

Real-Time and Integrated Measurement of Potential Human Exposure to Particle-Bound Polycyclic Aromatic Hydrocarbons (PAHs) from Aircraft Exhaust

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We used real-time monitors and low-volume air samplers to measure the potential human exposure to airborne polycyclic aromatic hydrocarbon (PAH) concentrations during various flight-related and ground-support activities of C-130H aircraft at an Air National Guard base. We used three types of photoelectric aerosol sensors (PASs) to measure real-time concentrations of particle-bound PAHs in a break room, downwind from a C-130H aircraft during a four-engine run-up test, in a maintenance hangar, in a C-130H aircraft cargo bay during cargo-drop training, downwind from aerospace ground equipment (AGE), and in a C-130H aircraft cargo bay during engine running on/off (ERO) loading and backup exercises. Two low-volume air samplers were collocated with the real-time monitors for all monitoring events except those in the break room and during in-flight activities. Total PAH concentrations in the integrated-air samples followed a general trend: downwind from two AGE units > ERO-loading exercise > four-engine run-up test > maintenance hangar during taxi and takeoff > background measurements in maintenance hangar. Each PAH profile was dominated by naphthalene, the alkyl-substituted naphthalenes, and other PAHs expected to be in the vapor phase. We also found particle-bound PAHs, such as fluoranthene, pyrene, and benzo[*a*]pyrene in some of the sample extracts. During flight-related exercises, total PAH concentrations in the integrated-air samples were 10–25 times higher than those commonly found in ambient air. Real-time monitor mean responses generally followed the integrated-air sample trends. These monitors provided a semiquantitative temporal profile of ambient PAH concentrations and showed that PAH concentrations can fluctuate rapidly from a baseline level < 20 to > 4,000 ng/m³ during flight-related activities. Small handheld models of the PAS monitors exhibited potential for assessing incidental personal exposure to particle-bound PAHs in engine exhaust and for serving as a real-time dosimeter to indicate when respiratory protection is advisable. **Key words** engine exhaust, human exposure, integrated-air samplers, JP-8 fuel, PAH, polycyclic aromatic hydrocarbons, real-time PAH monitors. *Environ Health Perspect* 108:853–862 (2000). [Online 31 July 2000]

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The potential exposure of maintenance personnel, flight crews, and passengers to aircraft fuels and exhaust is of concern to the military and the commercial airline industry. To address these concerns, the National Exposure Research Laboratory of the U.S. Environmental Protection Agency and the U.S. Air Force (USAF) Surgeon General's Office initiated a collaborative methods development program to characterize the exposure of military and civilian personnel to aircraft fuels and exhaust at or near airports, in maintenance hangars, and during flight-related activities.

To date, significant effort has been directed toward developing methods and making exploratory measurements to assess human exposure to volatile organic compounds (VOCs) in JP-8 aircraft fuel (1–3). Parallel efforts are currently under way to characterize exposure to VOCs, semivolatile organic compounds (SVOCs), and non-volatile organic compounds (NVOCs) in aircraft exhaust. One class of SVOCs and NVOCs associated with aircraft exhaust that is of particular concern is polycyclic aromatic hydrocarbons (PAHs). These compounds

are formed by the incomplete combustion of fossil fuels and other organic matter (4) and are distributed into the air in the vapor phase or the particulate phase through adsorption or condensation on the surface of respirable particles (5,6). Several PAHs are listed by the National Toxicology Program as “reasonably anticipated to be a human carcinogen” (7). PAHs ranked as probable human carcinogens are primarily associated with the particulate phase. Therefore, the characterization of incidental or chronic inhalation exposure to particle-bound PAHs in aircraft exhaust is critical to assessing the health risks related to aircraft support, maintenance, and usage.

PAH concentrations in ambient air or indoor microenvironments are typically determined by using integrated-air samplers to collect vapor-phase and particle-bound PAHs on a combination filter/sorbent cartridge (8). The collected PAHs are extracted from the cartridge with a suitable solvent and then quantified using an appropriate analytical technique such as gas chromatography/mass spectrometry (GC/MS) or high-performance liquid chromatography. This

multistep sampling and analysis method provides chemical speciation of the PAHs in the air sample and can be used to determine the average exposure to specific PAHs during a given monitoring period. This method, however, does not produce a direct report of real-time PAH concentrations or a temporal record of acute exposures during episodes of high PAH emissions. In addition, integrated-air sampling laboratory analysis procedures are time-consuming, labor intensive, and expensive. These drawbacks led to the development (9–13) and evaluation of real-time PAH monitors (14–23).

One real-time monitor for measuring airborne particle-bound PAHs is based on a photoelectric aerosol sensor (PAS) (9–13). When particles coated with a submonolayer of PAH are irradiated with ultraviolet (UV) light that has an energy above the photoelectric threshold of the surface-bound PAH, the particle will emit a photoelectron and become positively charged. In a PAS system these positively charged particles are collected on a filter electrometer. The current measured across the electrometer is proportional to the number of charged particles created by the photoemission process. Strong correlations between the PAS response and total PAH (13–16,22,23) or individual PAHs, such as benzo[*a*]pyrene (17), have been

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documented in laboratory and field experiments. The PAS response is related to particle size, surface coverage, photoionization potential, molecular structure, and geometry of specific PAHs (12,16). The photoelectric threshold is lower for PAHs with a large π -electron system (12). Therefore, the photoionization process is more efficient for larger PAHs, i.e., those containing four or more fused aromatic rings, which are typically associated with the particulate phase (5,6). Vapor-phase PAHs are not photoionized by UV light (22), and large particles have a high probability of recapturing the emitted photoelectron. The PAS system therefore is presumed to respond to surface-bound PAHs on ultrafine particles only.

Different versions of prototype and commercially available PAS systems have been used to measure PAHs in cigarette smoke (17) and respirable particles from environmental tobacco smoke (18), in an occupied townhouse during typical daily activities (19), in motor vehicles during commuting (20), in emissions from oil-burning stoves (16), in ambient air impacted by vehicle emissions (16,21), and in indoor and ambient air of homes and offices (22,23). Because the PAS signal represents the sum of the photoelectric responses of all surface-bound PAHs (24), these monitors do not provide information about the presence or concentrations of individual PAHs. Therefore, a combination of integrated-air samplers and real-time monitors should be used to completely characterize the PAH emissions from a specific source.

We conducted preliminary studies with a prototype handheld PAS at Little Rock Air Force Base, Little Rock, Arkansas, and Hartsfield Airport, Atlanta, Georgia (25). These studies showed that the monitor exhibited an elevated response during various flight-related activities and that JP-8 fuel vapors did not interfere with the baseline response of the monitor. Based on these results, a more detailed assessment of flight personnel exposure to PAHs was conducted during a USAF-sponsored engine emission surveillance of C-130H aircraft flight crews and ground personnel during various training exercises at the Savannah Air National Guard base, Savannah, Georgia, from 4 to 6 May 1999. We used three types of real-time monitors to measure in duplicate the concentrations of airborne PAHs in a break room, downwind from a C-130H aircraft during a four-engine run-up test, in a maintenance hangar, in the cargo bay of a C-130H aircraft during cargo-drop training exercises, downwind from aerospace ground equipment (AGE), and in the cargo bay of a C-130H aircraft during an engine running on/off (ERO) loading maneuver and backup

exercises. Two of each type of real-time PAH monitor and two low-volume air samplers equipped with an XAD-2/quartz-fiber filter cartridge and a particle-size selective inlet were collocated during all of the monitoring events except for those in the break room and during in-flight activities.

These studies were conducted to characterize the PAH profile of JP-8 exhaust and identify specific sources of PAHs associated with various flight-related activities; to determine the relative concentrations of PAHs present during each activity to help USAF personnel ascertain which activities warrant the use of personal respiratory protective equipment; and to evaluate the use of a handheld PAS as a screening tool for estimating real-time concentrations of PAHs in engine exhaust.

