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As jet fuel is a common occupational exposure among military and civilian populations, this study was conducted to characterize jet fuel (JP8) exposure among active duty US Air Force Personnel. Personnel (n=24) were divided a priori into high, moderate, and low exposure groups. Questionnaires and personal air samples (breathing zone) were collected from each worker over 3 consecutive days (72 worker-days) and analyzed for total hydrocarbons (THC), benzene, toluence, ethylbenzene, xylenes, and napthalene. Air Samples were collected from inside the fuel tank and analyzed for the same analytes. Linear mixed-effects models were used to evaluate the exposure data. Our results show that the correlation of THC (a measure of overall JP8 inhalation exposure) with all other analytes was moderate to strong in the a priori high and moderate exposure groups combined. Inhalation exposure to all analytes varied significantly by self-reported JP8 exposure (THC levels higher among workers reporting JP8 exposure), a priori exposure group (THC levels in high group > moderate group > low group, and more specific job

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Inhalation Exposure to Jet Fuel (JP8) Among U.S. Air Force Personnel

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As jet fuel is a common occupational exposure among military and civilian populations, this study was conducted to characterize jet fuel (JP8) exposure among active duty U.S. Air Force personnel. Personnel (n = 24) were divided a priori *into high, moderate, and low exposure groups. Questionnaires and personal air samples (breathing zone) were collected from each worker over 3 consecutive days (72 worker-days) and analyzed for total hydrocarbons (THC), benzene, toluene, ethylbenzene, xylenes, and naphthalene. Air samples were collected from inside the fuel tank and analyzed for the same analytes. Linear mixed-effects models were used to evaluate the exposure data. Our results show that the correlation of THC (a measure of overall JP8 inhalation exposure) with all other analytes was moderate to strong in the* a priori *high and moderate exposure groups combined. Inhalation exposure to all analytes varied significantly by self-reported JP8 exposure (THC levels higher among workers reporting JP8 exposure),* a priori *exposure group (THC levels in high group > moderate group > low group), and more specific job task groupings (THC levels among workers in fuel systems hangar group > refueling maintenance group > fuel systems office group > fuel handling group > clinic group), with task groupings explaining the most between-worker variability. Among highly exposed workers, statistically significant job task-related predictors of inhalation exposure to THC indicated that increased time in the hangar, working close to the fuel tank (inside > less than 25 ft > greater than 25 ft), primary job (entrant > attendant/runner/fireguard > outside hangar), and performing various tasks near the fuel tank, such as searching for a leak, resulted in higher JP8 exposure. This study shows that while* a priori *exposure groups were useful in distinguishing JP8 exposure levels, job task-based categories should be considered in epidemiologic study designs to improve exposure classification. Finally, the strong correlation of THC with naphthalene suggests that naphthalene may be an appropriate surrogate of JP8 exposure.*

[Supplementary materials are available for this article. Go to the publisher's online edition of the *Journal of Occupational and Environmental Hygiene* for the following free supplemental resource: a pdf file containing a table detailing concentrations of JP8 components.]

Keywords exposure assessment, inhalation exposure, jet fuel, JP8

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INTRODUCTION

Jet propulsion fuel 8 (JP8) is the primary military fuel used by the United States and North Atlantic Treaty Organization (NATO) member countries, with over 5 billion gallons used per year.[1] Due to the widespread use of JP8 and similar jet fuels in the military and commercial airline industry, over 2 million people per year are occupationally exposed.[1]

Information on the health consequences of human exposure to JP8 is limited,[1,2] though there is some evidence that JP8 may be toxic to the immune system, respiratory tract, and nervous system at exposure concentrations near 350 mg/m^3.[3] The current ACGIH® threshold limit value (TLV®) for kerosene and jet fuels is 200 mg/m^3 (total hydrocarbon vapor),[4] which is also the current occupational exposure limit (OEL) recommended by the U.S. Air Force for 8-hour exposure (though there is no enforced Air Force-wide standard for JP8 exposure). Although occupational standards are set for inhalation exposure to JP8, there are no such standards for dermal contact, which is another route of occupational exposure that has been shown to contribute to total absorbed dose.[5–8]

The composition of JP8 is similar to kerosene and varies by batch, containing many aliphatic and aromatic hydrocarbon compounds (C9-C17+), including varying concentrations of toxic components, such as benzene and naphthalene, plus nonhydrocarbon performance additives.[1–3,9]

The primary objectives of this study were to (1) quantify personal exposure to JP8 using total hydrocarbons (THC) as well as constituents of JP8, including benzene, toluene, ethylbenzene, *m-/p*-xylene, *o*-xylene (BTEX), and naphthalene; (2) determine if JP8 exposure differs between our *a priori* assigned (high, moderate, low) exposure groups and evaluate multiple JP8 exposure metrics to assess their utility; and (3) identify potential job-related predictors of JP8 exposure within the high exposure group.

