# 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 × 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]
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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 $C_6$ to $C_{18}$ range; the $C_9$ to $C_{14}$ *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 multipoint 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 multiion 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 | Pope AFB, Fayetteville, NC |
| | | C-130H | Garden City ANGB, Savannah, GA |
| | | C-17, C-141 | Charleston AFB, Charleston, SC |
| | | B-1 | Robins AFB, Warner-Robins, GA |
| | | KC-135 | 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). $CO_2$ assays of breath samples were performed by using a CA-1 $CO_2$ analyzer (Sable System, Henderson, NV) calibrated with a clinical blood–gas mixture certified at 5.00% $CO_2$ 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 $C_6$ to $C_{12}$; 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 $CO_2$ level normalized to a factor set arbitrarily to 5% for internal consistency. Although individual concentrations were available, for graphing purposes the $C_9$ to $C_{12}$ *n*-alkanes (nonane, decane, undecane, and dodecane) were summed to provide a simple indicator of JP-8 fuel exposure, and the $C_6$ and $C_7$ *n*-alkanes (hexane and heptane) were summed to present a non JP-8 comparison. The $C_8$ *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 air-shops 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

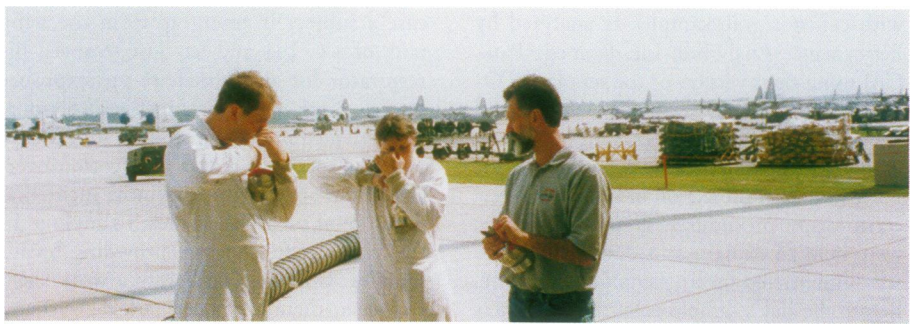


**Figure 3.** Typical incidental exposure breath sampling outdoors before beginning a work shift. The subjects provide breath samples while at equilibrium with the ambient environment of their AFB; the ambient air is impacted by the general profusion of A-10 and C-130 aircraft and various ground support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

**Table 2.** Sample categories.

| Major category | Subdivision: First | Second | Third | Fourth | Sample subtotals (*n*) | Sample major totals (*n*) |
|---|---|---|---|---|---|---|
| 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 $C_9$ to $C_{12}$ *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).

| | Control (RTP) ($n$ = 22) | | Control (LA) ($n$ = 22) | | Indoor air levels AFB shops ($n$ = 5) | | Aircraft cold-start exhaust exposure ($n$ = 23) | | Fuel tank maintenance around aircraft ($n$ = 9) | | Fuel tank maintenance inside fuel tanks ($n$ = 16) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Compounds | 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 |
| *m,p*-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 |
| *o*-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 | – | – |
| *p*-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.