Materials and Methods

Photoelectric aerosol sensors. We used three types of PAS monitors during this study: the PAS1002i; the PAS2000; and the PAS2000CE (EcoChem Analytics, West Hills, CA). Although the physical phenomenon measured by each instrument is the same, these monitors differ in many aspects, including the type of excitation sources used to photoionize the particle-bound PAHs, the sample flow rate, data storage and retrieval capabilities, power requirements, and size. Salient characteristics of the three types of PAS monitors used in this study are summarized in Table 1.

The PAS1002i model uses a 185-nm emission line from a mercury arc lamp to photoionize particle-bound PAHs. This desktop model is 17.5 × 45 × 32.5 cm, weighs 10.5 kg, and operates on 115-V/60-Hz power. The Hg arc lamp needs approximately 0.5 hr to warm up before data are collected. Air is drawn into the instrument by an internal pump at a flow rate of 4 L/min. The monitor output is in picoamps and is not precalibrated. General calibrations based on empirical evidence indicate that the PAS1002i monitor output corresponds to approximately 1,000 ng/m³ total PAH per picoamp (22). The continuous output of the monitor over the 0–20 pA range was sampled and stored at 10-sec intervals with an external data logger (Rustrak, East Greenwich, RI).

The PAS2000 desktop monitor uses a KrCl excimer laser operating at 222 nm as the photoionization source. In contrast to the continuous operation of the Hg arc lamp in the PAS1002i, the excimer laser of the PAS2000 operates on an on/off cycle. The cycle of the excimer laser is typically 4 sec on and 4 sec off. The PAS2000 is microprocessor controlled with internal data acquisition and storage. Approximately 14,000 data points can be stored in the internal memory. Stored data can be downloaded to a personal computer (PC) via an RS-232 cable. The PAS2000 output can also be monitored and stored on a PC or data logger in real time. Several parameters must be selected on the PAS2000 before collecting data, including measuring range, current output, signal filtering, and lamp parameters. These parameters were set as follows for this study: measuring range, 0–1,000 fA; current output, 0–20 mA; signal filtering, 48 sec; and duty cycle, 4 sec. This desktop model is 13.5 × 31.5 × 23.5 cm, weighs 9.1 kg, and operates on either 115 V/60 Hz or 220 V/50 Hz. The monitor is designed to operate in an ambient temperature range of 5–40°C and does not require a warm-up period. The sample flow rate is 2 L/min. The output of the monitor is in femtoamps, with an approximate calibration of 0.3–1 ng/m³ particle-bound PAHs per femtoamp.

The PAS2000CE monitor is based on the same operating principle as the PAS2000 except that the excitation source is a KrBr excimer laser operating at 207 nm. We refer to it as the handheld monitor to distinguish it from the larger models (Table 1); for most of these tests it was not literally handheld but collocated with the other monitors. Like the PAS2000, the excimer laser of the PAS2000CE is cycled on and off. The displayed measurement value represents an average value of the last six measurements. Measurements can be taken at 10-, 20-, 30-, 60-, and 120-sec intervals. For this study we took measurements at 10-sec intervals. Approximately 7,500 measurement values can be stored in the internal memory. Stored data can be downloaded from the internal memory to a PC and cleared as warranted. The sample flow rate is 1 L/min. The PAS2000CE is smaller (7.5 × 13 × 18 cm) than the PAS2000 and weighs only 1.4 kg.

Table 1. Operational characteristics of real-time PAH monitors.

Model no.	Mounting requirements	UV source	Operating wavelength (nm)	Dimensions (cm)	Weight (kg)	Power requirements
PAS1002i	Desktop or rack mount	Hg arc lamp	185	17.5 × 45 × 32.5	10.5	115V/60Hz
PAS2000	Desktop or rack mount	KrCl excimer laser	222	13.5 × 31.5 × 23.5	9.1	115V/60Hz or 220V/50Hz
PAS2000CE	Handheld	KrBr excimer laser	207	7.5 × 13 × 18	1.4	Internal battery or 110V/220V

This monitor is battery operated, with a capacity between 4 and 6 hr of continuous operation, and does not require a warm-up period. The instrument can also be powered directly with an external power supply/charger that can be operated at either 230 or 110 V. The output of this monitor is a direct reading of the total concentration of particle-bound PAHs in nanograms per cubic meter and is calibrated by the manufacturer.

Integrated-air samples. We collected integrated-air samples using Zephyr low-volume air samplers (Battelle, Columbus, OH) designed for sampling PAHs and related SVOCs in indoor air for chemical analysis (26). These samplers consist of a carbon vane pump, a manual valve to set the flow rate, and an aluminum canister to hold the XAD-2/filter cartridge. The pump and associated hardware are contained in a transportable 35 × 51 × 21 cm case. A 2.5- μ m cut-point inlet, which is designed for use at 10 L/min, was positioned upstream from the cartridge assembly (27). The flow rate of the sampler is adjustable from approximately 5–25 L/min and was set at 10 L/min to meet the specifications of the inlet device. We measured the flow rate once the cartridge was loaded into the canister and after sampling was completed. We multiplied the average of these two values by the elapsed sampling time to determine the total volume of air sampled during each monitoring session.

We prepared the XAD-2 resin (Amberlite XAD-2 resin; Supelco, Inc., Bellefonte, PA), quartz-fiber filters, and associated hardware for the sample cartridges by established procedures (26,28). Each cartridge contained one quartz-fiber filter, which was backed by approximately 30 g cleaned XAD-2 resin. The sample cartridges used during this study had been previously assembled and stored. Before the field study, the cartridges were extracted for 18–24 hr in dichloromethane in a Soxhlet apparatus, dried in a vacuum oven at 60°C under nitrogen for 4–6 hr, packed in a precleaned glass jar, and sealed for transport to the field site. After sampling in the field, the cartridges were stored in a freezer and then transported to the laboratory in an ice chest packed with blue ice.

On return from the field, the sampled XAD-2/quartz-fiber filter cartridges were unpacked, examined, logged in a notebook, and then stored at –20°C; maximum storage time for cartridges was 12 days. Before extraction of the analyte chemicals, we allowed the cartridges to equilibrate to room temperature. We added a 10- μ L aliquot of a surrogate recovery standard solution containing 100 ng/ μ L fluorene-*d*₁₀ and fluoranthene-*d*₁₀ (AccuStandard, New Haven, CT) to each cartridge before extraction. The assembled XAD-2/quartz-fiber filter cartridge

was inserted into the Soxhlet head and the cartridges were extracted for 24 hr in 300 mL dichloromethane. The sample extracts were concentrated to approximately 5 mL using a rotary evaporation apparatus and then transferred to concentrator tubes. The flask was rinsed with 1–2 mL dichloromethane, which was also transferred to the concentrator tubes. We added a 0.9-mL aliquot of toluene to the concentrator tube to exchange the solvent. The extract was further concentrated to approximately 0.5 mL with mild warming under a gentle nitrogen stream. A 10- μ L aliquot of an internal standard solution containing 100 ng/ μ L perdeuterated naphthalene, acenaphthene, chrysene, and perylene (AccuStandard) was added to the extract and the volume was adjusted to 1.0 mL with toluene. The extracts were then transferred to 1.5-mL sealed vials and stored at 4°C. Maximum storage time for extracts was 10 days.

We used laboratory and field blanks to determine if any contamination occurred during sampling, shipping, and sample preparation. We used one laboratory blank and one field blank during this study. These blank cartridges were extracted and analyzed by the same procedures used for the field samples.

