-04***		
PZ996059	12-Aug	44 min		3979	3960	EC	5040	driver	1062		0.050	0.050	0.500			
PZ996060	12-Aug	46 min		4064	4057	PAH	5506	spotter #1	1095					***5.E-04***		
PZ996061	12-Aug	44 min		4064	4064	EC	5040	spotter #1	1070		0.010	0.078	0.114			
PZ996062	12-Aug	46 min		4099	4124	PAH	5506	spotter #2	1101					***5.E-04***		
PZ996063	12-Aug	45 min		4074	4089	EC	5040	spotter #2	1074		0.077	0.066	0.538			
PZ996064	12-Aug	183 min		3976	3985	PAH	5506	loadmaster	1064	pump 1102 for sample 6064 quit; switched to pump 1064				***1.E-04***		8.E-04
PZ996065	***Delete sample number***															

Sample Number	Date	Time On	Time Off	Flow Rate [Pre] (L/min)	Flow Rate [Post] (L/min)	Analyte of Interest	NIOSH Method	Name or Position	Pump S/N	Notes	EC (mg/m^3)	OC (mg/m^3)	EC/TC	PAH [Filter] (mg/m^3)	PAH [ESP] (mg/m^3)	PAH [PAS TWA] (mg/m^3)
PZ996067	12-Aug	185 min		4019	4000	PAH	5506	cargo bay	1104	static at loadmaster seat				***1.E-04***		
PZ996068	12-Aug	184 min		3961	3979	EC	5040	cargo bay	1099	static at loadmaster seat	0.041	0.033	0.554			
PZ996069	***Delete sample (due to Brooks $$ shortage)***									blind blank (heptane)						
PZ996070	***Delete sample (due to Brooks $$ shortage)***									blind blank (PTFE)						
PZ996071	***Delete sample (due to Brooks $$ shortage)***									blind blank (quartz)						
PZ996072	***Delete sample (due to Brooks $$ shortage)***									blind blank (heptane)						
PZ996073	***Delete sample (due to Brooks $$ shortage)***									blind blank (PTFE)						
PZ996074	***Delete sample (due to Brooks $$ shortage)***									blind blank (quartz)						
PZ996075	BLANK (PAH) (PTFE)															
PZ996076	***Delete sample (due to Brooks $$ shortage)***									blank (PTFE)						
PZ996077	BLANK (PAH) (heptane extract)															
PZ996078	***Delete sample (due to Brooks $$ shortage)***									blank (heptane)						
PZ996079	BLANK (EC)															
PZ996080	***Delete sample (due to Brooks $$ shortage)***									blank (quartz)						
PZ996081	BLIND BLANK (EC)										***0.003***	0.075				
PZ996082	BLIND BLANK (EC)										***0.003***	0.081				
PZ996083	***Delete sample (due to Brooks $$ shortage)***									blind blank (PTFE)						

Bold italics data values represent method detection limits

Table A2.2.
Raw Data
Little Rock AFB

Sample Number	Date	Time On	Time Off	Flow Rate [Pre] (L/min)	Flow Rate [Post] (L/min)	Name or Position	Pump S/N	TIT (deg C)	Wf (lb/hr)	Wind direction @ speed (kts)	Aircraft Heading	EC (mg/m^3)	OC (mg/m^3)	EC/TC	PAH [PAS TWA] (mg/m^3)
PZ009000	23-Feb	1237	1312	4039	4022	ILM	566038	650	600	170/12	067 (COL) 247 (ERO)	0.230	0.280	0.451	3.E-03
PZ009001	23-Feb	1239	1312	4037	3979	ILM (shadow)	566368	"	600	"	"	0.210	0.260	0.447	3.E-03
PZ009004	23-Feb	1238	1313	4007	3965	student LM	566435	"	600	"	"	0.210	0.290	0.420	
PZ009007	24-Feb	0848	0939	4022	4157	ILM	566038	"	630	190/7	"	0.083	0.140	0.372	1.E-03
PZ009002	24-Feb	0848	0939	4013	3926	ILM (shadow)	566370	"	630	"	"	0.090	0.140	0.391	1.E-03
PZ009006	24-Feb	0848	0939	3965	3995	student LM	566435	"	630	"	"	0.094	0.220	0.299	
PZ009005	24-Feb	0840	0939	3979	3955	static near left rear hatch	566368	"	630	"	"	0.073	0.090	0.448	6.E-06
PZ009008	24-Feb	BLIND BLANK													
PZ009009	25-Feb	BLANK													

