



**CHARACTERIZATION OF JET FUEL COMBUSTION EMISSIONS DURING A  
C-130 AEROMEDICAL EVACUATION ENGINES RUNNING ONLOAD**

THESIS

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AFIT-ENV-MS-17-M-211

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Michelle L. Page

USAF

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### **Abstract**

The purpose of this research was to characterize jet fuel combustion emissions (JFCE) on the ground for potentially hazardous occupational contaminants. JFCE have been extensively characterized due to environmental pollution. Prior research demonstrated that aircraft emit hazardous species, especially at engine start-up and ground idle. Complaints of severe eye, nose, and throat irritation from occupational exposures near aircraft exist. In this study JFCE were tested during an aeromedical evacuation engines running patient onload (ERO) on a C-130 Hercules at the 179<sup>th</sup> Airlift Wing, Mansfield-Lahm Air National Guard. The following research questions were investigated: 1) do JFCE migrate into occupational breathing zones during engine start-up and ground idle operations such as AE ERO; 2) what are the contaminants and concentrations.

Ultrafine particles, VOC, formaldehyde, carbon monoxide (CO), sulfuric acid, and metals were sampled simultaneously in approximate crew and patient breathing zones. Testing methods were portable condensation particle counters (CPC), polycarbonate filters (PC) and thermophoretic samplers (TPS) for electron microscopy, Multi-gas monitors, EPA methods TO-17 and TO-11, and National Institute of Occupational Safety and Health (NIOSH) methods N0600, N7908, N7300.

Contaminants detected in this study were ultrafine particulate matter, VOC including Environmental Protection Agency hazardous air pollutants (EPA HAP), formaldehyde, CO, and unburned jet fuel. The particles were dominated by soot in

concentrations up to  $3.4E+06$  particle/cc. Particle size distributions were varied with most sizes less than 100 nanometers (nm). Particle morphology was highly irregular. Soot elemental composition was predominantly carbonaceous with trace oxygen, sulfur and a few metals. VOC were detected in ppb, and formaldehyde in ppm. Additive or synergistic effects associated with the JFCE mixture may intensify irritation. Health implications from inhaling nano-sized soot particles are inconclusive.

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# **CHARACTERIZATION OF JET FUEL COMBUSTION EMISSIONS DURING A C-130 AEROMEDICAL EVACUATION ENGINES RUNNING ONLOAD**

## **I. Introduction**

### **General Issue**

Many AF personnel are exposed to aircraft exhaust in the course of a normal workday. Jet fuel constituents and combustion products represent the largest chemical exposure of DOD Military and civilian workforce (1). Severe eye, nose and throat irritation from exposure to jet fuel combustion emissions (JFCE) have been reported (2) (3) (4) (5). Increased overall health concerns from occupational exposure to jet fuel since the conversion to kerosene-based jet fuels in the mid – late 1990s led to reduction of the American Conference of Governmental Industrial Hygienists (ACGIH) 8-hour threshold limit value (TLV)-time-weighted average (TWA) from 350 mg/m<sup>3</sup> to 200 mg/m<sup>3</sup> (1). Occupational exposure guidance exists for jet fuel vapors and aerosols (6), but is lacking for its combustion emissions.

### **Background**

The vast inventory of aircraft in service is essential to the United States Air Force mission to fly, fight, and win in air, space, and cyberspace (7). The current USAF inventory is forecasted to evolve alongside that of the Army and Navy inventories through procurement and modernization efforts necessary to support the Department of Defense's (DOD) growing security challenges (8). The USAF inventory exceeds 5,000 aircraft, and comprises approximately 35% of DOD total inventory (8).

The Air Force Air Mobility Command (AMC) consumes the greatest amount of aviation fuel within the Air Force (9). The AMC fleet alone consumes 28% of DOD aviation fuel. AMC's intensive fuel consumption arises from its varied mission requirements and continuous operational tempo. Its fleet of heavy aircraft provide strategic airlift, aeromedical evacuations, air refueling, and humanitarian aid worldwide.

The primary jet fuel used by the US military since the mid-1990s was Jet Propulsion Fuel number 8 (JP-8) (10). JP-8 replaced JP-4 due to improved safety and operational characteristics. With lower volatility and higher kerosene content, JP-8 greatly reduced the likelihood of post-crash fires and fires arising from maintenance accidents. Operationally, JP-8 provides improved thermal stability and heat sink capability over its JP-4 predecessor (11). Now, the Air Force is converting its primary aviation fuel from JP-8 to commercial Jet A with additives. The conversion significantly reduces extra costs associated with the purchase, transportation, distribution, and storage of JP-8 (12) (13). The major difference between Jet A and JP-8 is the absence of additives such as ice and corrosion inhibitor in the Jet A formulation. Since JP-8 formulations include the additives, segregated transportation and storage has been required, and at high costs to DOD. With Jet A, additives are injected into bulk storage after receipt of the shipment, so that the fuel can be acquired through open markets (12).

The chemical constituents of JP-8 and Jet A + additives are very similar. Both JP-8 and Jet A are kerosene-based fuels, which are complex mixtures of hydrocarbons. Their multicomponent formulations lead to dynamic composition of exhaust species that form under varying conditions. Jet fuel emissions and concentrations also vary in different weather conditions, engine type and engine throttle setting.

## **Problem Statement**

Aircraft emissions have been extensively characterized due to concern for environmental air pollution. Degradation of air quality near airports has been reported. Considering wide acceptance of environmental concern for public health exposure to aviation air pollution, occupational exposure guidance for populations working in close proximity to aircraft exhaust emissions is warranted. Anecdotal accounts of severe eye, nose and throat irritation from exposure to JFCE have been reported in prior studies, AF consults, and interview with AE crew members (2) (3) (4) (5) (14) (15).

JFCE have been found to contain many products, including unburned jet fuel, ultrafine particulate matter, and hazardous air pollutants (HAPs) identified by the US Environmental Protection Agency (EPA) (2) (5) (16) (17) (18) (19). The US EPA has also conducted National Air Toxics Assessments (NATA) as a tool used in efforts to reduce HAPs (20). The 2011 NATA concluded that the pollutants contributing the most to overall cancer risks are formaldehyde, benzene, and acetaldehyde (21). All three were found in JFCE in prior studies.

## **Research Objectives**

Multiple groups are exposed to JFCE on flight lines. Exposure populations include crew chiefs, aircraft maintainers, aircrew members, aeromedical evacuation crews, and patients. Occupationally focused JFCE studies and hazards characterized in those studies are limited. **The goal of this research was to characterize JFCE on the ground during an occupational process to fill testing gaps in prior occupationally focused studies.**

This research characterized the engine start-up and ground idle emissions during an aeromedical evacuation engines running patient onload (AE ERO), an operation necessary for patient extraction in contingency operations or when minimum ground time is required by the mission (22). The hypothesis is that during ERO, emissions from the engine propeller wash migrate into the aircraft because the troop doors and cargo ramp remain open. Exposed personnel include AE crew members, patients, flight crews, loadmaster, spotter, and ground personnel. Of particular concern is exposure to the loadmaster who stands off the foot of the ramp observing for threats and ensuring safety compliance, and spotter who stands 50 feet aft of the ramp directing the flow of patients (22). Figure 1 shows the loadmaster during this study.



*Courtesy of the 179th Airlift Wing Public Affairs*

**Figure 1: Loadmaster during C-130 AE ERO**

## **Research Questions**

1. Do JFCE migrate into occupational breathing zones during engine start-up and ground idle operations such as AE ERO?
2. What are the contaminants and concentrations?

## **Methodology**

1. Literature review: The types of literature reviewed include JP-8 fuel and vapor toxicity studies, journal articles characterizing JFCE, USAF consultative letters and guidelines on jet fuel exposure, occupational exposure limits (OEL), and Air Force Instructions (AFI).
2. Sampling Plan: Simultaneous sampling at 5 aircraft locations was conducted on a C-130 Hercules at the 179<sup>th</sup> Airlift Wing, Mansfield-Lahm Air National Guard Base on two non-consecutive days, 01 June and 09 November 2016.
3. Implications: This research identified JFCE contaminants that are known irritants and some carcinogens, and provided valuable information on emissions migration and particle characteristics. The literature compilation and testing results provide supporting information for mitigation considerations such as alternative fuels conversion and testing suite for future investigations.

## **II. Literature Review**

### **Background**

Much research exists on JFCE from conventional petroleum derived kerosene jet fuels and renewable source derived alternative jet fuels. Prior characterization efforts tested emissions with extractive sampling directly behind the engine and with remote

sampling at downstream locations. Some testing was performed off-wing where the engines were mounted on test stands, while others were conducted on-wing to better represent the exhaust environment on flight lines.

Many prior studies characterizing JFCE were prompted by the 1990 Amendments to the Clean Air Act and the Strategic Environmental Research and Development Program (SERDP). SERDP pursues solutions to the DOD's environmental challenges while sustaining military readiness (23) (24). These prior studies identified a variety of hazardous compounds in petroleum based JFCE. Most of the hazardous species identified are common among different aircraft. Those compounds commonly found in prior JFCE characterizations served as valuable reference in selecting the tests for this study. A consensus drawn from prior studies is that the majority of hazardous species and in highest concentrations are emitted at engine start-up and ground idle (25).

### **Prior Research**

Spicer *et al* (2009) characterized JP-8 exhaust by downstream extractive sampling of both C-130 and F-15 aircraft (19). C-130 emissions were tested at low speed ground idle, high speed idle, flight idle, cruise, and maximum power. F-15 emissions were tested at engine ground idle, low intermediate, high intermediate, military, and afterburner throttle settings. Emission factors were reported for more than 60 hazardous organic gases as well as carbon and nitrogen oxides. They targeted 9 of these compounds for either prevalence in engine ground idle emissions or potential toxicity. Results for the 9 targeted compounds were compared at all 5 throttle settings on both airframes, then between C-130 and F-15 airframes with engines operating at ground idle only. Of the 9

compounds the following prevailed at engine idle on both airframes, and more so in the C-130 emissions: carbon monoxide, ethylene, 1,3-butadiene, benzene, toluene, styrene, formaldehyde, and acrolein. Pleil *et al* (2000) found elevated benzene levels in the exhaust relative to JP-8 fuel benzene content, likely due to alkylbenzene conversion to benzene during incomplete combustion (26).

Corporan *et al* characterized JP-8 combustion emissions from a C-17 Globemaster III in a study comparing JP-8 combustion emissions with those of JP-8/alternative fuel blends for certification of the aircraft on JP-8/AJF blends (17). Gas and particle emissions were measured at engine throttle settings ranging from 4% (idle) to 63% for 15 minutes per throttle setting in high temperature and low humidity weather. The exhaust was sampled 42 centimeters behind the engine using rake-style gas probes and valve box directing the exhaust to various analyzers and active samplers. The testing system was a mobile laboratory, Air Force Research Laboratory – Fuels and Energy Branch Turbine Engine Research Transportable Emissions Laboratory (TERTEL). Particle measurements included particle concentration, mass, and size distribution. Gaseous measurements included HAPs, PAH, carbon monoxide, nitrogen oxides, and sulfur dioxides. The researchers found CO and HAP concentrations from JP-8 combustion emissions highest at engine idle, with formaldehyde dominating the HAP content, followed by acetaldehyde and benzene. Mean particle diameters and particle concentrations increased with increased throttle settings. Combustion emissions particles contained organic carbon (OC) and elemental carbon (EC), with more OC than EC at engine idle. Mean particle diameters for JP-8 and JP-8/alternative fuel blends were less than 100 nanometers. The

researchers reported significant reductions in CO, sulfur oxides, HAP, and particulate matter emissions compared to those from JP-8.

Many other research efforts certifying alternative jet fuel (AJF) blends in civilian and military aviation has been underway due to increased air travel, petroleum fuel costs, environmental air pollution impacts, and energy security concerns. In fact, since March, 2016 United Airlines has been using a 30/70 AJF blend of bio-based/traditional petroleum jet fuel at the Los Angeles airport, reducing emissions by up to 60% (27). An energy and chemical company of Johannesburg, South Africa, Sasol Ltd., developed a jet fuel produced from synthetic coal to liquids (CTL) process that has been approved for use on commercial aircraft (28).

AJF are synthetic paraffinic kerosene (SPK) fuels produced from renewable sources that mimic the chemical properties, safety, and operational performance of petroleum derived jet fuel (29). AJF are often referred to as “drop-in” fuels because they can be used in aircraft with no engine modifications or infrastructure changes. Common types of AJFs and their feedstocks include 1) Fischer-Tropsch (FT) produced from gasification of coal, natural gas, or biomass; 2) hydroprocessed renewable jet (HRJ) produced from bio-oil (also called hydroprocessed esters and fatty acids (HEFA) or synthetic paraffinic kerosene (Bio-SPK); 3) alcohol-to-jet (ATJ), oligomerization of alcohols derived from fermentation of starch and sugar crops; and 4) pyrolysis oil jet fuel produced from biomass (30) (31) (32).

The US Air Force Research Laboratory (AFRL) conducted numerous JFCE characterization campaigns certifying military aircraft for use with alternative jet fuels blended with conventional JP-8 or Jet A fuels. These effort were prompted by concern of

DOD impact on environmental pollution and the DOD Assured Fuels Initiative, whose goal was reducing high fuel costs and dependence on foreign oil (33) (34) (17).

Alternative fuels and JP-8 blended with alternative fuels were tested in parallel with JP-8 on B-52, UH-60 Black Hawk and AH-64 Apache helicopter engines, and C-17 (17) (18) (33) (34). The alternative jet fuels that were tested included coal-derived Fischer-Tropsch (FT) fuel and beef tallow derived hydroprocessed renewable jet (HRJ) fuel blend. Timko et al conducted emissions testing of Jet A, Jet A/FT fuel blends, and biomass fatty acid methyl ester (FAME) fuels on the CFM56 engine, which is the engine used on 737 aircraft (30). A similar effort was conducted on a commercial business class jet engine, PW308 (35). In a series of smog chamber experiments on a T63 engine, Miracolo et al confirmed SOA formation in JP-8 JFCE, and also reported SOA reductions with JP-8/FT fuel blend (36).

JFCE tested in these campaigns include engine smoke number, particle number, mass concentration and size distribution, OC (VOC: HAPs, aromatics, aldehydes, unburned jet fuel), EC, SO<sub>x</sub>, NO<sub>x</sub>, CO, and PAH. In all campaigns, JFCE were significantly lower with alternative fuels/blends than with pure JP-8 or Jet A (17) (18) (30) (33) (34) (35). Reduced particle count, mass, and sizes were also observed with alternative fuel blends, which is expected due to less OC, aromatics, and SO<sub>x</sub> precursors available for particle nucleation and growth. Smoke number and soot reductions were most pronounced at engine idle and lower engine power, which also results from lower aromatic and sulfur content in synthetic jet fuels. EC and OC reductions are in agreement with particle count reductions. In general, the higher the synthetic fuel percentage in the JP-8, Jet A/alternative fuel blends, the greater the JFCE emissions reductions. Also, many

of these “drop in” fuels conform to military and ASTM standards with performance comparable to conventional Jet A and JP-8 fuel (37).

AJFs contain negligible aromatic and sulfur compounds as compared to petroleum based JP-8 and Jet A fuels. Substantial reductions in combustion emissions from use of AJF blends have been reported. National Aeronautics and Space Administration (NASA) reports greater than 50 percent reduction in particle emissions from AJF blended with petroleum based jet fuel (38). Reductions in occupational exposures to combustion emissions from AJF blends would therefore be reasonably anticipated. Although the certification campaigns were successfully completed, the AF is not planning conversion or use of AJFs or blends at the time of this publication.

### **US Air Force Consults**

Part of the literature reviewed were USAF consultative letters associated with complaints of eye, nose, and throat irritation from aircraft exhaust. Exposure assessments have been conducted on crew chiefs during launch and recovery operations for F-15's on Otis Air National Guard Base, MA (39), on KC-135's on Pease Air National Guard Base, NH (40), and on a C-130 AE crew at the 156 AES, Charlotte, NC in (41). The same testing methods were used in all 3 consults: aldehydes (acetaldehyde, acrolein, crotonaldehyde, and formaldehyde), benzene, toluene, ethylbenzene, xylenes (BTEX), JP-8 fuel, and polycyclic aromatic hydrocarbons (PAH) using active sampling methods, and oxide gases measured with direct reading monitors.

The conclusion for all consults was that the personnel were not overexposed to the contaminants measured and no corrective action was needed due to the results being

less than exposure or detection limits. However, the cause of irritation was still unknown. For all above consults, important to note is that ultrafine particles were not tested, and the weather conditions were mild. Extensive environmental campaigns that have characterized JFCE since these consults demonstrated that JFCE contain significant levels of ultrafine particles and higher content of organic hydrocarbon compounds in cold weather. Also, results for the aldehyde samples were not reported for the AE crew consult due to the samples being lost. The author noted possibility of inefficient capture of the contaminants due to speed of the propeller wash. They recommended following the local policy of performing patient onloads with the engines off, and that follow on studies would ensue. Since the 1999 consult from the 156<sup>th</sup> Aeromedical Evacuation Squadron two other efforts investigated exhaust exposure during ERO (14) (42).

A prior AFIT thesis study investigated C-130 JFCE in response to a request by the Air Force Institute of Environment Safety and Health Risk Analysis (14). The investigator interviewed 12 loadmasters, all whom reported poor air quality in cargo bay after ERO. They reported symptoms of eye, nose, throat irritation, and difficulty breathing. The investigator tested the exhaust for soot-bound PAH, elemental carbon, and carbon monoxide during a mock C-130 ERO cargo onload/offload. The author found that PAH and CO were below OELs. However, EC results periodically exceeded excursion limits of working OELs. He recommended future testing for aldehydes and 2- 3- ring PAH.

Childers *et al* investigated exposures to vapor and particle-bound PAH (42). Particle-bound PAH were measured with photoelectric aerosol sensors (PAS). Vapor phase PAH were collected with XAD-2 filter cartridges and analyzed by gas

chromatography-mass spectrometry (GC-MS). Area samples were collected on the flight line, in a break room, downwind of a four engine run-up, downwind of aerospace ground equipment (AGE), in a hangar, in the cargo bay during a cargo drop exercise, and in a cargo bay during ERO. Total PAH concentrations for all activities/locations were less than  $10 \mu\text{g}/\text{m}^3$ . The largest contributor of PAHs on the flight line was from ground support equipment, followed second by ERO. They found that naphthalene and alkyl-substituted naphthalenes dominated the PAH content, but were less than exposure limits.

Another AF inquiry involving JFCE exposure was made in 2013. The 109<sup>th</sup> Air Lift Wing-Stratton Air National Guard Base, NY requested recommendations for respiratory protection and sampling in extreme cold during LC-130H defueling operations at McMurdo Station, Antarctica (4). Engines running and aircraft movement are required during defueling due to low confidence of engine restart and to keep the plane from sinking into the ice. “Pockets” or “clouds” of contaminated air developing around the rear of plane were reported. They sought respiratory protection effective to  $-50 \text{ }^\circ\text{C}$  with communication capability. Only one type mask, Promask 2000, was found certified at  $-50 \text{ }^\circ\text{C}$  and was recommended, however, the mask did not meet the communication criteria.

Another study was conducted due to complaints of eye and throat irritation from ground crews and pilots exposed to JFCE at Misawa Air Base, Japan (5). Kobayashi and Kikukawa (2000) investigated formaldehyde content in F-4 aircraft exhaust due frequent accounts of irritation after conversion from JP-4 to JP-8. The irritation was more frequent and severe in winter months. They conducted personal sampling with diffusive samplers and area sampling with active samplers 50 – 75 meters behind the engines where the

personnel normally worked. The researchers sampled in summer and winter, and with varied engine throttle settings. They found high concentrations of formaldehyde with highest concentrations at engine idle and with decreased temperature and humidity. The researchers recommended that personnel avoid working within 75 meters behind the engines, schedule crew activity to avoid the exhaust whenever possible, or use of full face respirators when avoidance was not feasible.

Special consideration should be directed towards exhaust exposures at locations in cold and extreme cold climates where the jet fuel combustion is significantly less efficient and greater content of unburned fuel arises.

### **Jet Fuel Combustion Emissions Overview (JFCE)**

As found in the literature, aircraft engines emit a variety of hazardous species that have potential to adversely impact human health. These emissions include carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>), and ozone (O<sub>3</sub>), volatile and semi-volatile organic compounds (VOC/SVOC) from inefficient combustion of the fuel, unburned jet fuel vapors and aerosols, ultrafine particles, and metals (43) (44). Many of the VOC emissions contain compounds listed as hazardous air pollutants (HAPs) by the US Environmental Protection Agency and in the Agency for Toxic Substances and Disease Registry (ATSDR) (25) (45). HAPs are compounds known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects (46) (47).

## **Carbon Monoxide (CO)**

Carbon Monoxide (CO) concentrations have been found highest at engine start up and ground idle (19) (48) (49). This finding is supported with results from tandem testing of carbon dioxide (CO<sub>2</sub>). As the throttle setting increased from idle, carbon dioxide concentration increased, indicative of increasing combustion efficiency with engine power (24). CO is a respiratory health concern because it competes with oxygen to bind with hemoglobin (50). In fact, hemoglobin has such a greater affinity for carbon monoxide that it displaces oxygen in red blood cells, depriving body tissues of oxygen. This action can lead to carbon monoxide-induced hypoxia where symptoms include dizziness, fainting, increased heart rate, headaches, muscular weakness, and nausea. Symptoms of CO exposure generally do not occur below 100 ppm. However, chronic exposure to CO can lead to central nervous system damage, loss of peripheral sensations, poor memory, and general mental deterioration.

## **Nitrogen Oxides (NO<sub>x</sub>)/ Sulfur Oxides (SO<sub>x</sub>)**

Nitrogen and sulfur oxides arise in the exhaust from oxidation during combustion. The gases adsorb onto soot particles, facilitated by condensation and surface oxygen groups (44). Nitrogen and sulfur oxides found in aircraft exhaust are nitric oxide (NO), nitrogen dioxide (NO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), sulfur trioxide (SO<sub>3</sub>), and sulfate (SO<sub>4</sub>). The sulfur species dominating at engine idle are sulfate, which can react with water in air or on the surface of soot particles to form sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), especially in humid air (18).

Nitrogen and sulfur oxides have high water solubility, and therefore are absorbed primarily into the upper respiratory tract (50). Nitrogen dioxide odor and taste can be observed at as low as 1 ppm, while sulfur dioxide odor and taste are observed between 3 – 5 ppm. Symptoms of nitrogen and sulfur oxides exposure are eye, upper respiratory tract, and skin irritation that can occur at levels as low as 15 ppm for nitrogen oxides and 8 ppm for sulfur oxides.

Both nitrogen and sulfur oxides were found in the literature to increase with engine throttle setting, with relatively low concentrations emitted at ground idle and highest concentrations at maximum power (19). Due to sulfate tendency to form sulfuric acid, sulfuric acid testing was included in this research. Nitrogen oxides were not tested in this study, but should be considered in follow on work, especially on busy flight lines.

### **Ozone**

Ozone is also a product of JFCE. Reactive alkenes and alkynes hydrocarbons in low power engine emissions are precursors to ozone formation (49). They are highly susceptible to oxidation by hydroxyl radicals also present in the exhaust. Alkenes have the highest affinity for ozone production, but ozone can also form from oxidation of CO. Ozone was not tested in this study but should be included in follow on assessments because of its low regulatory limits. Potential health effects from ozone exposure are eye and mucous membrane irritation. Ozone can also cause pulmonary edema and respiratory disease (51) (52).

## **VOC**

As with all internal combustion engines, combustion efficiency increases with increasing engine power due to higher temperature and pressure. Conversely, combustion at engine start-up and idle is much less efficient. At engine start-up and idle volatile organic compounds (VOCs) from fuel cracking and unburned jet fuel exit the engine (53). Fuel cracking products include alkenes and alkynes ethylene, propylene, and acetylene, single-ring aromatic hydrocarbons such as benzene and substituted benzenes, and intermediate volatility organic compounds (IVOC- C<sub>12</sub> to C<sub>22</sub> hydrocarbons) (26) (36) (49).

In aging exhaust VOC and IVOC undergo transformations to become different compounds called secondary organic aerosol (SOA) (36). Transformations from which SOA evolve as the exhaust “ages” include oxidation of alkenes by hydroxyl radical ( $\bullet\text{OH}$ ), ozone (O<sub>3</sub>), and nitrate radical (NO<sup>-3</sup>), fragmentation induced by photo oxidation, and condensation and adsorption of VOCs onto soot particles upon cooling and dilution with ambient air (43) (49) (36) (54).

Ethylene and formaldehyde are the most abundant VOC at low engine power, and have been used as fuel cracking tracers for scaling hydrocarbons emission indices to compensate for inter-engine variability (49).

## **Formaldehyde**

Formaldehyde is a VOC that is widely used in industry. It is commonly used in the medical laboratories, wood processing industries, building materials, household products, as an industrial disinfectant, and is found in cigarette smoke (55).

Formaldehyde is also a combustion product of automobile and aircraft exhaust, and power plant emissions (5) (56). The majority of formaldehyde entering the environment is from combustion processes.

A substantial amount of literature confirms formaldehyde in JFCE (5) (24) (49) (57) (30) (33). In fact, Formaldehyde dominates the VOC content at engine start-up and idle. It is not contained in jet fuel formulations. Rather, it forms from partial oxidation of ethylene. Cold weather conditions exacerbate formaldehyde formation because of decreased combustion efficiency described earlier.

Formaldehyde is a HAP, toxic and carcinogenic at high levels, and an eye, nose, and throat irritant at low levels (56). Concentrations in air less than 1 ppm can irritate mucous membranes and eyes (50). American Conference of Governmental Industrial Hygienists, ACGIH, report that in the presence of other pollutants formaldehyde can irritate eyes at concentrations between 0.05 – 0.5 ppm (58). The current ACGIH threshold limit value-time weighted average, TLV-TWA, is 0.1 ppm, and the short term exposure limit, TLV-STEL, is 0.3 ppm. The maximum exposure allowed by OSHA during a 15 minute period, OSHA STEL, is 2 ppm (55). OSHA states to “Identify all workers who may be exposed to formaldehyde at or above the action level or STEL through initial monitoring and determine their exposure”. Formaldehyde testing was include in this study.

### **Unburned Jet fuel**

Aircraft exhaust emissions at engine start-up and idle also contain alkanes and aromatics from unburned jet fuel that exit the engine as vapors and aerosols (2) (49). As

with formaldehyde, the amount of unburned jet fuel exiting the engine at start-up and idle increases with decreasing temperatures. Accounts of a visible floating “cloud” or plume of unburned jet fuel emitted at engine start in cold weather climates have been observed (4) (26). Figure 2, “KC-135 Engine Cold Start at Eielson AFB” from the work of Pleil et al illustrates this.



**Figure 2: KC-135 Engine Cold Start at Eielson AFB (26)**

### **Particulate Matter/Soot**

The evolution of particulate matter (PM) in JFCE is complex. In the combustor, EC and OC are formed from pyrolysis or “cracking”, and combustion of fuel hydrocarbons. The ideal combustion products are carbon dioxide and water. However, inefficient combustion of jet fuel at engine start and idle produces primary PM emissions

consisting of elemental carbon (EC) and organic carbon (OC). OC was described previously as VOC (24) (25). EC are graphitic particles whose surface structures are irregular and readily support condensation and adsorption. EC serve as nuclei or “seeds” for other volatile species in the exhaust (e.g. OC, NO<sub>x</sub>, SO<sub>x</sub>) to condense or adsorb onto causing soot particle growth.

In addition to carbon, elemental analysis of soot from commercial aircraft has revealed content of nitrogen, sulfur, sodium and trace amounts of metals (53), indicating a hydroscopic nature of the soot particles. Volatile species and water vapor that condense or adsorb onto particles make the particles increasingly hydroscopic, which supports further growth (24). OC and EC both increase with engine throttle setting; however, OC content at engine idle is much higher than that of EC due to lower temperature and pressure (25).

Prior studies demonstrated that the particle mass, number concentrations, and geometric mean diameters increased with increased engine power. Coagulation of primary combustion particles are believed to cause this growth (24) (59). Coagulation occurs as a result of particle collisions in the turbulent post exhaust (59) (60). Nevertheless, particle sizes at all engine throttle settings are only in the nanoparticle range, less than 100 nanometers (nm), which is concerning for respiratory health (24) (48).

For perspective, particulates 5 micrometer (µm) or larger are trapped in the upper respiratory tract (nose) and expelled through nasal discharge (19) (50). Soluble particles however can dissolve and diffuse into the bloodstream. Particles in the 2 – 5 µm size range can get trapped in the tracheal and bronchial regions (back of the throat) where

they are swallowed or coughed and spit out (37). However, particles smaller than 100 nm can lodge into lung capillaries or diffuse into the bloodstream and carried to other body parts.

Health hazards associated with EC and OC diesel engine emissions are well reported. Exposures to high concentrations include headache, dizziness, and eye, nose and throat irritation (61). Chronic exposure can cause cardiovascular, cardiopulmonary and respiratory disease and lung cancer. Diesel exhaust particulate emissions, as with all hydrocarbon fueled engines, are also nano-sized (37). In 2012, diesel exhaust was classified as a known human carcinogen by the International Agency for Cancer Research (IARC) (61).

Nanoparticles may be classified into different types: 1) naturally occurring, which include volcanic ash and forest fire combustion products, 2) incidental, such as welding fumes or diesel exhaust, and 3) engineered (manufactured), such as carbon nanotubes or nano-metals and metals oxides used in ceramics (62). In recent years occupational exposure to nanoparticles have gained much interest due to the health risks associated with the engineered nanoparticle industry (62) (63). Engineered nanoparticles are suspected as more toxic than larger particles because of their increased surface area and surface reactivity, and similarity to biological structures. Combustion emissions have long time been an anthropogenic source of nanoparticles. Properties that combustion emissions share with engineered nanoparticles are increased surface area and surface reactivity. However combustion generated nanoparticles (soot) have irregular shapes. The biological activity of combustion emitted particles once inhaled is unknown. Like engineered nanoparticles, detailed information on the morphology, surface structures and

composition of combustion emitted particles and how these properties may impact worker health should be a topic of interest to occupational safety professionals.

### **Polycyclic Aromatic Hydrocarbons (PAH)**

PAH are a class of SVOC that form in post combustion processes. PAH and soot form from fuel cracking products and unburned fuel precursors in JFCE at low engine power (42) (49). PAHs that dominate in aircraft engine idle exhaust are naphthalene and alkyl-substituted naphthalenes. At high engine power, PAH and soot grow from aromatics formed via the hydrocarbon abstraction acetylene adsorption (HACA) process and coagulation from particle collisions (49). As engine power increases, PAH sizes and concentrations increase.

Naphthalene was tested in this study by TO-17. However, follow on work should characterize PAH in occupational settings on flight lines, especially those with heavy ground aircraft traffic and ground support activities.

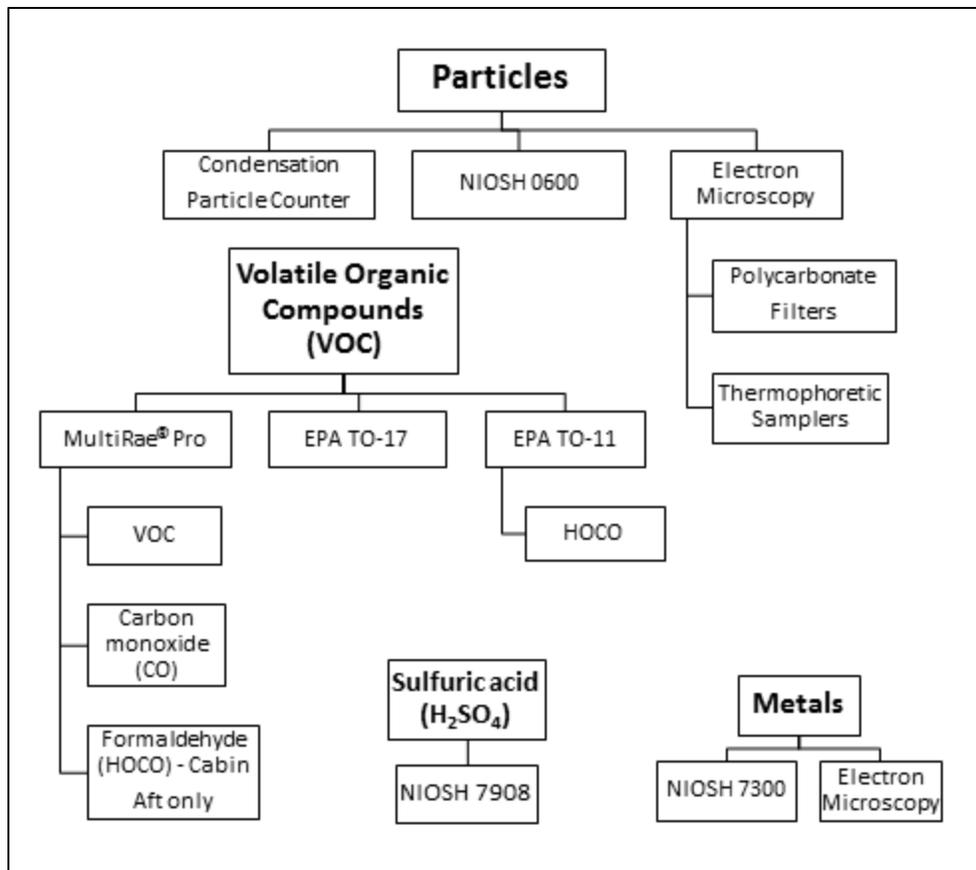
### **Metals**

Soot particles containing metals or metal oxides may arise in aircraft exhaust from engine erosion or combustion of fuel additives or lubricants from leaky seals (53). The metals content in exhaust is a function of engine age and maintenance. Transition and heavy metals Aluminum, Strontium, Barium, Sodium, Nickel, Cobalt, Chromium, and Tin, are used in bond coatings, bearings, and underlying alloys. Metals testing was included in this study.