GC/MS analysis of sample extracts. All GC/MS analyses were carried out on a Hewlett-Packard (HP) (Palo Alto, CA) 5989A mass spectrometer, which was interfaced to an HP-5890 Series II GC. The GC was equipped with a 25-m × 0.2-mm DB-5MS capillary fused-silica column with 0.33- μ m film thickness (J&W Scientific, Folsom, CA) and a 5-m × 0.32-mm uncoated deactivated fused-silica guard column. We made a 1- μ L injection of each sample extract using the manual on-column injector. The GC/MS

system was operated in the electron-impact mode with a source voltage of 70 eV and a source temperature of 275°C. The transfer line was also held at 275°C. The oven temperature was programmed as follows: hold for 1 min at 100°C, increase at 4°C/min to 310°C, and hold for 5 min. Quantitative data for the target PAHs were acquired in the selected-ion monitoring mode. The GC/MS system was tuned to perfluorotributylamine and calibrated with standard solutions (AccuStandard) with concentrations ranging from 20 to 2,000 pg/ μ L of the target PAH. A stock solution (AccuStandard) containing 4.0 mg/mL perdeuterated naphthalene, acenaphthene, chrysene, and perylene was diluted to 100 ng/ μ L in toluene and added to each calibration standard as an internal standard at a final concentration of 1,000 pg/ μ L. The GC/MS analysis reported the concentration of each target PAH in picograms per microliter. These concentrations were normalized to those of the surrogate recovery standards fluorene-*d*₁₀ or fluoranthene-*d*₁₀ to correct for sample loss during the extraction and concentration steps. The normalized concentrations were then corrected for the field blank by subtracting the concentration values of the field blank from those in the sample extracts. We used these blank-corrected concentrations in picograms per microliter to determine the total mass in nanograms of the target PAH in the sample extracts. We determined ambient concentrations in nanograms per cubic meter by dividing the mass of the target PAH in the sample extract by the total volume of air sampled during the monitoring event.

Results

The dates, start time, end time, location, descriptions, and brief notes for each sampling event are given in Table 2. In general,

Table 2. Sampling schedule during field study.

Date, start–end time	Location	Event	Monitors/samplers	Notes
4 May 1999, 1152–1307	Break room	Background measurements	All PAS monitors	No known emission sources
4 May 1999, 1405–1517	Tarmac	Four-engine run-up tests	All PAS monitors and integrated-air samplers	Intermittent power failures
5 May 1999, 1047–1333	Hangar	Background measurements	All PAS monitors and integrated-air samplers	Hangar door partially closed because of rain
5 May 1999, 1343–1617	Hangar	Taxi and takeoff maneuvers	PAS1002i, PAS2000, and integrated-air samplers	Samplers near open door
5 May 1999, 1343–1617	Cargo bay of C-130H aircraft	Training drop	PAS2000CE monitors	Monitors in cargo bay during flight operations
6 May 1999, 1030–1145	Tarmac	AGE equipment	All PAS monitors and integrated-air samplers	Generator and heater units operating
6 May 1999, 1219–1313	Cargo bay of C-130H aircraft	ERO-loading exercise	All PAS monitors and integrated-air samplers	Cargo bay and aft doors open
6 May 1999, 1314–1330	Cargo bay and cockpit of C-130H	Backup maneuver	PAS2000CE monitors in cockpit and cargo bay	Cargo bay open

the weather was sunny, breezy, and warm, ranging from approximately 24 to 32°C; at one time (approximately noon on 5 May) there was a brief light rain. The sampling schedule was dictated by the training schedule of the Air National Guard unit and coordinated with the personal exposure sampling that was being conducted by the USAF personnel. Where possible, two real-time monitors of each type and two integrated-air samplers were collocated during the sampling event. Unless otherwise noted, the response of the real-time monitors is reported as the average between two similar collocated instruments. During some exercises—for example, the cargo-drop training flight—only the battery-operated PAS2000CE monitors were used because of power restrictions onboard the aircraft. During this training flight the PAS1002i and PAS2000 desktop monitors and the integrated-air samplers were located in the maintenance hangar.

Background measurements in break room. We measured indoor levels of PAHs in a break room of a building attached to the maintenance hangar with the real-time monitors on 4 May 1999. Measurements were not taken with the integrated-air samplers in this location because of the low PAH levels and the relatively short sampling time. This room is located down a hallway from an entrance to the maintenance hangar and is adjacent to a room used by base personnel for lunch breaks. The building is designated a nonsmoking area and there are no known emission sources near the room. All six real-time monitors were set up in the break room and were allowed to warm up for approximately 1 hr. Data were recorded from 1152 to 1307 hr. The mean responses of each type of monitor during this period were 14.1 ng/m³ for the PAS2000CE, 0.04 pA for the PAS1002i, and 3.23 fA for the PAS2000 (Table 3). These values were near the baseline response of each type of monitor and indicated that the PAH concentrations in the break room were negligible and that the monitors all agreed qualitatively. To provide a link between various instrument responses and ambient concentrations, we also converted

the picoamp and femtoamp outputs to estimated nanograms per cubic meter based on the manufacturer's recommended conversion factors and included the conversion in Table 3. We realize that the use of universal conversion factors is not the optimal method of generating quantitative concentration data; this issue is discussed further in "Conclusions."

Downwind measurements during four-engine run-up test on flight tarmac. We used the real-time monitors and integrated-air samplers to measure ambient PAH concentrations on the flight tarmac during a four-engine run-up test on 4 May 1999. The equipment was set up on a table that was located approximately 20 m downwind and to the side of the C-130H aircraft (Figure 1). Sampling began at 1405 and the four-engine run-up test started at 1414 when the auxiliary power unit (APU) of the aircraft was engaged. There were intermittent power outages to the monitoring equipment during this exercise; therefore, the real-time data collected by the PAS1002i and PAS2000 monitors for this event have some short breaks. The pumps on the integrated-air samplers also shut off during these power outages. For all subsequent calculations and comparisons, we adjusted the total sampling times for the integrated-air samplers and used only the simultaneously collected real-time data. As such, the comparisons in Table 3 are all valid. We found that the monitors were not obviously affected by these power interruptions, nor were they susceptible to any obvious memory effects from overranging events; we tested this in the laboratory with qualitative sources and filtered air and also observed it in the field sampling as indicated by the example data plots in Figure 2. However, without a reliable in-field zero and span check method these issues are open to further investigation.

The two handheld battery-operated PAS2000CE monitors provided a complete profile of the ambient PAH concentrations during this test. The average response of these monitors fluctuated between the baseline noise level and nearly 1,000 ng/m³

before the engines were started (Figure 2). One engine was started at 1436 and the remaining engines were started in sequence over the next 4 min. The average response of the PAS2000CE monitors increased to approximately 2,500 ng/m³ during the engine startup sequence and reached a level of 4,000 ng/m³, the maximum output of the monitor, during the high-idle engine test. We moved the monitoring equipment approximately 10 m further away from the aircraft at 1450 to escape the swirling winds generated by the aircraft engines. The average response of the PAS2000CE monitors decreased after this move, although they still registered values > 2,000 ng/m³. The engines were put on low idle at 1509 and three of the engines were shut off at 1512. The average response of the PAS2000CE monitors decreased to < 500 ng/m³ at this time. One engine and the APU were still on when the monitoring equipment was turned off at 1517. The responses of the other real-time monitors exhibited similar trends during this exercise, although significant segments were missed because of the intermittent power outages. The mean responses of the PAS2000CE, PAS1002i, and PAS2000 monitors during this exercise were 568 ng/m³, 6.41 pA, and 774 fA, respectively (Table 3). Again, we also included estimated concentration values.

The ambient PAH concentrations measured by the integrated-air samplers during the four-engine run-up test are reported in Table 4. The sample extract from one of the integrated-air samples collected during this test did not meet the quality control (QC) requirements ($\pm 50\%$) for the surrogate recovery standard and is not included in the data set. The PAH concentration profile of this activity was dominated by naphthalene, the alkyl-substituted naphthalenes, and other PAHs expected to be in the vapor phase. The concentrations of PAHs expected to be in the particulate phase (i.e., fluoranthene and larger PAHs) were, with the exception of benzo[a]pyrene and perylene, below the method detection limits (MDLs).