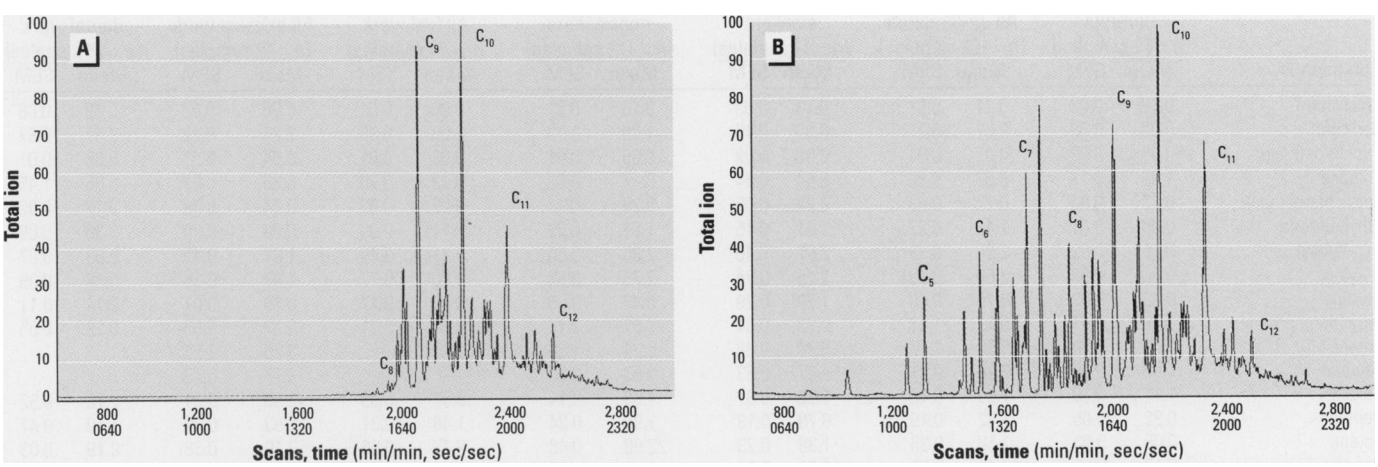



**Figure 4.** Chromatographic comparison of the expected vapor phase contribution from (*A*) evaporating JP-8 and (*B*) a typical ambient sample collected inside a hangar that contained multiple F-15 and F-16 aircraft undergoing fuel tank maintenance. Both chromatograms exhibit the JP-8 fingerprint compounds as annotated ($C_9$ to $C_{12}$ *n*-alkanes), but the ambient hangar air is also contaminated with a variety of other compounds (including the annotated $C_5$ to $C_8$ *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 $C_9$ to $C_{12}$ *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).

| | | | | | All samples subdivided by smoking | | | | All samples subdivided by work activity | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Controls (*n* = 19 samples) | | All JP-8 related (*n* = 162 samples) | | All JP-8 related smokers (*n* = 41 samples) | | All JP-8 related nonsmokers (*n* = 121 samples) | | All fuel work (*n* = 85 samples) | | All exhaust work (*n* = 49 samples) | | All incidental work (*n* = 28 samples) | |
| Compounds | 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 |
| *m,p*-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 |
| *o*-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 |
| *p*-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

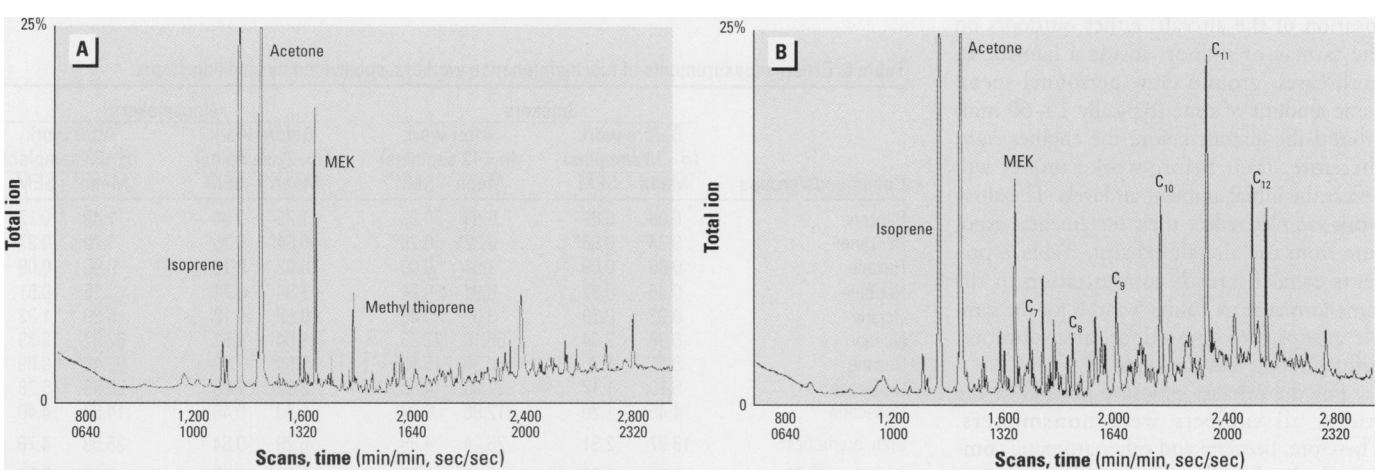



**Figure 5.** Chromatographic comparison of (*A*) preexposure and (*B*) postexposure exhaled breath chromatograms of a fuel tank maintenance attendant who is not wearing a respirator and is handling removed foam from an F-15 fuel tank. The inhalation exposure corresponds to the ambient hangar sample 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).