### **III. Methodology**

#### **Sampling Plan Overview**

This chapter describes the testing methods and equipment employed and problems encountered. Sampling occurred on two nonconsecutive days- June 1 and November 9, 2016. Additional tests were added to the return visit on November 9, 2016. The sampling strategy was simultaneous sampling at all locations using DRI and traditional active sampling methods. All measurements, including background/pre-run readings, commenced prior to auxiliary power unit (APU) and engine start up, and continued simultaneously for at least 30 minutes, the maximum time it typically takes to load patients during AE ERO. Figure 3, “Summary of Contaminants and Test Methods” summarizes the total testing between both sampling days, June 1 and November 9, 2016.

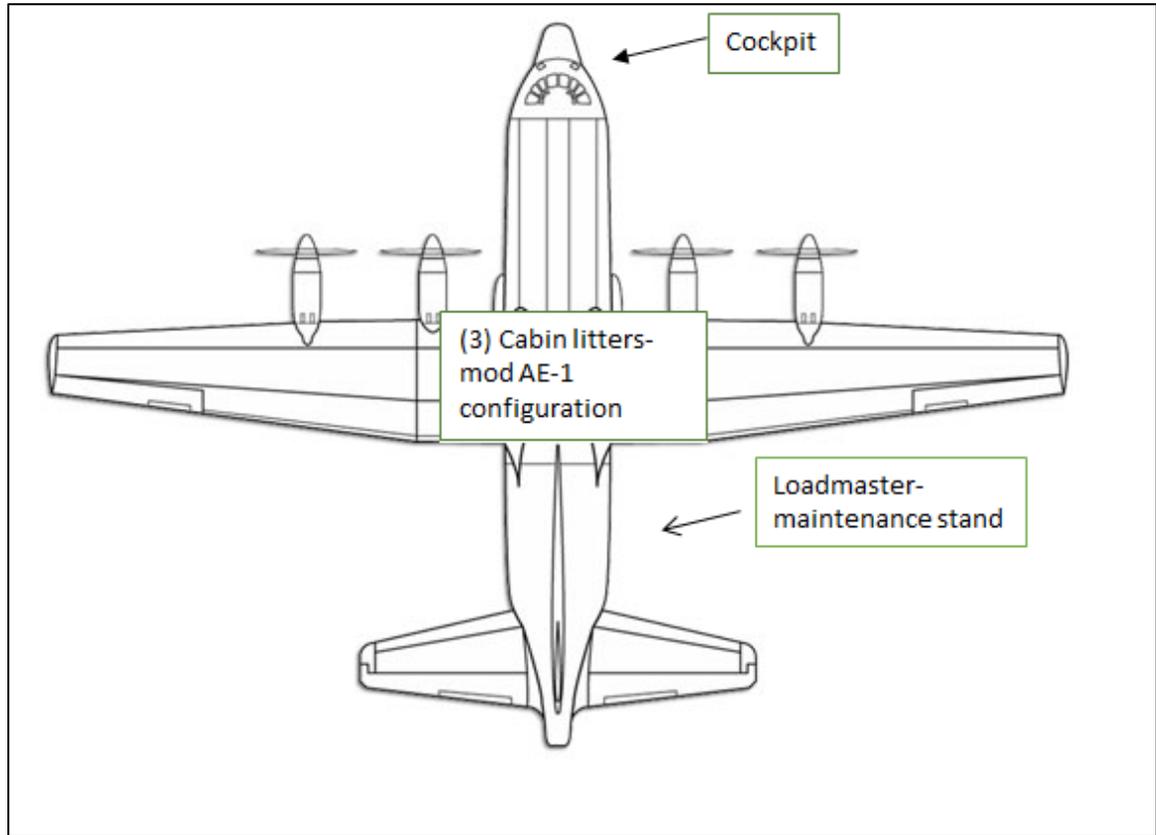


**Figure 3: Summary of Contaminants and Test Methods**

Ultrafine particles, VOC, CO, and formaldehyde contaminants were tested because of their known content in JFCE. Metals were selected due to limited information in prior studies and potential contribution from engine erosion. Sulfuric acid was added because sulfur oxides are known emissions from which sulfuric acid can form via condensation in aging exhaust. Traditional active sampling methods (NIOSH, EPA) were chosen for specific contaminants because of proven reliability and routine use in occupational exposure assessments.

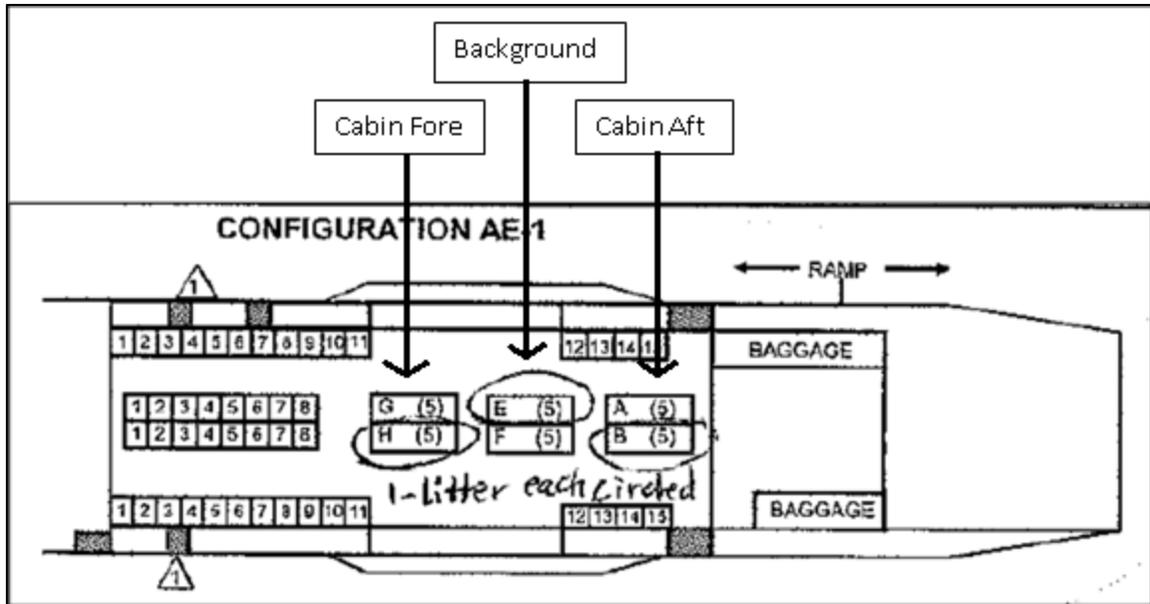
Consultation with a flight nurse and aeromedical evacuation technician from the US Air Force School of Aerospace Medicine (USAFSAM) provided familiarization with

C-130 AE ERO procedures and aircraft configuration (64). The sampling locations are shown in Figure 4, “C-130 Sampling Locations”.



**Figure 4: C-130 Sampling Locations**

This process was a simulated ERO. This research did not involve human subjects and no patients were involved. Sampling equipment was not placed on personnel. Rather, area sampling was conducted in approximate personal breathing zones. Stanchions and Litters were set-up as a Modified AE-1 configuration. See Figure 5, “Cabin Litter Set-up”. The seats in Figure 5 were not installed.



**Figure 5: Cabin Litter Set-up**

Whenever possible the sampling equipment was set up to sample in simulated personnel breathing zones. Equipment was attached to the bottom of shallow plastic crates. Figure 6, "Sampling Equipment Set-up", shows an example of the equipment during set-up at the aircraft.



*Courtesy of the 179th Airlift Wing Public Affairs*

### **Figure 6: Sampling Equipment Set-up**

Crates were placed on the navigator's table and on the crew rest cot (Nov. 9, 2016 only) inside the cockpit, on three patient litters inside the cabin, and on a maintenance stand at the loadmaster location. See Figures 7 and 8, "Cockpit, Navigator's Table Set-up" and "Cockpit, Crew Rest Cot Set-up (November 9, 2016)", Figure 9, "Cabin Set-up (June 1, 2016)", and Figure 10, "Loadmaster Location Set-up (June 1, 2016)".



*Courtesy of the 179th Airlift Wing Public Affairs*

**Figure 7: Cockpit, Navigator's Table Set-up**



*Courtesy of the 179th Airlift Wing Public Affairs*

**Figure 8: Cockpit, Crew Rest Cot Set-up (November 9, 2016)**



*Courtesy of the 179th Airlift Wing Public Affairs*

**Figure 9: Cabin Set-up (June 1, 2016)**



*Courtesy of the 179th Airlift Wing Public Affairs*

**Figure 10: Loadmaster Location Set-up (June 1, 2016)**

## **Test Methods**

### **Particles/Aerosols**

JFCE particles/aerosols were characterized with multiple testing approaches. Condensation particle counters (CPC) were used for particle counts and migration information. NIOSH 0600 method was used for gravimetric testing. Particle size

distribution, count, morphology, and elemental composition were tested with electron microscopy techniques.

### **Particle Count by TSI® 3007 CPC**

Condensation particle counters are ideal for sampling particles in the nano-size range, which are not detectable by optical particle counters or photometers (62). Inside the CPC the stream of particles pass through a region saturated with isopropyl alcohol (IPA) vapors. The IPA vapors condense onto the particles making them “grow” into an optically detectable size. Then the enlarged particles are optically detected when subjected to laser light of which the particles scatter.

TSI® Model 3007 handheld condensation particle counters were used in this study. These models are portable, lightweight, and battery operated. The detectable particle size range of the TSI® Model 3007 is 10 nm to greater than 1  $\mu\text{m}$  with a maximum particle concentration of  $10^5$  particles/ $\text{cm}^3$ . However CPC are limited to count concentrations, not providing other important particle information such as particle size, distribution, morphology, and chemical composition. For works requiring particle characterization, supplementing CPC with additional equipment/testing that provide this information is ideal.

### **CPC preparations**

All CPCs were prepared per TSI® operating manual. The wicks charged with IPA, and zero checks taken prior to both sampling days.

Due to visual observation of all CPC readings at or above the instruments' maximum range of  $10^5$  particles/cc during the June 1, 2016 sampling, diluters were

installed onto the CPCs for the November 9, 2016 return visit as in Figure 11, “CPC + Diluter”.

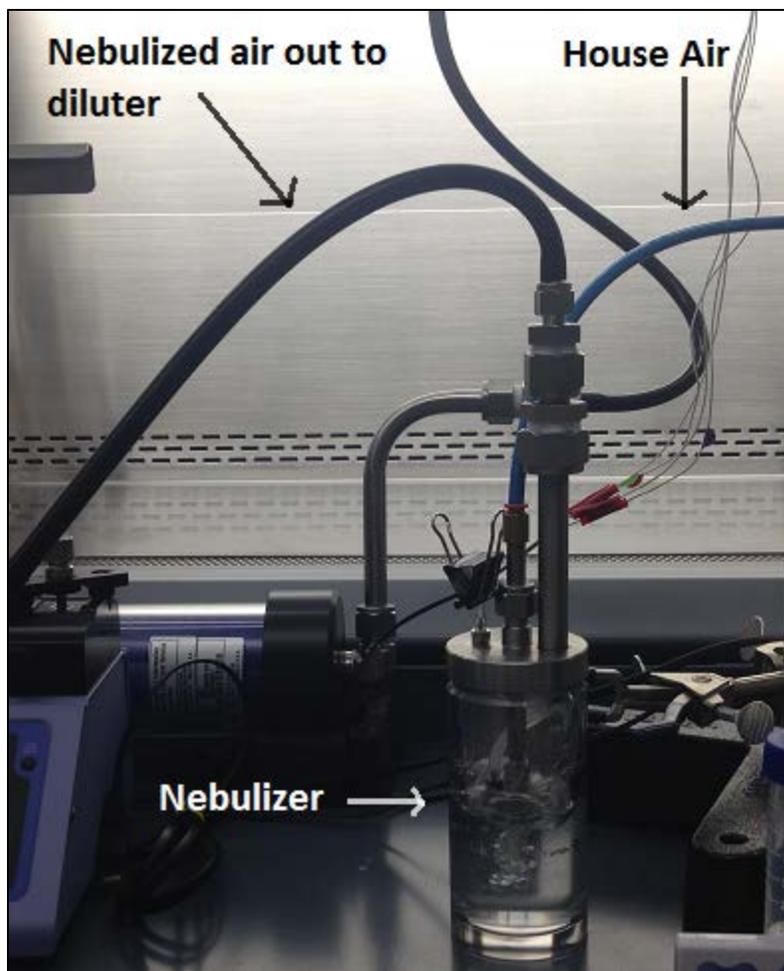


*Courtesy of the 179th Airlift Wing Public Affairs*

**Figure 11: CPC + Diluter**

A dilution factor of 10X was chosen based on the results of the TPS units from the June 1, 2016 sampling. Dilution lines made of conductive silicone tubing attached the diluters to the CPCs. Sufficient mixing of the aerosol with filtered air was checked by rotating the diluter and observing no change in concentration other than minor fluctuations normally observed.

Next inter-unit variability checks were conducted on all CPCs using nebulized DI water. The nebulized DI water apparatus is shown in figure 12, “Nebulized Deionized Water Apparatus”.



**Figure 12: Nebulized Deionized Water Apparatus**

One diluter was connected to a manifold, and all CPCs were connected off the manifold, operating simultaneously as in Figure 13, “Inter-unit Variability Checks”.



**Figure 13: Inter-unit Variability Checks**

Since the manufacturer calibration dates among the units ranged from November 2009 to August 2016, the CPC most recently calibrated (OET ECN 101382) was used as the benchmark for the inter-variability checks. The hoses connecting the manifold to the CPCs were of equal length, 55 in. All units were zero checked simultaneously with a Hepa filter attached to the bottom of the manifold, and completely closing the diluter shutoff valve. All CPC's maintained 0 reading for 1 minute. The inter-unit variability checks were verified at 10,000 pt/cc reading by setting this value on the diluter of the most recently calibrated CPC. The standard deviation among the 5 CPC average readings was 1,224 particles/cc, indicating 12 % variability in readings among the units.

Next the CPCs + diluters were connected to the manifold individually and the diluters set to 10X dilution of the CPC theoretical maximum count of  $10^5$  particles/cc. This was accomplished by adjusting the diluter valve to read as close to 10,000 particles/cc as possible. Zero checks were conducted again with the individual CPC's. The ability of each unit to read at or above the maximum count was verified by opening the diluter valves completely. To check the dilution factor, the CPCs + diluters were disconnected from the manifold, and the diluted ambient air reading was observed. Then the diluter was removed from the CPC and the undiluted ambient reading was observed. However, the difference observed between the diluted reading and ambient reading was not a 10X difference. So the dilutions were re-set on each CPC based on ambient readings and not nebulized air charging (Ex. CPC + diluter disconnected from the manifold, if ambient reading was 4000 particles/cc, the valve was dialed down to 400 particles/cc).

Once set to 10X dilution with ambient conditions, the diluter valve positions were marked and taped to secure the valve knobs. The ambient readings varied among the CPC's due to variations in the laboratory ambient air. So 10X dilution was set for each CPC based on the individual ambient readings. This was accomplished by logging ambient readings for one-minute, then immediately installing and setting the diluters to 10X of ambient reading, and then logging the dilution readings for one-minute as well. The diluters were post checked the day after the sampling (November 10, 2016).

## **Particles by TPS100<sup>®</sup> Samplers and PC Filters**

The most definitive approach to characterizing ultrafine particles in post combustor emissions is electron microscopy (EM) (62). EM techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), scanning transmission electron microscopy (STEM), and computer controlled scanning electron microscopy (CCSEM) provide comprehensive particle information, including morphology, elemental composition, sizing, and count.

With SEM the particle is subjected to a finely focused electron beam. In interaction with the particle's surface, secondary and backscatter electrons evolve, creating a visible image of the particle (65). With TEM finely focused high energy electrons interact with the particle and either scatter (disappear) into the particle or pass on through to a detection screen (ex. fluorescent) which gives rise to a "shadow" image. The image is described by varied darkness that is dependent on particle density.

In this study EM grids were collected with thermophoretic samplers, TPS100<sup>®</sup>, and polycarbonate filters (PC) with conductive cowls, provided by the RJ Lee Group of Monroeville, Pennsylvania. The TPS100<sup>®</sup> and PC filters were analyzed by RJ Lee Group using a 30kV Hitachi<sup>®</sup> S-5500 high resolution field-emission SEM/STEM equipped with a Bruker silicon drift detector for energy dispersive X-ray spectroscopy (EDS). The PC filters were prepared prior to analysis by removing a portion of the filter and placing the filter portion onto a SEM stub (66). A thin layer of carbon was deposited onto the filter with vacuum deposition techniques. The samples were then analyzed by SEM. Bright-field STEM (BF-STEM) images were also acquired for the TPS100<sup>®</sup> samples loadmaster and cockpit (June 1, 2016), and cabin aft (November 9, 2016), which were

further processed using National Institutes of Health (NIH) ImageJ, version 1.45r to obtain particle concentrations.

The TPS100<sup>®</sup> unit is a self-contained handheld sampler equipped with a micro-pump and battery capable of 8 hours of continuous sampling at 5 mL/min (63) (66). Operation of the TPS100<sup>®</sup> is based on thermophoretic force in which a relatively large temperature gradient is applied to a narrow flow channel. The temperature gradient is created between a hot plate and a cold plate. Gas molecules become heated on the hot side of the gradient and gain high kinetic energy, resulting in higher number of collisions. The collisions cause increased momentum propelling the particles in the direction of decreasing temperature and subsequent collection onto the EM grid. The EM grid is a nickel TEM grid coated with a carbon film that the particles are deposited onto. The EM grid sits directly underneath the hot plate, and is in thermal contact with the cold plate, sustaining the thermophoresis zone. Collection efficiency of the TPS100<sup>®</sup> sampler is greater than 90% between 10 and 500 nm equivalent particle diameters.

On June 1, 2016 two TPS100<sup>®</sup> units were sampled, one in the cockpit and the other at the loadmaster location. Also on that day five (plus one field blank) 0.4 µm porosity PC filters with conductive cowls were sampled at a flow rate of 4 L/min using SKC, Inc. AirChek XR5000<sup>®</sup> model personal pumps. The PC filters were sampled at all five locations: Cockpit, Cabin Fore, Background, Cabin Aft, and Loadmaster.

On November 9, 2016 four more TPS100<sup>®</sup> were employed, one each in the cockpit, cabin fore, cabin aft, and loadmaster location. However, there were issues with the TPS sampling on November 9, 2016. The first issue was that the cabin and Loadmaster TPS units were not entering into sampling mode. The cold and hot plate

temperatures were initially set to 31 °C and 105 °C. After lowering the cold plate temperatures to 25 °C, the samplers entered into sampling mode except for the Loadmaster TPS. The cold, windy conditions outside of the cabin may have prevented the Loadmaster TPS from reaching the initial cold plate temperature. The Loadmaster TPS was swapped with that of Cabin Fore, which was sampling. Neither the APU nor engines were started when the TPS units were swapped. The original Loadmaster sampler was then re-assigned as the Background TPS since sampling the background was initially planned but missed in the equipment set-up. The engines were started after all TPS units were sampling. Another issue was that the background TPS sampler (originally the Loadmaster TPS) was mistakenly not turned off until after engine start.

**NIOSH 0600, Particulates Not Otherwise Regulated, Respirable/NIOSH 7300, Elements by ICP (Nitric/Perchloric Acid Ashing)**

Ultrafine particulates and metals were sampled at all sampling locations (Cockpit, Cabin Forward, Background, Cabin Aft, and Loadmaster) plus a field blank by gravimetric method NIOSH 0600, Particulates Not Otherwise Regulated, Respirable and NIOSH 7300 method, Elements by Inductively Coupled Argon Plasma, Atomic Emission Spectroscopy on June 1, 2016 (67) (68). Both tests were collected on the same cassette using tared 5 µm PVC filter cassettes provided by RJ Lee Group and SKC, Inc. AirChek XR5000<sup>®</sup> model personal pumps and Aluminum Cyclones. The pumps were calibrated the day before sampling on May 31, 2016 at flow rate of 2.5 mL/min. Post calibrations were conducted the day after sampling on June 2, 2016. This flow rate was selected based on the maximum flow rate recommendation in N0600 and the minimum flow rates

recommended in Table 1 of N7300 method. The samples were analyzed by RJ Lee Group. The N7300 analyses included the following metals: Aluminum, Barium, Beryllium, Cadmium, Chromium, Cobalt, Copper, Iron, Lead, Molybdenum, Nickel, Strontium, Tin, Titanium, Vanadium, and Zinc.

### **NIOSH 7908, Non-Volatile Acids (Sulfuric Acid)**

Sulfuric acid was also sampled at all locations plus a field blank on June 1, 2016 by NIOSH 7908 method, Non-volatile Acids (69). Quartz fiber filter media provided by RJ Lee Group were sampled using SKC, Inc. AirChek XR5000<sup>®</sup> personal pumps. Pump pre- and post-calibrations were conducted on May 31, 2016 and June 2, 2016 at the sampling flow rate of 4 mL/min. These samples were also analyzed by RJ Lee Group.

### **VOC**

VOC were characterized with multiple methods. VOC speciation and quantitation were obtained with Compendium Method TO-17 and TO-11 for Formaldehyde. VOC were also sampled with MultiRae Pro<sup>®</sup> multi-gas meters. Carbon media passive dosimeters were also sampled for VOCs by NIOSH 1501 method for Benzene, Toluene, Ethylbenzene, and Xylene (BTEX) alongside this campaign by another investigator.

### **Compendium Method TO-17, Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling onto Sorbent Tubes**

VOC were sampled at all locations by Compendium Method TO-17, Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling onto Sorbent Tubes (70). This analysis and the sorbent tubes, Tenax thermal desorption tubes, were provided by USAFSAM/FHOF. Since the ERO is a short process, the

minimum volume required to collect was calculated using a VOC HAP with a low the short term occupational exposure limit (OEL), Benzene. The laboratory reporting limit (RL) for TO-17 is 2 ppbv. The minimum volume for TO-17 was calculated in Equation 1 using the Cal/OSHA short term exposure limit (STEL) for Benzene, which is 5 ppm (71) (72).

**Equation 1**

$$V_{min} = \frac{RL}{E * F}$$

Where: RL = Reporting Limit in  $\mu\text{g} = 2 \mu\text{g}$

E = Benzene Exposure Limit = 5 ppm = 15.95 mg/m<sup>3</sup>

F = Estimated % exposure limit in the sampling environment = 10% = 0.1

$$V_{min} = \frac{RL}{E * F}$$

$$V_{min} = \frac{2\mu\text{g} * \frac{1\text{mg}}{1000\mu\text{g}}}{15.95\text{mg}/\text{m}^3 * \left(\frac{1\text{m}^3}{1000\text{L}}\right) * 0.1} = 1.2 \text{ L}$$

This test was sampled on June 1, 2016 and again on November 9, 2016 due to the pumps shutting down intermittently on June 1, 2016. Pre- and post-calibrations were conducted on May 31 and June 2, 2016 and were noted as difficult, but successful. On June 1, 2016, SKC, Inc. AirChek XR5000<sup>®</sup> model personal pumps with adjustable low flow tube holders adjusted at a flow rate of 50 mL/min were used. The samples from June 1, 2016 were analyzed, but the data not reliable due to unknown collection volumes.

Realizing unsuitability of the AirChek XR5000<sup>®</sup> pumps, the TO-17 testing was repeated on November 9, 2016 using Gilian GilAir Plus<sup>®</sup> personal pumps at 50 mL/min flow rate. The pumps were pre- and post-calibrated on November 8 and November 10, 2016 with no difficulty.

### **Compendium Method TO-11A, Determination of Formaldehyde in Ambient Air by High Performance Liquid Chromatography (HPLC)**

Formaldehyde was sampled at all locations by Compendium Method TO-11, Determination of Formaldehyde in Ambient Air using Adsorbent Cartridge Followed by High Performance Liquid Chromatography (HPLC) (66). The analysis and the sorbent tubes, 2,4-dinitrophenylhydrazone treated silica gel with ozone scrubber, were provided by RJ Lee Group. The same personal pumps with an adjustable low flow tube holder used for the TO-17 testing were used with TO-11, but the flow rate was 500 mL/min. The flow rate within the range recommended by the TO-11 method, 100 – 2,000 mL/min, was selected. As with the TO-11 testing, the pumps were intermittently shutting down and the samples from June 1, 2016 were not used. This testing was also repeated on November 9, 2016 using Gilian GilAir Plus<sup>®</sup> personal pumps with pre- and post-calibrations performed on November 8 and November 10, 2016.

### **VOC by MultiRae<sup>®</sup> Pro Multi-gas Meter**

VOC, CO, and Formaldehyde were sampled by Rae Systems, Inc. MultiRae Pro<sup>®</sup> monitors during the November 9, 2016 sampling. Four monitors were sampled, one each in the Cockpit, Cabin Forward, Cabin Aft, and Loadmaster locations. All were equipped

with VOC and CO sensors. However, only Cabin Aft monitor was equipped with a Formaldehyde sensor due to availability of only one sensor.

### **Weather by TSI® Velocicalc Meter**

Weather data was obtained by the Mansfield ANG installation weather office and TSI, Inc. Velocicalc® model 9565-P meters.

### **Testing Summary**

#### **01 June 2016 Sampling**

Problems were experienced on the first sampling day. The sampling pumps used for TO-11 and TO-17 collections kept shutting down. As a result the sample volumes collected were unknown for TO-11 and TO-17 and the data was not useable. It was later realized that the model pumps used were not suited for low flow, even with low flow adaptors. These tests were repeated on November 9, 2016 using different pumps suited for low flows. Another problem was that data was not logged on the CPC units.

Therefore, particle migration information was not available for the June 1, 2016 testing. However, overall instrument readings were visually observed and noted. Another issue was that less volume was collected on the cockpit TPS than the loadmaster unit.

Therefore, the cockpit TPS results may be underestimated. Also, MultiRae® testing was excluded from the June 1, 2016 suite due to time constraints.

During the November 9, 2016 sampling, the TPS units lagged in reaching their temperature set points that were manually entered, which prevented the units from going into sampling mode. TEM grid issues with two of the TPS units (Cockpit and Loadmaster) were observed during laboratory analysis, which resulted in loss of the

electron microscopy data for those TPS units. Another problem on the second testing day was that CPC post dilutor checks were not in agreement with the dilution factors set on the units. Therefore the CPC data were used for qualitative migration information only.

**09 November 2016 Sampling:**

Each location had the same sampling set up and sampled for the same contaminants simultaneously, with 3 exceptions. 1.) No DRI were placed at the Background location 2.) Formaldehyde was tested by MultiRae<sup>®</sup> at the Cabin Aft location only due to availability of only one Formaldehyde sensor. 3.) Two CPCs sampled in the cockpit due to availability of an additional unit. One sampled on the navigator's table and one on the crew rest cot.

Figures 14 and 15 summarize the tests, sampling locations, and problems encountered on each day.

June 1, 2016							
Test	CPC*	TPS	SEM PC filters	TO-17**	TO-11**	N7300, N0600	N7908
Hazard	Respirable particulates			VOC	HOCO	Metals, Respirable particulates	H <sub>2</sub> SO <sub>4</sub>
Sampling Location							
Cockpit (CP)	✓	✓	✓	X	X	✓	✓
Cabin Fore (CF)	✓		✓	X	X	✓	✓
Background (B)			✓	X	X	✓	✓
Cabin Aft (CF)	✓		✓	X	X	✓	✓
Loadmaster (LM)	✓	✓	✓	X	X	✓	✓
* data not logged, visual indication only							
** Tests excluded due to pumps shutting down							
X = Data not useable							

Figure 14: Test Methods Summary- June 1, 2016

November 9, 2016							
Test	CPC*	TPS **	TO-17	TO-11	MultiRae Pro <sup>®</sup>		
Hazard	Respirable Particulates		VOC	HOCO	VOC****	CO	HOCO
Sampling Location							
Cockpit (CP)	✓	X***	✓	✓	✓	✓	
Cabin Fore (CF)	✓		✓	✓	✓	✓	
Background (B)		✓	✓	✓	✓	✓	✓
Cabin Aft (CA)	✓	✓	✓	✓	✓	✓	✓
Loadmaster (LM)	✓	X***	✓	✓	✓	✓	
* Diluters attached to CPCs, 2 CPCs in cockpit (navigator's table, crew rest cot)							
** TPS units not entering sampling mode, lowered cold plate set points- units went into sampling mode prior to engine start							
***CP and LM not analyzed- TEM grid issues observed during lab analysis							
****Qualitative only- Isopropanol carryover from CPCs							
X = Data not useable							

Figure 15: Test Methods Summary- November 09, 2016

## Limitations

**Table 1: Test Method Limitations**

Tests	Limitations
All	Area sampling is not representative of actual breathing air.
	This research was investigative only. More rigorous follow-on work is required for assessing representative personal exposures.
TSI® 3007 CPC	Manufacturer calibration is only up to 10,000 particles/cc.
	All results were qualitative due to the issues previously described.
	Does not provide particle sizing.
	IPA vapors interfered with VOC multi-gas testing.
N0600	Ultrafine particles have negligible mass, are susceptible to electrical static forces. Volatile particulate matter cannot be determined.
TO-17	Only detects were calibration mix compounds. Library searches identified other chromatography peaks, but only qualitatively.
TPS100®	Equivalent circular diameter calculations are necessary.
	Particle clumping prior to loading can lower the particle count and increase size distribution.
	Low collection efficiency outside 10 – 500 nm particle size range. Does not provide real time data.

See Appendix A, “Equipment List, November 9, 2016” for equipment listing, and Appendix B, “Sampling Information, Methods N0600/N7300/7908, TO-17/TO-11 and SEM PC Filters” for sampling information.

Not all contaminants found in prior studies were sampled in this campaign due to resources and funding limitations. Those contaminants not tested here but are inherent in JFCE are sulfur and nitrogen oxides, ozone and PAH. Including these species in future occupationally focused research would supplement the JFCE exposure information reported in this study and fill testing gaps in the literature.

### **Suggested Testing Methods for Future Research**

Although a single comprehensive personal sampling method is unrealistic for this exposure, one method that may be worth exploring in future investigations is NIOSH 3800, Organic and Inorganic Gases by Infrared Spectrometry (74). This method may be an ideal application for JFCE because it provides analyses for the majority of organic and inorganic gases in JFCE. Sulfur and nitrogen oxides are inherent in the JFCE, but were not tested in this study. NIOSH 3800 can provide analysis of nitrous oxide and sulfur dioxide. An important consideration with this method is minimizing cross-sensitivities. PAH cannot be analyzed with this method, but can be sampled by NIOSH 5506 method, Polynuclear Aromatic Hydrocarbons by HPLC (75).

A method that may be of value in assessing soot exposures from JFCE is NIOSH 5040 method, Diesel Particulate Matter (as Elemental Carbon) (76). This method analyzes total carbon (OC and EC) as well as EC using quartz fiber filters and thermo-

optical analysis. EC results have been used as an exposure marker. Currently there are no regulatory exposure limits for elemental carbon. However, results from this method could provide overall insight into the particle mass concentration exposures.

A suitable method for sampling personal exposures to unburned jet fuel is NIOSH 1550, Naphthas (77). This method analyses various types of hydrocarbon mixtures by Gas Chromatography, Flame Ionization Detector (GC-FID). A limitation of this method is that it does not speciate individual organic compounds in hydrocarbon mixtures. However, NIOSH 1550 can provide quantitative analysis of unburned jet fuel in JFCE. JP-8, Jet A, and total hydrocarbons can be analyzed by N1550 method.

Table 2, “Suggested Methods for JFCE Occupational Exposure Investigations” summarizes a comprehensive testing suite suggested for future JFCE occupational investigations.