Table 3. Summary of mean responses of real-time monitors during each monitoring event.

Date	Location/event	PAS2000CE ^a	PAS1002i ^a	PAS2000 ^b
04 May 1999	Break room/background	14.1 ng/m ³	0.04 pA (40 ng/m ³)	3.23 fA (0.97–3.2 ng/m ³)
04 May 1999	Tarmac/engine run-up	568 ng/m ³	6.41 pA (641 ng/m ³)	774 fA (232–774 ng/m ³)
05 May 1999	Hangar/background	14.8 ng/m ³	0.05 pA (50 ng/m ³)	4.37 fA (1.3–4.4 ng/m ³)
05 May 1999	Hangar/taxi and takeoff	NA ^c	0.40 pA (400 ng/m ³)	55.7 fA (16.7–56 ng/m ³)
05 May 1999	Cargo bay/training drop	50.6 ng/m ³	NA ^c	NA ^c
06 May 1999	Tarmac/AGE	21.9 ng/m ³	0.78 pA (780 ng/m ³)	NA ^d
06 May 1999	Cargo bay/ERO-loading	1,009 ng/m ³	4.42 pA (4,420 ng/m ³)	496 fA (149–496 ng/m ³)

The nanogram per cubic meter values in parentheses for PAS1002i and PAS2000 instruments are estimated based on the manufacturer's recommendations.

^aReported as the average response of two collocated monitors. ^bThe response of only one PAS2000 monitor is reported.

^cThe measurement is not available for that monitor. ^dThe PAS2000 monitor exhibited an erratic baseline during this monitoring period.



Figure 1. Photograph of the sampling equipment positioned downwind from a C-130H aircraft during a four-engine run-up test on 4 May 1999.

Measurements in maintenance hangar.

Two sets of measurements were taken in the maintenance hangar on 5 May 1999. We took background measurements from 1047 to 1333, when there was minimal flight and ground-support activity, and we took another set of measurements from 1343 to 1617, when two C-130H aircraft were prepared for flight, taxied, and then took off on a nearby runway. The monitoring equipment was set up near the main door of the hangar, which was completely open during most of the background measurements. The main door was partially closed at 1135 because of the onset of light rain and then reopened at approximately 1340 before the taxi and takeoff.

The mean responses of the real-time monitors during the background measurements in the maintenance hangar were similar to those measured the previous day in the break room (Table 3). The PAH concentrations in the integrated-air samples collected during this monitoring period were higher than those in the field blank but were generally lower than those measured during the four-engine run-up test (Table 4). Again, naphthalene, the alkyl-substituted naphthalenes, and other vapor-phase PAHs exhibited the highest concentrations. The concentrations of the particle-bound PAHs were below the MDLs for this activity. Because the extract for one of the integrated-air samples did not meet the QC requirements for the surrogate recovery standard, we report the concentration data for only one sample extract. However, this invalid sample extract was from a different sampler than the extract that failed the QC requirements for the four-engine run-up test.

After the background measurements in the maintenance hangar were completed, two C-130H aircraft were prepared for takeoff.

The PAS1002i and PAS2000 desktop monitors and integrated-air samplers remained in the doorway of the maintenance hangar and the battery-operated PAS2000CE monitors were placed onboard one of the C-130H aircraft. Figure 3 shows the average response of

the two PAS1002i monitors during this period. The two C-130H aircraft taxied and turned approximately 50 m in front of the door so that aircraft engine exhaust was directed toward the door of the maintenance hangar. The average response of the

Table 4. Average \pm SD PAH concentrations (in ng/m^3) in integrated-air samples.

Activity/location	Engine run-up ^a	Hangar/background ^b	Hangar/taxiing ^b	AGE ^c	ERO loading ^c
Naphthalene	756.1	137.0	245.3 \pm 5.9	1363.5 \pm 84.4	1714.3 \pm 428.6
2-Methylnaphthalene	733.4	154.2	251.5 \pm 15.7	2128.5 \pm 174.4	1694.8 \pm 378.6
1-Methylnaphthalene	517.3	91.7	164.3 \pm 5.4	1457.9 \pm 154.9	1361.9 \pm 266.6
1,1'-Biphenyl	171.1	35.0	50.1 \pm 5.8	515.6 \pm 34.3	270.7 \pm 55.8
1-Ethyl/2-ethylnaphthalene	146.6	29.2	59.8 \pm 6.0	597.8 \pm 21.2	410.9 \pm 73.3
2,6-Dimethylnaphthalene	137.3	35.8	51.5 \pm 3.9	691.7 \pm 11.4	338.8 \pm 75.2
1,6-Dimethylnaphthalene	196.6	46.4	73.0 \pm 1.8	879.2 \pm 34.8	475.7 \pm 77.2
Acenaphthylene	16.4	2.3	6.3 \pm 1.9	142.3 \pm 11.1	104.2 \pm 14.8
Acenaphthene	28.8	9.8	15.3 \pm 1.3	87.5 \pm 11.6	36.8 \pm 2.8
2,3,5-Trimethylnaphthalene	9.7	10.2	24.7 \pm 0.7	242.0 \pm 7.1	42.5 \pm 3.7
Fluorene	20.8	10.5	18.9 \pm 0.9	231.7 \pm 31.1	82.0 \pm 5.3
1-Methyl-9H-fluorene	23.8	8.4	16.8 \pm 0.8	279.2 \pm 26.2	72.6 \pm 26.8
Dibenzothiophene	2.3	1.4	1.3 \pm 0.4	14.7 \pm 5.5	1.5 \pm 1.4
Phenanthrene	25.0	16.6	24.1 \pm 5.0	278.5 \pm 31.3	70.1 \pm 4.0
Anthracene	9.7	1.7	0.0 \pm 0.0	27.8 \pm 14.7	6.6 \pm 2.3
2-Methylphenanthrene	0.9	7.0	12.9 \pm 0.0	342.8 \pm 23.4	35.9 \pm 3.3
2-Methylanthracene	0.0	1.5	0.9 \pm 0.8	41.1 \pm 11.7	1.2 \pm 0.1
1-Methylphenanthrene	0.0	1.9	3.7 \pm 0.1	120.6 \pm 27.7	12.9 \pm 0.7
9-Methylanthracene	0.0	0.0	0.7 \pm 0.7	9.9 \pm 0.0	1.8 \pm 1.8
3,6-Dimethylphenanthrene	0.0	0.0	2.4 \pm 0.4	101.1 \pm 12.0	11.9 \pm 3.8
Fluoranthene	0.0	0.0	0.0 \pm 0.0	17.8 \pm 7.2	0.0 \pm 0.0
Pyrene	0.0	0.0	0.9 \pm 1.4	189.4 \pm 25.8	42.9 \pm 3.7
9,10-Dimethylanthracene	0.0	0.0	0.0 \pm 0.0	30.0 \pm 13.2	0.0 \pm 0.0
1-Methylpyrene	0.0	0.0	0.0 \pm 0.0	14.6 \pm 1.6	2.7 \pm 2.7
Benz[<i>a</i>]anthracene	0.0	0.0	0.0 \pm 0.0	0.0 \pm 0.0	0.0 \pm 0.0
Chrysene	0.0	0.0	0.0 \pm 0.0	0.0 \pm 0.0	0.0 \pm 0.0
Benzo[<i>b</i>]fluoranthene	0.0	0.0	0.0 \pm 0.0	0.0 \pm 0.0	0.0 \pm 0.0
Benzo[<i>k</i>]fluoranthene	0.0	0.0	0.0 \pm 0.0	0.3 \pm 0.6	0.0 \pm 0.0
Benzo[<i>e</i>]pyrene	0.0	0.0	0.0 \pm 0.0	0.0 \pm 0.0	0.0 \pm 0.0
Benzo[<i>a</i>]pyrene	4.1	0.1	0.5 \pm 0.0	4.0 \pm 0.6	0.8 \pm 1.0
Perylene	2.9	0.1	0.5 \pm 0.1	1.4 \pm 0.4	1.9 \pm 2.1
Indeno[1,2,3- <i>cd</i>]pyrene	0.0	0.0	0.0 \pm 0.0	0.0 \pm 0.0	0.0 \pm 0.0
Dibenzo[<i>ah</i>]anthracene	0.0	0.0	0.0 \pm 0.0	0.0 \pm 0.0	0.0 \pm 0.0
Benzo[<i>ghi</i>]perylene	0.0	0.0	0.0 \pm 0.0	0.0 \pm 0.0	0.0 \pm 0.0
Total PAH	2802.7	601.1	1025.4	9811.1	6795.3
Total parent PAH	1034.8	213.3	361.9	2859.8	2330.2
Parent PAH fluoranthene	7.0	0.3	1.9	213.0	45.5

^a4 May 1999. ^b5 May 1999. ^c6 May 1999.