While previous studies have characterized occupational exposure to JP8,[5–7,10–17] this study adds to our limited understanding of JP8 exposure in a number of ways. First, the repeated measures study design allows for a characterization of JP8 exposures that can vary considerably over a workweek while performing multiple tasks. Second, in addition to THC, we quantified JP8 constituents that are potentially neurotoxic and/or carcinogenic (BTEX and naphthalene). Third, JP8 exposures are likely to vary by base and time due to different job characteristics (type of aircraft maintained and ventilation inside of the hangar) and variations in fuel composition. Fourth, personal air exposure was measured throughout the entire work shift but excluding the time while the worker was wearing a respirator and while smoking, thus focusing more specifically on personal exposure to JP8.

MATERIALS AND METHODS

Study Population

Three groups of active duty personnel ($n = 24$) were recruited from an active U.S. Air Force base and assigned to *a priori* low ($n = 6$), moderate ($n = 9$), and high ($n = 9$) exposure groups based on the likelihood of JP8 exposure in their jobs (determined by a review of historical exposure records and information collected during preliminary base visits). This categorization scheme was chosen to facilitate comparison of our results with previous JP8 studies (e.g., Egeghy et al.[7]) and to reflect a scheme that may be used in epidemiologic studies assessing exposure and health outcomes.

The high exposure group included aircraft fuel systems maintenance workers with routine direct contact with JP8. These participants worked primarily either in the hangar performing maintenance activities on KC-135 Stratotanker refueler aircraft or in an office attached to the hangar performing administrative duties. KC-135 Stratotanker refueler aircraft carry fuel stores for in-air refueling and do not routinely contain fire suppressant foam (the aircraft worked on in this study did not contain fire suppressant foam). The moderate exposure group included workers with regular contact with JP8 via fuel handling (fuels storage, distribution, laboratory testing) or refueling maintenance (performed maintenance activities on fuel distribution trucks). The low exposure group worked in office jobs (health clinic) and did not have regular contact with JP8. This group was categorized as "low" (rather than "no") exposure because there is the potential for everyone on an Air Force base to have some exposure to JP8.[11]

Exposure measurements were collected from the 24 participants during 3 consecutive days (72 worker-days) while performing their normal duties. Each worker-day included collection of questionnaires and personal air and dermal tape-strip samples. Fuel tank air samples were also collected each day. Liquid JP8 samples were collected to determine the concentrations of various components of the fuel (see supplemental material in online edition). The protocol was approved by Army (U.S. Army Research Institute of Environmental Medicine) and Air Force (Wright-Patterson Air Force Base) institutional review boards, and written informed consent was obtained from all participants.

Study Design

A baseline questionnaire was collected from each participant, prior to the work shift on the first sampling day, to obtain information about demographic factors, work history, and tobacco use. Daily post-shift questionnaires were also collected to obtain information about tobacco use, chemical exposures, and protective equipment during each work shift. The high exposure group was asked to provide additional information about exposure scenarios specific to their work environment and duties (e.g., entering fuel tanks, approximate distance from the tank). An observation log detailing work tasks and personal protective equipment was recorded daily by study personnel.

Personal air samples were collected from the breathing zone of each worker during the entire duration of each work shift. The air samples were collected using an active sampling method in accordance with National Institute for Occupational Safety and Health (NIOSH) methods 1501[18] and 1550,[19] a method that has been used in previous assessments of JP8 exposure.[10,12,15,17] Battery-operated sampling pumps were used to collect vapor samples on coconut shell charcoal in two-section (100 mg/50 mg) glass sorbent tubes (Anasorb; SKC Inc., Eighty Four, Pa.) at a flow rate of 0.2 L/min (0.195–0.205 L/min). Personal pumps were paused if the worker left the work area (e.g., for lunch, an errand, or a cigarette break) or entered the fuel tank (when wearing a respirator). A minimum of one sample was collected each day for approximately 30 min from within the fuel tank while an entrant (high exposure group member) was working inside of the tank. Field blanks ($n = 12$) were collected on each day of sampling. The sorbent tubes were wrapped in foil and shipped in coolers to the Organic Chemistry Analytical Laboratory at the Harvard School of Public Health (HSPH) in Boston, Massachusetts, where the samples were stored at approximately $-1°C$ until analyzed.