**Table 2: Suggested Methods for JFCE Occupational Exposure Investigations**

<b>Contaminant</b>	<b>Test Methods</b>	<b>Rationale</b>
Formaldehyde	NIOSH 2016/EPA TO-11	Known content in JFCE, occupational carcinogen
Ultrafine soot particles	Direct reading instrument, electron microscopy	Real time particle count, migration indication, soot morphology
Total and Elemental Carbon	N5040	EC as a marker for exposure
Sulfuric Acid	N7908	Suspected in humid conditions
Unburned Jet Fuel	N1550	Found in engine start & ground idle; higher content in cold weather
Volatile organic, Inorganic gases	N3800	One test to provide real-time analyses of multiple hazards
PAH	N5506	Higher concentrations suspected on busy flight lines

#### **IV. Results and Discussion**

##### **Particles/Aerosols**

##### **Particle Count by TSI® 3007 CPC**

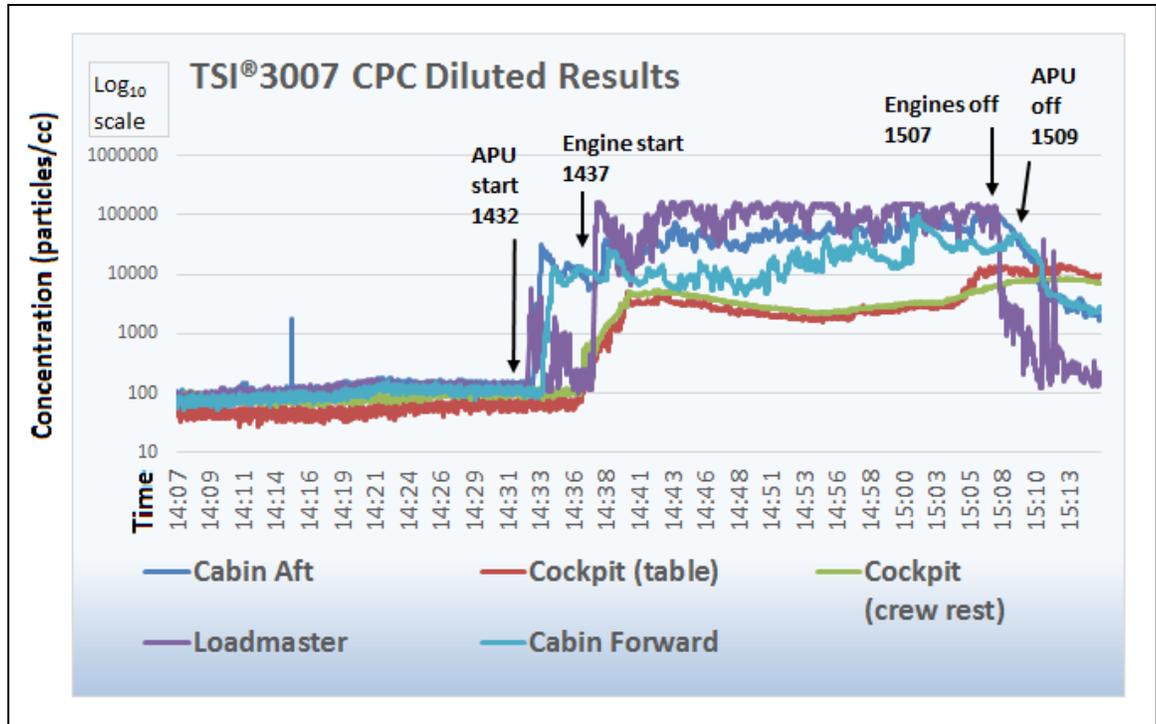
CPC particle concentrations from June 01, 2016 sampling exceeded the unit's maximum range,  $10^5$  particles/cc. Therefore diluters were installed for the return sampling on November 09, 2016. Post dilution checks were conducted on November 10, 2016, which did not match the dilution readings set on November 08, 2016. Figure 16, "CPC Dilution Readings Comparison", shows comparison between the dilution factors set prior to sampling and post dilution checks. The post dilution factors except for Cabin

Aft CPC deviated considerably from the original 10X dilution factor that was set on the diluters.

CPC	Location	Dilution Setting		Dilution factor (10X)	Post Dilution Checks		Dilution factor check
		11/08/2016 Ambient Readings	11/08/2016 Dilution Readings		11/10/2016 Ambient Readings	11/10/2016 Dilution Readings	
100656	Cabin Aft	7070	711.4	9.9	7670	513	15.0
100657	Cockpit	5500	526.9	10.4	9890	189.5	52.2
101382	Loadmaster	6890	721	9.6	20300	376.5	53.9
RHDJ	Cabin Forward	10100	948.5	10.6	10300	241.8	42.6
RHXBC	Cockpit	3820	381.9	10.0	4030	1010	4.0

**Figure 16: CPC Dilution Readings Comparison**

A summary of the CPC results from November 09, 2016 are illustrated in Figure 17, “CPC Results, November 09, 2016”.



**Figure 17: CPC Results, November 09, 2016**

The dilutions disparity is not consistent with the CPC results. For example results for both CPCs in the cockpit were expected to deviate considerably from each other based on the dilution factor disparity. However, the data for both Cockpit CPCs follow each other closely throughout the engine run, which was expected based on the duplicate testing in the cockpit. Also all CPC data follow each other tightly in the background readings (prior to APU start). All data with detects follow a trend among the sampling locations similar to TO-11, MultiRae® CO, and TO-17, and EM data during the engine run. The concentrations increased from the cockpit through the cabin and out to the Loadmaster location, where the highest concentrations were observed in all tests. It is possible that the dilutions were consistent when set and remained so during the engine run. The deviations in the post checks may have been due to varying ambient background

particles in the laboratory or CPC overload from the sampling. Nonetheless, the CPC data provided valuable qualitative particle migration information. Also of value are that the actual concentrations are at least some degree higher than the diluted results displayed in Figure 17 (and as visually indicated at the CPC maximum count during the June 01, 2016 sampling).

### **Particles by TPS100<sup>®</sup> and PC Filters**

Overall the TPS and PC filter results were dominated by soot. Results summary of the TPS100<sup>®</sup> and PC filters are displayed in Tables 2 and 3, “Polycarbonate (PC) Filter Results” and “TPS100<sup>®</sup> Results”.

**Table 3: Polycarbonate (PC) Filter Results**

Sampling Campaign	Collection Date	Location	Duration (min)	Vol. (L)	Observations
First Sampling Campaign	6/1/2016	Load master	31	124	Very heavy particle loading; Primarily soot
	6/1/2016	Cabin AFT	33	132	Moderate particle loading; Primarily soot
	6/1/2016	Cabin Forward	30	120	Moderate/light particle loading; Primarily soot
	6/1/2016	Cockpit	32	129	Low particle loading; Primarily soot
	6/1/2016	Background	44	171	Consistent with a blank
	6/1/2016	Field blank	0	0	Consistent with a blank

*Courtesy of RJ Lee Group*

**Table 4: TPS100® Results**

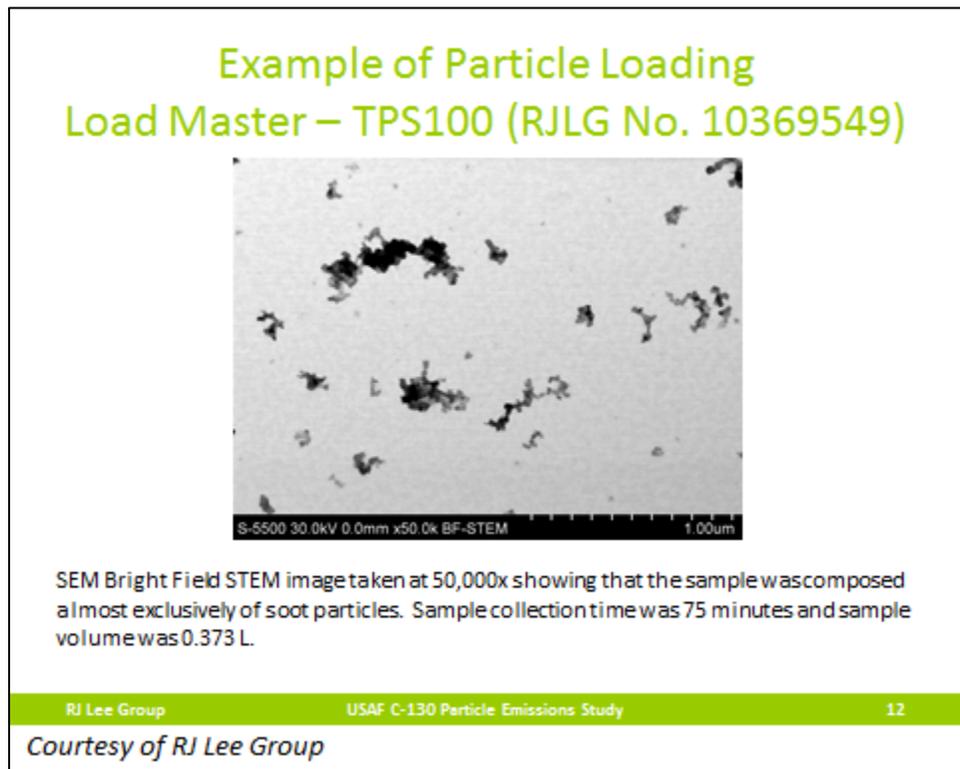
Sampling Campaign	Collection Date	Location	Duration	Vol. (L)	Hot Plate (°C)	Cold Plate (°C)	Ambient Temp. (°C)	Rel. Humidity	Comments	Concentration (particles/cc) from Offline Sizing	
First Sampling Campaign	6/1/2016	Loadmaster	1 hr. 15 min.	0.373	110	25	NA	NA	Good loading. Sizing data provided.	3.40E+06	
16-Jun	6/1/2016	Cockpit	20 min.	0.1	110	25	NA	NA	Lighter loading than LM. S-rich volatiles also observed.	1.60E+06	
Second Sampling Campaign	11/9/2016	Background (re-assigned from original Loadmaster location)	18 min.	0.089	105	25	7	46	Sparse loading, almost blank; a few soot particles documented	NA	
	11/9/2016	Cabin AFT	48 min.	0.238	105	25	8	68	Lightly loaded. Collected during second campaign.	8.60E+05	
	16-Nov	11/9/2016	Loadmaster (re-assigned from Cabin Forward)	1 hr. 15 min.	0.373	105	25	8	66	No Grid in Cartridge	NA
	11/9/2016	Cockpit	1 hr. 15 min.	0.373	105	31	11	45	Problem with sample; Grid not analyzed	NA	

*Courtesy of RJ Lee Group*

The TPS100® samplers analyzed were the Cockpit and Loadmaster samplers from June 1, 2016 and the Background and Cabin Aft samplers from November 9, 2016. The

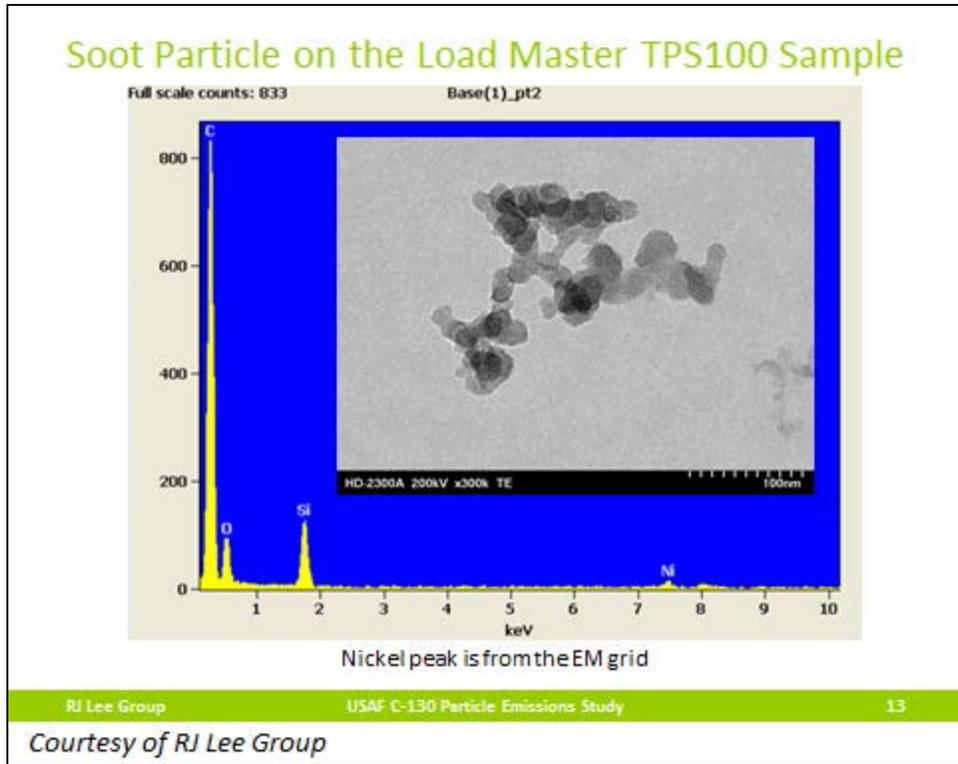
Loadmaster and Cockpit TPS samplers from the November 9, 2016 sampling were lost due to grid issues discovered during analysis at the laboratory.

The Loadmaster location (June 1, 2016) had the highest loading of soot particles as qualitatively seen in the PC filter and TPS concentration of  $3.40E+06$  particles/cc (66). Particle loading in the Loadmaster TPS sample is displayed in Figure 18, “Loadmaster TPS100<sup>®</sup> Particle Loading”.



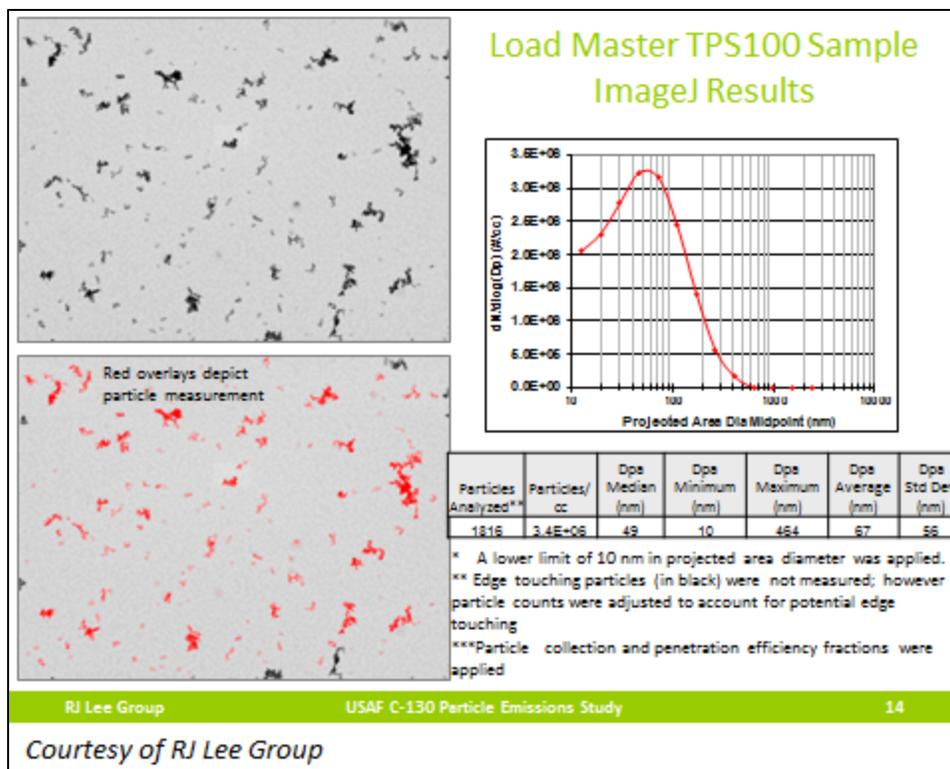
**Figure 18: Loadmaster TPS100<sup>®</sup> Particle Loading**

Enlarged view and elemental analysis of a soot particle from the Loadmaster TPS sample reveals primarily carbon content with small amount of oxygen and silicon. See Figure 19, “Elemental Composition of Soot Particle – Loadmaster TPS100<sup>®</sup>”.



**Figure 19: Elemental Composition of Soot Particle – Loadmaster TPS100®**

Particle diameter, concentration, and size distribution results for the Loadmaster TPS are summarized in Figure 20, “Loadmaster TPS100® ImageJ Results”.

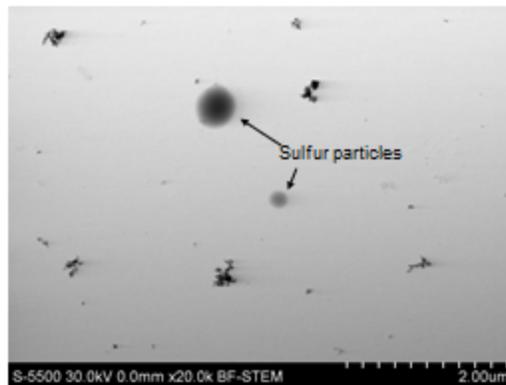


**Figure 20: Loadmaster TPS100® ImageJ Results**

The particle size range was 10 – 464 nm, with median of 49 nm, and average size of 67 nm. Particle size standard deviation corresponds to the wide size distribution. However, the largest concentrations were of particle sizes less than 100 nm.

Lower concentrations of soot and low numbers of sulfur-containing particles assumed to be secondary organic aerosols (SOA) were observed in the cockpit TPS sample (June 1, 2016). Less volume was recorded in the Cockpit sampler (0.1 L) compared to that of the Loadmaster (0.373 L) on June 1, 2016 due to operator error. Particle loading in the Cockpit TPS sample are shown in Figure 21, “Cockpit TPS100® Particle Loading”.

## Example of Particle Loading Cockpit – TPS100 (RJLG No. 10369548)



Bright Field STEM image taken at 20,000x showing that the sample was composed almost exclusively of soot particles. Sulfur containing particles were also present on the sample. Sample collection time was 20 minutes and sample volume was 0.10 L.

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### **Figure 21: Cockpit TPS100® Particle Loading**

Enlarged view and elemental analysis of a soot particle from the Cockpit TPS sample resembles that of the Loadmaster TPS soot particle, as shown in Figure 22, “Elemental Composition of Soot Particle – Cockpit TPS100®”.

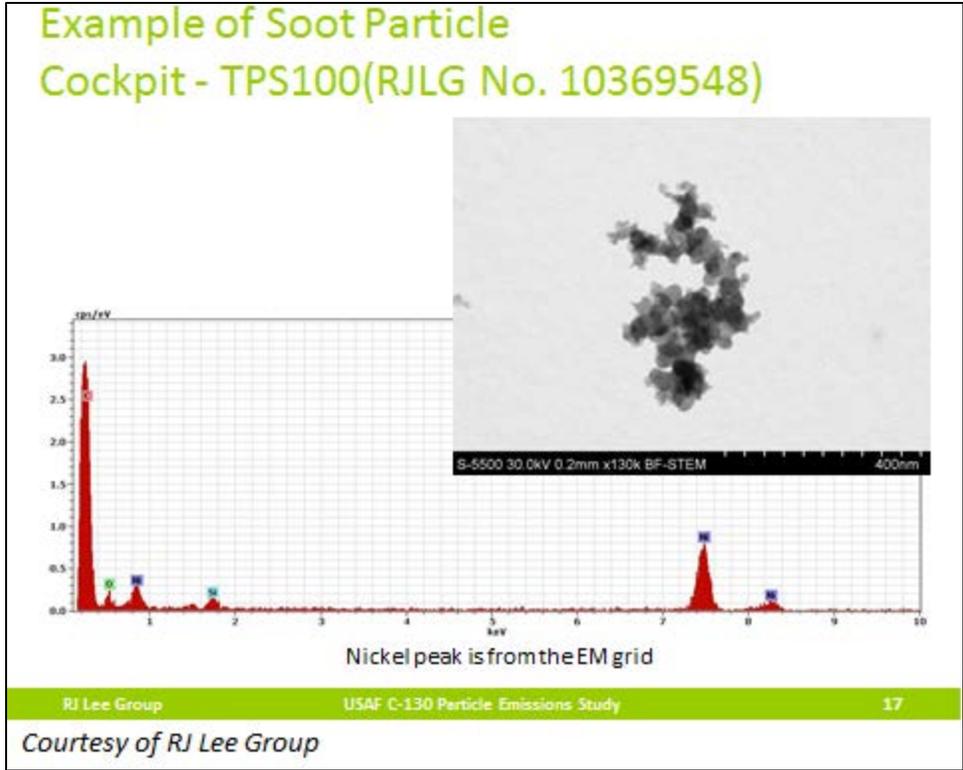
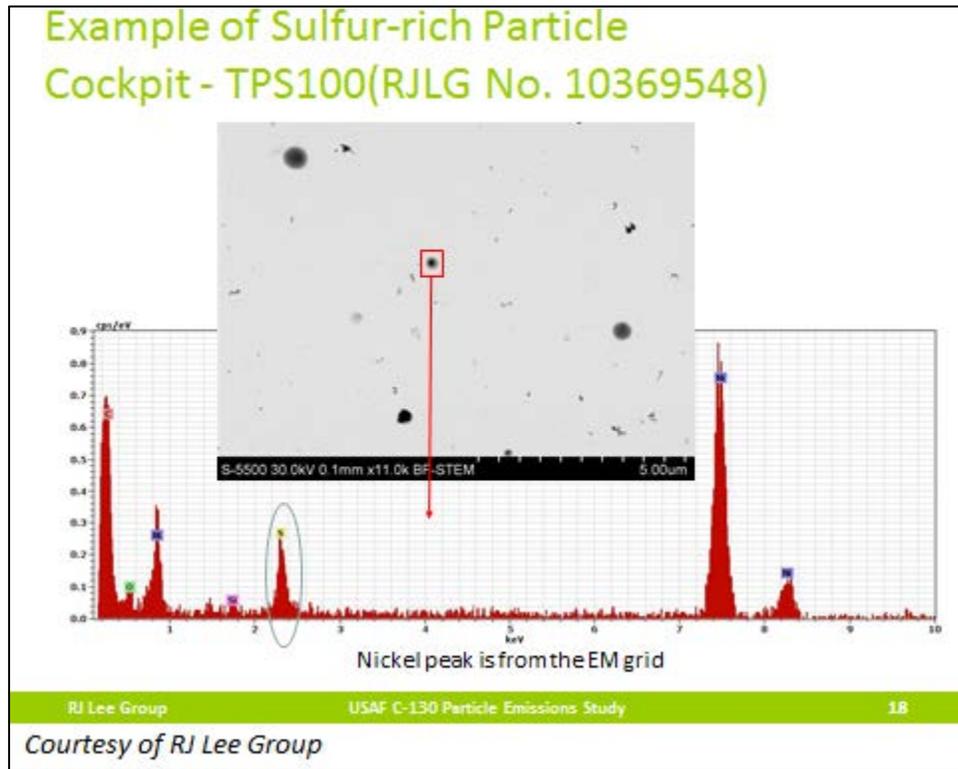


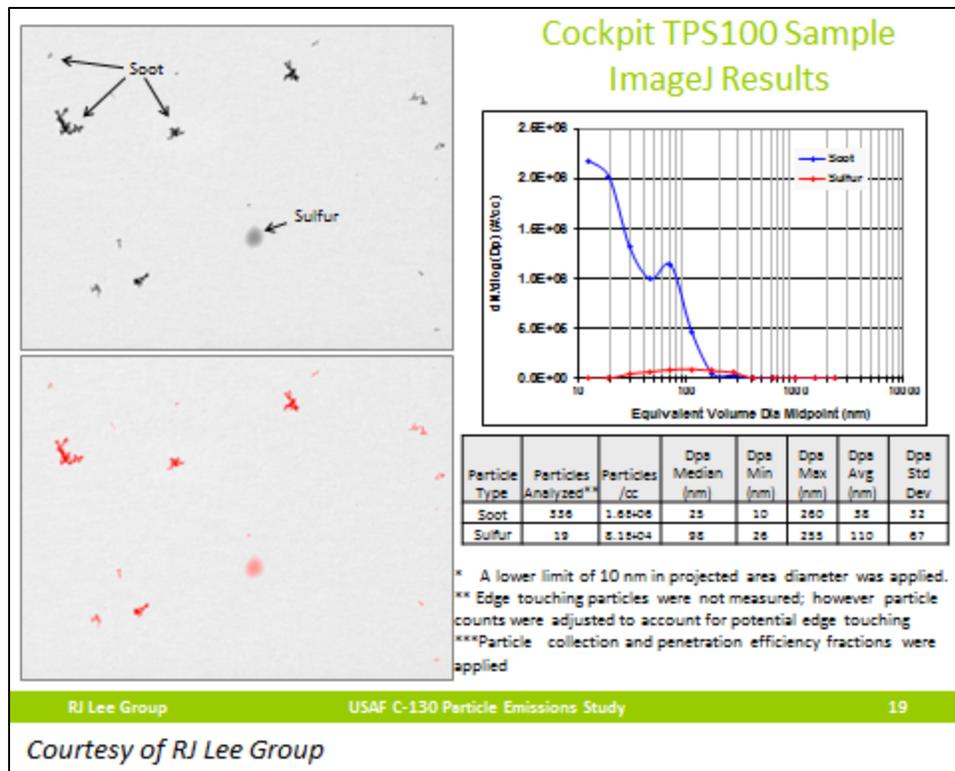
Figure 22: Elemental Composition of Soot Particle – Cockpit TPS100®

Enlarged view and elemental analysis of a sulfur containing soot particle from the Cockpit TPS sample is shown in Figure 23, “Elemental Composition of Sulfur-rich Particle – Cockpit TPS100®”.



**Figure 23: Elemental Composition of Sulfur-rich Particle – Cockpit TPS100®**

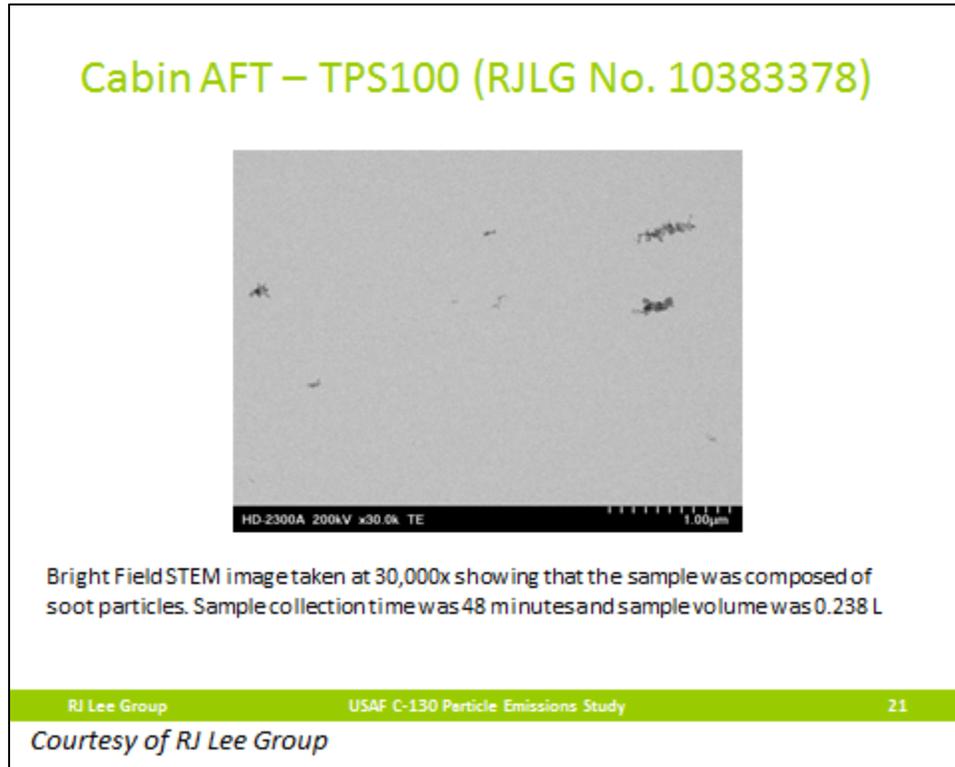
Particle diameter, concentration, and size distribution results for the Cockpit TPS sample are summarized in Figure 24, “Cockpit TPS100® ImageJ Results”.



**Figure 24: Cockpit TPS100® ImageJ Results**

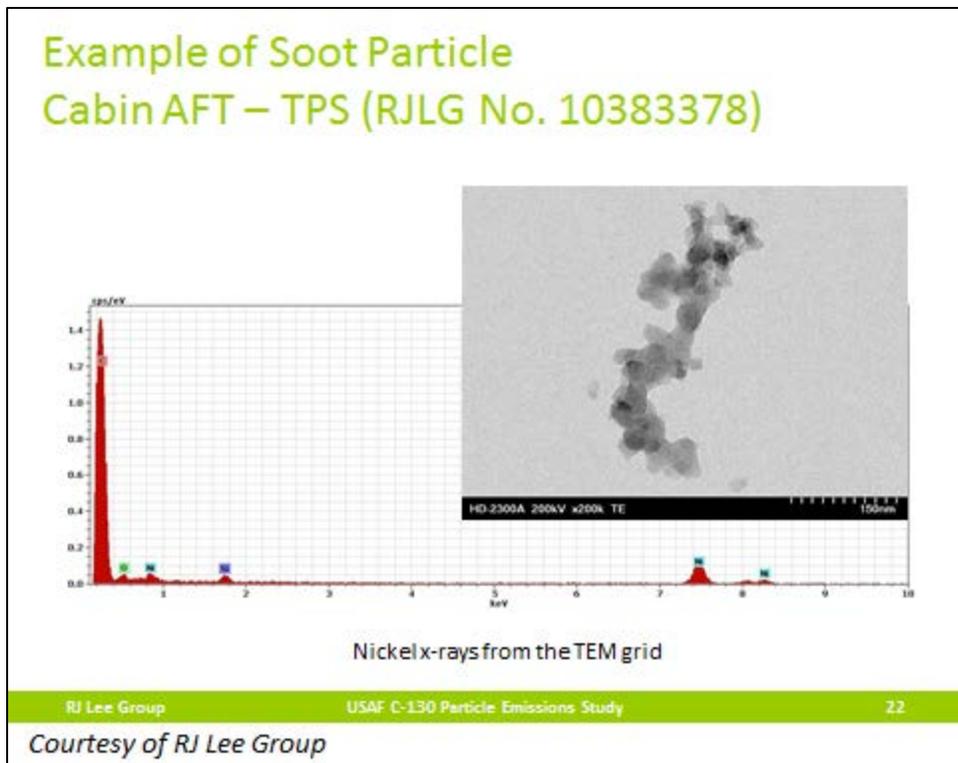
Particle concentrations in the Cockpit TPS sample were  $1.6E+06$  particles/cc of soot and  $8.1E+04$  of sulfur containing particles assumed to be secondary organic aerosols (SOA) (66). The soot particle size range was 10 – 260 nm, with median of 25 nm, and average size of 38 nm. As with the Loadmaster location TPS results, the soot particle size standard deviation of 32 nm corresponds to the wide size distribution, and the largest concentrations were of particle sizes less than 100 nm. The sulfur containing particle size range was comparable to the soot at 26 – 255 nm. However, the median and average sizes are larger than the soot particle at 98 nm (median) and 110 nm (average).

The Cabin Aft TPS sample from November 9, 2016 was lightly loaded with soot particles. Particle loading in the Loadmaster TPS sample is displayed in Figure 25, “Cabin Aft TPS100<sup>®</sup> Particle Loading”.



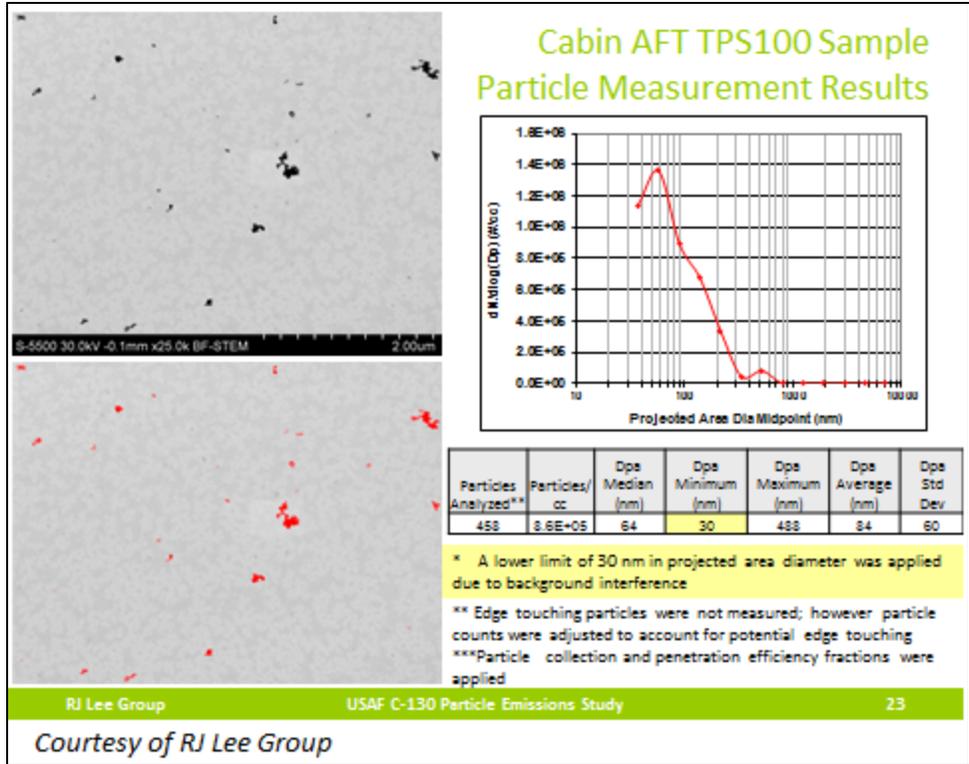
**Figure 25: Cabin Aft TPS100<sup>®</sup> Particle Loading**

Enlarged view and elemental analysis of a soot particle from the Cabin Aft TPS sample is shown in Figure 26, “Elemental Composition of Soot Particle – Cabin Aft TPS100<sup>®</sup>”.