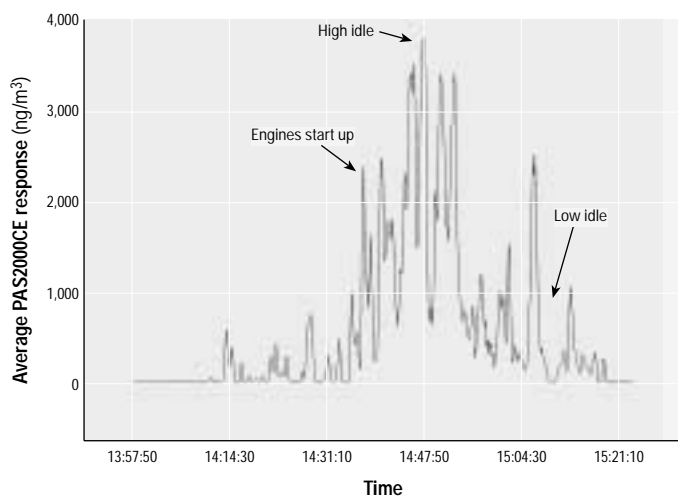


Figure 2. Average PAS2000CE response during a four-engine run-up test on 4 May 1999.

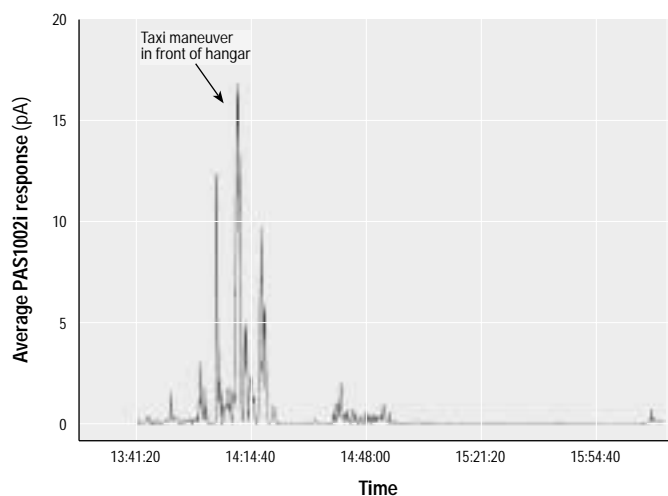


Figure 3. Average PAS1002i response in maintenance hangar during C-130H taxi and takeoff on 5 May 1999.

PAS1002i monitors reached a maximum of approximately 17 pA during the taxi maneuvers of the two aircraft. The average response of the PAS1002i monitors returned to baseline levels after both aircraft took off. A series of positive responses due to unknown origins was recorded for approximately 15 min starting at 1430 and a small response was registered at 1628. The mean response of the PAS1002i monitors was 0.40 pA during this monitoring session; that of the PAS2000 monitor was 55.7 fA. Both of these responses were at least 10 times higher than those observed during the background measurements in the break room and at least 8 times higher than those recorded earlier in the maintenance hangar when there was little to no flight activity (Table 3).

The concentrations of the vapor-phase PAHs in the integrated-air samples collected in the maintenance hangar during the taxi maneuvers were, on average, nearly 2 times greater than those measured during the background measurements in the hangar (Table 4). However, as was the case with the background measurements, the concentrations of most of the particle-bound PAHs were below the MDLs.

Measurements onboard a C-130H aircraft during practice cargo drops. The two handheld PAS2000CE monitors were taken onboard a C-130H aircraft during a cargo-drop training exercise on 5 May 1999. The average response of these two monitors during this activity is shown in Figure 4. The monitors were placed in a jump seat against the wall in the cargo bay of the C-130H aircraft at 1343. The average response of the PAS2000CE monitors was slightly above background levels during flight preparations. The aircraft prepared for takeoff at 1406 and began taxi maneuvers behind another C-130H aircraft at 1412. During this time, a

strong odor of engine exhaust was noticeable in the cargo bay and the average response of the PAS2000CE monitors exceeded 400 ng/m³. The aircraft took off at 1421 and flew in formation behind the other C-130H aircraft to an altitude of 3,000 ft. During normal flight operations, the average response of the PAS2000CE monitors was near background levels. At 1501 the ramp door at the rear of the cargo bay was opened and the simulated cargo was dropped at an altitude of 700 ft. The PAS2000CE monitors reached a maximum average response of approximately 100 ng/m³ while the rear door to the cargo bay was open. This door was closed at 1505 and the average response of the PAS2000CE monitors leveled off at approximately 30 ng/m³. At 1538 the aft port door was opened and the average response of the PAS2000CE monitors again reached approximately 100 ng/m³. The simulated cargo was dropped at 1543 and the aft port door was closed at 1544, after which the response again leveled off at approximately 30 ng/m³. The landing gear was engaged at 1603 and the aircraft landed at 1609. The bow port door was opened at 1611; the average response of the PAS2000CE monitors immediately exceeded 150 ng/m³ and then decreased to approximately 50 ng/m³ while the crew disembarked. The monitors were removed from the aircraft just after the engines were shut down. The mean response of the two PAS2000CE monitors during the simulated cargo-drop exercise was 50.6 ng/m³—more than 3 times the typical background levels.

Measurements downwind from aerospace ground equipment. On 6 May 1999 the monitoring equipment was set up on a table on the tarmac approximately 10 m downwind from two AGE units. Emissions from a diesel-powered electrical generator and a diesel-powered heater unit were monitored

during this activity. The average response of the two PAS2000CE portable monitors reached a maximum of approximately 1,750 ng/m³ when the generator and heater were started at 1032 (Figure 5). The average response was near baseline levels except when the AGE units were shut off at 1145, at which time the response reached a maximum of approximately 250 ng/m³. The mean response of the PAS2000CE monitors during this monitoring event was 21.9 ng/m³; that of the PAS1002i monitors was 0.78 pA (Table 3). The PAS2000 monitors exhibited erratic behavior during this event, so the data for these monitors are not reported. Although the mean response of the PAS2000CE handheld monitors during this event was only slightly higher than that observed during the background measurements, the mean response of the PAS1002i desktop monitors was approximately 20 times greater than the background levels.

The concentrations of the target PAHs in the integrated-air samples collected during this event were almost 10 times higher than those collected in the maintenance hangar during the taxi maneuvers and approximately 3.5 times higher than those collected on the tarmac during the four-engine run-up test (Table 4). Several PAHs that were not detected during the four-engine run-up test—for example, the methyl-substituted phenanthrenes and anthracenes, as well as fluoranthene and pyrene—were detected in the integrated-air samples collected downwind from the AGE units. The particle-bound PAHs larger than pyrene were generally below the MDLs for this event.