| | Before work (all samples) ($n$ = 40 samples) | | After work: All samples ($n$ = 45 samples) | | After work: Tank entry ($n$ = 15 samples) | | After work: Attendants ($n$ = 30 samples) | |
|---|---|---|---|---|---|---|---|---|
| Compounds/groups | 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[a] | 12.00 | 1.51 | 25.76 | 3.66 | 22.03 | 4.61 | 27.62 | 4.99 |
| Sum, non-JP-8[b] | 1.51 | 0.42 | 2.77 | 0.41 | 2.56 | 0.68 | 2.87 | 0.52 |
| Sum, JP-8 fingerprint[c] | 18.28 | 2.94 | 172.94 | 20.69 | 158.66 | 42.51 | 180.08 | 23.08 |

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

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

| | Smokers: Before work ($n$ = 18 samples) | | Smokers: After work ($n$ = 12 samples) | | Nonsmokers: Before work ($n$ = 22 samples) | | Nonsmokers: After work ($n$ = 33 samples) | |
|---|---|---|---|---|---|---|---|---|
| Compounds/groups | 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[a] | 9.24[b] | 0.86[b] | 6.32[b] | 0.28[b] | 0.84[c] | 0.25[c] | 1.70[c] | 0.27[c] |
| 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[d] | 18.97 | 2.31 | 26.24 | 4.38 | 6.29 | 0.84 | 25.58 | 4.76 |
| Sum, non-JP-8[e] | 1.08 | 0.16 | 2.01 | 0.25 | 1.87 | 0.75 | 3.05 | 0.55 |
| Sum, JP-8 fingerprint[f] | 24.84 | 4.12 | 179.94 | 45.87 | 12.91 | 3.86 | 170.39 | 23.21 |

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

with statistical comparison among all nonsmokers 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 7.** Breath measurements of exhaust workers, subdivided by aircraft location (all data in ppbv).

| | Indoor start | | | | Outdoor start | | | |
|---|---|---|---|---|---|---|---|---|
| | Before work ($n$ = 6 samples) | | After work ($n$ = 7 samples) | | Before work ($n$ = 12 samples) | | After work ($n$ = 24 samples) | |
| Compounds/groups | 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[a] | 36.21 | 7.68 | 13.67 | 2.11 | 6.91 | 1.01 | 8.45 | 1.32 |
| Sum, non-JP-8[b] | 8.52 | 0.98 | 2.70 | 0.37 | 3.87 | 1.14 | 4.52 | 0.56 |
| Sum, JP-8 fingerprint[c] | 52.96 | 4.89 | 10.53 | 1.83 | 1.38 | 0.35 | 3.50 | 0.65 |

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

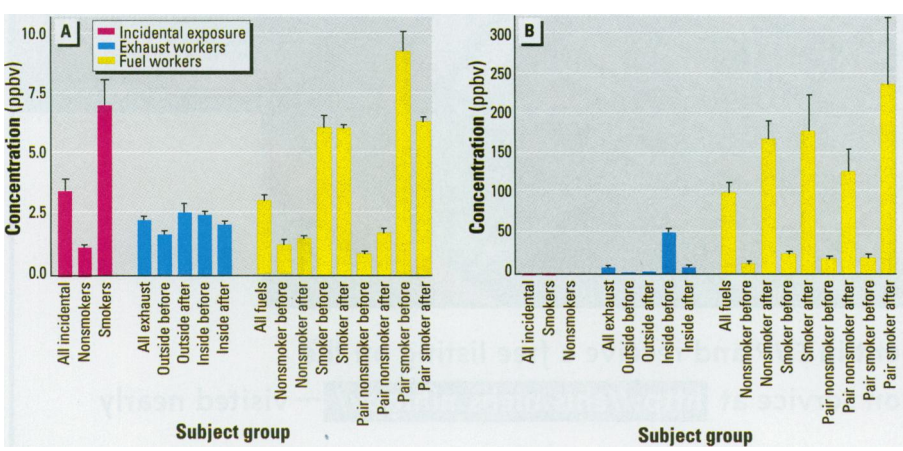



**Figure 6.** Mean breath concentrations and estimated standard errors for subdivided groups of samples from JP-8-exposed subjects. The exhaust workers were all nonsmokers. Most group descriptions are self-explanatory; however, the four "pair" values are the results of just the subset of samples taken 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.