**Figure 26: Elemental Composition of Soot Particle – Cabin Aft TPS100®**

Particle diameter, concentration, and size distribution results for the Cabin Aft TPS sample are summarized in Figure 27, “Cabin Aft TPS100® ImageJ Results”.



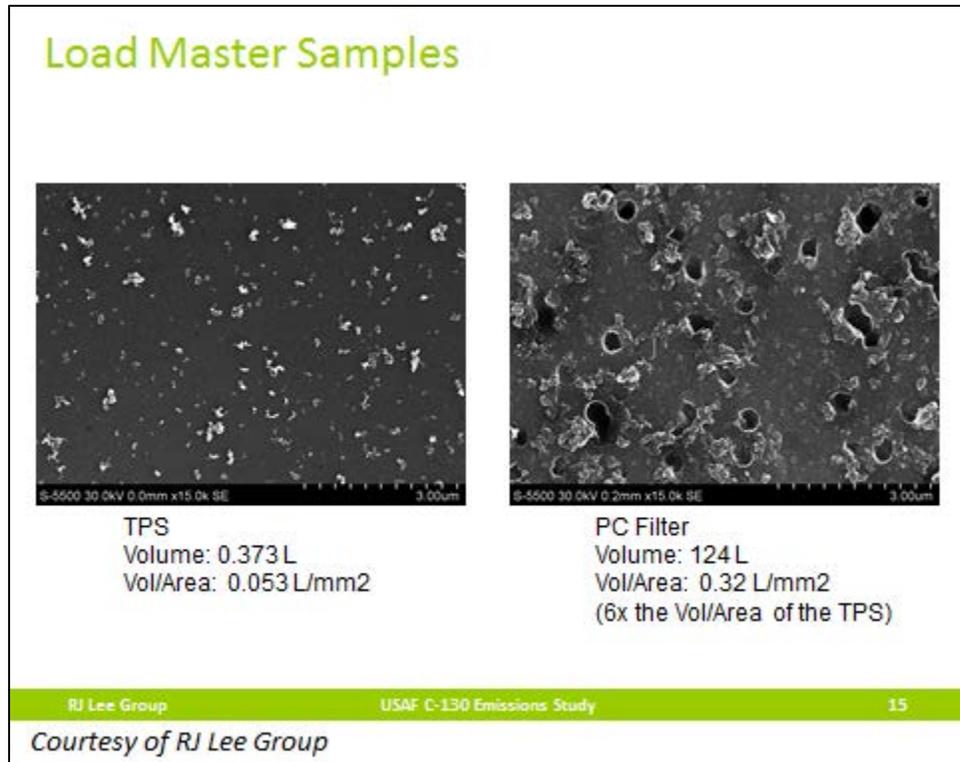
**Figure 27: Cabin Aft TPS100® ImageJ Results**

Particle concentrations in the Cabin Aft TPS sample were 8.6E+05 particles/cc of soot. The particle sizing was close to that of the Loadmaster location, with a range of 30 – 488 nm (exception is the range low end of 30 nm due to background interference), median of 64 nm, and average size of 84 nm. As with the Loadmaster and Cockpit TPS samples, the highest concentrations were of particle sizes less than 100 nm.

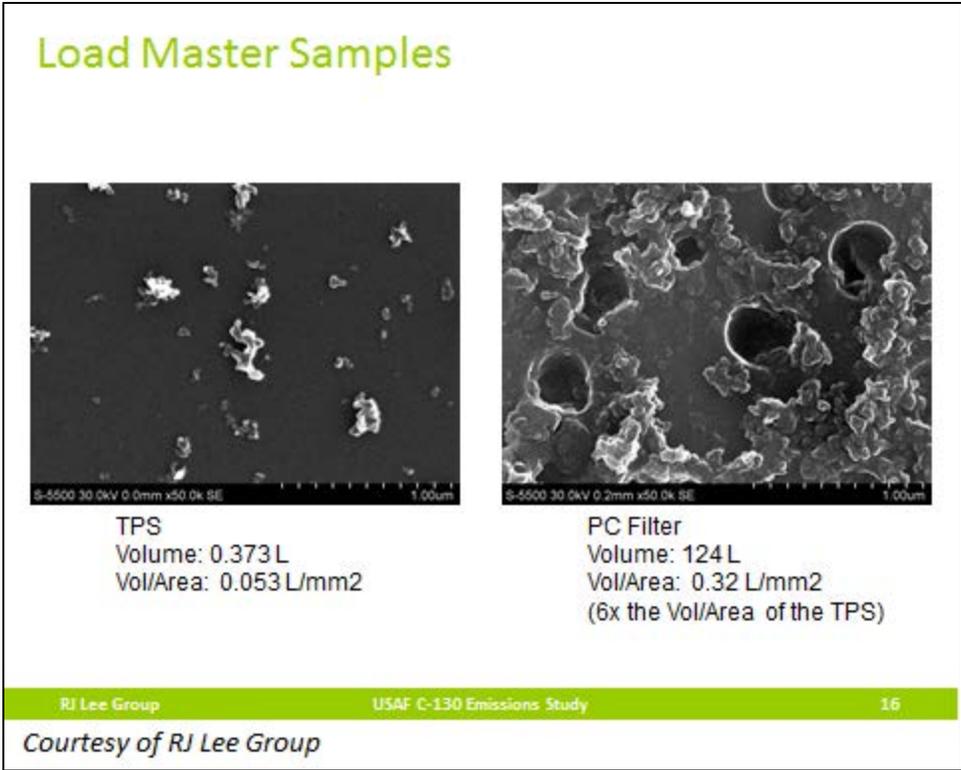
As compared to the TPS sample, results from the PC filters provide qualitative confirmation of soot dominance in the particulate matter. However, these samples were heavily loaded due to the much higher flow rate (4 L/min) than the TPS. Therefore particle separation and count could not be determined. In future investigations, sampling

PC filters with a much lower flow rate would be more suited in high particle environments such as JFCE.

Figures 28, “Loadmaster, TPS100<sup>®</sup> SEM Comparison, 3 μm Resolution” and Figure 29, “Loadmaster, TPS100<sup>®</sup> SEM Comparison, 1 μm Resolution” show side by side comparisons of the Loadmaster TPS and PC filter samples.

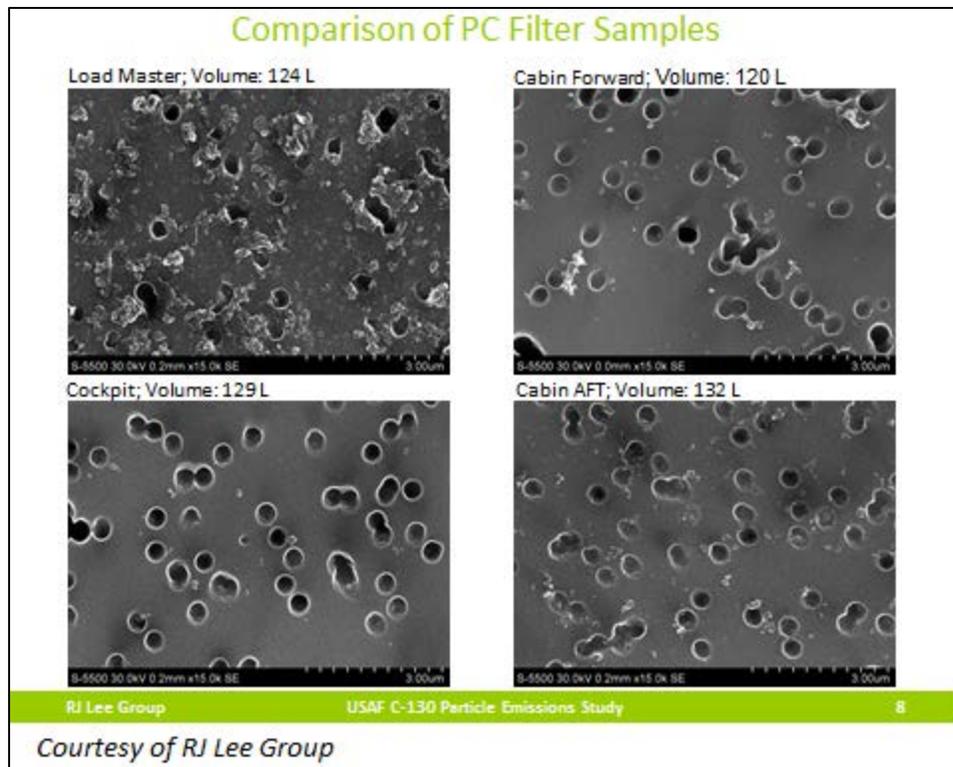


**Figure 28: Loadmaster, TPS100<sup>®</sup> SEM Comparison, 3 μm Resolution**



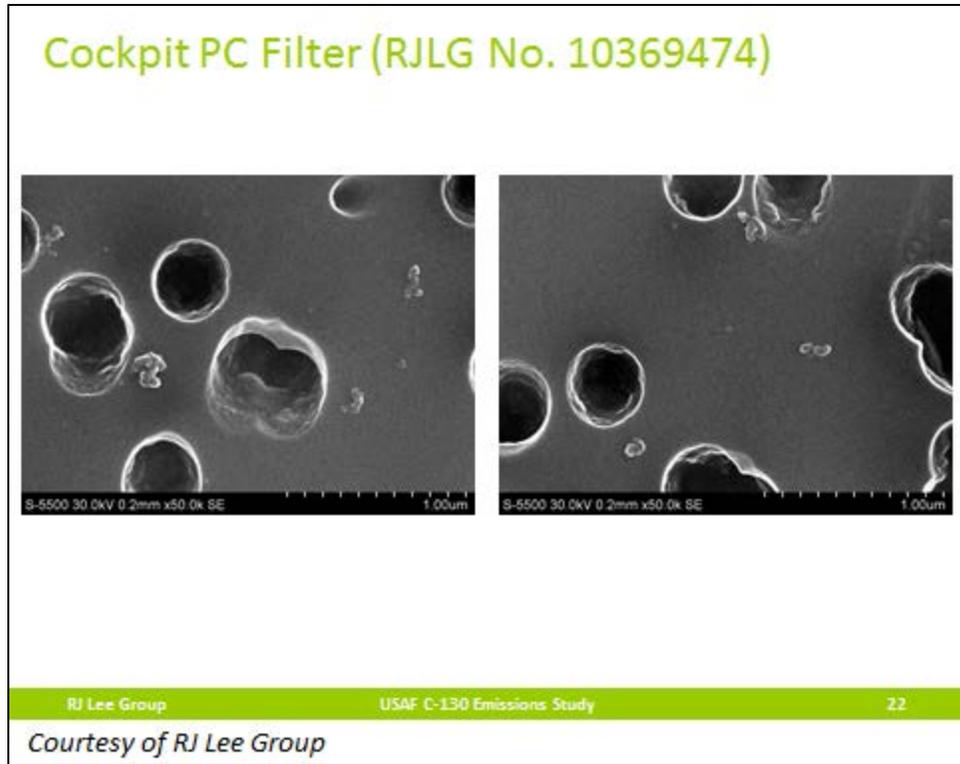
**Figure 29: Loadmaster, TPS100<sup>®</sup> SEM Comparison, 1 μm Resolution**

PC filter particle loading showed a visible trend of highest to lowest from the Loadmaster-to-Cabin Aft-to-Cabin Fore-to-Cockpit as visible in Figure 30, “PC Filters Particle Loading Trend”.



**Figure 30: PC Filters Particle Loading Trend**

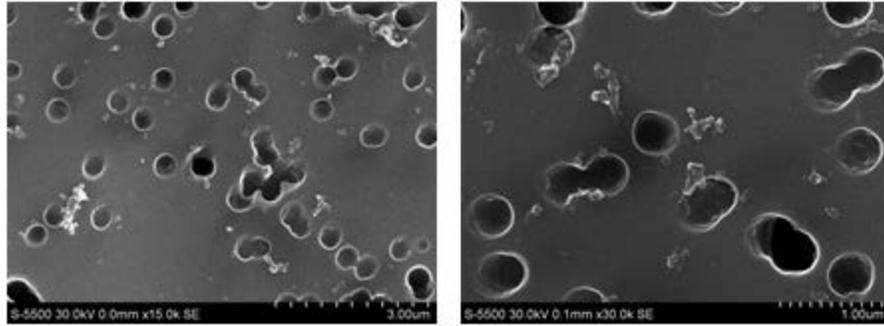
The Cockpit PC filter was less loaded than that of the TPS as shown in Figure 31, “Cockpit PC Filter SEM Images”.



**Figure 31: Cockpit PC Filter SEM Images**

Irregular shapes and cluster morphology are also observed in the PC filters. Cabin PC Filter SEM Images are shown in Figures 32 – 34.

## Cabin Forward PC Filter (RJLG No. 10369475)



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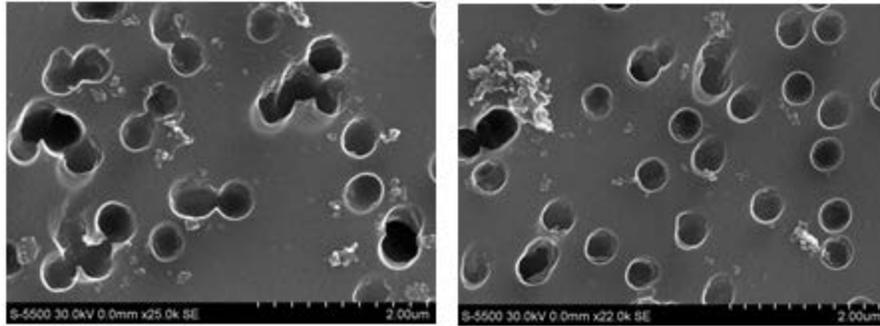
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*Courtesy of RJ Lee Group*

**Figure 32: Cabin Forward PC Filter SEM Image, (1  $\mu\text{m}$ , 3  $\mu\text{m}$  Resolution)**

## Cabin Forward PC Filter (RJLG No. 10369475)



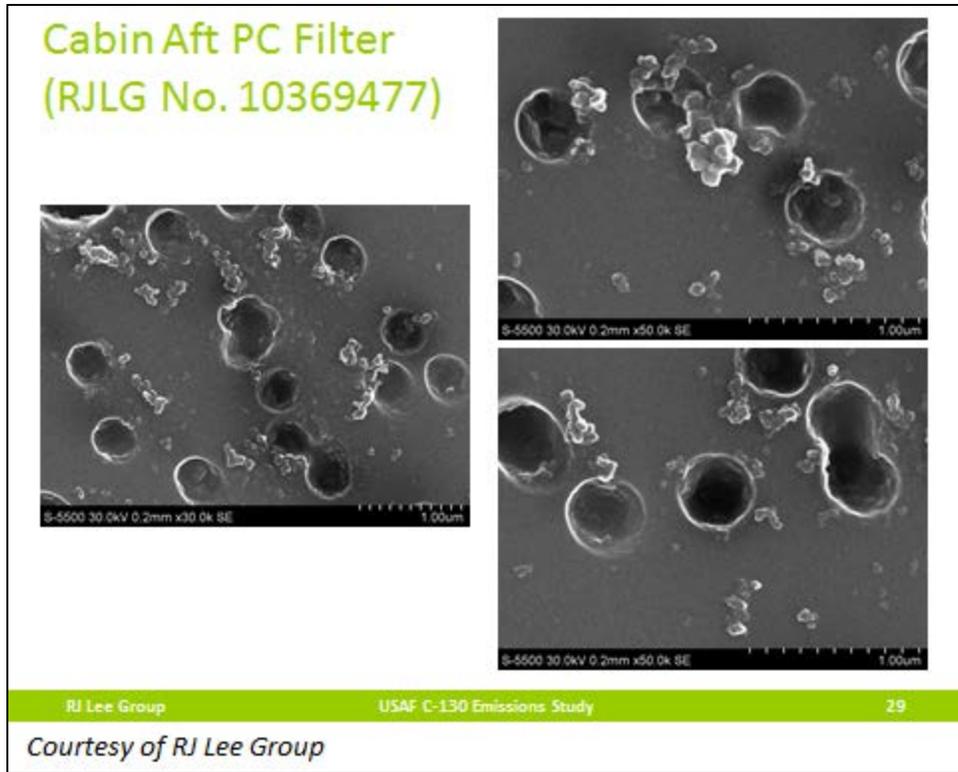
RJ Lee Group

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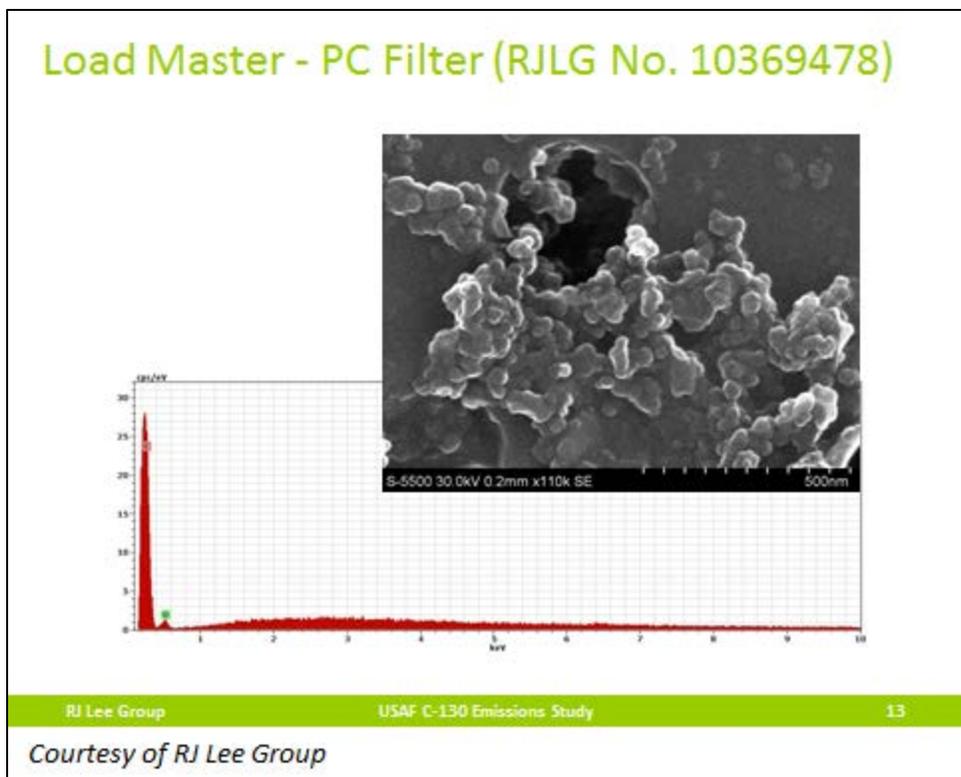
*Courtesy of RJ Lee Group*

**Figure 33: Cabin Forward PC Filter SEM Image, (2  $\mu$ m Resolution)**



**Figure 34: Cabin Aft PC Filter SEM Image, (1 µm Resolution)**

As with the TPS samples elemental composition of the PC filters were predominantly carbon with small amounts of oxygen in all samples. The Cabin samples had trace amounts of sulfur, aluminum, and sodium. Aside from the carbon content, the elemental analysis may not absolutely represent all particles because larger clusters from the heavier loading may mask internal particle composition. Elemental analyses results from the PC filters are shown in Figures 35 – 40.



**Figure 35: Elemental Composition of Soot Particle – Loadmaster PC Filter (500 nm)**

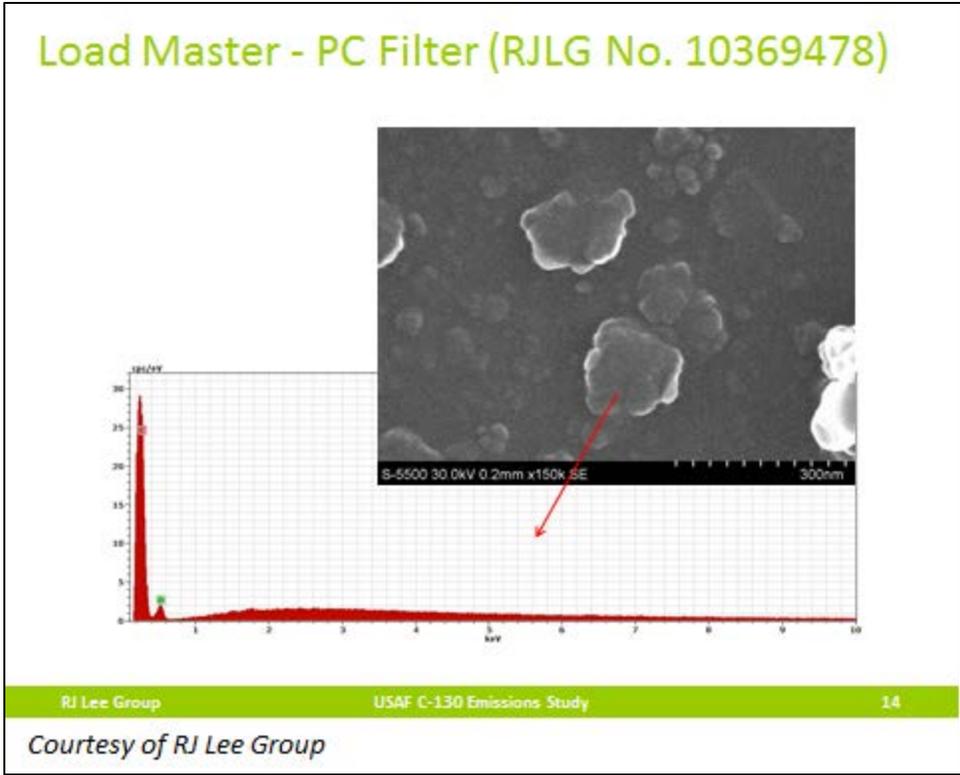


Figure 36: Elemental Composition of Soot Particle – Loadmaster PC Filter (300 nm)

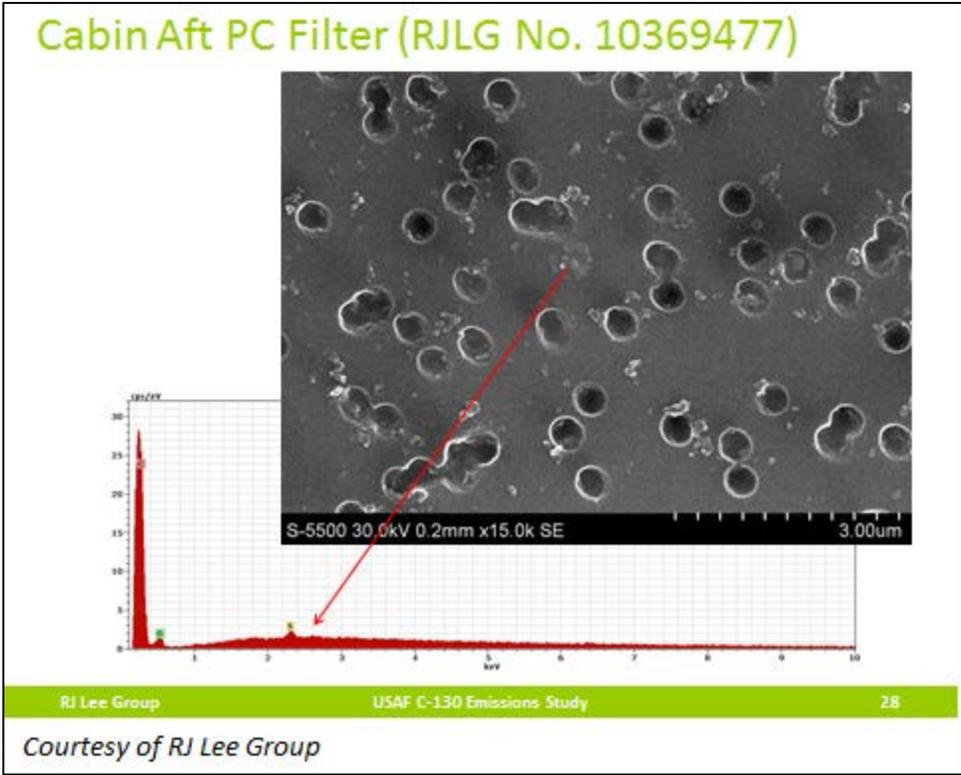
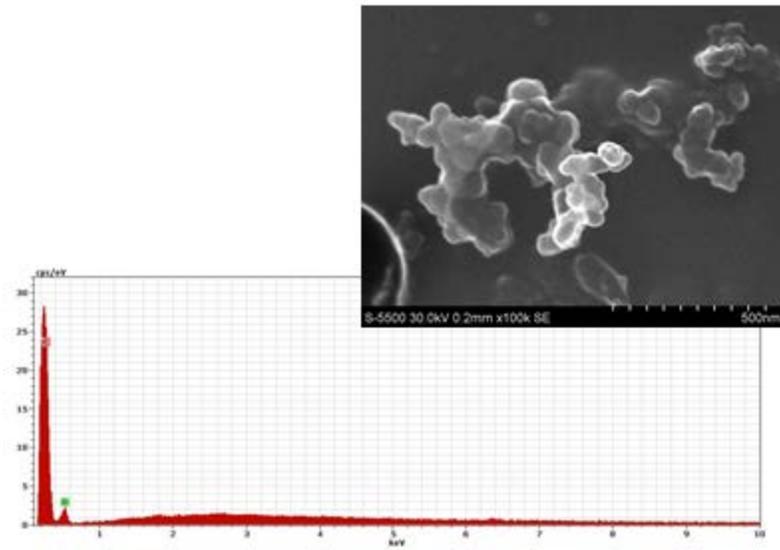


Figure 37: Elemental Composition of Soot Particle – Cabin Aft PC Filter (3  $\mu\text{m}$ )

### Cabin Aft PC Filter (RJLG No. 10369477)



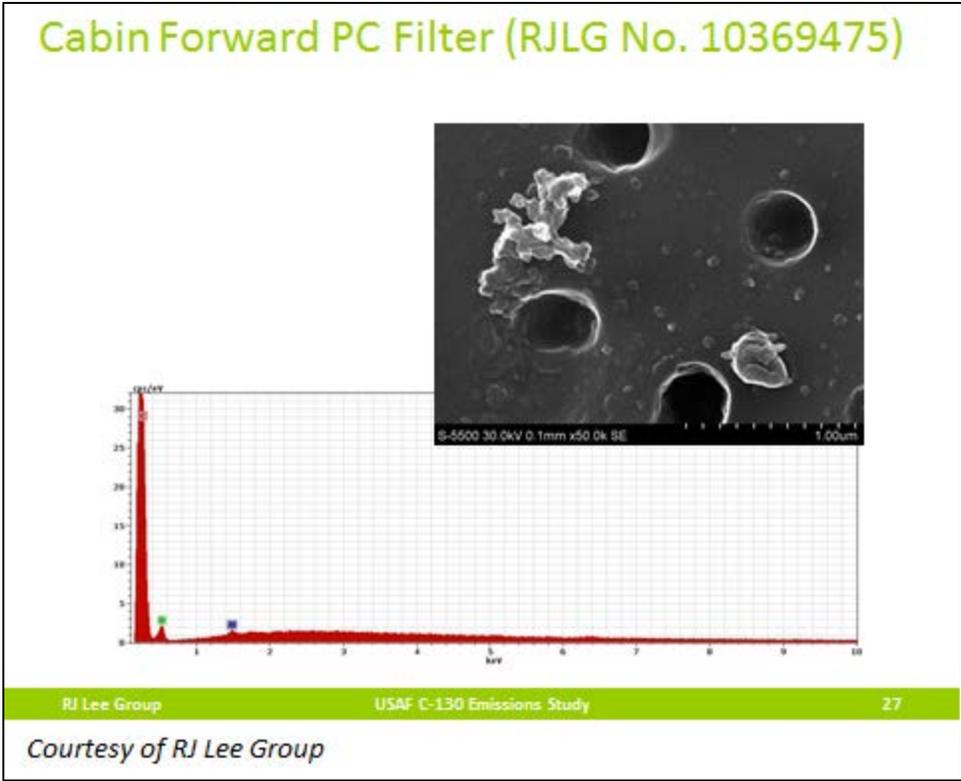
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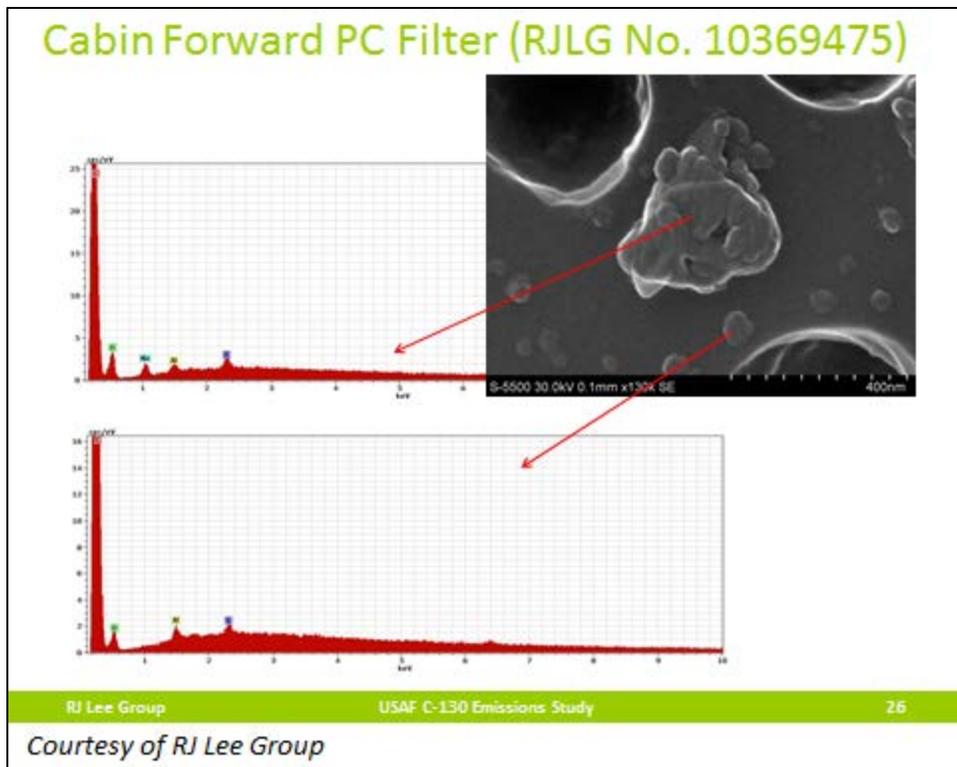
30

*Courtesy of RJ Lee Group*

**Figure 38: Elemental Composition of Soot Particle – Cabin Aft PC Filter (500 nm)**



**Figure 39: Elemental Composition of Soot Particle – Cabin Forward PC Filter (1  $\mu\text{m}$ )**



**Figure 40: Elemental Composition of Soot Particle – Cabin Forward PC Filter (400 nm)**

### **NIOSH 0600, Particulates Not Otherwise Regulated, Respirable**

Results from the N0600 testing were below the reporting limit at all locations. However, gravimetric measurement by N0600 in this exposure environment is challenging since nanoparticles have negligible mass and are susceptible to electrical static forces. Another consideration is that this method is only suitable for non-volatile particulate matter (68). The particles at engine start-up and idle contain more OC than EC. OC cannot be assessed with N0600 method. The limitations of N0600 method most likely accounts for the disparity with the N0600 and CPC and TPS results. This method is therefore not suitable for JFCE application.

### **NIOSH 7300, Elements by ICP (Nitric/Perchloric Acid Ashing)**

All sample results from the NIOSH 7300 testing were below minimum reporting limits. Consistent with findings from prior studies, some trace metals were detected with elemental analysis in the electron microscopy.

### **NIOSH 7908, Non-Volatile Acids (Sulfuric Acid)**

Sulfuric acid results from the NIOSH 7908 testing were below minimum reporting limits. However, sulfuric acid forms from oxidation of sulfur dioxide by water vapor, increasingly more so in humid environments (25). This test is more suited for JFCE testing in humid locations.

Sulfur-containing soot was detected as SOA in the electron microscopy results. Sulfur dioxide was not tested in this effort, but its inclusion in future investigations should be considered.

### **Compendium Method TO-11A, Determination of Formaldehyde in Ambient Air by High Performance Liquid Chromatography (HPLC)**

Formaldehyde was detected above the reporting limit but less than regulatory exposure limits in all sample locations. The Background and blanks results were less than the reporting limit. These results also showed a trend of increasing concentrations from Cockpit to Cabin to Loadmaster locations, indicative of migration into the aircraft. The highest result at the Loadmaster location was above a voluntary exposure limit, NIOSH REL 15-minute ceiling of 0.1 ppm. Formaldehyde is also an occupational carcinogen, and should be closely investigated in follow-on work.