Measurements onboard a C-130H aircraft during ERO-loading and backup maneuvers. The monitoring equipment was set up on a table in the cargo bay of a C-130H aircraft during an ERO-loading

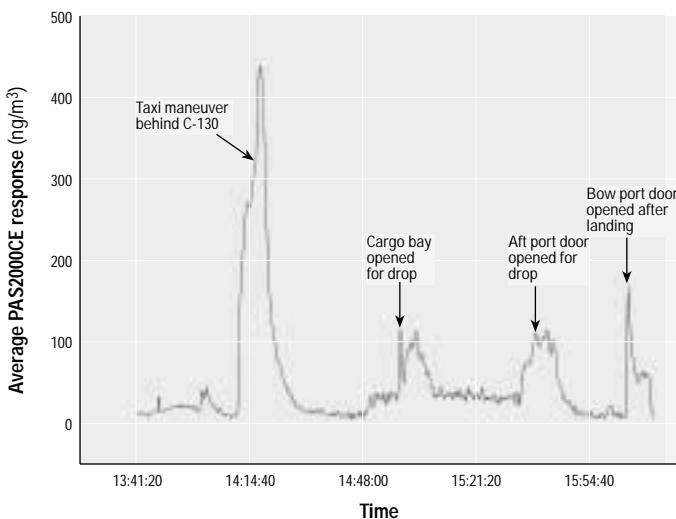


Figure 4. Average PAS2000CE response onboard a C-130H aircraft during a cargo-drop training exercise on 5 May 1999.

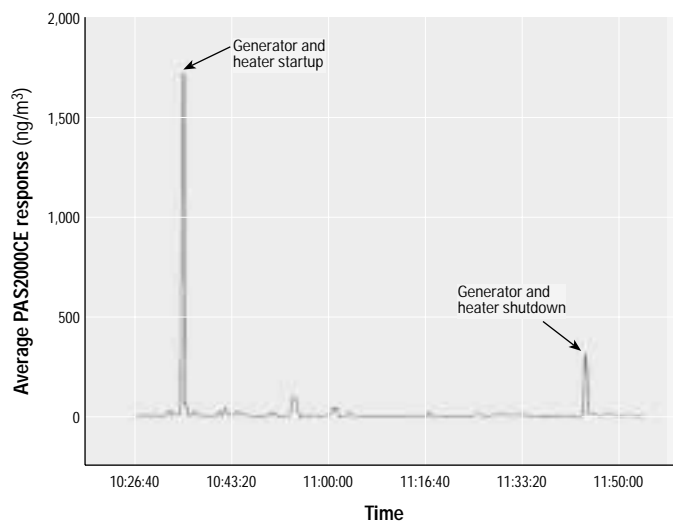


Figure 5. Average PAS2000CE response downwind from AGE units on 6 May 1999.

exercise on 6 May 1999 (Figure 6). The aft doors and the ramp to the cargo bay remained open during this event. Because the two PAS2000CE handheld monitors were positioned in different locations during some of these maneuvers, the monitor responses are plotted individually (Figure 7). The monitoring equipment was started at approximately 1219, before any activity commenced on the aircraft. A C-130H aircraft took off on an adjacent runway at approximately 1236, during which the responses of both PAS2000CE monitors approached 1,000 ng/m³. The APU to the C-130H aircraft on which the monitoring equipment was located was started at 1248; the engine startup sequence began at 1252. Soon after this sequence was completed, the response of both PAS2000CE monitors approached 4,000 ng/m³, the maximum output value of these instruments. The response of both monitors remained near this maximum throughout the high-idle engine tests. At 1258 the PAS2000CE monitors were briefly removed from the cargo bay and carried down the cargo ramp by the load master to the rear of the aircraft. No changes in the responses were observed during this time. The two PAS2000CE monitors were carried to the cockpit at 1307, at which time the response of the two monitors returned to baseline levels. The monitors were returned to the cargo bay at 1310 and the response returned to the maximum value of 4,000 ng/m³. The mean response of the two PAS2000CE monitors during this exercise was 1,009 ng/m³; the mean responses of the PAS1002i and PAS2000 monitors were 4.42 pA and 496 fA, respectively (Table 3).

At 1313, one PAS2000CE monitor was moved to the cockpit; the other PAS2000CE monitor remained in the cargo bay of the

aircraft. The other monitoring equipment was removed from the aircraft at this time. The aircraft then taxied to the runway and executed a backup maneuver with the cargo ramp door open. The response of the monitor in the cargo bay reached a maximum of 4,000 ng/m³ during this maneuver, whereas the maximum response of the monitor in the cockpit was < 1,000 ng/m³. The response of the PAS2000CE monitor in the cockpit during the backup maneuver was significantly higher than that measured in the cockpit during the ERO-loading exercise.

The monitors were removed from the aircraft at 1330 and returned to the maintenance hangar. The PAH concentrations in the hangar were slightly elevated from typical background levels during the time period immediately after the ERO-loading and backup exercises but returned to baseline values approximately 15 min after the maneuvers were completed.

The PAH concentrations in the integrated-air samples collected during the ERO-loading exercise were higher than those collected during all other events except the downwind monitoring of the AGE units (Table 4). Although the concentrations of selected PAHs, such as naphthalene, 2-methylnaphthalene, and 1-methylnaphthalene, were similar in the integrated-air samples collected during these two events, the concentrations of most of the target PAHs were significantly higher during the AGE monitoring session.

Discussion

We discuss the results from this preliminary study in terms of using integrated-air samplers and real-time monitors to produce concentration profiles of PAHs in engine exhaust associated with various flight-related activities;

comparing the capabilities of different types of real-time monitors for measuring PAH concentrations in ambient air and in microenvironments impacted by engine exhaust; investigating the relationship between the responses of the real-time monitors and total PAH concentrations determined from integrated-air samples; and estimating the airborne PAH concentrations to allow USAF personnel to assess the risks associated with different flight-related activities.

Concentration profiles of PAHs associated with various flight-related activities. The total PAH concentrations in integrated-air samples associated with various flight-related activities followed a general trend: downwind from two AGE units > ERO-loading exercise > four-engine run-up test > maintenance hangar during taxi and takeoff > background measurements in maintenance hangar. The PAH profiles for each activity were dominated by naphthalene, the alkyl-substituted naphthalenes, and other PAHs expected to be in the vapor phase. However, except for samples collected downwind from the AGE units and during the ERO-loading exercise, none of the integrated-air samples contained appreciable levels of particle-bound PAHs.

Overall, the same trends were evident in the mean responses of the real-time PAH monitors (with two exceptions). One deviation from this pattern was observed during the monitoring session conducted downwind from the AGE units. This event produced the highest PAH concentrations in the integrated-air samples. In contrast, except for peak responses during the startup and shutdown sequences of the AGE units, the mean response of the PAS2000CE handheld monitors was similar to the background levels in the break room and maintenance



Figure 6. Photograph of the real-time PAH monitors in the cargo bay of a C-130H aircraft during an ERO-loading exercise on 6 May 1999.

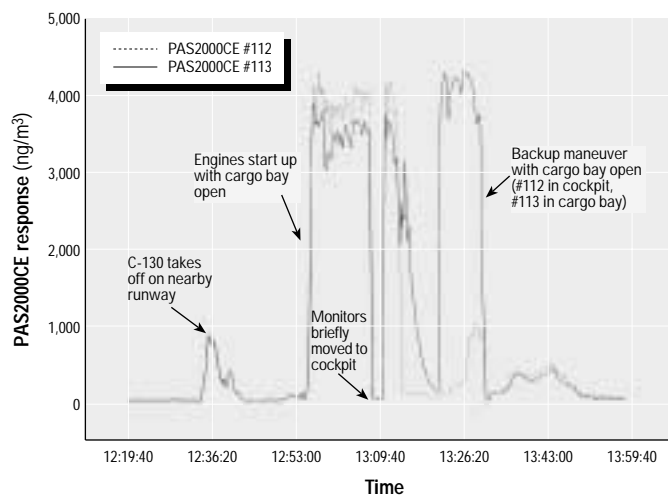


Figure 7. Response of two different PAS2000CE monitors in the cargo bay of a C-130H aircraft during an ERO-loading exercise and backup maneuvers on 6 May 1999.

hangar during limited or no flight activity. The mean response of the PAS1002i desktop monitors was nearly 2 times higher than typical background levels but did not approach the magnitude of responses observed during the four-engine run-up tests and ERO-loading exercises. One explanation for the apparent discrepancy between the response of the real-time monitors and the total PAH concentrations in the integrated-air samples while monitoring the AGE emissions is that the inlets for the collocated integrated-air samplers were positioned approximately 1 m above the inlets to the real-time monitors. An exhaust plume was observed when the AGE units were started; the plume was dispersed in the direction of the monitoring equipment by the prevailing wind. This plume appeared to intersect with the inlets of the integrated-air samplers but pass above the inlets of the real-time monitors. Therefore, although the real-time monitors registered a response during the high-emission events of startup and shutdown, they apparently were not in a position to monitor a representative volume of the exhaust plume from the AGE units.