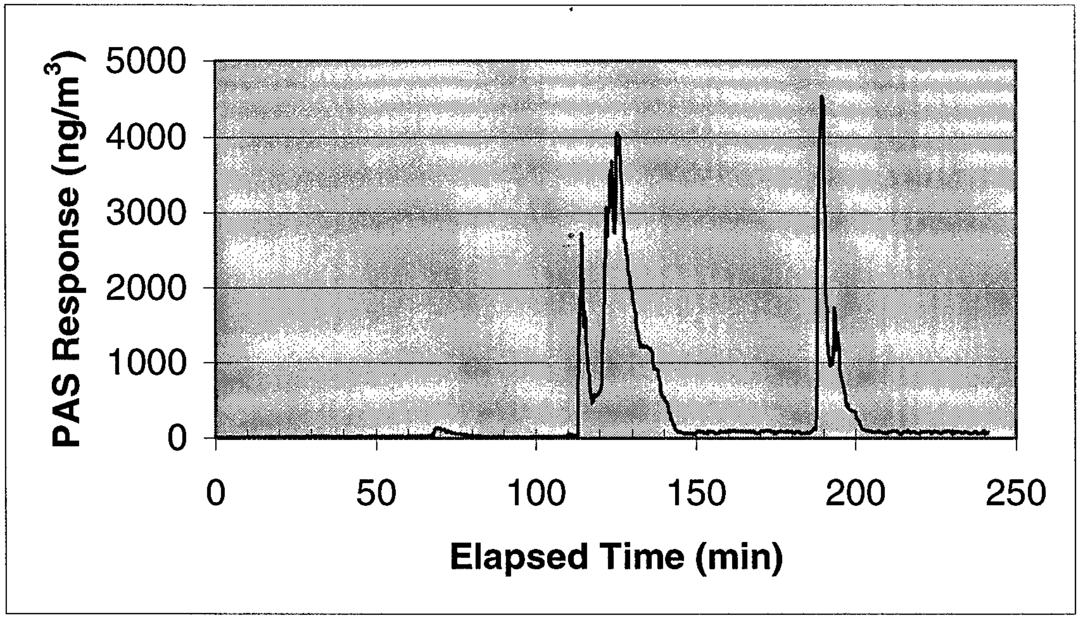


Figure A2.1. C-130 Cargo Area during Troop Drop and ERO Pickup Mission at Pope AFB, Aug 1999

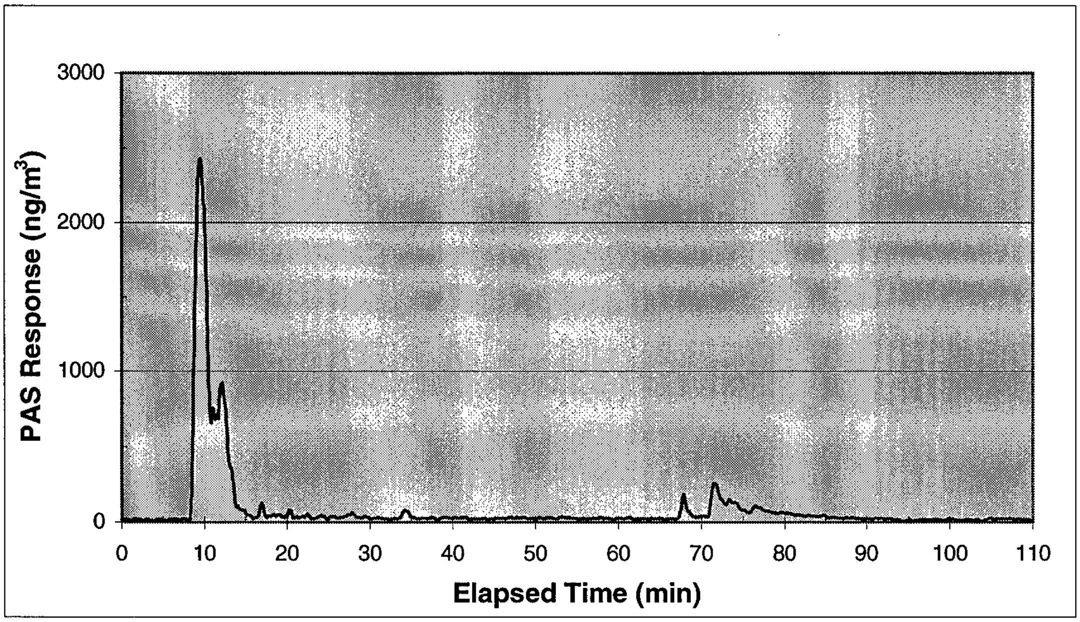


Figure A2.2. C-130 Hangar During Launch. Savannah ANGB, Aug 99.