**Table 8.** Benzene exposure significance for nonsmokers (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 |

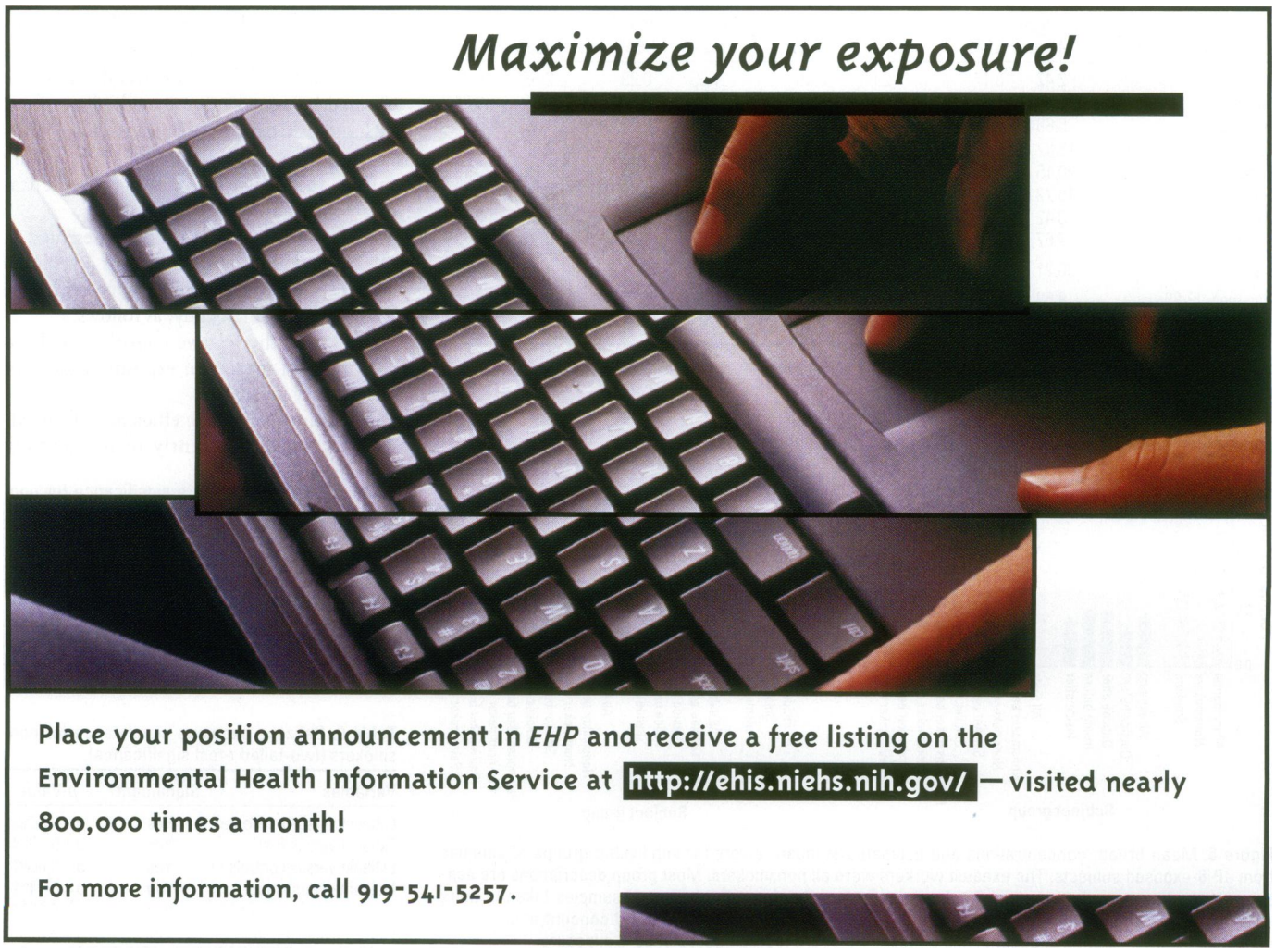
**Table 9.** Benzene exposure significance for nonsmokers (two-tailed *t*-test significance).

| Variables | Significant? | *p*-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 | $p = 0.0087$ |

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 particleborne 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.

## References and Notes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