The other deviation from the general trend observed with the integrated-air samplers was that the PAS1002i and PAS2000 desktop monitors exhibited the highest mean responses during the four-engine run-up test as opposed to the ERO-loading exercise. However, these monitors were off during extended times during the four-engine run-up test because of several intermittent power failures. The mean responses reported for these monitors were most likely artificially high because data were not recorded during low-emission periods before the engines were in the high-idle mode. The mean response of the battery-operated PAS2000CE monitors more accurately represents the relative concentrations of ambient PAHs during this test because these monitors were on during the entire monitoring period.

Comparison of real-time monitors. The response of each real-time monitor generally exhibited a good correlation with that of the collocated monitor of the same type. For example, the correlation coefficient (r^2) for the linear least-squares regression of the response of one PAS2000CE monitor versus that of the other PAS2000CE monitor during the four-engine run-up exercise was 0.95 with a slope (m) of 0.93 and intercept (b) of 19.7. The correlation between the two PAS2000CE monitors was better for the measurements onboard the C-130H aircraft during the training flight for practice cargo drops ($r^2 = 0.99$). Similarly, the correlation between the two PAS1002i desktop monitors during the engine run-up exercise was very good ($r^2 = 0.99$; $m = 0.92$; $b = -0.31$).

There were, however, significant differences between the responses of the two PAS2000 desktop monitors. The response of one PAS2000 monitor was nearly half that of the other during the engine run-up exercise ($m = 0.59$) and exhibited similar behavior during the other monitoring events. The excimer laser on one monitor had been replaced shortly before this study. At that time, the lamp frequency on the other PAS2000 monitor was adjusted so that its output under laboratory conditions matched that of the monitor with the new excimer laser. This adjustment, however, did not lead to similar outputs for these two monitors over the dynamic range of PAH concentrations observed during the monitoring events surveyed in this field study. Therefore, we report only the response of the PAS2000 monitor with the new excimer laser.

The relative responses of the different types of PAS monitors for each monitoring event cannot be directly compared because the output of the monitors either exhibited a limited range of values or exceeded the linear dynamic range of the instrument. When monitoring downwind from the AGE units, for example, each monitor exhibited peaks that corresponded to the startup and shutdown of the units but registered a response near the baseline for the remainder of the monitoring period. Therefore, most of the responses measured during this event were baseline values. In contrast, the output range of each type of monitor was exceeded for several minutes during the ERO-loading exercise, which prevented making a quantitative comparison of the monitors. Also, in some cases a direct comparison was not possible because the monitors were positioned in different locations. During the training cargo-drop exercise, for example, the PAS1002i and PAS2000 desktop monitors were located in the maintenance hangar, whereas the portable PAS2000CE instruments were onboard the aircraft. However, some comparisons of the different types of monitors can be made for selected monitoring events.

Time-series plots of the responses of each type of monitor generally exhibited the same trends and peak responses for each monitoring event. Even though the data for the PAS1002i monitor were incomplete for the four-engine run-up test because of intermittent power failures, there were enough data to allow the desktop PAS1002i monitor response to be compared with that of the handheld PAS2000CE monitor. The correlation between these two types of monitors for this activity is good ($r^2 = 0.76$, $m = 144$ ng/m³/pA, and $b = 375$ ng/m³). However, if a calibration factor of 1,000 ng/m³/pA is assumed for the PAS1002i monitor (22), the linear least-squares regression coefficients

indicate that, for example, a direct reading of 1,000 ng/m³ on the PAS2000CE monitor corresponds to a calibrated response of 4,332 ng/m³ on the PAS1002i. The response of the PAS2000 monitor generally did not correlate as well with the other real-time monitors and was often nonlinear relative to the responses of the other monitors.

Relationship between real-time monitors and integrated-air samplers. We investigated the relationship between the response of the real-time monitors and the total PAH concentrations in the integrated-air samplers by developing calibration factors for the real-time monitors. These calibration factors were estimated by dividing the total parent PAH concentrations determined from the integrated-air samples by the mean response of the real-time monitor during each monitoring period. We calculated calibration factors for each monitoring period during which the real-time monitors exhibited a mean response higher than background levels, including the four-engine run-up test; in the maintenance hangar during taxi and takeoff; downwind from the AGE units; and in the cargo bay of a C-130H aircraft during the ERO-loading exercise.

The response of the PAS1002i real-time monitor relative to the total concentration of parent PAH compounds in integrated-air samples has been reported as approximately 1,000 ng/m³/pA (22). Although the PAS devices in principle only respond to particle-bound PAHs, the calibration factors are generally reported in terms of the total (vapor phase and particle bound) integrated PAH concentrations. The estimated calibration factor of the PAS1002i monitors for measurements in the maintenance hangar during taxi and takeoff was 904.8 ng/m³/pA, which is near the reported value (22). However, the calibration factors for the PAS1002i monitors estimated during the four-engine run-up test and the ERO-loading exercise, 161 and 527 ng/m³/pA, respectively, were significantly lower than the expected value. This result indicates that for these two activities the response of the PAS1002i monitors was higher than expected relative to the total parent PAH concentrations in the integrated-air samples.

The estimated calibration factors of the small portable PAS2000CE monitors were similar during the four-engine run-up test and the ERO-loading exercise, e.g., a ratio of 1.8 and 2.3, respectively. The linear dynamic range (0–1,000 ng/m³) and the maximum output (4,000 ng/m³) of these monitors were exceeded during these tests. As a result these monitors most likely read lower than expected during the tests, which would yield an artificially high calibration factor. The calibration factor for these monitors during

the measurements downwind from the AGE units, a ratio of 131, was significantly higher than those measured during the other exercises. The PAS1002i monitors had an abnormally high calibration factor (3,666 ng/m³/fA) for this test. These estimated calibration factors are consistent with the conclusion that the exhaust plume from the AGE units was not adequately sampled by the real-time monitors during this event.

The calibration factors ranged from 1.3 to 6.5 ng/m³/fA for the PAS2000 desktop monitor during the different monitoring events. During the four-engine run-up test the calibration factor for this monitor, 1.3 ng/m³/fA, was similar to that of the PAS2000CE monitors, which was 1.8 for this event. However, the calculated calibration factors for the PAS2000 monitor were higher during the ERO-loading exercise (4.7 ng/m³/fA) and for measurements in the maintenance hangar during taxi and takeoff (6.5 ng/m³/fA).

Calibration factors for the real-time monitors' response to PAHs in aircraft engine exhaust were difficult to establish because of the small number of sampling events, the limited amount of monitoring time during each event, and the fact that the response of each type of monitor reached the upper limit of the dynamic range during some of the monitoring sessions. The number of sampling events and the amount of time allowed for each monitoring session were dictated by the training schedule of the National Guard unit. Therefore, we could only make a brief survey of the PAH concentrations associated with each flight-related activity.