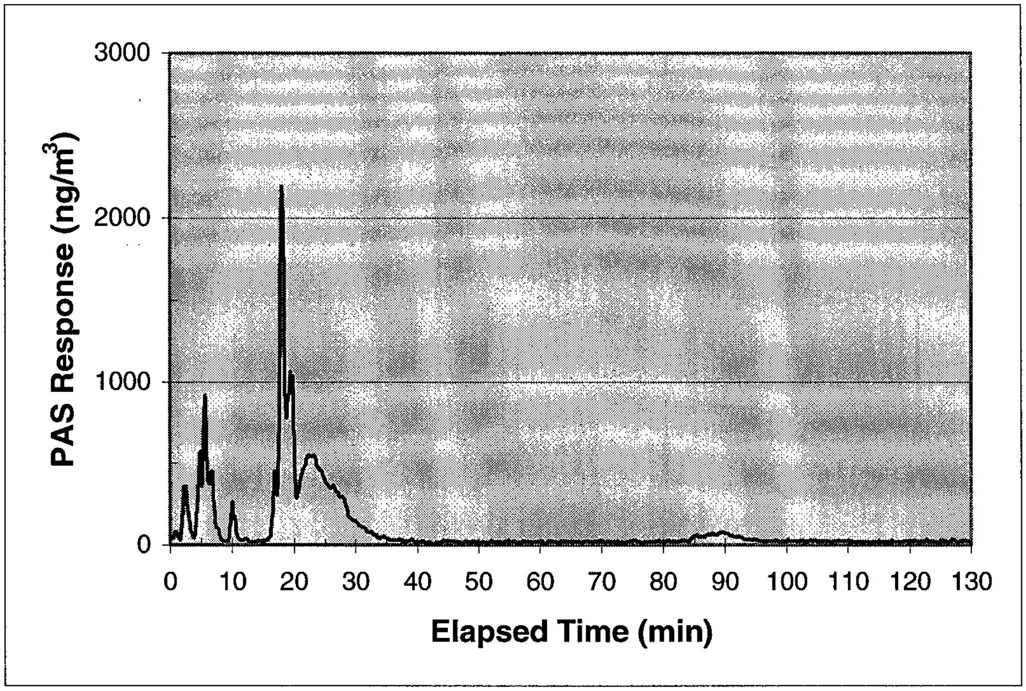
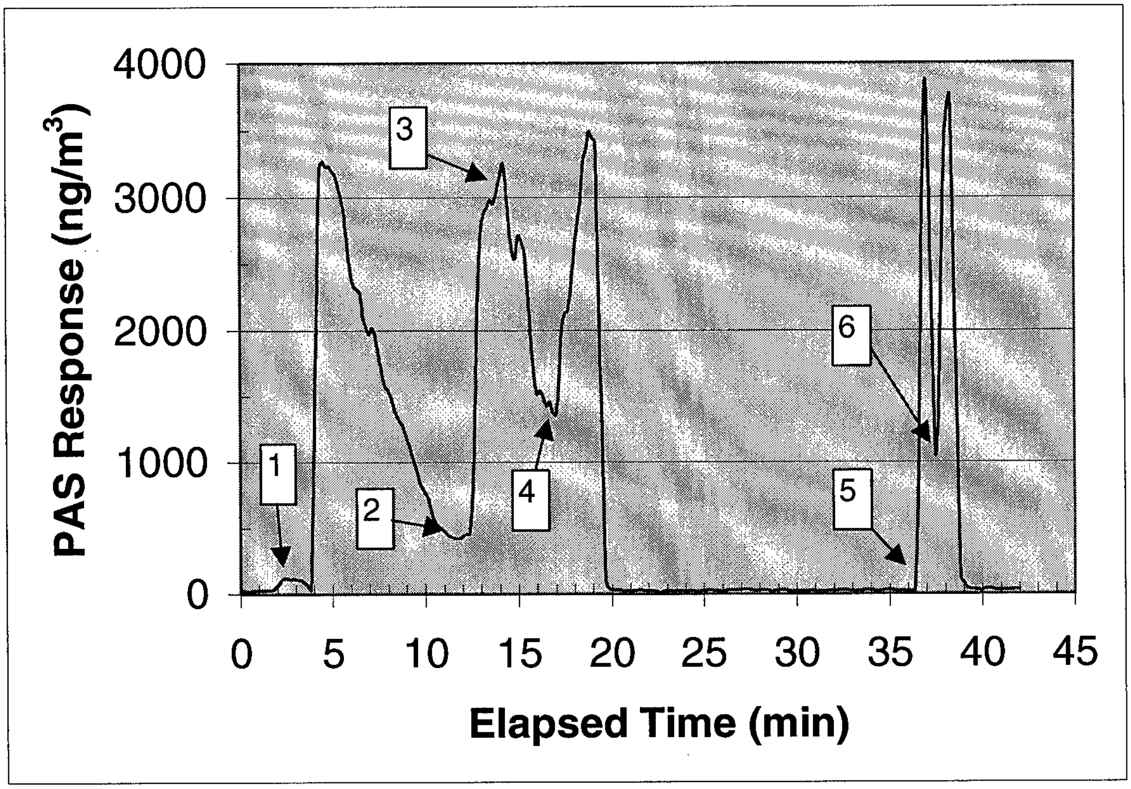