## Compendium Method TO-17, Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling onto Sorbent Tubes

The results were corrected for the instrument calibration volume of 500 mL as in Equation 2, TO-17 Volume Correction Calculation” then Equation 3, “Result Correction Calculation”.

$$V_{\text{corr}} = \frac{V_{\text{samp}}}{V_{\text{cal}}}$$

**Equation 2**

Where:

$V_{\text{corr}}$  = Volume corrected for the instrument calibration volume

$V_{\text{samp}}$  = Sampled volume

$V_{\text{cal}}$  = Instrument calibration volume = 500 mL

$$\text{ppbv}_{\text{corr}} = \frac{\text{ppbv}_{\text{raw}}}{V_{\text{corr}}}$$

**Equation 3**

Where:

$\text{ppbv}_{\text{corr}}$  = TO-17 instrument results corrected for calibration volume

$\text{ppbv}_{\text{raw}}$  = TO-17 raw instrument results

Acetone and methylene chloride were detected in the blanks and samples, including the Background sample. Methylene chloride results are suspected as laboratory contamination since all results are consistent. Acetone results however are higher in the samples than the blanks and Background sample, especially the Cockpit. The

Background acetone result is much less than the samples, but higher than the blanks. This suggests possibility of laboratory carryover as well as contribution from aircraft emissions. The source of Background acetone may be contribution from the plane that taxied and took off as the researchers were setting up equipment.

Small amounts of n-hexane were detected in the blanks but not the samples, which are also suspected as laboratory carryover. Large amounts of isopropyl alcohol (IPA) were detected in all samples and background sample but not the blanks. This was realized to have occurred from IPA vapors from the CPCs, and therefore cannot be assessed in this study.

In the Cockpit, 1,1-dichloroethene (also known as vinylidene chloride) was detected, and had the highest concentration second to acetone (excluding IPA and methylene chloride as they were detected due to carryover). Although detected in the ppbv level, this compound is listed as a carcinogen by the American Conference of Governmental Industrial Hygienists.

In general the number of compounds detected and concentrations show an increasing trend from Cabin to Loadmaster locations, indicative of propeller wash emissions migrating into the cabin. Many of the compounds detected are HAPs, listed on the ATSDR, and most are irritants. Benzene, 1,4-dioxane, and formaldehyde are potential carcinogens (51). The results from the TO-11 and TO-17 sampling are displayed in Table 4, "VOC Results Summary (ppbv)".

**Table 5: VOC Results Summary (ppbv)**

<b>TO-17 Results (ppbv)</b>	<b>Field Blank</b>	<b>Trip Blank</b>	<b>Background</b>	<b>Cockpit</b>	<b>Cabin Forward</b>	<b>Cabin Aft</b>	<b>Loadmaster</b>
Acetone	7.96	9.04	7.63	144.97	10.84	13.08	10.31
1,1-Dichloroethene				18.93			
MEK				1.84	1.08	1.74	3.70
Benzene				1.00	2.69	4.22	9.96
Toluene				0.39	0.90	1.51	3.88
Cyclohexane					0.62	1.04	2.24
4-Ethyltoluene					0.82	1.19	3.43
Styrene						0.52	1.44
Naphthalene						0.51	1.58
1,4-Dioxane							0.61
2-Hexanone							0.64
m,p-Xylene							1.20
o-Xylene							0.66
1,3,5-Trimethylbenzene							0.48
<b>Formaldehyde (TO-11)</b>				9.00	40.00	73.00	210.00
Results were corrected for instrument calibration volume of 0.550 L							
Compounds are not listed in elution order.							

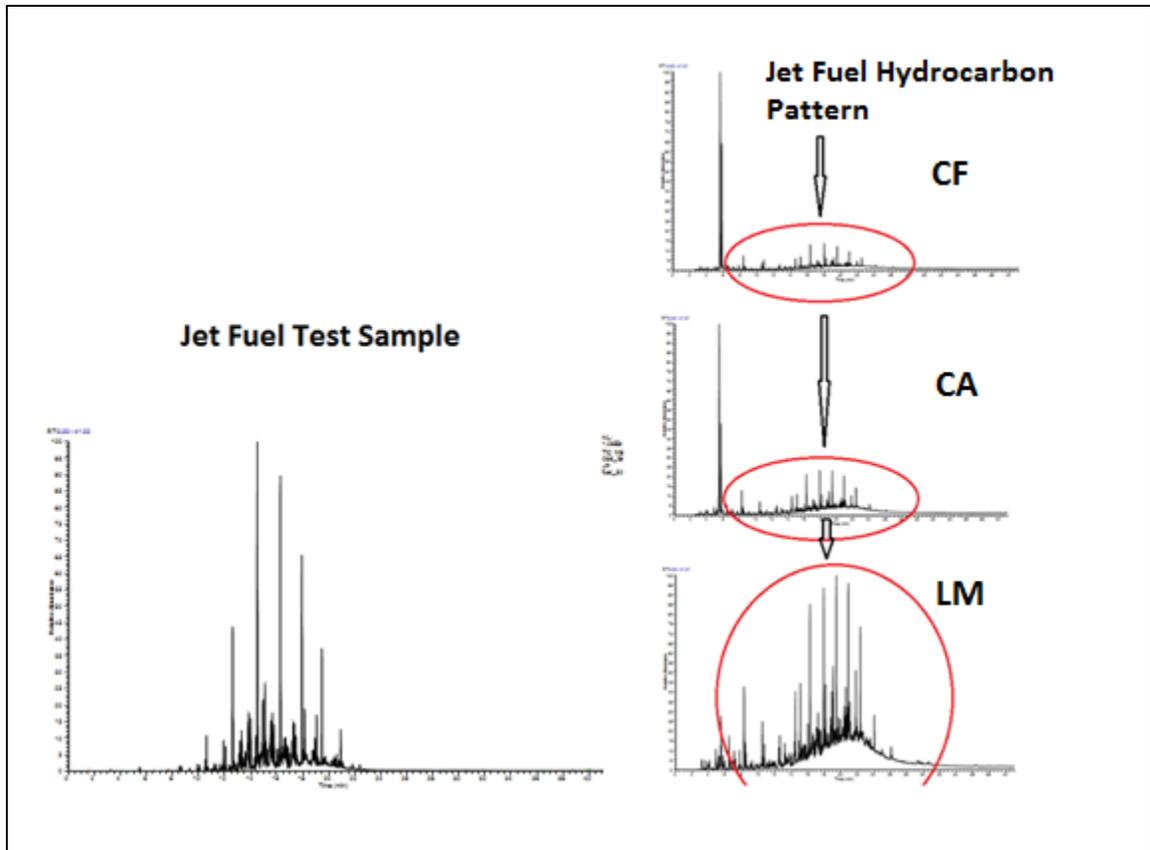
Table 5, “VOC Health Effects” shows the health hazards associated with the compounds detected by TO-11 and TO-17 analyses. The TO-17 results were in the ppb range and all below the respective OELs (52). However, formaldehyde result at the Loadmaster location as previously stated was above the NIOSH REL 15-minute STEL of 0.1 ppm.

**Table 6: VOC Health Effects**

Compound	Health Effects	Compound	Health Effects
Benzene (HAP)(ATSDR)	<b>Irritation</b> eyes, skin, nose, respiratory system; dizziness; headache, nausea, staggered gait; anorexia, lassitude (weakness, exhaustion); dermatitis; bone marrow depression; [potential occupational <b>carcinogen</b> ]	Acetone	<b>Irritation</b> eyes, nose, throat; headache, dizziness, central nervous system depression; dermatitis
1,4-Dioxane (HAP)(ATSDR)	<b>Irritation</b> eyes, skin, nose, throat; drowsiness, headache; nausea, vomiting; liver damage; kidney failure; [potential occupational <b>carcinogen</b> ]	Cyclohexane	<b>Irritation</b> eyes, skin, respiratory system drowsiness; dermatitis; narcosis, coma
Toluene (HAP)(ATSDR)	<b>Irritation</b> eyes, nose; lassitude (weakness, exhaustion), confusion, euphoria, dizziness, headache; dilated pupils, lacrimation (discharge of tears); anxiety, muscle fatigue, insomnia; paresthesia; dermatitis; liver, kidney damage	1,1-Dichloroethene (ATSDR)	Damage to central nervous system, liver, kidney, and lungs
Styrene (HAP)	Nervous system effects	4-Ethyltoluene	No exposure data found
Naphthalene (HAP)(ATSDR)	<b>Irritation</b> eyes; headache, confusion, excitement, malaise (vague feeling of discomfort); nausea, vomiting, abdominal pain; irritation bladder; profuse sweating; jaundice; hematuria (blood in the urine), renal shutdown; dermatitis, optical neuritis, corneal damage	2-Hexanone	<b>Irritation</b> eyes, nose; peripheral neuropathy: lassitude (weakness, exhaustion), paresthesia; dermatitis; headache, drowsiness
m,o, p-Xylene (HAP)(ATSDR)	<b>Irritation</b> eyes, skin, nose, throat; dizziness, excitement, drowsiness, incoordination, staggering gait; corneal vacuolization; anorexia, nausea, vomiting, abdominal pain; dermatitis	MEK (2-Butanone) (ATSDR)	<b>Irritation</b> of the nose, throat, skin, and eyes
Formaldehyde (HAP)(ATSDR)	<b>Irritation</b> eyes, nose, throat, respiratory system; lacrimation (discharge of tears); cough; wheezing; [potential occupational <b>carcinogen</b> ]	1,3,5-Trimethylbenzene	<b>Irritation</b> eyes, skin, nose, throat, respiratory system; bronchitis; hypochromic anemia; headache, drowsiness, lassitude (weakness, exhaustion), dizziness, nausea, incoordination; vomiting, confusion; chemical pneumonitis (aspiration liquid)
HAP = Hazardous Air Pollutant			
ATSDR = Agency for Toxic Substances and Disease Registry			

The Loadmaster sample also contained unburned jet fuel visible as a distinct hydrocarbon pattern in the chromatography, which is consistent with literature findings of unburned jet fuel in engine start-up and ground idle emissions in cold weather. A comparison sample was prepared and analyzed to for qualitative confirmation. Thermal desorption tubes were prepared with a pure bulk sample of JP-8 jet fuel and analyzed to compare the jet fuel observed in the Loadmaster and Cabin chromatograms with a known sample. A small amount of the JP-8 bulk sample was spiked into a Tedlar bag filled with ultra-high purity nitrogen and allowed to stabilize for a five minutes. Then thermal desorption (TD) tubes were sampled from the bag using a gastight syringe and then

injecting the JP-8 enriched gas into the TD tubes. Nitrogen carrier gas was plumbed through the TD tubes to establish a carrier gas while the tubes were spiked. Qualitative comparison of the aircraft cabin and Loadmaster samples with the jet fuel test sample GC-MS chromatography is shown in Figure 41, “Unburned Jet Fuel in Cabin, Loadmaster Locations”.



**Figure 41: Unburned Jet Fuel in Cabin, Loadmaster Locations**

As compared to the compounds detected in the jet fuel test sample, some of the TO-17 compounds detected in the aircraft samples appear to be contributions from unburned fuel while others appear to have formed in the combustion and post-combustion environment as postulated from the literature. Compounds detected in both aircraft and

jet fuel test sample are indicative of unburned jet fuel in the emissions. Those compounds are cyclohexane, toluene, 4-ethyltoluene, naphthalene, ethylbenzene, o-xylene, and 1,3,5-trimethylbenzene, and alkane hydrocarbons nonane, decane, undecane, dodecane, and tetradecane. Compounds detected in only the aircraft samples and postulated as combustion by-products are acetone, 1,1-dichloroethene, methyl ethyl ketone, benzene, styrene, 1,4-dioxane, 2-hexanone, and benzaldehyde. The alkane hydrocarbons nonane, decane, undecane, dodecane, and tetradecane and benzaldehyde peaks were identified by GC-MS library search, and are tentatively qualitative detections because they were not part of the TO-17 calibration mix. Benzaldehyde may be a false positive as it can form from oxidation of the Tenax<sup>®</sup> polymer in ozone rich environments such as jet fuel combustion exhaust (49) (70). Table 6, “Qualitative Comparison of Aircraft and Jet Fuel Test Sample Results” summarizes the comparison.

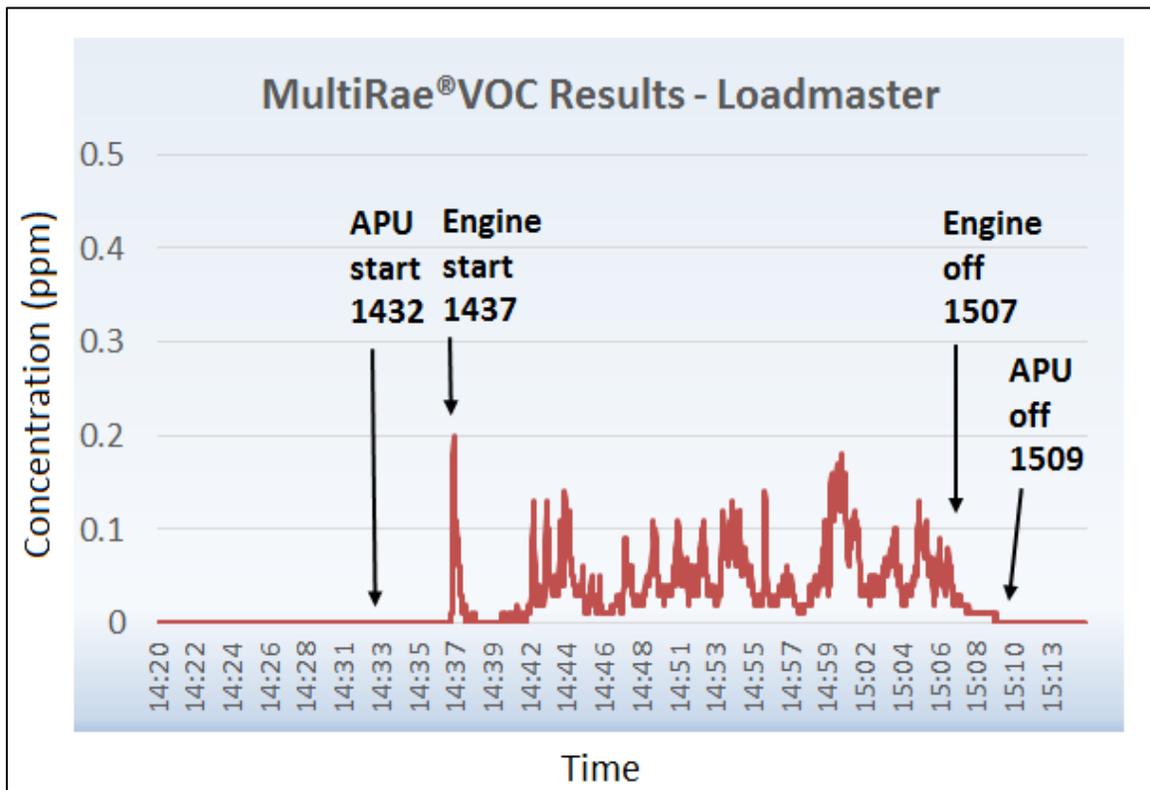
**Table 7: Qualitative Comparison of Aircraft and Jet Fuel Test Sample Results**

<b>Qualitative TO-17 Results</b>	<b>Field blank</b>	<b>Trip Blank</b>	<b>Background</b>	<b>Cockpit</b>	<b>Cabin Forward</b>	<b>Cabin Aft</b>	<b>Loadmaster</b>	<b>Jet Fuel Test sample</b>
<b>Compound</b>	<b>X = Detected above RL (2.000 ppbv)</b>							
Acetone	X	X	X	X	X	X	X	
1,1-Dichloroethene				X				
MEK				X	X	X	X	
Benzene				X	X	X	X	
Toluene				X	X	X	X	X
Cyclohexane					X	X	X	X
4-Ethyltoluene					X	X	X	X
Styrene						X	X	
Naphthalene						X	X	X
1,4-Dioxane							X	
2-Hexanone							X	
m,p-Xylene							X	X
Ethylbenzene							X	X
o-Xylene							X	X
1,3,5-Trimethylbenzene							X	X
Methyl Isobutyl Ketone								X
Bromodichloromethane								X
n-Heptane								X
1,2,4-Trimethylbenzene								X
Table lists compounds detected prior to correction for instrument calibration volume.								
<b>GC-MS Library Search Detects</b>	<b>X = Detected</b>							
Benzaldehyde							X	
Nonane								X
Decane					X	X	X	X
Undecane					X	X	X	X
Dodecane					X	X	X	X
Tetradecane					X	X	X	X

**VOC by MultiRae® Pro Multi-gas Meter**

VOC were detected in all locations. However IPA carryover from the CPCs occurred. The highest VOC were in the Cockpit, which is expected because of the 2 CPCs sampled there and the small area inside the Cockpit. At the Loadmaster location, VOC were not detected until engine start, were fairly continuous throughout the engine run, as with formaldehyde and CO, and dropped off at engine shut down. IPA carryover from the Loadmaster CPC does not appear to have occurred since VOC were not detected

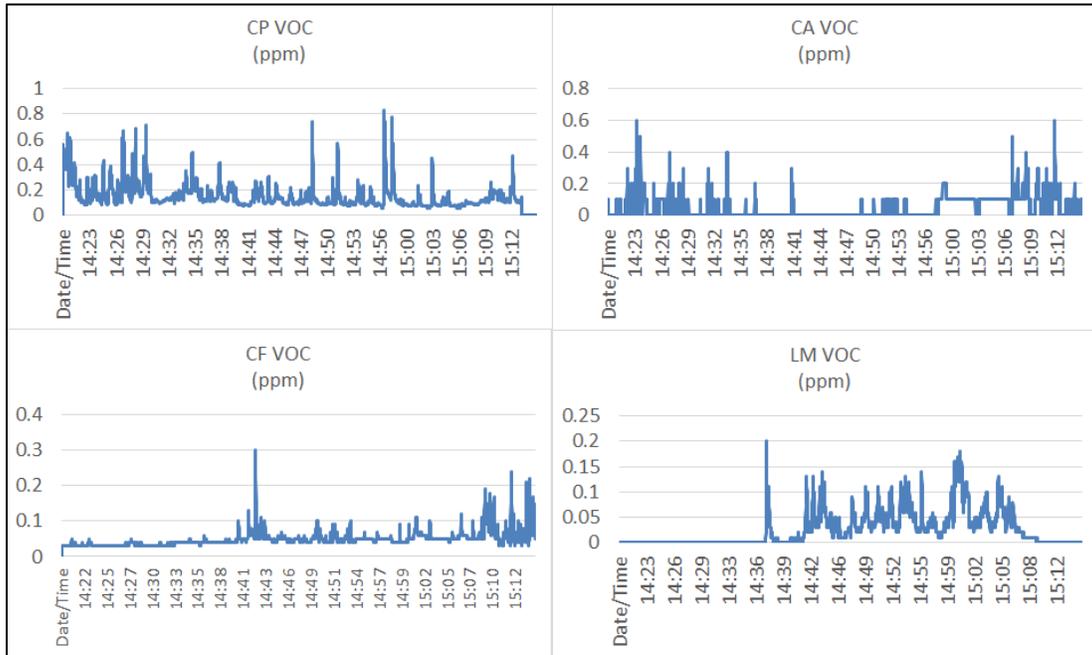
during background sampling prior to engine start. The hot turbulent propeller wash likely dissipated the IPA vapors. The maximum VOC reading at the Loadmaster location was 0.2 ppm, which occurred at engine start. This maximum result is in agreement with the TO-11 formaldehyde result (0.21 ppm) at the Loadmaster location. VOC results at the Loadmaster location are displayed in Figure 42, “MultiRae® VOC Results – Loadmaster (November 9, 2016)”.



**Figure 42: MultiRae® VOC Results – Loadmaster (November 9, 2016)**

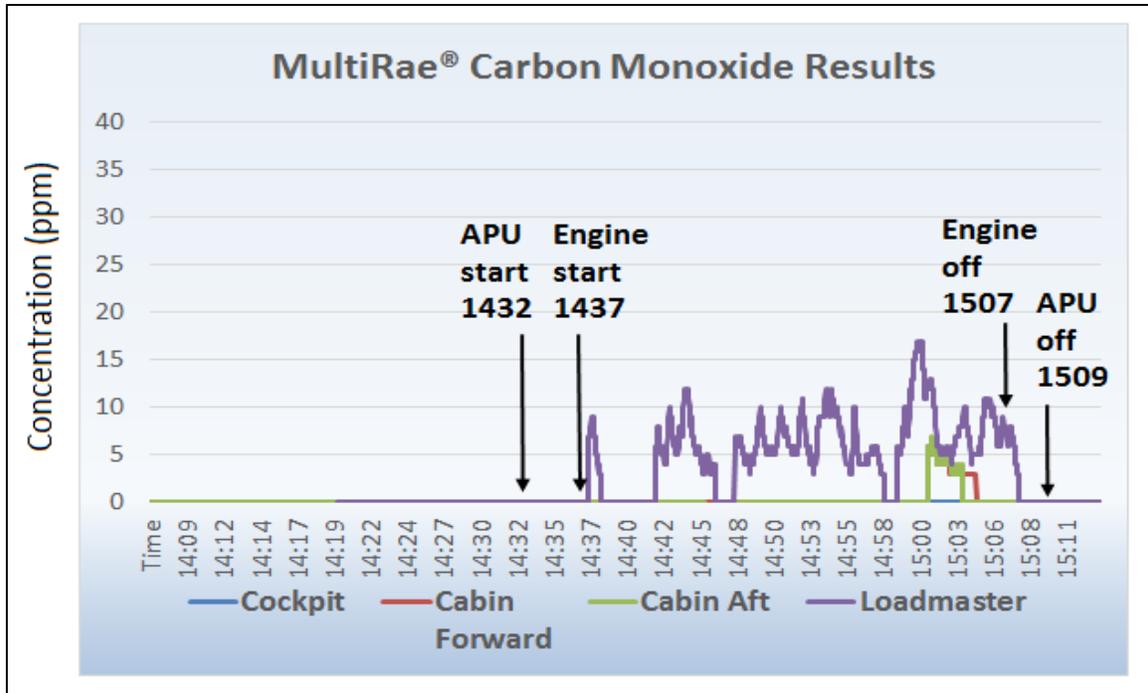
VOC results at all locations sampled are shown in Figure 42, “MultiRae® VOC Results Summary (November 9, 2016)”. A sensor issue may have occurred with the Cabin Aft VOC test. During the sampling, VOC readings did not appear on the display screen. However, as observed in Figure 43, “MultiRae® VOC Results Summary

(November 9, 2016)”, the Cabin Aft monitor recorded readings that appear irregular as compared to the other sampling locations, and are suspected as erroneous.



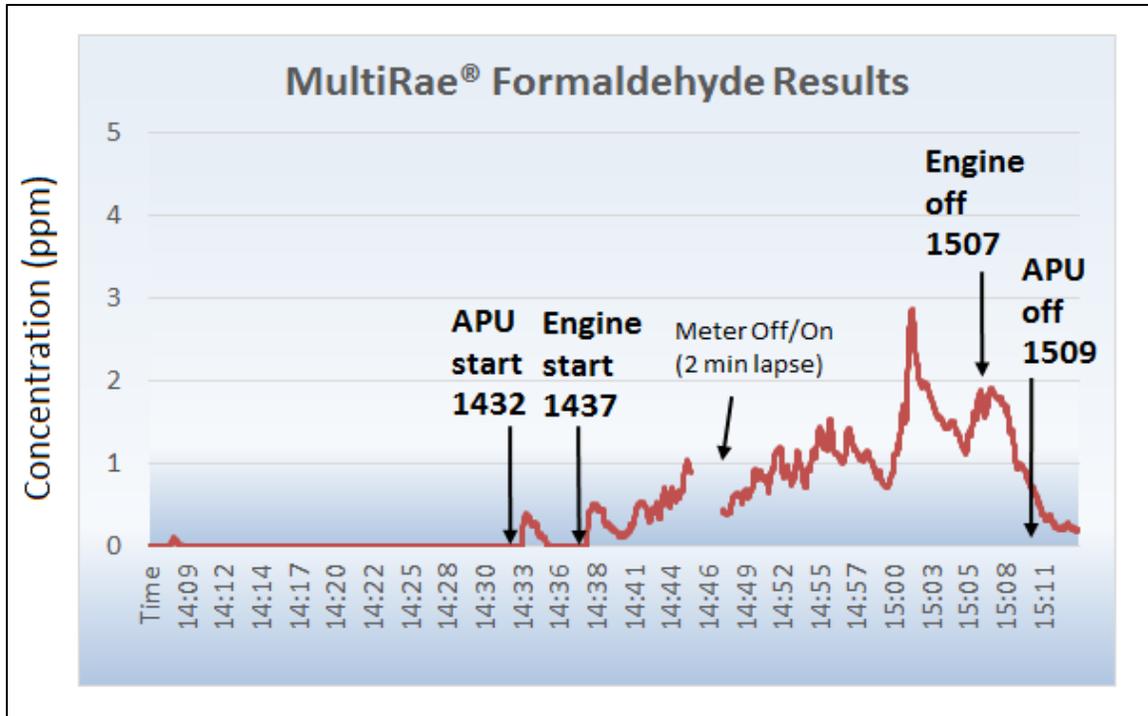
**Figure 43: MultiRae® VOC Results Summary (November 9, 2016)**

CO was detected in the ppm range at the Cabin and Loadmaster locations. Results show CO detection was fairly continuous throughout the engine run at the Loadmaster location despite the turbulent propeller wash, while readings were not observed in the Cabin until ~20 minutes into the run, indicating migration into the cabin. Loadmaster CO concentrations reached a maximum of 17 ppm, while maximum cabin readings were 7 ppm at Cabin Aft location and 6 ppm at Cabin Forward locations. CO was not detected in the Cockpit. The CO results are displayed in Figure 44, “MultiRae® CO Results (November 9, 2016)”.



**Figure 44: MultiRae® CO Results (November 9, 2016)**

Formaldehyde was detected by MultiRae® (Cabin Aft location) at APU start, then throughout the engine run except for a 2 minute lapse due to the meter being turned off then on again. The results are shown in Figure 45, “MultiRae® Formaldehyde Results (November 9, 2016)”. Concentrations steadily increased up to a maximum of 2.86 ppm, then dropped off after engine shutdown.



**Figure 45: MultiRae® Formaldehyde Results (November 9, 2016)**

The MultiRae® formaldehyde results are not in agreement with the TO-11 results, most likely due to cross-sensitivities. Cross-sensitivities are a limitation with MultiRae® in exhaust applications due to the complex mixture. Negative and positive cross sensitivities can occur that underestimate or overestimate the concentrations (78). Sulfur dioxide and nitrogen oxides cause slight positive cross sensitivity with the CO sensor, while CO cause significant positive cross-sensitivity with the formaldehyde sensor (78) (79). Cross-sensitivity most likely explains the disparity between the TO-11 and MultiRae® formaldehyde results. Installing chemical interference scrubbers onto direct reading monitors and using 2,4-DNPH treated silica gel media with potassium iodide ozone scrubbers (employed in this study) for active sampling will prevent cross-sensitivities (80).

## **Weather by TSI® Velocicalc Meter**

Weather conditions on June 1, 2016 were mild with a temperature of 86° F, relative humidity of 36%, barometric pressure of 28.6 inHg, and calm winds. The temperature reached at the Loadmaster location during the engine run was 107°F. Weather conditions on November 9, 2016 were windy and colder with temperature of 45° F, winds at 9 mph with gusts to 17 mph, and 76% relative humidity.

## **V. Conclusions**

All tests with detects reveal a trend of increasing emissions and concentrations from Cockpit to Cabin to Loadmaster locations, which confirms migration of emissions into the cabin. Overall the Loadmaster location contained the highest amounts of all hazards detected. Patient exposure to the emission are also of concern, especially the Critical Care Air Transport (CCAT) patients whom are typically loaded in the aft most litter and stanchion next to the cargo ramp, and whose health is already compromised.

Based on the results of this study the primary contaminants of interest with JFCE exposure during AE ERO, especially at the Loadmaster location, are ultrafine soot particles, formaldehyde, and unburned jet fuel. Although VOC results were below regulatory OELs, those detected are irritants and have health effects associated with chronic exposure. Additive or synergistic effects of the overall mixture of emissions are likely occurring and potentially influencing irritation.

The particle testing in this campaign provided valuable information on soot particles in JFCE. Although there were problems with the CPC testing, the CPC data still provided relevant real-time qualitative information on particle count and migration. The results from June 1, 2016 were visually indicated at or above the CPC maximum count of

$10^5$  particles/cc. Results from November 9, 2016 actual concentrations were at least some degree higher than the diluted results. With appropriate dilution techniques or models with higher maximum count capacity, CPC proved as valuable tools for assessing JFCE particle concentrations and migration behavior.

The EM results from the TPS and PC filter samples provided valuable information on the morphology, composition, size, and concentration of soot particles in C-130H JFCE at engine ground idle. All particle sizes were in nanometers. Soot concentrations found were  $1.6E+06$  particles/cc in the Cockpit on June 1, 2016 and  $3.4E+06$  particles/cc at the Loadmaster location on November 9, 2016. The thermophoretic nanoparticle samplers were portable, lightweight, and provided impressive particle separation, sizing, concentration, and morphology information that agree with current understanding of soot evolution.

As seen in the EM images JFCE particle composition is dominated by soot of highly irregular shapes, varied equivalent particle diameters, most less than 100 nm. The highest soot concentration was at the Loadmaster location. Soot morphology showed much irregularity, which may have important implications on bioactivity.

The large standard deviation in TPS particle sizes indicates soot particle coagulation/agglomeration in aging exhaust as discussed previously. The smaller particle size distribution in the cockpit may be attributed to the source of air entering the cockpit. Aircraft environmental systems draw engine bleed air from the engine compressor stages, pre-cool and condition the bleed air prior to distribution into the cockpit (and cabin), which may explain the formation of the sulfur containing SOA, 1,1-dichloroethene, and much larger concentration of acetone in the cockpit. At altitude intake air is clean.

However, parked on the ground with the engines running, and nearby aircraft and ground support activity, combustion emissions are likely re-entrained into the engine intake.

The PC filter results could not be compared to those of the TPS. Particle loading on the PC filters was too heavy for effective particle separation because of the high flow rate (4 L/min). However, a significantly lowered flow rate will improve particle separation in high particle environments such as JFCE. This testing application could still provide valuable information in future research efforts.

TPS and PC filter elemental analyses confirmed the dominance of soot in JFCE particles and revealed small amounts of sulfur species in the cockpit (as SOA in the TPS sample) and cabin samples. Trace amounts of aluminum, sodium, and silicon were found in the cabin PC filters. NIOSH 7300 results were below reporting limits, which is in agreement with findings in the literature. Trace amounts of sulfur and oxygen found in the particles support literature discussions of soot hydroscopic quality and propensity to form layers.

Small amounts of sulfur were detected with the TPS, while the NIOSH 7908 results for sulfuric acid were below reporting limits. However, sulfuric acid may be detected in high humidity conditions due to increased likelihood of its formation in ambient air with high water vapor content.

### **Limitations and Considerations**

Assessing occupational exposures to JFCE is challenging. Planned sampling campaigns can be suddenly canceled due to inclement weather or unexpected

unavailability of aircraft. Back-up dates should be included in aircraft scheduling discussions.

Not only are JFCE multi-component mixtures, but the component mixture and concentrations vary as the exhaust ages, in different climates, and with different engine types and airframes. Engine oil, lubricant leaks, aircraft auxiliary power units (APU) and ground support equipment emissions also contribute to the exposure. JFCE from multiple flight line activities occurring at the same time, such as nearby aircraft taxiing and taking-off, are common on busy flight lines and increase emission concentrations. Sampling and mitigation considerations are especially challenging in cold and extreme cold climates due to the high content of unburned fuel aerosol and trouble with sampling equipment (4). Establishing monitoring programs unique to process, location, and airframe will be more effective than a universal approach.

The overall emissions concentrations in this study are considered conservative since only one aircraft was operating at the time of the study, and this project only characterized exhaust emissions on one airframe (C-130H) during one process. On busy flight lines multiple aircraft and ground support equipment often operate simultaneously, increasing emissions concentrations.

Data sets and test selections in this campaign are limited due to the sampling issues experienced and limited resources. Not all contaminants found in prior research were sampled in this campaign. A more rigorous approach that includes a comprehensive testing suite with replicate parallel measurements on multiple days, in different weather conditions, and per airframe will yield statistical confidence in exposure decision making.

In this occupational setting, assessing exposures to particles are challenging because no regulatory limits are established for combustion emission particles. Gravimetric methods are not suitable due to negligible mass and volatile hydrocarbon layers associated with soot nanoparticles. Applying a count based approach to regulatory limits, similar to that used for asbestos OELs, may be more appropriate for combustion particles than mass based approaches ( $\text{mg}/\text{m}^3$ ).

### **Summary**

Many of the individual contaminants found in the engine start-up and idle JFCE from this research have known health effects and regulatory limits. However, no occupational exposure limits for combustion particles exist. Health effects from occupational exposure to JFCE are unknown and should be investigated since JFCE are a complex mixture of gases, vapors, and ultrafine particles of which additive or synergistic effects are likely.