The calibration factors calculated for each type of real-time monitor were variable and, in the case of the PAS1002i monitor, did not always agree with values reported previously. One reason for this variability was the low concentrations of particle-bound PAHs in the integrated-air samples during the monitoring events. The low-volume air samplers were designed to operate for 12–24 hr in ambient or indoor air to collect enough PAH sample for chemical analysis. During these monitoring events the measurement time ranged from 45 to 135 min. Although the concentrations of the PAH compounds in the microenvironments associated with the various flight-related activities were significantly higher than those typically found in ambient air, the concentrations of the particle-bound PAHs were below the MDLs of the integrated-air sampling method. These results were consistent with the personal exposure sampling for particulate matter conducted by USAF staff using an elemental carbon-base method (29), in which all of the samples were below the MDLs. The real-time monitors, in theory, only respond to

particle-bound PAHs. Extensive experiments showed that predecessors to the PAS1002i monitor did not respond to vapor-phase PAHs (22). Therefore, the mean responses of the real-time monitors during each monitoring period should be comparable to the quantitative results obtained for particle-bound PAHs in the integrated-air samples. Because of the low concentrations of particle-bound PAHs measured in the integrated-air samples, comparisons between the real-time monitor response and speciated PAHs were inconclusive in this study. Establishing defensible response factors for JP-8 fuel exhaust should become a major part of continuing work with these instruments.

Estimation of the health risk associated with various flight-related activities. The health risk associated with each flight-related activity is difficult to assess because there are currently no occupational exposure standards for specific PAHs (7). In lieu of workplace standards for PAHs, the exposure of flight crew and ground-support personnel to PAHs during the various flight-related activities surveyed in this study can be put into context by comparing these results to those obtained in other studies using comparable monitoring equipment. For example, the mean responses of the desktop PAS1002i monitors during background measurements in the break room and maintenance hangar were similar to those observed in ambient air near a residential site in a major metropolitan area (30). The maximum incidental exposure to PAHs in the maintenance hangar during taxi and takeoff maneuvers was nearly 2 times higher than that observed previously with the PAS1002i monitors in an office occupied by one to two smokers (31). The peak PAH concentrations measured by the portable PAS2000CE monitors in the cargo bay of a C-130H aircraft during the training cargo drop were similar to those measured with a prototype handheld monitor during a general aviation flight in a four-passenger aircraft but significantly lower than those observed in an automobile in heavy traffic (25).

The highest potential for flight crew and ground-support personnel exposure occurred during the four-engine run-up tests, the ERO-loading exercises, and the reverse taxi maneuver with the cargo ramp door down. The real-time monitor response during these events often exceeded the upper limit of the dynamic range of the instruments, so a definitive assessment of the exposure cannot be made based on the real-time monitor response alone. The average concentrations of the target PAHs in the integrated-air samples during the four-engine run-up test and the ERO-loading exercise were approximately 10 (engine run-up) to 25 (ERO-loading) times higher than the average concentrations

measured in a 24-hr air sample near a residential site in a metropolitan area during the heating season (30). In comparison, the target PAH concentrations in the integrated-air samples collected in the maintenance hangar during the taxi and takeoff maneuvers were approximately equal to the average indoor PAH concentrations in residences in a major city (30).

Although no exposure limits have been set for individual PAHs, exposure standards have been recommended for emission products containing PAHs; thus some indirect limits to PAH exposure can be inferred. The National Institute for Occupational Safety and Health, for example, recommends a 10-hr time-weighted average (TWA) of 0.1 mg/m³ as a workplace standard for coal tar products (32). In addition, the Occupational Safety and Health Administration (OSHA) set an 8-hr TWA of 0.2 mg/m³ for coal tar pitch volatiles and a permissible exposure limit of ≤ 0.15 mg/m³ as an 8-hr TWA for coke oven emissions. Although TWAs for specific PAHs are not given in these workplace standards, the OSHA analytical method for coal tar pitch volatiles specifies target concentrations for selected PAHs, including phenanthrene, anthracene, pyrene, chrysene, and benzo[*a*]pyrene (33).

To gain an appreciation for the results of this study relative to the target PAH concentrations in the OSHA analytical method, the average exposures of these five PAHs during selected monitoring events are summarized in Table 5. Specifically, the integrated-air concentrations of these PAHs as measured by the low-volume air samplers and the mean and maximum particle-bound PAHs as measured by the PAS2000CE handheld monitors are compared to the OSHA-method target concentrations. In general, the average concentrations of the five target PAHs in integrated-air samples associated with different aircraft exhaust monitoring events were appreciably lower than the OSHA target concentrations for coal tar pitch volatiles. Likewise, the mean values for particle-bound PAHs as measured by the PAS2000CE monitors were below the individual target concentrations of pyrene, chrysene, and benzo[*a*]pyrene, which are expected to be in the particulate phase. However, the mean values of the PAS2000CE response were often exceeded for short periods of time during high-emission events. Because the peak particle-bound PAH levels measured by the PAS2000CE monitors often exceeded the maximum output range of the instrument (4,000 ng/m³), the actual mean and peak values of particle-bound PAHs were probably higher than reported by the instruments. Depending on the extent that the concentrations of particle-bound PAHs are

Table 5. Compilation of selected PAH concentration data from flight-related activities.

Activity/location	Engine run-up/ tarmac (ng/m ³)	Background/ hangar (ng/m ³)	Taxi/ hangar (ng/m ³)	AGE/ tarmac (ng/m ³)	ERO-loading/ C-130H cargo bay (ng/m ³)	OSHA target concentrations (ng/m ³) ^a
Phenanthrene	25.0	16.6	24.1	278.5	70.1	8,880
Anthracene	9.7	1.7	< MDL	27.8	6.6	790
Pyrene	< MDL	< MDL	0.9	189.4	42.9	9,000
Chrysene	< MDL	< MDL	< MDL	< MDL	< MDL	3,270
Benzo[a]pyrene	4.1	0.1	0.5	4.0	0.8	2,490
Mean PAS2000CE	568	14.8	NA	21.9	1,009	—
Max PAS2000CE	3,804	67.0	NA	1,712	4,010	—

^aData from OSHA (33).

underestimated, the concentrations of these compounds during flight-related activities might actually approach the OSHA target concentrations. For future work, this problem could be circumvented with a simple dilution system that would keep the high ambient concentration on scale.

Conclusions

The combined use of real-time monitors and integrated-air samplers provided complementary information during this study. The real-time monitors produced a temporal profile with a resolution of a few seconds of the PAH concentrations associated with different flight-related activities, whereas the integrated-air samplers provided concentrations of individual PAHs in emissions from JP-8-fueled engines and AGE units. The speciated integrated PAH data were consistent with respect to time averages of total PAH concentrations measured with the real-time monitors. However, comparisons between these two methods suffer from the lack of a common method to calibrate the responses of the real-time monitors. Some means for calibrating or spanning the real-time monitors before field use must be devised before quantitative data can be obtained with the instruments. Until the calibration issues are addressed, these monitors can only be used to provide semiquantitative screening estimates of PAH exposure.

We conclude that the exposure to PAHs during flight-related activities can become significant but most likely is below typical workplace standards for PAH-related emissions. However, the large dynamic range of concentration values reported by the real-time monitors during short exposure periods suggest that a high acute exposure to PAHs occurs during some flight-related activities. Therefore, despite the inability to use real-time monitors as an exact quantitative tool, the monitors can provide insight into those relatively brief times during the work day when the use of respiratory protection (personal protective equipment) would be advised. Because of their small size and use of battery power, the PAS2000CE handheld units would be particularly useful as

microenvironmental or personal dosimetry monitors for such an advisory role.

Future studies will include making measurements of aircraft emissions in different climate conditions and of different types of aircraft under scenarios that are representative of typical flight-related activities. We will pursue the development of a laboratory-based calibration instrument and a dilution option to keep very high ambient levels from saturating the instrument response.

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