Figure A2.3. C-130 Airborne Cargo Drop Mission (Loadmaster Position) at Savannah ANGB, Aug 99



1	Front crew door closed; begin taxi
2	Cargo door open; load payload (truck)
3	Stop truck and secure it
4	Load crew depart the aircraft
5	Start truck and unload it
6	Ground depart the aircraft (again)

Figure A2.4. Shadow Loadmaster during ERO at Dobbins ARB, Aug 99

VITA

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Work Experience
Commander, Bioenvironmental Engineering Flight, USAF Academy, CO, Jun 96-Jul 98
Bioenvironmental Engineering Fellow, USAF Surgeon General's Office, Bolling AFB, DC, Aug 1995-Jun 1996
Deputy Chief, Bioenvironmental Engineering Flight, Little Rock AFB, AR, Jul 92-Aug 95
Propulsion Flight Test Engineer, Edwards AFB, CA, Apr 89-Jul 92
Wind Tunnel Engineer, Texas A&M Low-Speed Wind Tunnel, May 87-Apr 89

Certifications
Certified Industrial Hygienist (#7946), Nov 99
Certified Acquisition Professional, Level II, Test & Evaluation Management, Jun 94

Education
M.S. Industrial Hygiene, Texas A&M University (AFIT Program), May 00
B.S. Aerospace Engineering, Texas A&M University (USAF Scholarship), Dec 88

Technical Presentations and Publications
Pirkle, P.S.: "Investigation of Cadmium in Engine Compressor Wash Water Effluent." Paper presented at the Air Force Worldwide Pollution Prevention Conference, San Antonio, TX, Jan 1995.

U.S. Air Force: *Propulsion Evaluation of the F100-PW-220 Engine with 5.2.0 DEEC Logic in the F-16 Aircraft* by P.S. Pirkle (AFFTC-TR-92-09). Edwards AFB, CA: U.S. Air Force Flight Test Center, Oct 1992.

U.S. Air Force: *F-16/F100 Howl Investigation* by P.S. Pirkle (AFFTC-TR-91-05). Edwards AFB, California: U.S. Air Force Flight Test Center, Jul 1991.

Texas A&M: *Wind Tunnel Test of the 1/25th Scale Space Shuttle in a Landing Configuration* by P.S. Pirkle (TEES Report No. TR-8825). College Station, TX: Texas A&M Low-Speed Wind Tunnel, Sep 1988.

Significant Accomplishments and Activities
Meritorious Service Medal as Captain (usually reserved for higher ranked persons), 1998
Successfully completed 350-mile Ride the Rockies bicycle trek with USAF team, 1998
10th Aerospace Medicine Squadron Company Grade Officer of the Year, 1997
Escorted Olympic Torch in Mount Vernon, Virginia, 1996
Race director for National Military Cycling Championships, 1995
Air Combat Command Outstanding Environmental Leadership Award, 1995
Served in Ross Volunteer Company, Honor Guard for the Governor of Texas, 1986-87