## Appendix A: Equipment List, November 9, 2016

Location	Equipment	Manuf	Model #	S/N	OET ECN	Vendor Cal date	Start Time	Stop Time
<b>Cockpit</b>	VelociCalc®	TSI, Inc.	9565-P	9565P1625001		Jun-16	1307	1324
	Thermoanemometer probe	TSI, Inc.	964	P16250019		Jul-16		
	Hand-held Condensation Particle	TSI, Inc.	3007	3007-04160001	RHXBC	Apr-16	1322	1524
	Hand-held Condensation Particle	TSI, Inc.	3007	3007-07080002	100657	Dec-09	1322	1523
	MultiRae Pro	Rae Systems					1313	1521
	Thermophoretic sampler	RJ Lee Group	TPS100					
	air sampling pump 1	Sensidyne, LP	Gilian GilAir® Plus				1417	1521
	air sampling pump 2	Sensidyne, LP	Gilian GilAir® Plus				1417	1521
	air sampling pump tubing							
	TD tube							
SG tube				6441000360/lot10302				
<b>Cabin Background</b>	VelociCalc®	TSI, Inc.	9565-P	9565P1625001		Jun-16	1325	1529
	Thermophoretic sampler	RJ Lee Group	TPS100					
	air sampling pump 1	Sensidyne, LP	Gilian GilAir® Plus				1328	1421
	air sampling pump 2	Sensidyne, LP	Gilian GilAir® Plus				1328	1421
	air sampling pump tubing							
	TD tube							
	SG tube				6441000355/lot10302			
<b>Cabin Fore</b>	Thermoanemometer probe	TSI, Inc.	964	P16250019		Jul-16		
	Hand-held Condensation Particle	TSI, Inc.	3007	3007-02120016	RHDJ	Apr-15	1321:55:00	1517
	MultiRae Pro	Rae Systems					1314	1532
	Thermophoretic sampler	RJ Lee Group	TPS100					
	air sampling pump 1	Sensidyne, LP	Gilian GilAir® Plus				1420	1517
	air sampling pump 2	Sensidyne, LP	Gilian GilAir® Plus				1420	1517
	air sampling pump tubing							
	TD tube							
	SG tube				6441000353/lot10302			
<b>Cabin Aft</b>	Thermoanemometer probe	TSI, Inc.	964	P16250019		Jul-16		
	Hand-held Condensation Particle	TSI, Inc.	3007	3007-07080003	100656	Nov-09	1321	1530
	MultiRae Pro	Rae Systems					1321	1532
	Thermophoretic sampler	RJ Lee Group	TPS100					
	air sampling pump 1	Sensidyne, LP	Gilian GilAir® Plus				1422	1509
	air sampling pump 2	Sensidyne, LP	Gilian GilAir® Plus				1422	1509
	air sampling pump tubing							
	TD tube							
	SG tube				6441000351/lot10302			
<b>Loadmaster</b>	VelociCalc®	TSI, Inc.	9565-P	9565P1625001		Jun-16	1317	1515
	Thermoanemometer probe	TSI, Inc.	964	P16250019		Jul-16		
	Hand-held Condensation Particle	TSI, Inc.	3007	3007-12090003	101382	Aug-16	1321	1515
	MultiRae Pro	Rae Systems					1419	1516
	Thermophoretic sampler	RJ Lee Group	TPS100					
	air sampling pump 1	Sensidyne, LP	Gilian GilAir® Plus				1425	1312
	air sampling pump 2	Sensidyne, LP	Gilian GilAir® Plus				1425	1312
	air sampling pump tubing							
	TD tube							
SG tube				6441000356/lot10302				
<b>Blanks</b>	SG tube field blank							
	SG tube trip blank							
	SG tube lab blank							

**Appendix B: Sampling Information, Methods N0600/N7300/7908.TO-17/TO-11 and  
SEM PC Filters**

Test	Start Time	Stop Time	Sample Duration (min)	Volume (L)	Sample Date	Media	Flow rate (L/min)	Results (mg/m <sup>3</sup> )
CP N7908	1338	1410	32	159.94	June 1, 2016	Quartz fiber filter	4.998	<RL
CF N7908	1342	1412	30	150.81	June 1, 2016	Quartz fiber filter	5.027	<RL
B N7908	1229	1314	45	224.91	June 1, 2016	Quartz fiber filter	4.998	<RL
CA N7908	1342	1415	33	165.89	June 1, 2016	Quartz fiber filter	5.027	<RL
LM N7908	1349	1420	31	153.95	June 1, 2016	Quartz fiber filter	4.966	<RL
FB N7908	*	*	0	0.00	June 1, 2016	Quartz fiber filter	N/A	<RL
CP N7300/N0600	1338	1410	32	78.66	June 1, 2016	PVC filter	2.458	<RL
CF N7300/N0600	1342	1412	30	73.83	June 1, 2016	PVC filter	2.461	<RL
B N7300/N0600	1231	1314	43	106.43	June 1, 2016	PVC filter	2.475	<RL
CA N7300/N0600	1342	1415	30	72.66	June 1, 2016	PVC filter	2.422	<RL
LM N7300/N0600	1349	1420	31	76.35	June 1, 2016	PVC filter	2.463	<RL
FB N7300/N0600	*	*	0	0.00	June 1, 2016	PVC filter	N/A	<RL
CP-SEM	1338	1410	32	128.90	June 1, 2016	Polycarbonate filter, conductive cartridge	4.028	See SEM results
CF-SEM	1342	1412	30	119.79	June 1, 2016	Polycarbonate filter, conductive cartridge	3.993	See SEM results
B-SEM***	1230	1314	44	175.87	June 1, 2016	Polycarbonate filter, conductive cartridge	3.997	See SEM results
CA-SEM	1342	1415	33	131.93	June 1, 2016	Polycarbonate filter, conductive cartridge	3.998	See SEM results
LM-SEM	1349	1420	31	124.50	June 1, 2016	Polycarbonate filter, conductive cartridge	4.016	See SEM results
FB-SEM	*	*	0	0.00	June 1, 2016	Polycarbonate filter, conductive cartridge	N/A	See SEM results
CP TO-11	1417	1521	64	32.00	Nov. 9, 2016	2,4-DNP treated silica gel	0.5	0.01
CF TO-11	1420	1517	57	28.50	Nov. 9, 2016	2,4-DNP treated silica gel	0.5	0.049
B TO-11	1328	1401	33	16.50	Nov. 9, 2016	2,4-DNP treated silica gel	0.5	<RL
CA TO-11	1422	1509	47	23.50	Nov. 9, 2016	2,4-DNP treated silica gel	0.5	0.089
LM TO-11	1425	1512	47	23.50	Nov. 9, 2016	2,4-DNP treated silica gel	0.5	0.26
FB TO-11	*	*	0	0.00	Nov. 9, 2016	2,4-DNP treated silica gel	N/A	ND
CP TO-17	1417	1521	64	3.20	Nov. 9, 2016	Thermal desorption tubes	0.05	See TO-17 Results Table
CF TO-17	1420	1517	57	2.85	Nov. 9, 2016	Thermal desorption tubes	0.05	See TO-17 Results Table
B TO-17	1328	1401	33	1.65	Nov. 9, 2016	Thermal desorption tubes	0.05	See TO-17 Results Table
CA TO-17	1422	1509	47	2.35	Nov. 9, 2016	Thermal desorption tubes	0.05	See TO-17 Results Table
LM TO-17	1425	1312	47	2.35	Nov. 9, 2016	Thermal desorption tubes	0.05	See TO-17 Results Table
FB TO-17	*	*	0	0.00	Nov. 9, 2016	Thermal desorption tubes	0.05	See TO-17 Results Table
* Field Blank samples were collected prior to Background sampling								
** Pre- and post- pump calibrations were conducted using a Bios Defender™ calibrator by averaging 10 measurements.								
***B-SEM volume was incorrectly entered on the laboratory analytical request form as 171 L.								

## Appendix C: TO-17 Results Summary

TO-17 Results (ppbv)	Field blank	Trip Blank	Background	Cockpit	Cabin Forward	Cabin Aft	Loadmaster	
Volume (L)	N/A	N/A	1.65	3.20	2.85	2.35	2.35	
Corrected Volume (L)	N/A	N/A	3.00	5.82	5.18	4.27	4.27	
<b>Compound</b>	<b>Uncorrected Instrument Results</b>							
Acetone	7.96	9.04	22.89	843.47	56.15	55.87	44.07	
1,1-Dichloroethene (Only in ther Cockpit)	→			110.15				
IPA (Carryover from CPCs)	→			284.16	1142.04	1399.10	688.95	95.13
MEK				10.71	5.59	7.43	15.82	
Benzene				5.82	13.96	18.01	42.56	
Cyclohexane					3.23	4.46	9.57	
Methylene Chloride (Lab Carryover)	→ 19.16	23.77	17.88	14.97	16.63	14.24	14.88	
n-Hexane	2.54	4.48						
Toluene				2.26	4.68	6.43	16.58	
4-Ethyltoluene					4.22	5.07	14.67	
Styrene						2.21	6.17	
Naphthalene						2.17	6.73	
1,4-Dioxane							2.62	
2-Hexanone							2.72	
m,p-Xylene							5.13	
Ethylbenzene							3.34	
o-Xylene							2.82	
1,3,5-Trimethylbenzene							2.03	
<b>Compound</b>	<b>Results Corrected for Calibration Volume</b>							
Acetone	7.96	9.04	7.63	144.97	10.84	13.08	10.31	
1,1-Dichloroethene (Only in ther Cockpit)	→			18.93				
IPA (Carryover from CPCs)	→			94.72	196.29	270.00	161.24	22.26
MEK				1.84	1.08	1.74	3.70	
Benzene				1.00	2.69	4.22	9.96	
Cyclohexane					0.62	1.04	2.24	
Methylene Chloride (Lab Carryover)	→ 19.16	23.77	5.96	2.57	3.21	3.33	3.48	
n-Hexane	2.54	4.48						
Toluene				0.39	0.90	1.51	3.88	
4-Ethyltoluene					0.82	1.19	3.43	
Styrene						0.52	1.44	
Naphthalene						0.51	1.58	
1,4-Dioxane							0.61	
2-Hexanone							0.64	
m,p-Xylene							1.20	
Ethylbenzene							0.66	
o-Xylene							0.66	
1,3,5-Trimethylbenzene							0.48	

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<b>14. ABSTRACT</b> The purpose of this research was to characterize jet fuel combustion emissions (JFCE) in an occupational setting. Prior research demonstrated that aircraft emit hazardous species, especially at engine start-up and ground idle. Complaints of eye, nose, and throat irritation from occupational exposures near aircraft exist. In this study JFCE were tested during an aeromedical evacuation engines running patient onload (ERO) on a C-130 Hercules at the 179 <sup>th</sup> Airlift Wing, Mansfield-Lahm Air National Guard. Ultrafine particles, VOC, formaldehyde, carbon monoxide (CO), sulfuric acid, and metals were sampled simultaneously in approximate crew and patient breathing zones. Testing methods were portable condensation particle counters (CPC), polycarbonate filters (PC) and thermophoretic samplers (TPS) for electron microscopy, MultiRae <sup>®</sup> gas monitors, EPA methods TO-17 and TO-11, and NIOSH methods N0600, N7908, N7300. Ultrafine particulate matter, VOC including EPA HAPs, formaldehyde, CO, and unburned jet fuel were detected. Particles were dominated by soot that was predominantly carbonaceous with trace oxygen, sulfur and few metals in concentrations up to 3.4E+06 particles/cc. Particle size distributions were varied with most sizes less than 100 nanometers (nm). Particle morphology was highly irregular. VOC were detected in ppb, and formaldehyde in ppm. Additive or synergistic effects are suspected and may intensify irritation. Health implications from inhaling nano-sized soot particles are inconclusive.					
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## Personal Exposure to JP-8 Jet Fuel Vapors and Exhaust at Air Force Bases

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JP-8 jet fuel (similar to commercial/international jet A-1 fuel) is the standard military fuel for all types of vehicles, including the U.S. Air Force aircraft inventory. As such, JP-8 presents the most common chemical exposure in the Air Force, particularly for flight and ground crew personnel during preflight operations and for maintenance personnel performing routine tasks. Personal exposure at an Air Force base occurs through occupational exposure for personnel involved with fuel and aircraft handling and/or through incidental exposure, primarily through inhalation of ambient fuel vapors. Because JP-8 is less volatile than its predecessor fuel (JP-4), contact with liquid fuel on skin and clothing may result in prolonged exposure. The slowly evaporating JP-8 fuel tends to linger on exposed personnel during their interaction with their previously unexposed colleagues. To begin to assess the relative exposures, we made ambient air measurements and used recently developed methods for collecting exhaled breath in special containers. We then analyzed for certain volatile marker compounds for JP-8, as well as for some aromatic hydrocarbons (especially benzene) that are related to long-term health risks. Ambient samples were collected by using compact, battery-operated, personal whole-air samplers that have recently been developed as commercial products; breath samples were collected using our single-breath canister method that uses 1-L canisters fitted with valves and small disposable breathing tubes. We collected breath samples from various groups of Air Force personnel and found a demonstrable JP-8 exposure for all subjects, ranging from slight elevations as compared to a control cohort to  $> 100 \times$  the control values. This work suggests that further studies should be performed on specific issues to obtain pertinent exposure data. The data can be applied to assessments of health outcomes and to recommendations for changes in the use of personal protective equipment that optimize risk reduction without undue impact on a mission. *Key words:* breath sampling, gas chromatography/mass spectrometry, human exposure, JP-8 jet fuel. *Environ Health Perspect* 108:183–192 (2000). [Online 19 January 2000] <http://ehpnet1.niehs.nih.gov/docs/2000/108p183-192pleil/abstract.html>

JP-8 jet fuel, presently in use by the U.S. Air Force in its entire aircraft inventory, consists of a complex mixture of aliphatic and aromatic hydrocarbons. Although concentration varies from lot to lot, the liquid fuel contains a mean of 14.5% aromatic hydrocarbons, and the remainder consists of most of the possible structural isomers for aliphatic hydrocarbons in the C<sub>6</sub> to C<sub>18</sub> range; the C<sub>9</sub> to C<sub>14</sub> *n*-alkanes constitute approximately 28% of the bulk fuel (1,2). U.S. Air Force personnel encounter JP-8 in various forms on their bases. In addition to straightforward occupational exposure from fueling operations, aircraft maintenance, and aircraft operation, there are incidental exposures, primarily through the inhalation of vapors during social and work contact with exposed individuals who may have residual fuel on their clothing and skin. Additionally, most military vehicles and auxiliary ground equipment are fueled with JP-8. Therefore, encountering the odor of JP-8 (or its exhaust) on a U.S. Air Force base (AFB) is a common occurrence.

Occupational exposure to JP-8 has been studied by the military using industrial

hygiene sampling techniques to measure breathing zone ambient concentrations over whole working shifts at three AFBs. All exposures fell below current permissible exposure limits, and mean ambient levels were 1.33 parts per million by volume (ppmv) for naphthas (in this instance defined as all vapor phase hydrocarbons expected from JP-8) and 0.01 ppmv for benzene (3). This type of ambient air sampling is indicative only of the inhalation exposure route during work activities that directly involve JP-8. Potential occupational dermal and ingestion exposures and incidental exposures from nonwork contact were not studied. In a more recent series of measurements, U.S. Air Force investigators focused on aircraft fuel maintenance operations, found that certain activities could result in exposures of concern, and made a variety of recommendations concerning personal protective equipment (4).

To understand the ubiquitous nature of JP-8 exposure, we extended this type of work and collected samples of both ambient air and exhaled breath from various small groups of U.S. Air Force personnel in settings that included direct occupational exposure and in

settings that did not involve direct contact with aircraft and aircraft maintenance operations. Although microenvironmental monitoring of the ambient air in the workplace can give a good estimate of potential exposure, the additional collection of exhaled breath samples is a more direct measure because all exposure routes (dermal, inhalation, and ingestion) are represented and because each individual's activities, physiology, and physical characteristics are reflected in the samples. In addition, breath measurement incorporates exposures before work as well as during breaks for lunch and errands.

The volatile organic compounds (VOCs) in breath are directly related to their blood levels by liquid/gas partitioning through the lung's alveolar membranes, similar to the oxygen and carbon dioxide exchange. A classic example of the linkage between the blood and breath level of a volatile substance is the breathalyzer, which tests for ethanol inebriation (5). The study of blood and breath relationships of various VOCs from environmental exposure is extensive;

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some recent examples include a paper by Pleil et al. (6), which presents uptake and elimination kinetics of trichloroethene, and a paper by Buckley et al. (7), which discusses similar activity for methyl-*tert*-butyl ether. A breath sample is arguably a better estimator of individual exposure and associated body burden than an ambient air sample; additionally, the presence of exogenous compounds (such as JP-8 fingerprint organic compounds) in the breath is an unambiguous indication of exposure.

For this work, all breath samples were collected by using the single breath canister (SBC) methodology (8,9). Most microenvironmental samples were collected with whole-air time-integrated sampling using a battery-operated personal whole-air sampler (PWAS) (10). Occasional canister "grab" samples were collected in the subject's breathing zone to characterize potential inhalation exposure. Analyses of canister samples were performed via gas chromatography/mass spectrometry (GC/MS) using protocols derived from U.S. Environmental Protection Agency (EPA) method TO-14 (11).

In this paper we present data collected at various AFBs subject to the availability of volunteers, logistics, and opportunity. No efforts were made to choose specific subjects or to ensure a statistically balanced population; however, various career fields, a wide range of ages, and both sexes were represented. We concentrated on three types of JP-8 exposure scenarios: incidental, exhaust, and fuel vapor. Data are additionally grouped and analyzed by subject smoking status to separate this important confounding factor for certain volatile compound exposure (12). We also present control group breath data and ambient data for comparison.

## Materials and Methods

**Ambient air sampling.** For most of the ambient air samples of the subjects' breathing air, we used portable, battery-operated PWAS units that use mass flow control to collect a constant flow of air into an evacuated sampling container. PWAS prototypes (10) were originally developed by the EPA under a research contract with the Research Triangle Institute (Research Triangle Park, NC; contract 68-02-4544) and have since been redesigned as a commercially available package under a Cooperative Research and Development Agreement (CRADA file 0121-95) between the National Exposure Research Laboratory of the EPA (Research Triangle Park, NC) and Environmental Supply Corporation (Durham, NC). Sample-collection canisters are stainless steel, with an interior surface deactivation based either on the Summa electropolish technique as supplied by SIS, Inc. (Moscow, ID) and Biospherics,

Inc. (Hillsboro, OR), or by the SilcoSteel fused-silica vapor deposition method as supplied by the Restek Corporation (Bellefonte, PA). A variety of canister sizes was used based on availability; these included 1, 1.8, 3, and 6 L volumes. Samples were collected during the subject briefings, during exposure activities, and during subsequent breath sample collection activity.

**Breath sampling.** The SBC sampling apparatus consists of an evacuated 1-L canister from any of the above-mentioned suppliers. This canister is fitted with a small Teflon (E.I. DuPont de Nemours, Wilmington, DE) tube used as a mouthpiece. As the subject closes his or her lips on the tube and exhales, he or she opens the canister valve and the breath is collected in the evacuated volume. The subject is instructed to begin sample collection at the "bottom" (or end) of a normal resting tidal breath to achieve an alveolar sample; the tracheal dead volume is expelled well before the canister sample valve is opened. Pleil and Lindstrom (9,10) described this procedure in detail and investigated the alveolar nature of an SBC sample in contrast to other techniques.

**Analysis.** Although subsequent laboratory analysis can be performed with any of a variety of GC/MS methods for air, we used an enhanced version of standard EPA method TO-14 (11). Briefly, each ambient or breath sample was transported to the laboratory, where it was pressurized with a neutral gas (Scientific Grade Zero Air; National Specialty Gases, Durham, NC), and a dilution factor was calculated based on pre- and postpressurization absolute pressure. The carbon dioxide level of the breath samples was assayed to assure the level of the alveolar content. The analytical instrumentation was fully

automated to extract a 100-mL aliquot from the canister, to cryogenically concentrate the extract and thermally desorb/inject it onto a capillary column, and then to analyze the extract with a mass spectrometer. All analyses were performed with a Graseby-Nutech 3550A cryoconcentrator (Graseby-Nutech, Smyrna, GA) with a 16-canister autosampler interfaced to a Magnum ITS40 GC/MS ion trap instrument (Finnigan MAT, San Jose, CA). For most routine analyses, we used an XTI-5 analytical column (30-m length × 0.25-mm i.d., with 1.0 μm stationary phase) (Restek Corp., Bellefonte, PA). Although it was beyond the scope of this paper, for some analytical sets we used an experimental dual sequential column approach to help resolve endogenous compounds in breath (primarily oxygenated compounds) in addition to measuring the compounds of interest discussed here. Quantitation was achieved by using external standards; system linearity was confirmed over the sample range with multi-point calibration. Daily response factors and system integrity were determined via single-point calibration standards and canister blanks. Replicate analyses of real samples were performed to continually assess system precision. Concentrations of analytes were aggressively calculated from extracted multi-ion chromatograms down to 3:1 signal-to-noise ratios [corresponding to approximately 0.01 parts per billion by volume (ppbv)]. Because of the complexity of the samples, occasional interferences or other GC-related upsets prevented unambiguous trace-level quantitation of an individual compound; these were treated as missing values. Calibration standards were independently prepared and assessed by our onsite contractor, ManTech Environmental Technology,

**Table 1.** Sampling scenarios.

Date	Situation	Aircraft	Location
March 1997	Cold-engine start procedures	KC-135	Eielson AFB, Fairbanks, AK
June 1997	Cold-engine performance tests	C-130J	Climatic chamber, Eglin AFB, Fort Walton Beach, FL
June 1997	Incidental human exposure	Not applicable	BEE, 16MXS, and 33MS shops, Eglin AFB, Fort Walton Beach, FL
July 1997	Fuel tank entry work	A-10 C-130H C-17, C-141 B-1 KC-135	Pope AFB, Fayetteville, NC Garden City ANGB, Savannah, GA Charleston AFB, Charleston, SC Robins AFB, Warner-Robins, GA McGee-Tyson ANGB, Knoxville, TN
July 1997	Fuel tank entry work	A-10	Davis-Montham AFB, AZ; Nellis AFB, Las Vegas, NV; and McClellan AFB, CA
February 1998	Cold-engine start procedures	KC-135, F-16, A-10	Eielson AFB, Fairbanks, AK
February 1998	Incidental human exposure		BEE shop and clinic personnel, Eielson AFB, Fairbanks, AK
August 1998	Fuel system maintenance incidental human exposure	F-15, F-16	Edwards AFB, CA
September 1998	Aircraft maintenance and incidental human exposure	F-16	Kelly AFB, San Antonio, TX

Abbreviations: ANGB, Air National Guard base; BEE, bioenvironmental engineering.

Inc. (Research Triangle Park, NC), using certified standards from Alphagaz (Morrisville, PA) and Scott Specialty Gases (Plumsteadville, PA). CO<sub>2</sub> assays of breath samples were performed by using a CA-1 CO<sub>2</sub> analyzer (Sable System, Henderson, NV) calibrated with a clinical blood-gas mixture certified at 5.00% CO<sub>2</sub> in air (National Specialty Gases).

We included some example ambient air data sets from EPA studies in the Los Angeles (LA) basin (Asuza, CA) and in Research Triangle Park [(RTP); NC] to put the overall human exposure levels into perspective. These studies were conducted under contract by ManTech Environmental Technology, Inc. (13) for the EPA as part of other research efforts. We also present a data set from tank entry work where high ambient levels inside fuel tanks were documented with canister grab samples as analyzed by Performance Analytical, Inc. (Canoga Park, CA) using their version of the standard TO-14 method (14).

**Human subjects.** Subjects were volunteers with informed consent under standard Air Force and EPA protection of human subjects certification procedures. Detailed briefings were held to explain and demonstrate the self-administered breath sampling procedure. Before the day's sample collection, canisters and subjects were assigned simple code numbers; these were cross-referenced only at the laboratory to maintain subject confidentiality. Samples were collected before and after normal activities; subjects were not deliberately exposed to JP-8. All normal safety procedures, work times, and break protocols were followed. Protective equipment, such as respirators, special clothing, gloves, etc., was used as usual for the specific routine tasks.

**Experimental design.** The data collected for this study are a subset drawn from various investigations into the performance of aircraft and human exposure to JP-8 jet fuel. In most experiments, the primary focus was breath

and environmental sampling; however, we also included example data from incidental sampling during other Air Force studies involving heat stress, diagnostic instrumentation tests, and respirator tests. Specifically, we include samples from the situations listed in Table 1.

Figure 1 illustrates the typical engine run-up plume of a KC-135 aircraft during a cold weather (-10°C) start. Because JP-8 is a low volatility fuel, cold weather starts require longer preflight procedures and may create more unburnt fuel aerosol; we studied crew chiefs and other ground crew personnel to assess this issue. Fuel tank entry procedures require maintenance personnel to work in potentially high inhalation and dermal exposure situations. Figure 2 is an example of tank-entry personnel breath sampling; in this case a subject is emerging from the wing tank of a C-141 and has just removed his respirator for an immediate postexposure sample. Tank-entry personnel wear personal protective equipment including forced supply-air respirators, gloves, and cotton overalls. Figure 3 illustrates typical incidental exposure or preexposure breath sampling. In this case the subjects are providing breath samples while outside before a work shift. However, there are many parked A-10 and C-130 aircraft as well as a lot of ground support equipment in the background. All of these contribute to the incidental exposure at an AFB. Throughout these experiments, we also collected breath data from subjects that had not recently been at an AFB and ambient data from downtown LA and from RTP to use as comparisons.

Although each situation was slightly different, two types of breath sample sets were collected. The first set was the incidental sample set; a subject group was sampled during the workday in a common area or outdoors. These subjects were essentially in equilibrium with their environment and

represent a typical loading of analytes of interest. The second type was the before and after sample set; breath samples were collected both before and after the performance of some job function. The difference in analyte levels demonstrates incremental exposure attributable to that specific job. For all cases, we collected samples of ambient air to confirm the potential for inhalation exposure.

#### Data categorization and reduction.

Samples were quantified for a) a variety of common ambient pollutants as listed in method TO-14 (11), including single-ring aromatics (benzene, toluene, styrene, xylenes, etc.); b) some chlorinated compounds; and c) the series of *n*-alkanes from C<sub>6</sub> to C<sub>12</sub>; for some samples we also measured *n*-butane and *n*-pentane. Raw analyte concentrations were corrected according to the dilution factor calculated from sample pressurization and a measured CO<sub>2</sub> level normalized to a factor set arbitrarily to 5% for internal consistency. Although individual concentrations were available, for graphing purposes the C<sub>9</sub> to C<sub>12</sub> *n*-alkanes (nonane, decane, undecane, and dodecane) were summed to provide a simple indicator of JP-8 fuel exposure, and the C<sub>6</sub> and C<sub>7</sub> *n*-alkanes (hexane and heptane) were summed to present a non JP-8 comparison. The C<sub>8</sub> *n*-alkane (octane) values were not included in either set because these are variable in JP-8 and they occupy an overlap region among JP-8 and other fuels. The sum of the single-ring aromatic compounds (benzene, toluene, ethylbenzene, *m,p*-xylene, *o*-xylene, and styrene) was also treated as a group for comparisons. Benzene data were treated as a separate entity because of current interest and the potential for long-term adverse health impact.

Processed concentration data were placed in a variety of categories for interpretation based on activity, exposure scenario, job classification, etc. Simple mean and standard error values were calculated for the data



**Figure 1.** Typical exhaust plume from an engine run-up procedure for a KC-135 aircraft in a cold climate (-10°C). During aircraft warm up, the exhaust contains unburnt and partially burnt JP-8, exposing crew chiefs and other ground personnel to JP-8. During multiple-aircraft starts, a low-hanging exhaust cloud may form over the whole tarmac area.



**Figure 2.** Fuel tank entry worker exiting wing tank of a C-141 aircraft after routine maintenance procedures. Immediately after removing his forced air respirator, the subject provides a postexposure breath sample.

subsets to allow fair comparisons. These categories and the number of samples in each category are given in Table 2. For the breath samples, we counted samples, not subjects; on average, we collected approximately 3.4 samples per individual subject.

Relatively fewer ambient than breath samples were collected because one ambient sample usually characterized the breathing zone for multiple subjects. Also, the primary focus was on confirming human exposure via breath. For general comparison, we included all control data from EPA studies of ambient levels from the LA basin as an indicator of urban exposure, and from RTP as an indicator of suburban/rural exposure. In each case, we present hourly averages for one typical day.

The ambient JP-8-related data were segregated into four categories. The indoor airshops category included integrated samples taken in various common areas such as break rooms, office areas, etc., during the time that breath samples were also collected from subjects. These samples were used to assess preexposure or incidental exposure levels. The exhaust exposure category contained integrated samples taken during aircraft cold-start operations at temperatures ranging from -20 to +5°F. These samples were indicators of exposure to ground crew personnel. The tank exposure around aircraft category included grab and integrated samples collected in the vicinity of aircraft undergoing fuel tank maintenance. These samples were indicators of exposure of attendants and fireguards during fuel tank entry operations. The tank exposure inside tank category included grab samples collected inside fuel tanks while fuel tank entry personnel were working; these samples indicated the potential exposure if personnel were not using effective personal protective equipment. Venting flow levels varied in these tanks before and during sample collections.

The primary focus of this work is directly demonstrating human exposure by using breath samples. As listed in Table 2, the all controls category includes samples collected from various subjects who had not recently (or ever) been on an AFB or who had not traveled by commercial airline within the past week.

The JP-8 related category in Table 2 is subdivided in two ways. The first is a simple division of all subjects based strictly on their self-description as a smoker or nonsmoker, regardless of the amount of smoking, sex, age, job-related activity, or any other activity. This division is necessary to determine the contribution of benzene exposure from JP-8 with respect to benzene exposure from cigarettes. The second type of subclassification is based strictly on job type, regardless of sex, age, or smoking status.

We used three categories of job type samples. The all fuel workers samples were from subjects who had job-related fuel exposure through tank entry or related job activity. The all exhaust workers samples were from subjects involved with ground crew activity during cold-weather starts of various aircraft. The all incidental workers designate samples from subjects who did not have a direct aircraft-related mission; rather, they are members of Bioenvironmental Engineering shops or hospital/clinic staff. As indicated in Table 2, these three categories were further subdivided into various groups, including before and after job activity, specific job, or location. These details and their exposure implications are discussed in "Breath Measurements—Detailed Results."

**Statistical comparisons.** Concentration data for single or summed compounds within all categories and subdivisions of categories were combined as arithmetic means and SEMs. When appropriate, we used a two-tailed Student's *t*-test to calculate the confidence that the mean concentrations of various sample groups were significantly different. Raw data were organized, categorized, and quantified by using Lotus 1-2-3 rev. 4 software (Lotus Development Corp., Cambridge, MA); statistical analyses and graphs were produced with GraphPad Prism version 2 (GraphPad Software, Inc., San Diego, CA).

## Results and Discussion

Concentration data for individual compounds and subsets of combined compounds



**Figure 3.** Typical incidental exposure breath sampling outdoors before beginning a work shift. The subjects provide breath samples while at equilibrium with the ambient environment of their AFB; the ambient air is impacted by the general profusion of A-10 and C-130 aircraft and various ground support equipment visible in the background.

**Table 2.** Sample categories.

Major category	Subdivision				Sample subtotals (n)	Sample major totals (n)
	First	Second	Third	Fourth		
Breath	All controls	—	—	—	—	19
	All JP-8 related	—	—	—	—	162
	—	All smokers	—	—	41	—
	—	All nonsmokers	—	—	121	—
	—	All fuel workers	—	—	85	—
	—	—	Before working	—	40	—
	—	—	Immediately after	—	45	—
	—	—	—	Tank entry	15	—
	—	—	—	Attendants/ fireguard	30	—
	—	All exhaust workers	—	—	49	—
	—	—	Before working	—	18	—
	—	—	—	Outdoor start	12	—
	—	—	—	Indoor start	6	—
—	—	Immediately after	—	31	—	
—	—	—	Outdoor start	24	—	
—	—	—	Indoor start	7	—	
—	All incidental workers	—	—	28	—	
Ambient	All controls	—	—	—	—	44
	—	Los Angeles	—	—	22	—
	—	Research Triangle Park	—	—	22	—
	All JP-8 related	—	—	—	—	53
	—	Indoor air, shops	—	—	5	—
	—	Exhaust exposure	—	—	23	—
	—	Tank exposure around aircraft	—	—	9	—
—	Tank exposure inside tank	—	—	16	—	

were interpreted as means and their respective SEMs within various groups of samples. No attempt was made to elicit uptake or elimination kinetics because this would have required interference with normal operations and a detailed study of time-dependent exposure levels. Our discussion is based on simple comparisons of sample group means and their overall implications with respect to human exposure.