In addition to air samples, dermal samples were collected at the end of the work shift using a tape stripping method that has been previously described.[5,20,21] Adhesive tape (Cover-Roll stretch; BSN medical GmbH, Hamburg, Germany) was precut to 2 × 4 cm, and two successive samples were collected from the same location on the back of the dominant hand. The hand has been shown to be among the two body regions (the arm is the other) most frequently exposed to JP8[5] and thus was chosen for this study. Although a previous dermal JP8 exposure study[5] assessed three body surfaces, additional body regions were not assessed in this study to minimize the burden on study participants as extensive exposure sampling (in addition to that presented here) was conducted.

Each tape strip was applied with constant pressure, left in place for 2 min, removed using clean forceps, and placed in a clean scintillation vial (20 mL; Wheaton, Millville, N.J.) containing 5 mL of acetone. Field blank tape strips were collected each day ($n = 12$), while duplicate samples were not collected to minimize the burden on study participants. The vials were wrapped in foil and shipped in coolers to the Organic Chemistry Analytical Laboratory at the HSPH (Boston, Mass.) where the samples were stored at approximately −1°C until analyzed.

Air and Dermal Sample Analyses

Air and dermal samples were analyzed for BTEX and naphthalene using gas chromatography mass spectrometry (GC/MS) in selective ion monitoring (SIM) mode,[20,21] and for THC using gas chromatography with flame ionization detection (GC/FID) (NIOSH 1550).[19] Air samples were extracted using NIOSH method 1550.[19] Briefly the charcoal from the sorbent tube was placed in a vial with a Teflon-lined cap, 1 mL of CS_2 was added, and stood for 30 min. An aliquot of the extract was transferred to a GC vial for analysis. Dermal samples were extracted using a previously described method.[21] Briefly the vials containing 5 mL of acetone and the tape strip were placed on a shaker table for 30 min, and the acetone extracts were concentrated from 5 to 0.5 mL. For BTEX and naphthalene, 10 μL of internal standard Napthalene-d8 was added to each sample. A 100 μL aliquot of the extract was transferred to a GC vial for analysis. Following procedures of Chao et al.,[5] we made the *a priori* decision not to analyze the second tape strips if the first tape strips were below the limit of detection.

BTEX and naphthalene were analyzed by GC/MS in SIM using a Hewlett-Packard 6890 GC with temperature and pressure programming capabilities and a split/splitless injector. A capillary column (HP-5MS, 30 m, 250 μm diameter, 0.25 μm film thickness; J&W Scientific, Folsom, Calif.), was used along with the following instrument conditions: injector at 250°C, MS source at 230°C, initial oven temperature at 45°C, held for 2 min, heated to 72°C at 2°/min, then to 280°C at 50°/min, and held for 2 min. The column flow was ramped from 1.5 mL/min (held for 22.0 min) to 1.8 mL/min at a rate of 10 mL/min and then held for 3 min.

THC was analyzed by GC/FID using a Hewlett-Packard 6890 GC. A capillary column (DB-1, 60 m, 250 μm diameter, 1.0 μm film thickness; J&W Scientific) and the following instrument conditions were used: injector at 300°C, detector at 250°C, initial oven temperature at 100°C, held for 5 min, heated to 230°C at 8°/min, and held for 10 min. The column flow was constant at 1 mL/min. FID hydrogen flow was 40 mL/min, airflow was 450 mL/min, and the make-up gas was helium at a flow rate of approximately 45 mL/min.

Statistical Analyses

Air data were analyzed using descriptive statistics, scatter plots, correlation coefficients, and linear mixed-effects models. Units for THC are presented as mg/m^3, whereas units for BTEX and naphthalene are presented as μg/m^3. Values were blank corrected as appropriate using the mean of the field blanks, and all values less than the LOD were replaced with LOD/2. Personal air values exhibited a log-normal distribution and were natural log-transformed prior to analysis. All statistical analyses were conducted using SAS statistical software version 9.1.3 (SAS Institute Inc, Cary, N.C.), and statistical significance is reported at the 0.05 level. The dermal data were not included in statistical analyses due to the low percent of detected measurements (0–24% detect for all of the analytes).