**Ambient measurements.** Inhalation is most likely the primary exposure route for this work. As such, the ambient air (breathing zone) measurements reflect the potential of the eventual dose. Table 3 contains the summary statistics (number, mean, and SEM) for all individual compounds for each group of ambient samples. In addition to the aromatic hydrocarbons and *n*-alkanes that

are expected from the fuel source, we also presented data from some commonly seen chlorinated compounds (chloroform, trichloroethene, tetrachloroethene, and *p*-dichlorobenzene) that are associated with nonfuel sources or activities. To demonstrate the relative issues of ambient levels, Figure 4 presents chromatograms of GC/MS analyses as a comparison of the airborne volatile fraction of JP-8 and a typical "in hangar" ambient sample collected during routine tank entry work and other maintenance procedures on F-15 and F-16 aircraft. The airborne fraction of JP-8 (Figure 4A) is dominated by the fingerprint compounds of the C<sub>9</sub> to C<sub>12</sub> *n*-alkanes. These compounds are represented in the overall ambient sample (Figure 4B). However, JP-8 is not the only source of inhalation exposure; maintenance activities

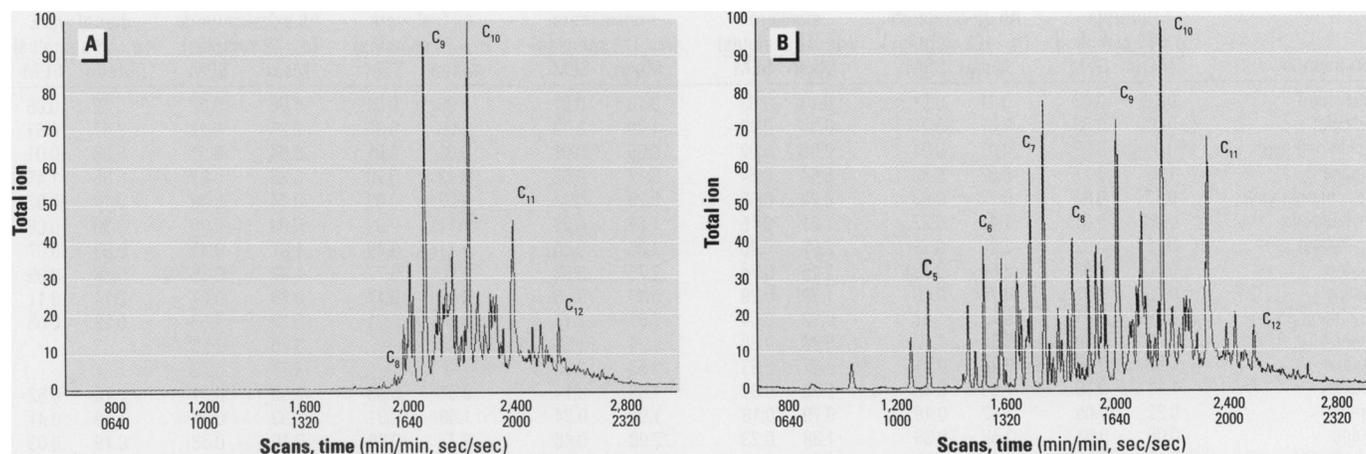
in the hangar obviously contribute other compounds to the chromatogram that must be considered in any eventual health risk assessments.

As expected, the suburban/rural controls from RTP are typically an order of magnitude lower than the controls from the LA basin for most compounds. Also, the indoor air levels for most VOCs in various common areas at AFBs are essentially indistinguishable from the outdoor levels in LA except for an obvious elevation of the JP-8 fingerprint compounds nonane, decane, and undecane. (Data for dodecane, the fourth of the JP-8 indicators, were not available as part of the control data.) In environmental VOC measurement work, ambient levels like these (at or below a few ppbv) are considered unremarkable. However, all hydrocarbon concentrations

**Table 3.** Ambient measurements (all data in ppbv).

Compounds	Control (RTP) ( <i>n</i> = 22)		Control (LA) ( <i>n</i> = 22)		Indoor air levels AFB shops ( <i>n</i> = 5)		Aircraft cold-start exhaust exposure ( <i>n</i> = 23)		Fuel tank maintenance around aircraft ( <i>n</i> = 9)		Fuel tank maintenance inside fuel tanks ( <i>n</i> = 16)	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Chloroform	0.03	0.01	0.02	0.00	0.05	0.01	0.22	0.12	0.54	0.46	—	—
Benzene	0.37	0.05	1.19	0.08	1.05	0.33	13.04	4.80	17.64	7.52	2,987	1,113
Trichloroethene	0.00	0.00	0.01	0.00	0.35	0.33	0.03	0.01	0.09	0.08	—	—
Toluene	0.44	0.08	3.22	0.31	2.51	0.91	8.87	2.73	53.15	22.21	16,026	5,928
Tetrachloroethene	0.01	0.00	0.15	0.04	0.07	0.03	0.00	0.00	0.00	0.00	—	—
Ethylbenzene	0.08	0.01	0.43	0.04	0.40	0.12	3.13	1.41	74.87	45.42	9,588	3,473
<i>m,p</i> -Xylene	0.26	0.05	1.52	0.15	1.01	0.23	5.13	2.40	112.22	57.26	14,246	3,545
<i>o</i> -Xylene	0.10	0.02	0.62	0.05	0.69	0.21	4.83	2.30	195.88	109.63	6,747	1,849
Styrene	0.10	0.01	0.53	0.15	0.33	0.08	4.49	3.23	0.93	0.45	—	—
<i>p</i> -Dichlorobenzene	0.01	0.00	0.11	0.02	0.09	0.02	0.01	0.01	0.91	0.65	—	—
Butane	0.05	0.04	1.55	0.41	5.73	NA	19.57	10.55	—	—	—	—
Pentane	0.29	0.06	3.20	0.41	2.76	NA	7.50	2.65	—	—	—	—
Hexane	0.12	0.02	1.56	0.35	0.42	0.30	7.06	3.58	19.19	9.63	4,296	1,606
Heptane	0.05	0.01	0.67	0.12	0.14	0.10	1.19	0.45	18.82	8.03	16,130	6,406
Octane	0.03	0.00	0.58	0.10	0.18	0.08	3.13	1.36	65.71	25.47	5,984	2,086
Nonane	0.05	0.00	0.17	0.02	1.19	0.87	9.72	4.50	1,823.74	1,378.73	34,138	11,530
Decane	0.03	0.00	0.16	0.04	2.70	1.98	9.35	4.63	612.47	370.17	31,344	10,596
Undecane	0.03	0.00	0.31	0.10	2.54	1.37	6.71	3.60	159.33	63.91	31,007	12,161
Dodecane	—	—	—	—	7.60	4.41	3.65	1.25	69.79	19.56	7,465	2,267

NA, not applicable.



**Figure 4.** Chromatographic comparison of the expected vapor phase contribution from (A) evaporating JP-8 and (B) a typical ambient sample collected inside a hangar that contained multiple F-15 and F-16 aircraft undergoing fuel tank maintenance. Both chromatograms exhibit the JP-8 fingerprint compounds as annotated (C<sub>9</sub> to C<sub>12</sub> *n*-alkanes), but the ambient hangar air is also contaminated with a variety of other compounds (including the annotated C<sub>5</sub> to C<sub>8</sub> *n*-alkanes) from various maintenance procedures.

measured in the aircraft exhaust exposure scenario are significantly higher in the ambient air (5–10 times greater) than in their indoor air counterparts, and the measurements made around aircraft undergoing fuel tank maintenance are appreciably higher than those from the exhaust, ranging from 17 ppbv benzene to > 1,800 ppbv nonane. Finally, measurements made inside vented fuel tanks are extremely high, presumably because of continually evaporating residual fuel.

Of particular interest are the elevated benzene concentrations relative to the other compounds in the exhaust measurements. U.S. Air Force chemical assays of liquid JP-8 fuel stock worldwide show a mean volume/volume ratio of 270 mg/L benzene versus 1,750 mg/L toluene, for a ratio of approximately 0.15 (2); EPA laboratory tests with various samples taken from aircraft and fuel trucks resulted in a mean ratio of 0.18 (15). Because the equilibrium vapor pressures of neat benzene and toluene are 95.2 and 28.4 mmHg, respectively, at 25°C, we expected a somewhat higher volatilization rate from bulk fuel of benzene versus toluene, depending on the ventilation rate and availability of fresh liquid fuel. Therefore, the measurements of indoor air, ambient air near aircraft undergoing fuel maintenance, and internal fuel tank vapors (Table 3) that result in mean ratios of 0.41, 0.33, and 0.19 suggest evaporated fuel as the most likely source. During aircraft cold starts, however, the mean measured benzene/toluene ratio is 1.47. Here, the benzene concentration is approximately 8 times higher than would be expected from the toluene level and 180 times higher than would be expected from the nonane measurement of evaporating fuel.

This phenomenon is most likely caused by a combination of the differential vapor pressures of benzene and toluene versus the JP-8 fingerprint compounds and the conversion of alkylbenzenes to benzene during incomplete combustion (16).

Air impacted by automobile traffic shows a similar effect. The liquid (benzene volume)/(toluene volume) ratio of unweathered fresh automobile gasoline has a mean national average of 0.25, and the weathered fuel ratio is even lower (0.15 as measured by the EPA) (16). Typically, when automobile engine exhaust and related evaporative fuel emissions are the primary source, benzene/toluene ratios in ambient air are higher, at approximately 0.8, as reflected in the ambient RTP control samples, which demonstrates an enhancement in relative benzene. In a more industrial environment there are additional sources of toluene (for example, from printing and painting operations); therefore, the ratio is expected to be lower, as reflected in the LA control samples in Table 3, where the ratio is 0.37. We defend our conjecture that exhaust from internal combustion presents a relatively higher benzene exposure than a strict headspace or fuel content measurement would indicate. However, the absolute levels of benzene in evaporating fuel are higher than in their respective exhaust emissions.

**Breath measurements—general results.** Breath measurements are presented in Table 4 by the major study categories and their summary statistics per compound. Data are presented in three distinct comparison divisions as outlined in Table 2. First, we compare controls with all JP-8 related breath samples. Then we subdivide all JP-8 related

samples into a comparison of smokers and nonsmokers. Last, we resubdivide the same data set by work/activity into groups of fuel work, exhaust work, and incidental work.

Figure 5 is an example of before and after chromatograms of the exhaled breath of a fuel system maintenance attendant who performed a fuel tank foam removal operation. The attendant did not enter the fuel tank and therefore did not wear a respirator (resulting in relatively high inhalation exposure). He also had some potential dermal exposure from handling the removed foam. Figure 5A, the before-exposure chromatogram, exhibits the standard major endogenous compounds, isoprene and acetone, some methyl ethyl ketone presumably from an unrelated exposure, and a variety of other compounds often found in human breath. The after-exposure chromatogram (Figure 5B) shows the additional C<sub>9</sub> to C<sub>12</sub> *n*-alkanes from the jet fuel exposure as well as some other compounds from the hangar air; the corresponding analysis of the ambient air for the inhalation exposure of this subject is shown in Figure 4B.

The initial comparisons in Table 4 between controls and all JP-8 related samples demonstrate essentially no difference for chloroform and trichloroethene and a moderate absolute increase in tetrachloroethene exposure. This indicates that the use of dry cleaners, consumer products, and chlorinated water is similar between the groups. The elevation of *p*-dichlorobenzene in the JP-8 group is driven by some outlier samples (as indicated by the high relative SEM). Although this is of no real concern, it does indicate that some individuals are likely exposed to consumer products such as mothballs or certain air fresheners. On review of

**Table 4.** Breath measurements (all data in ppbv).

Compounds	Controls		All JP-8 related		All samples subdivided by smoking				All samples subdivided by work activity					
	(n = 19 samples)		(n = 162 samples)		All JP-8 related smokers		All JP-8 related nonsmokers		All fuel work		All exhaust work		All incidental work	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Chloroform	0.18	0.03	0.11	0.01	0.13	0.03	0.10	0.01	0.08	0.01	0.08	0.02	0.19	0.06
Benzene	0.60	0.08	2.87	0.21	6.33	0.40	1.70	0.13	3.03	0.30	2.25	0.22	3.47	0.67
Trichloroethene	0.05	0.02	0.07	0.01	0.08	0.02	0.06	0.01	0.08	0.01	0.04	0.01	0.05	0.01
Toluene	1.02	0.17	6.03	0.50	8.64	0.64	5.17	0.62	6.13	0.70	5.36	0.82	6.85	1.45
Tetrachloroethene	0.13	0.02	0.25	0.03	0.24	0.05	0.26	0.03	0.22	0.03	0.44	0.09	0.17	0.02
Ethylbenzene	0.09	0.01	1.46	0.22	1.01	0.15	1.61	0.29	2.11	0.39	0.96	0.20	0.39	0.06
<i>m,p</i> -Xylene	0.15	0.02	2.28	0.29	2.07	0.45	2.36	0.36	3.11	0.49	1.81	0.40	0.63	0.07
<i>o</i> -Xylene	0.10	0.02	2.59	0.43	2.15	0.74	2.75	0.53	4.00	0.77	1.47	0.35	0.36	0.05
Styrene	0.19	0.02	0.75	0.09	1.79	0.29	0.40	0.05	0.98	0.17	0.36	0.07	0.74	0.11
<i>p</i> -Dichlorobenzene	0.08	0.01	5.12	1.57	0.28	0.04	7.07	2.17	7.31	2.21	0.27	0.05	0.22	0.05
Butane	1.49	0.18	5.90	1.27	6.39	0.38	5.74	1.68	—	—	9.20	2.36	—	—
Pentane	1.02	0.10	2.98	0.21	4.47	0.23	2.50	0.20	—	—	3.77	0.23	—	—
Hexane	1.11	0.19	1.60	0.13	1.62	0.31	1.60	0.14	0.84	0.05	2.59	0.31	2.76	0.52
Heptane	0.22	0.05	1.62	0.19	0.79	0.13	1.90	0.24	1.48	0.31	1.93	0.27	1.19	0.41
Octane	0.08	0.03	2.58	0.36	1.38	0.23	2.99	0.48	2.77	0.56	2.10	0.38	0.19	0.03
Nonane	0.17	0.05	19.85	3.82	22.20	7.87	19.05	4.38	36.13	6.83	1.01	0.19	0.22	0.03
Decane	0.12	0.03	22.01	3.32	27.21	7.04	20.24	3.75	41.38	5.63	0.65	0.15	0.19	0.03
Undecane	0.16	0.03	8.82	1.41	8.86	1.88	8.81	1.78	15.59	2.42	0.93	0.19	0.24	0.05
Dodecane	3.33	1.36	5.19	1.12	5.79	2.10	4.98	1.32	8.86	2.04	0.92	0.15	0.30	0.06

some field notes, we found that the subject exhibiting the highest *p*-dichlorobenzene levels had just recently returned from overseas deployment, and we surmise that his uniforms and other clothing or furnishings had been stored with such products. As expected, hydrocarbon compounds were significantly elevated in the JP-8 subjects. One exception was the unexpectedly high dodecane mean in the control subjects, which at 3.33 ppbv is more than half of the JP-8 mean of 5.19. On more detailed examination, we found that a subset of the controls taken from inside the EPA building had high dodecane levels, presumably from some unknown exposure route from one of the laboratories. Controls from subjects outside of our building had a mean concentration of 0.30 ppbv. Results showing that an individual compound can have an unexpected source reinforces our choice of treating JP-8 exposure as a fingerprint of a group of major constituents rather than targeting one individual compound.

The comparison between JP-8 related samples for all smokers and nonsmokers shows a significant elevation of benzene, toluene, and styrene, regardless of job function or activity for the smokers. Although heptane and octane concentrations are unexpectedly lower in smokers, the JP-8 fingerprint compounds are statistically identical at  $p < 0.05$  (unpaired, two-tailed *t*-test).

The overall results of exposure categorized by work activity demonstrate unambiguously that the JP-8 fingerprint compounds are the highest for subjects related to fuel work, and that those dealing primarily with exhaust exposure, though appreciably lower than their fuel counterparts, are still 5 times higher than the incidental exposure group. With the exception of the anomalous dodecane exposure for a subset of controls, we find a

slight, yet statistically significant, elevation of JP-8 fingerprint compounds in the incidental samples as compared to the controls. The benzene and toluene exposures among the three groups are similar, yet the exhaust work subjects were all nonsmokers. Because these data contain other subgroups such as before and after working and type or location of job activity, more detailed interpretation is required to deduce potential confounding factors.

#### Breath measurements—detailed results.

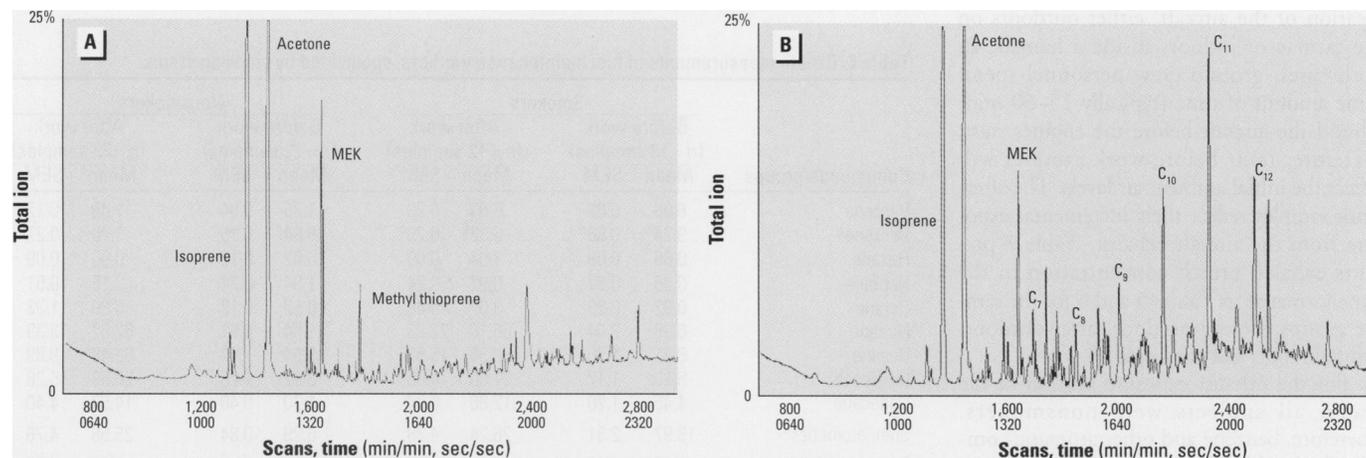
To focus more precisely on fuel- and exhaust-related exposure, we further subdivided samples according to activity and location, as indicated in Table 2. The most important distinction is the before and after occupational activity comparison. The before samples show any potential long-term cumulative exposure, and the difference between the after and before samples is indicative of the incremental exposure. Some further subdivisions with respect to specific job, location, and smoking status were also considered. For the following analyses we include three groupings of compounds in Tables 5 and 6: the sum of aromatics, the sum of non JP-8, and the sum of the JP-8 fingerprint, as defined in “Data Categorization and Reduction.”

The before- and after-work comparison for all fuel workers demonstrates the expected behavior of a significant increase in JP-8 fingerprint compounds and the sum of the aromatics, as presented in Table 5. Surprisingly, there is a significant net decrease in benzene breath concentration; this indicates that working with fuel is not the most important source for benzene exposure. The before-work samples in Table 5 show a consistent elevation of JP-8 fingerprint compounds over the controls, incidental, and exhaust composite data in Table 4. This indicates that the

fuel maintenance workers have a chronic accumulated exposure.

Further subdivision of the after-work samples is made between subjects who physically enter the fuel tanks (referred to as tank entry) and those who do not (referred to as attendants; these subjects also include runners, fireguards, foam handlers, etc.). Tank entry and attendants data indicate no significant differences in the summed groupings; however, the distribution of individual JP-8 fingerprint compounds is appreciably different. As compared to the attendants samples, the tank entry samples exhibit less of the higher vapor pressure compounds and relatively more of the less volatile undecane and dodecane. This could be attributable to exposure route; that is, dermal absorption of undecane and dodecane would be favored because they would evaporate more slowly from the skin than the more volatile JP-8 constituents. Conversely, the higher relative vapor pressure of nonane and decane would tend to favor inhalation exposure. This deduction is consistent with observations that tank entry personnel are much more likely to contact liquid fuel than attendants.

A second important observation concerns the apparently effective decoupling of inhalation exposure for the tank entry personnel. Table 3 shows that the aggregate JP-8 fingerprint mean exposure for attendants is approximately 2,700 ppbv (ambient levels around aircraft undergoing fuel tank maintenance), whereas the potential inhalation exposure for tank entry personnel is on average approximately 104,000 ppbv (measurements inside fuel tanks). As such, we could expect to see a factor of 40 difference in exhaled breath levels. Because the results indicate essentially identical exposure for both groups, and because we have already deduced that there is



**Figure 5.** Chromatographic comparison of (A) preexposure and (B) postexposure exhaled breath chromatograms of a fuel tank maintenance attendant who is not wearing a respirator and is handling removed foam from an F-15 fuel tank. The inhalation exposure corresponds to the ambient hangar sample in Figure 4B. The appearance of JP-8 fingerprint compounds ( $C_9$  to  $C_{12}$  *n*-alkanes) is obvious for this high-level exposure scenario. The labeled isoprene, acetone, and methyl thioprene peaks are common endogenous compounds found in all human breath; the solvent methyl ethyl ketone (MEK) is most likely from an incidental exposure from some other activity.

a component of dermal exposure for tank entry subjects, we find that the supplied air respirators routinely worn by tank entry subjects (but not by attendants) are extremely effective in reducing inhalation exposure.

Despite the fact that benzene is a constituent of the bulk fuel, the overall mean benzene exposure decreases during fuel work. To test the hypothesis that smoking is a primary source of benzene (and possibly other VOCs), Table 6 presents summary statistics for subdivisions of samples based on smoking status coupled to before and after work status. Mean benzene content of exhaled breath remains stable during fuel maintenance for smokers (approximately 6 ppbv) and mean benzene increases from 1.22 to 1.49 ppbv for the nonsmoker peer group. If the data generating these overall means are further reduced to account for only those subjects with paired immediate before and after data so as to include covariance, we find that the exhaled breath concentration of benzene for smokers decreases by 2.92 ppbv ( $n = 6$ , SEM = 0.768) and for nonsmokers increases by 0.84 ppbv ( $n = 22$ , SEM = 0.253). As such, we see that the incremental benzene exposure of fuel work is outweighed by the elimination of benzene from cumulative smoking exposure because fuel work precludes smoking because of the obvious fire risk. Additionally, the change in the levels of mean overall aromatics is moderately significant for smokers and highly significant for nonsmokers. JP-8 exposure, as deduced from the fingerprint compounds, is not obviously affected by smoking behavior.

Measurements for exhaust workers involved a cursory examination of data for ground crew personnel involved in aircraft start operations. This examination showed an obvious difference in the before- and after-work relationship depending on the initial location of the aircraft, either outdoors on the tarmac or indoors inside a hangar. In both cases, ground crew personnel spend some amount of time (typically 15–60 min) around the aircraft before the engines start; therefore, their before-work samples will reflect the initial ambient air levels. The after-work samples reflect their incremental exposure from the aircraft exhaust. Table 7 presents exhaled breath concentration in the same format as in Tables 5 and 6 for the sample groups (before-outdoor, after-outdoor, before-indoor, and after-indoor).

For the exhaust exposure portion of the study, all subjects were nonsmokers. Therefore, benzene and other aromatic compounds should reflect JP-8 and its exhaust as the primary source. Table 7 data demonstrate that subjects inside a hangar near an aircraft experience obviously elevated fuels exposure (approximately 40 times more)

over their colleagues who work outdoors, as reflected in the JP-8 fingerprint comparison of the before data. Once the hangar doors are opened and the aircraft engines started, the combination of fresh outdoor air and aircraft exhaust presents a much lower overall exposure for all fuel-related compounds. The outdoor starts of aircraft present a statistically significant increase in all compounds from the exhaust, but the absolute levels after working are still approximately 5 times less than the background levels found in fuel system workers before they begin work.

Benzene exposure for all groups merits separate treatment because of long-term health concerns at environmental exposure levels (17). To put benzene exposure in perspective, Figure 6A shows bar graphs of the means and SEMs for all breath sample subdivision groups, and Figure 6B presents the comparative data for the JP-8 fingerprint compounds. As seen in the overall comparison of major groups (Table 4), groups of smokers dominate for benzene exposure

levels, whereas groups of fuel workers dominate for JP-8 exposure levels. This is consistent in the subdivision data for the incidental and fuel workers in Figure 6A, where there are large benzene differences in exhaled breath based on smoker/nonsmoker classification, yet no apparent pattern based on work activity distinctions for the various fuel groups or for the nonsmokers studied in the exhaust categories. This is in sharp contrast to the data for JP-8 (Figure 6B), where smoking status is essentially irrelevant, but the before- and after-work issue (especially for fuel workers) is of primary importance.

The most striking comparison comes from the paired data from the fuel workers. Figure 6A shows that the benzene exposure increases after work for nonsmokers and that there is a strong anticorrelation for the smokers. Also, all exhaust worker subgroups (where all subjects are nonsmokers) exhibit higher mean benzene breath levels than their nonsmoker counterparts in the controls, incidental, and fuel groups. This is confirmed

**Table 5.** Breath measurements of fuel maintenance workers, subdivided by job (all data in ppbv).

Compounds/groups	Before work (all samples) ( $n = 40$ samples)		All samples ( $n = 45$ samples)		After work Tank entry ( $n = 15$ samples)		Attendants ( $n = 30$ samples)	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Benzene	3.42	0.52	2.70	0.33	1.91	0.54	3.09	0.41
Hexane	0.75	0.08	0.93	0.07	0.71	0.16	1.05	0.07
Heptane	0.78	0.42	1.83	0.39	1.85	0.62	1.82	0.50
Octane	0.75	0.12	4.55	0.98	3.65	1.23	5.00	1.34
Nonane	4.16	1.05	63.47	11.42	44.97	20.34	72.71	13.72
Decane	6.79	1.49	70.12	8.32	41.72	12.75	84.33	9.87
Undecane	4.40	0.86	25.26	4.01	42.16	10.65	16.81	1.35
Dodecane	2.93	0.63	14.09	3.65	29.81	9.56	6.23	1.35
Sum, aromatics <sup>a</sup>	12.00	1.51	25.76	3.66	22.03	4.61	27.62	4.99
Sum, non-JP-8 <sup>b</sup>	1.51	0.42	2.77	0.41	2.56	0.68	2.87	0.52
Sum, JP-8 fingerprint <sup>c</sup>	18.28	2.94	172.94	20.69	158.66	42.51	180.08	23.08

<sup>a</sup>Sum of benzene, toluene, ethylbenzene, *m,p*-xylene, *o*-xylene, and styrene. <sup>b</sup>Sum of hexane and heptane. <sup>c</sup>Sum of nonane, decane, undecane, and dodecane.

**Table 6.** Breath measurements of fuel maintenance workers, subdivided by smoking status.

Compounds/groups	Smokers				Nonsmokers			
	Before work ( $n = 18$ samples)		After work ( $n = 12$ samples)		Before work ( $n = 22$ samples)		After work ( $n = 33$ samples)	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Benzene	6.08	0.68	6.04	0.23	1.25	0.34	1.49	0.17
Benzene <sup>a</sup>	9.24 <sup>b</sup>	0.86 <sup>b</sup>	6.32 <sup>b</sup>	0.28 <sup>b</sup>	0.84 <sup>c</sup>	0.25 <sup>c</sup>	1.70 <sup>c</sup>	0.27 <sup>c</sup>
Hexane	0.66	0.09	1.04	0.09	0.82	0.12	0.90	0.09
Heptane	0.45	0.07	0.97	0.24	1.04	0.74	2.15	0.51
Octane	0.92	0.20	3.07	0.45	0.62	0.13	5.09	1.32
Nonane	6.98	2.04	65.10	22.83	1.84	0.61	62.87	13.39
Decane	8.31	1.70	80.36	15.58	5.54	2.32	66.40	9.89
Undecane	5.10	1.17	21.60	4.05	3.82	1.25	26.59	5.28
Dodecane	4.45	1.20	12.88	6.64	1.70	0.48	14.53	4.40
Sum, aromatics <sup>d</sup>	18.97	2.31	26.24	4.38	6.29	0.84	25.58	4.76
Sum, non-JP-8 <sup>e</sup>	1.08	0.16	2.01	0.25	1.87	0.75	3.05	0.55
Sum, JP-8 fingerprint <sup>f</sup>	24.84	4.12	179.94	45.87	12.91	3.86	170.39	23.21

<sup>a</sup>From paired samples immediately before and after work only. <sup>b</sup> $n = 6$  samples. <sup>c</sup> $n = 22$  samples. <sup>d</sup>Sum of benzene, toluene, ethylbenzene, *m,p*-xylene, *o*-xylene, and styrene. <sup>e</sup>Sum of hexane and heptane. <sup>f</sup>Sum of nonane, decane, undecane, and dodecane.

with statistical comparison among all non-smokers based on work activity, indicating two-tailed *t*-test significance, as shown in Tables 8 and 9. Benzene breath levels of incidental and fuel groups are statistically identical to each other but are statistically elevated over controls, suggesting that some incremental AFB exposure does exist.

## Conclusions and Recommendations

The combination of ambient and exhaled breath data collected from AFB personnel provides strong empirical evidence that there is measurable exposure to JP-8 jet fuel vapors and exhaust. The statistical results show general exposure trends for a variety of scenarios and indicate areas for further detailed study regarding exposure routes and exposure reduction with changes in behavior and the use of personal protective equipment.

We conclude that there is an overall elevation of ambient incidental exposure to JP-8-related hydrocarbon compounds at AFBs as

compared to ambient control measurements in urban and suburban locations and that incidental exposure to other commonly encountered VOCs is unremarkable. The highest overall exposures to JP-8 alkanes are experienced by fuel system maintenance workers; they exhibit a chronic elevated level of JP-8 fingerprint compounds in their breath and have the greatest incremental exposure from performing their job functions. Personnel exposed to aircraft exhaust in the typical outdoor scenarios have measurable exposure; however, this is at least 10 times less than their fuel-systems colleagues. When these exhaust workers perform their preflight duties inside a hangar, they exhibit elevated initial exposure levels that then decrease after the doors are opened and the aircraft engines are started. There is a slight measurable elevation in JP-8 fingerprint compounds in subjects at AFBs without direct aircraft or jet fuel contact as compared to the general population.

JP-8 exposure in fuel systems workers as measured in their breath is equivalent for tank

entry and attendant personnel, yet the ambient (potential) exposures are 40 times greater inside the fuel tanks. We therefore conclude that the full-face forced-air respirators worn by tank entry personnel (only while they are inside the tank) are extremely effective in eliminating inhalation exposure and that the JP-8 in their breath is primarily from their activity in the vicinity of the aircraft outside the fuel tanks (while they are not wearing respiratory protection). This is supported by the similar JP-8 breath levels found in exhaust workers during indoor preflight activity.

Benzene exposure has three distinct sources: cigarette smoking, aircraft exhaust, and jet fuel vapor. Smoking is by far the most important benzene source, and we conclude that fuel system maintenance is actually beneficial to smokers because it prevents them from smoking during work and thus reduces their overall benzene body burden. Comparisons among nonsmoker groups subdivided by job show that aircraft exhaust exposure is most significant in elevating benzene levels, that incidental and fuel systems work is equivalent in relevance for benzene exposure (at approximately half of the exhaust level), and that all U.S. Air Force-related groups exhibit statistically significant higher benzene levels than the controls. We conclude that there is an overall moderate elevated benzene exposure at the bases from fuel and exhaust (breath means of 1.7 ppbv vs. controls at 0.60 ppbv), but that smoking causes an additional 400% incremental mean body burden.

Based on the empirical data presented in this paper and on other questions asked during the VOC measurement experience, we recommend further study, as follows:

- Determine the relative contribution from dermal and inhalation exposure routes for tank entry personnel.
- Determine the precise efficiency of forced-air respirators currently in use by tank

**Table 8.** Benzene exposure significance for non-smokers (summary statistics).

Group	No.	Mean	SEM
Controls	19	0.602	0.0828
Incidental	17	1.151	0.1113
Exhaust	49	2.248	0.2224
Fuel	55	1.390	0.1688

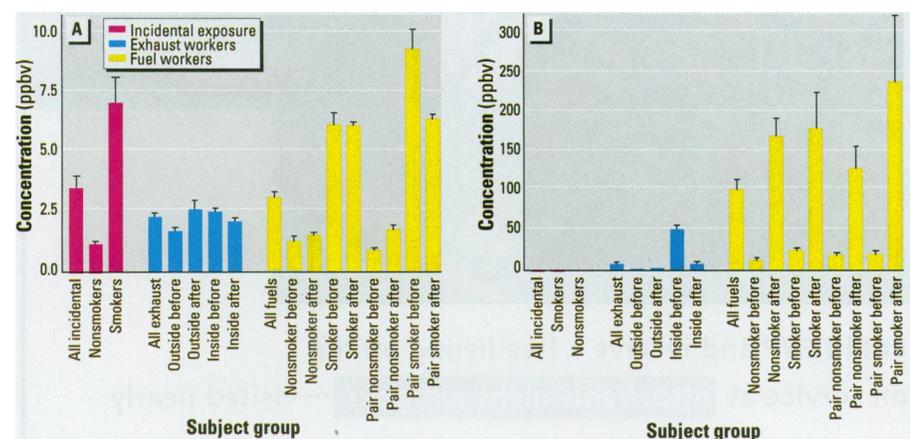
**Table 9.** Benzene exposure significance for non-smokers (two-tailed *t*-test significance).

Variables	Significant?	<i>p</i> -Value
Exhaust versus incidental	Yes	$p = 0.0059$
Exhaust versus fuel	Yes	$p = 0.0024$
Exhaust versus controls	Yes	$p < 0.0001$
Incidental versus fuel	No	$p = 0.4451$
Incidental versus controls	Yes	$p = 0.0003$
Fuel versus controls	Yes	$p = 0.0087$

**Table 7.** Breath measurements of exhaust workers, subdivided by aircraft location (all data in ppbv).

Compounds/groups	Indoor start				Outdoor start			
	Before work ( <i>n</i> = 6 samples)		After work ( <i>n</i> = 7 samples)		Before work ( <i>n</i> = 12 samples)		After work ( <i>n</i> = 24 samples)	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Benzene	2.42	0.17	2.08	0.19	1.65	0.29	2.55	0.42
Hexane	2.86	0.48	0.85	0.19	2.07	0.54	2.59	0.31
Heptane	5.66	0.58	1.85	0.34	1.80	0.68	1.93	0.27
Octane	13.82	1.10	4.70	0.97	0.95	0.65	2.10	0.38
Nonane	20.15	1.69	5.49	1.20	0.32	0.13	1.01	0.19
Decane	15.72	1.25	2.82	0.51	0.24	0.06	0.65	0.15
Undecane	9.42	0.86	1.41	0.19	0.31	0.11	0.93	0.19
Dodecane	7.67	2.74	0.80	0.10	0.54	0.17	0.92	0.15
Sum, aromatics <sup>a</sup>	36.21	7.68	13.67	2.11	6.91	1.01	8.45	1.32
Sum, non-JP-8 <sup>b</sup>	8.52	0.98	2.70	0.37	3.87	1.14	4.52	0.56
Sum, JP-8 fingerprint <sup>c</sup>	52.96	4.89	10.53	1.83	1.38	0.35	3.50	0.65

<sup>a</sup>Sum of benzene, toluene, ethylbenzene, *m,p*-xylene, *o*-xylene, and styrene. <sup>b</sup>Sum of hexane and heptane. <sup>c</sup>Sum of nonane, decane, undecane, and dodecane.



**Figure 6.** Mean breath concentrations and estimated standard errors for subdivided groups of samples from JP-8-exposed subjects. The exhaust workers were all nonsmokers. Most group descriptions are self-explanatory; however, the four "pair" values are the results of just the subset of samples taken in pairs immediately before and after fuel system work. (A) Benzene-only data. (B) Summed concentrations of the *n*-alkanes nonane, decane, undecane, and dodecane that are representative of JP-8 exposure.

- entry personnel and assess potential exposure reduction for attendants and other fuel system workers if they were to also use such respirators.
- Investigate exposure to volatile combustion products (aldehydes, furans, etc.) and particulate organic compounds such as polyaromatic hydrocarbons in aircraft exhaust.
- Investigate the benefit of the temporary use of cartridge-type respirators during aircraft start-up.
- Measure elimination kinetics from short-term high-level exposures (especially for benzene) in exhaust scenarios.
- Determine precise blood-breath relationships from various exposure scenarios.
- Investigate incidental JP-8 exposure for a wide variety of U.S. Air Force personnel, including flight crews.
- Extend this work to the commercial airline industry and other military services; include exposures to airline customers.
- Determine any acute or chronic health outcomes from the environmental levels of exposure measured in this work.

- Compare the precision and accuracy of sampling techniques using canisters to alternative methods using solid adsorbent tubes.

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## REVIEW

# The airport atmospheric environment: respiratory health at work

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**ABSTRACT:** Air traffic is increasing, raising concern about local pollution and its adverse health effects on the people living in the vicinity of large airports. However, the highest risk is probably occupational exposure due to proximity. Jet exhaust is one of the main concerns at an airport and may have a health impact, particularly on the respiratory tract. Current studies are neither numerous enough nor strong enough to prove this kind of association. Yet, more and more people work in airports, and occupational exposure to jet exhaust is a fact. The aim of this review was to evaluate the existing knowledge regarding the impact of airport pollution on respiratory health. We conducted systematic literature searches to examine workplace exposures.

**KEYWORDS:** Airport, air traffic, jet exhaust, occupational exposure, respiratory problems, respiratory tract

The International Air Transport Association announced a slight decline in air traffic in May 2012 due to the economic environment, but air flight transport should continue to grow in the future as there is a trend to optimise time over shorter distances. Major hub airports are not big enough and are in need of a geographic expansion, which is often discussed.

These changes cannot be made without taking into account the “expansion” of the adverse effects, both for workers who operate in the airport and for the surrounding neighbourhood. It is not sufficient only to discuss a landscape change or the risk of accident. Air pollution is a major concern for people situated at or near airports. These issues necessitate additional studies. The larger the airport, the stronger the impact on the population's health is [1]. Therefore, in this review, we discuss whether there is a correlation between atmospheric exposure at the airport, and exposure in the vicinity and occupational exposure (fig. 1).

### AIRPORT ATMOSPHERIC ENVIRONMENT

Different research teams have focused on the characterisation of air pollution in the airport area and its surroundings. The concentration of particulate pollutants seems to be inversely proportional to the distance from the airport: the further away you are from the airport platform, the lower the pollution is [2]. Kerosene is the major compound in jet fuel and has a specific odour,

especially before fuel combustion, which can be smelled >8 km from the airport [3].

The main polluting substances considered in this environment are nitrogen oxides, carbon dioxide, carbon monoxide, volatile organic compounds (VOCs) including polycyclic aromatic hydrocarbons (PAHs), sulfur dioxide [4], and fine and ultrafine particles (UFPs) [5].

PAHs are dangerous. They have been measured and characterised for decades. Thus, it has been established that aromatic hydrocarbons are a significant part of jet exhaust pollution [2, 6]. Different types of volatile PAHs were identified using a sampler placed outside in a residential area very close to an airport. It is interesting to note that the concentration of the particulate phase measured near homes was similar to that at the end of runways [7].

It has been suggested that aviation can cause large-scale increases (>30%) of black carbon particles in the upper troposphere and lowermost stratosphere of regions highly frequented by aircraft [8]. These particles are then disseminated in the atmosphere. UFPs represented 15–18% of the particulate concentration in an airport flight path atmosphere (Taiwan International Airport, Taipei, Taiwan) [9] and this rate varied depending on the engine, the type of fuel and climate conditions [10].

Some studies outline that soot particles could have adverse health effects, especially on the

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**FIGURE 1.** Jet exhausts in the sky.

respiratory tract, because of their tiny size [11]. Experimental studies have demonstrated that the elementary particle size in airports or close to aircrafts was between 23 and 36 nm [12, 13]. Recently, around Los Angeles International Airport (LAX; Los Angeles, CA, USA), aircraft UFP emissions with a median size of ~11 nm were observed [14]. This is consistent with the observation at LAX that there was a bimodal distribution of particle size showing peaks at ~12 and 80–90 nm diameter [15].

An analysis of atmospheric health impacted around O'Hare International Airport (Chicago, IL, USA) indicated that the concentrations of the aforementioned pollutants, although high, especially downwind, were similar to those from road traffic emissions in urbanised areas [16].

It is therefore difficult to focus specifically on air traffic pollution because the rates of pollutants are the same as those found in highly urbanised areas [17].

#### AIRPORT VICINITY

In fact, several studies, especially in Europe and North America, have been conducted since the 1990s to assess the health impact on people living close to airports, as well as air traffic risks such as noise and air pollution. However, there is a lack of data regarding relationships between airport atmospheric pollutants and respiratory disorders.

In the Netherlands, the health authorities are interested in the topic, and many studies have been conducted at the Schiphol hub airport (Amsterdam, the Netherlands) and in its vicinity. It has been determined that people living near Schiphol complained about respiratory problems [18] comprising coughing, an increase in the perception of shortness of breath and wheezing onset associated with a decreased lung function. An increase in the intermittent use of bronchodilators was noted for people previously suffering from chronic respiratory diseases; they decompensated more often [4]. These functional signs were most frequently identified near the hub and decreased with the distance from the airport [18]. This notion confirmed results of a study conducted in the USA. A significantly larger number of hospitalisations due to acute respiratory symptoms was highlighted for people living within 8 km of major airports like LaGuardia Airport (New York, NY, USA) or Greater Rochester International Airport (Rochester,

NY) compared with those living beyond 8 km [19]. The intensity of respiratory symptoms evolved according to the concentration of air pollution.

The Dutch Working Group focused on the issue of airport respiratory health impact on vicinity and concluded that currently there was no direct association between airport air pollution and other respiratory problems other than those encountered in areas of high urban pollution [4].

The various studies are very descriptive and include many confounding factors, so we cannot compare or draw conclusions with certainty. To further support the hypothesis of an impact on respiratory functions directly related to airport-specific air pollution, work should be carried out with the target populations that are most at risk, such as employees who work in hub airports.

#### AIRPORT WORKERS: THE POPULATION MOST EXPOSED

In 1999, the effect of occupational exposure to aircraft fuel and jet exhaust on pulmonary function and respiratory symptoms in Birmingham International Airport (Birmingham, UK) workers was reported. This work suggested that there was a link between high occupational exposure to aviation fuel or jet exhaust and excess respiratory tract symptoms, consistent with the presence of a respiratory irritant. It was a cross-sectional survey using a questionnaire filled out by the participants themselves. Respiratory and immunological function assessments and an exhaled carbon monoxide measurement were conducted with male full-time airport workers classified into three groups according to their exposure level [20].

Although neither spirometry nor skin tests demonstrated a difference between groups, it appeared that high exposure is significantly associated with a runny nose and a cough with phlegm. The odds ratios were 2.9 and 3.5, respectively ( $p < 0.05$ ), after adjustment for age, smoking and seasonal rhinitis. Furthermore, no obvious link was demonstrated between the presence of shortness of breath or wheeze and high exposure (table 1). Exhaled carbon monoxide, adjusted for smoking, was similar for all groups. However, these results need to be confirmed by further studies because they were limited by a lack of quantitative data on occupational exposure compared with unexposed workers and the small number of subjects involved [20].

In 2003, American researchers studied the prevalence of respiratory symptoms in flight attendants because the indoor environment in occupational settings had generated considerable concerns in the USA. An association between respiratory disorders after chronic and high exposure to aircraft air quality was suggested (long-haul rotations supported). It was stated that the aircraft cabin air supplies are first cycled through an aircraft engine. Flight attendants were asked standardised questions on respiratory health by telephone at three different international airports (Miami International Airport, Miami, FL, USA; Seattle-Tacoma International Airport, Seattle, WA, USA; and Detroit Metro Airport, Detroit, MI, USA) concerning their respiratory health. Teachers operating in the same areas constituted the control group (matched for sex and age, but with little air travel). Interviewers used a standardised questionnaire [21].

**TABLE 1** Occupational exposure of Birmingham International Airport (Birmingham, UK) workers and respiratory disorders

Exposure group	Workers	Subjects n	Comments	Median time spent in aircraft taxiing area h day <sup>-1</sup>	Crude prevalence of respiratory problems			
					Runny nose	Cough with phlegm	Shortness of breath	Wheezing
<b>High</b>	Baggage handlers	53	Considerable proportion of their working day in close proximity to in-service aircraft	8	58	36	25	13
	Airport hands							
	Marshalls							
<b>Medium</b>	Operational engineers	83	Some of their working time on the airport apron, some in reasonable proximity to aircraft and some within the terminal buildings	1	42	16	22	17
	Fitters							
	Engineering technicians							
<b>Low</b>	Security staff	86	Airfield operations managers	0	45	36	24	20
	Fire fighters							
	Terminal and office workers							

Data are presented as %, unless otherwise stated. Data from [20].

Flight attendants reported significantly more chest illnesses than teachers (33% and 19.3%, respectively), although doctor-diagnosed asthma was less common in flight attendants. The authors concluded that flight attendants had a higher respiratory disorder rate than other American female workers. The lack of asthma diagnosis might be explained by a work selection bias (inability to fly if asthma is pathology proven). The occupational origin of these symptoms was highlighted because the air cabin environment represented a unique occupational setting [21].

Pressure, humidity or many people in a small area (increased risk of infections) are specific to aircraft cabins, and the authors also outlined some contaminants that are more concentrated than in other environments: ozone, degradation products of the combustion of engine oils or hydraulic fluids. It remains difficult to go beyond hypothesis as clinical data were not associated with workplace metrology results or an objectification of medical symptoms. The link between cabin air potentially contaminated by particles of secondary emissions from jet-fuel combustion and respiratory problems could not be assessed here; there were too many missing data and too much bias [21].

In the early 2000s, a working group, appointed by the Committee on Toxicology of the US National Research Council, studied the issue of health effects of aviation fuel in the US Air Force (fig. 2). Several internal studies at the US Air Force were conducted with in the course of their work.

The working group reported the results of two studies concerning the breathing impact from Jet Propellant (JP)-8 (the main fuel used by military aviation): one by self questionnaire on respiratory symptoms of three groups of soldiers with different exposure levels; and the other based on a cohort followed by identifying the number of Air Force medical consultations for respiratory disorders compared with a control group that was not exposed. No significant difference could be demonstrated between these groups in both cases.

However, further investigations were recommended by conducting more rigorous studies taking into account the fuel in



**FIGURE 2.** High-idling aircraft engine.

its various states, to better characterise the workplace atmosphere and, therefore, collect clinical information and find an association with metrological data. *In vitro* studies on mice suggested that JP-8 aerosol is more toxic to the respiratory tract than JP-8 in vapour form [22].

To assess the potential exposure to PAHs emitted in airports, either due to the combustion of JP-8 or from other sources (road vehicles, maintenance operations, *etc.*), an American team attempted to characterise the ambient aerosol in various US Air Force workplaces (fig. 3).

Different kinds of measurements were used: 1) PAH concentration rendered in real-time monitoring (photoelectric aerosol sensor); and 2) low-volume air samplers for chemical analysis (gas chromatography (GC)/mass spectrometry (MS)). These monitors were used at the same time. The results were concordant on a significant increase in the concentration of PAHs in the different workplaces studied. The PAH rate was up to 25 times the content usually found in the ambient air. GC/MS clarified that PAHs were more present in a volatile phase with naphthalene and alkyl-substituted naphthalenes. Particulate-phase PAHs were below the method detection limits. It is interesting to note that GC/MS revealed specific PAHs in workplaces with a major diesel exhaust particle (DEP) exposure; these compounds were not detected close to jet exhaust.

They concluded that occupational exposure to PAHs is real but it is difficult to associate a potential impact on health with this exposure. In fact, the rate measured in the break room or in the hangar, in the absence of major maintenance activities on rolling aircraft, is similar to that which was measured with the same type of monitor in the ambient air of major urban residential areas. The maximum concentration “on the tarmac” during an engine test (four reactors) was twice as large as the rate measured in a “smoking office”. The emphasis was on high risk of acute exposure over short periods during certain activities (concentration peaks of PAHs) (table 2) [23].

These relatively low levels of exposure to PAHs from the combustion of aviation fuels were mainly related to the presence of naphthalene, alkyl-substituted naphthalenes and, in smaller

quantities, fluoranthene, pyrene and benzo[a]pyrene. Other studies confirm these data [24].

An assessment of the occupational exposure of the airport ground staff at the hub airport Charles de Gaulle (Paris, France) was carried out by occupational physicians. Atmospheric measurements were made from integrated-air samples and with individual portable tools (carbon monoxide analyser and aromatic hydrocarbons pump), specifically during the towing of the aircraft, near the towing personnel. The hydrocarbon emissions were higher under idle or low-load conditions compared with high-load conditions. It was during this activity that employees were most exposed. These results in commercial aircraft confirmed the report by CHILDERS *et al.* [23] that the rate of PAHs is very low, except at certain times when peaks were detected. Nitrogen oxides measured in a fixed position were below the occupational exposure limits. Carbon monoxide was below the detection limit of the device and stationary particles measured were 100 times lower than the regulatory values. The author states that all these data were conditional because the weather was not taken into account and, therefore, they only reflected the airport’s ambient environment at one moment [25].

To better characterise the occupational exposure to PAHs, an Italian team decided to assess the association between atmospheric metrology (measuring levels of 23 kinds of PAHs including 16 considered most dangerous by the US Environmental Protection Agency) and a urinary PAH indicator (1-hydroxypyrene) in the exposed population, and to assess micronucleus and comet assays in exfoliated buccal cells. PAHs were found in greater numbers on the Fiumicino–Leonardo da Vinci (Rome, Italy) apron with predominantly methyl-naphthalene and acenaphthylene compared with other areas (buildings and departure terminal). The authors associated PAHs with the incomplete combustion of jet exhaust. The analysis of the rate of 1-hydroxypyrene in urine, collected at the end of the fifth day of the work week showed no significant difference between the exposed workers and the control group. Conversely, although the micronucleus test was not significant, the comet assay (confirmed by secondary analyses after culture) showed the presence of oxidative stress-related damage to DNA. CAVALLO *et al.* [26] concluded that the comet assay on buccal cells was a good indicator of genotoxic and oxidative impact after chronic exposure to low doses of PAH. However, this is not clear; there are many biases in this study, with a lack of precision on the exposure time and a neglect of numerous confounding factors [26].

However, alkanes emitted by aircraft engines may be a specific aircraft emission indicator for occupationally exposed persons, as their concentration is higher than in DEPs [27], and the impact of other airport respiratory toxic products must not be neglected. Occupational physicians should consider the global exposure.

Paints may contain VOCs that are implicated in the exacerbation of pre-existing respiratory diseases such as asthma [28]. In addition, chromium found in spray paints used in the aviation industry seems to be deposited in the airway and alveolar tract [29]. Aircraft maintenance is often performed in closed, ventilated areas (hangars). These operations are very different and may require the use of paints, adhesives, oils or welding. It has been



**FIGURE 3.** Traffic vehicles on runways.

**TABLE 2** Airport occupational exposure to polycyclic aromatic hydrocarbons (PAHs)

Workplace	Monitor	Results
<b>Background in a break room close to maintenance hangar (no known emission sources near the room)</b>	RTM	0.97–40 ng·m <sup>-3</sup> Negligible The monitors all agreed qualitatively
	RTM	Maximum output of the monitor: 4000 ng·m <sup>-3</sup> (high-idle engine test)
<b>Downwind measurements during four engine run-up test on flight tarmac</b>	IAS	PAH vapour phase dominated by naphthalene, and alkyl-substituted naphthalenes <sup>#</sup> PAH particulate phase <LD except benzo[a]pyrene and pyrene
	RTM	Negligible (similar to the break room)
<b>Maintenance hangar, first step: minimal flight and ground-support activity (maintenance hangar background)</b>	IAS	PAH vapour phase dominated by naphthalene and alkyl-substituted naphthalenes <sup>#</sup> PAH particulate phase <LD
	RTM	PAHs were 10 times higher than in the break room, eight times higher than those recorded earlier in the maintenance hangar (first step), approximately equal to the average indoor PAH concentrations in residences in a major city
<b>Maintenance hangar, second step: doors opened; aircraft engine exhaust was directed toward the door of the maintenance hangar</b>	IAS	Vapour PAHs were two times greater than in the maintenance hangar (first step) PAH particulate phase <LD
	RTM	The response reached a maximum at the AGE units start and shut off 20 times greater than the background levels, 10 times higher than in the maintenance hangar (first step), 3.5 times higher than during the four-engine run-up test
<b>Downwind from aerospace ground equipment</b>	IAS	New vapour PAHs were detected: methyl substituted phenanthrenes, anthracenes, fluoranthene and pyrene PAHs particulate phase <LD

RTM: real time measurements; IAS: integrated air sampling associated with chemical analysis; LD: limit of detection; AGE: aerospace ground environment. <sup>#</sup>: present in the greatest quantities. Data from [23].

shown that this last activity is a source of not only organic UFPs but also metal UFPs such as aluminium, iron or zinc [30].

## DISCUSSION

The health impact of airport occupational exposure cannot be fully considered while the risks have not been clearly identified. No study has demonstrated a significant relationship between specific exposure to jet exhaust particles and respiratory symptoms because of many confounding factors (tobacco, DEPs, *etc.*), insufficient sample size and a lack of quantitative data; nobody has been able to correlate jet exhaust particles with respiratory symptoms in fact. Many studies on animals and humans (*in vitro* and *in vivo*) regard nanoparticle toxicity but this research focuses on workers in nanotechnology industries who are exposed to uniquely engineered nanomaterials. Therefore, it is easier to include this kind of person in an epidemiological study with few confounding factors. However, this field of study should also include nanoparticles generated by pollution as well as manmade nanoparticles, UFPs remain a background interest despite a larger number of people being exposed. This may be because natural UFPs were considered common in the atmosphere, but with the development of industry and travel traffic, people are exposed to significant levels.

Since the air in dense urban areas does not differ from that of an airport, we must take into account atmospheric pollution in its entirety. Traffic at an airport is not only limited to aircraft runways; it also has a lot of roads for cars and cargo trucks. Furthermore, it covers a larger number of activities on a smaller geographic scale. As in urban areas, where pollution

from DEPs has been proven, it is important to remember that the International Agency for Research on Cancer recently classified diesel engine exhaust as carcinogenic to humans (Group 1). This is based on sufficient evidence that exposure to DEPs is associated with an increased risk of lung cancer. The exhaust of gasoline engines is also suspected as carcinogenic (Group 2B) [31]. Therefore, toxicity due to other types of fuels must also be discussed.

Since the impact of respiratory UFPs derived from the combustion of diesel is more and more accurate, we can begin to question the existence of these particles in an airport, outdoors and indoors. We can also better characterise these particles since the majority of road vehicles use diesel, especially in France, and aeroplanes consume kerosene. A team of researchers in Marseilles has recently demonstrated *in vitro* that these UFPs can influence cytokine production and so impact inflammatory processes in humans [32]. For an improved approach to occupational exposure on airport aprons, the balance of each of these types of pollution should also be determined (diesel *versus* kerosene).

It would also be interesting to see if there is an association between ambient air metrology and objective respiratory health indicators (biometrology, functional medical exams, *etc.*). Depending on the impact that can be measured, key prevention and corrective methods may be considered, on a human scale (collective and individual) as well as an industrial scale.

Until a specific marker of incomplete combustion of kerosene is clearly identified, it is necessary to continue the process of

**TABLE 3** Airport pollution effects on the respiratory tract *in vivo*

People exposed	Respiratory symptoms	Ref.
Airport vicinity exposure	Coughing, shortness of breath, wheezing onset and decreased lung function	[18]
	Exacerbation of pre-existing respiratory diseases	[4]
Airport occupational exposure	A runny nose and a cough with phlegm	[20]
	Chest illnesses	[21]
	Exacerbation of pre-existing respiratory diseases	[28]
	Chromium can be deposited in the respiratory tract	[29]

measuring the concentration in ambient air on the workforce, and on a larger scale, for public health. The specificity of alkanes has been discussed and should continue to be studied before being used as a marker. The difference in size between UFPs from jet exhausts and those from DEPs must be taken into consideration.

It is important to continue studies in order to characterise these pollutant substances because data gathered from other sectors attributes toxicity to the nanometric size of these particles. We know these particles have different physical and chemical properties relating to their size.

Given the enormous increase in air traffic and the controversies it has generated in recent years, airport structures are changing, not only in terms of their architecture. The use of fuel in aircrafts and road vehicles is also being redesigned (electric vehicles, organic jet fuel, etc.). There are still insufficient data and new factors must also be considered. The monitoring of the Swiss Study on Air Pollution and Lung Disease in Adults cohort reported that an improvement in air quality due to behavioural changes had a positive impact on respiratory health [33].

## CONCLUSION

It is clear that airport activities are a source of air pollution. However, jet exhausts are not the only cause of this pollution. The wide range of operations on an airport base increases occupational exposures. Only a few studies have established a specific link between exposure to pollution in an airport work environment and respiratory problems (table 3). Moreover, the correlation is weak because there is a lack of power, a lack of precision over the types of jobs affected and the presence of confounding factors.

Additional studies, using more rigour and more biomonitoring in association with occupational aerosol measurements, are needed to support this hypothesis.

## STATEMENT OF INTEREST

Conflict of interest information can be found alongside the online version of the article at [err.ersjournals.com](http://err.ersjournals.com)

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## Bulletin of the World Health Organization

### News

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#### Improving the health impacts of airports

Airport and aviation authorities are starting to recognize that airports do not have to be unhealthy. Sima Barmania reports.

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When the Australian federal government approved plans to build a second international airport in Sydney two years ago, Professor Evelyne de Leeuw, director of the Centre for Health Equity Training, Research and Evaluation at the University of New South Wales (UNSW), joined the team, assessing the impact the project would have on people's health.



A moment to de-stress in Amsterdam Airport Schiphol  
Amsterdam Airport Schiphol

The assessment highlighted the potential effects of air pollution and noise from aircraft operations, as well as the effects of associated urban development and ground transportation, including impact on health and wellbeing, in local communities.

Inspired by the Healthy Cities movement, launched by the World Health Organization (WHO) in the 1980s, De Leeuw and her colleagues went on to develop a concept of how this traditionally unhealthy environment could be transformed to promote and protect health.

“Many cities that joined the Healthy Cities movement were moved to do something, because they knew they were not healthy and they had to change,” says de Leeuw.

“The same goes for airports. Airports are like cities, they are mini-hubs, so the same principles apply. But because airports move people around the world, they have far reaching effects on people’s health,” says de Leeuw, who with her colleagues set out their vision in a report entitled *Healthy airports*, that was released earlier this year.

“There’s nothing essentially healthy about an airport with all the noise, fumes, stress and overcrowding,” de Leeuw says.

Airport and aviation authorities are, however, starting to recognize that airports do not have to be unhealthy and unsustainable.

So far there has been no comprehensive or systematic effort to produce a model for the design of a healthy airport and its wider environmental and community footprint.

“It’s vital to integrate any airport infrastructure with the nearby city and community,” says Thiago Herick de Sa from the Department of Public Health, Environment and Social Determinants at the World Health Organization (WHO) in Geneva.

“Apart from being large trip generators – which have wide reaching environmental and health effects – airports are important waste generators, they are energy intensive and land consuming, factors that must be considered when refitting or planning airport infrastructure.”

Air pollution is one of the main challenges. It causes many diseases including respiratory conditions, heart disease and stroke. Air pollution affects people using the airport, including those living nearby, and is a major contributor to global warming and climate change.

The aviation industry is responsible for about 2% of global manmade carbon dioxide emissions, according to the Intergovernmental Panel on Climate Change report, *Aviation and the global atmosphere*.

Norway plans to have a carbon neutral aviation sector by 2030. Carbon neutral means no net emissions, meaning emissions are compensated, such as by planting trees, as opposed to zero carbon emissions.

Industry is now facing the challenge of the demand from Norway and other countries for environmentally friendly aircraft, especially since the 2015 Paris Accord on climate change, in which countries agreed to reduce their greenhouse gas emissions.

Several companies are developing electric-powered aircraft, moving towards a more sustainable aviation sector.

Some airports are using renewable energy, such as Frankfurt Airport in Germany, where waste is being turned into biokerosene and solar panel roofs generate electricity, and Amsterdam Airport Schiphol in the

Netherlands that uses electric vehicles for transportation within and beyond the airport terminals.

"We are trying to reduce the use of fossil fuels to improve the air quality," says Michelle Samson, advisor in Corporate Responsibility at Amsterdam Airport Schiphol.

"We have 35 airport buses and about 100 buses taking passengers to and from the city, these are all electric. The airport taxis also run on electricity. Our aim is to be a carbon neutral airport by 2040."

"However, airports play a positive economic and social role, as economic drivers and large employers. They connect people for business and holiday, and bring together friends and family, so they also make people happy." Samson says.

Samson adds that more than half of Amsterdam Airport Schiphol's commercial buildings are Building Research Establishment Environmental Assessment Method or BREEAM certified for their sustainability performance.

Some airports have sustainable design components and are branding themselves as "green", driven by global efforts to reduce carbon emissions and a desire to align with the 2030 Sustainable Development Agenda.

At some airport terminals, design features aim to alleviate people's anxiety and stress while travelling, such as the use of natural light, colours and materials, such as wood, or facilities that allow passengers to exercise and relax, such as gyms, swimming pools and yoga classes.

For example, at Changi International Airport Terminal 3 in Singapore, passengers can relax next to a giant waterfall surrounded by lush local flowering plants and butterflies as they wait for their flights.

When it comes to human health, there is an awareness of the risk of infectious diseases for travellers, but little has been done to date to create healthy environments for passengers and aviation-related personnel, where they can find healthy food and drinks, exercise or relax.

For Adrien Baudron, sustainable infrastructure designer specialised in airports at Suez company, airports are also a missed opportunity for health promotion and evidence-based health information.

"You could decrease some of the advertising space to allow for relevant information on health," says Baudron, who has worked on airport projects in southeast Asia for several years.

"Health information could be on screens related to smoking-related diseases, flight-related deep vein thrombosis or local diseases such as malaria, or posters in local languages on healthy diet and physical activity," he says.

In their report *Healthy airports*, De Leeuw and colleagues propose a new concept that goes beyond a few design features and services, by defining a healthy airport in terms of environmental sustainability and the health of all those affected: passengers, airport and airline personnel, local residents and the wider community.



Families relax by the Koi pond in Terminal 3 at Changi International Airport Singapore.

Changi Airport Group

“Airports have long been seen as negative forces for community health through noise and air pollution and diverse environmental impacts in various settings,” says co-author Robert Freestone, a professor in planning at the Faculty of Built Environment at the University of New South Wales (UNSW).

Rethinking airport design, however, is complex. Not all the environmental impact of aviation comes from air travel itself. Airport buildings have a large carbon footprint.

Urban planners need to look further than international carbon accreditation schemes, Freestone says.

While 44 airports including Amsterdam Airport Schiphol have achieved carbon neutrality according to Airports Council International Airport Carbon Accreditation, a monitoring scheme to which 200 airports are signed up, carbon neutrality is really just a starting point for a healthy space, the UNSW researchers say.

“The overall goal would be to integrate airport, urban and health planning thinking and strategies in unprecedented and innovative ways. If this is done well, airports could actually become engines of health,” Freestone says.

An airport’s sustainability and health-giving potential depends very much on its design.

“Airport design can promote or hinder the use of more sustainable modes of transport, such as walking, cycling and carbon-free public transport, so airport design has a direct impact on people’s health through changes in transport-related physical activity, road traffic injury and exposure to air and noise pollutants,” Herick de Sa says.

The UNSW researchers have been in discussions with airport management at the Calgary International Airport in Canada, Amsterdam Airport Schiphol and the Incheon International Airport in Seoul, the

Republic of Korea, as well as several aviation authorities on how airports can be designed or refitted to promote health.

“On our first meeting with engineers from the International Civil Aviation Organization, the engineers did not at first see the health dimension of airports,” De Leeuw says. She and the other researchers have also been talking to nongovernmental organizations, such as Airports Council International and the Liverpool City Council on the southwestern edge of the greater Sydney basin, where the new airport will be built.

The development corporation for the new Western Sydney Airport has just commissioned the first major earthworks to level its operations area, and key design parameters have been negotiated.

This new airport will serve Australia’s most populous city, with about 5 million people and communities beyond it, and is scheduled to open in 2026.

“We have been trying to change the discourse in airport design, and still have time to make health core to the development of the future Western Sydney Airport. That is why this is a once-in-a-lifetime opportunity for an airport project to contribute to better health and well-being, and to show the world that it can really be done, ” De Leeuw says.

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## Residential proximity to large airports and potential health impacts in New York State

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### Abstract

**Objective:** This study assessed whether residents living near commercial airports have increased rates of hospital admissions due to respiratory diseases compared to those living farther away from these airports.

**Methods:** This cross-sectional study included all residents living within 12 miles from the center of each three airports (Rochester in Rochester, LaGuardia in New York City and MacArthur in Long Island). We obtained hospital admission data collected by the NYS Department of Health for all eligible residents who were admitted for asthma, chronic bronchitis, emphysema, chronic obstructive pulmonary disease and, for children aged 0-4 years, bronchitis and bronchiolitis during 1995-2000. Exposure indicators were distance from the airport (< or =5 miles versus >5 miles) and dominant wind-flow patterns from the airport (>75th percentile versus < or =75th percentile), as well as their combinations.

**Results:** Increased relative risks of hospital admissions for respiratory conditions were found for residents living within 5 miles from the airports (1.47; 95% CI 1.41, 1.52 for Rochester and 1.38; 95% CI 1.37, 1.39 for LaGuardia) compared to those living >5 miles. We did not find positive associations between wind-flow patterns and respiratory hospital admissions among the residents in any airport vicinity. No differences were observed for MacArthur airport using either exposure measure.

**Conclusion:** There is the suggestion that residential proximity to some airports may increase hospital admissions for respiratory disorders. However, there are many factors that could influence this association that may differ by airport, which should be measured and studied further.

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## Public health impact of large airports

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### Abstract

Large airports with the related infrastructure, businesses and industrial activities affect the health of the population living, travelling and working in the surroundings of or at the airport. The employment and contributions to economy from the airport and related operations are expected to have a beneficial effect, which, however, is difficult to quantify. More pertinent data are available on the, largely negative, health effects of environmental factors, such as air and soil pollution, noise, accident risk, and landscape changes. Information on the concurrent and cumulative impact of these factors is lacking, but is of primary relevance for public health policy. A committee of the Health Council of The Netherlands recently reviewed the data on the health impact of large airports. It was concluded that, generally, integrated health assessments are not available. Such assessments, as part of sustainable mobility policy, should accompany the further development of the global aviation system.

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