Three air samples were excluded from the analysis. Two sorbent tubes (collected from the high exposure group) broke during the laboratory processing. A third sample (collected from the moderate exposure group) was excluded because there was evidence that the sample was an outlier value and not representative of the worker's actual exposure. The participant may have removed the air pump and placed it near an exposure source, or the sorbent tube may have become contaminated with liquid JP8. Thus, there were 69 air samples included in the final analysis. To address the potential influence of the outlier sample value on results, *post hoc* regression models were run with the sample.

Linear mixed-effects models were used to estimate correlation coefficients and analyze predictors of the exposure levels.[22,23] Models were constructed to assess three JP8 exposure metrics: (1) self-reported JP8 exposure (yes, no); (2) the *a priori* exposure group (high, moderate, low); and (3) job task group (fuel systems hangar, fuel systems office, refueling maintenance, fuel handling, and clinic) for all participants. The fuel handling task group includes those workers from fuels storage, distribution, and testing in the *a priori* moderate exposure group.

Among participants in the *a priori* high exposure group, a second set of models examined job-related predictors of JP8 exposure: time spent in the hangar (hours); distance from the fuel tank during tank work (inside the tank, <25 ft, >25 ft); primary job (entrant, attendant, runner or fireguard, or jobs outside the hangar); searched for a leak (inside or outside the fuel tank); repaired a leak (inside or outside the fuel tank); removed bolts from the tank door; removed the tank door; depuddled; held ventilation in place;, and handed tools to the entrant.

Additional covariates such as smoking status, seniority (based on Air Force specialty codes), and co-exposures to other

TABLE I. Personal Air Summary Statistics by Exposure Group

	N	Percent Detect (%)	GM^A	$(GSD)^B$	Range
THC ($LOD^C = 0.7$ mg/m^3)					
Overall	69	64	1.6	(4.3)	<0.7–45.7
High^D	25	92	5.1	(3.1)	<0.7–45.7
Moderate	26	81	1.7	(3.1)	<0.7–16.5
Low	18	0	<0.7	(NA)	NA–NA
Benzene ($LOD^C = 0.9$ μg/m^3)					
Overall	69	64	1.6	(3.5)	<0.9–36.4
High^D	25	80	2.9	(3.4)	<0.9–36.4
Moderate	26	81	2.1	(3.2)	<0.9–31.7
Low	18	17	<0.9	(NA)	<0.9–3.4
Toluene ($LOD^C = 0.2$ μg/m^3)					
Overall	69	100	5.4	(3.6)	0.4–134
High^D	25	100	11.2	(3.6)	1.3–134
Moderate	26	100	5.5	(3.2)	0.5–58.6
Low	18	100	1.8	(1.7)	0.4–6.6
Ethylbenzene ($LOD^C = 0.4$ μg/m^3)					
Overall	69	75	1.8	(6.0)	<0.4–92.1
High^D	25	96	6.8	(4.1)	0.7–92.1
Moderate	26	96	2.2	(3.7)	<0.4–34.4
Low	18	17	<0.4	(NA)	<0.4–1.0
m-/p-Xylene ($LOD^C = 0.2$ μg/m^3)					
Overall	69	99	5.3	(6.8)	<0.2–290
High^D	25	100	21.1	(4.0)	2.3–290
Moderate	26	100	7.1	(3.8)	0.3–107
Low	18	94	0.5	(2.0)	<0.2–3.3
o–Xylene ($LOD^C = 0.6$ μg/m^3)					
Overall	69	74	2.6	(6.5)	<0.6–148
High^D	25	96	10.6	(4.1)	1.0–148
Moderate	26	96	3.3	(3.8)	<0.6–54.7
Low	18	11	<0.6	(NA)	<0.6–1.0
Naphthalene ($LOD^C = 0.7$ μg/m^3)					
Overall	69	29	<0.7	(NA)	<0.7–6.6
High^D	25	52	0.9	(2.6)	<0.7–6.6
Moderate	26	27	<0.7	(NA)	<0.7–2.7
Low	18	0	<0.7	(NA)	NA–NA

Note: NA = not applicable.
^{A}Geometric mean (GM).
^{B}Geometric standard deviation (GSD).
^{C}Average limit of detection (LOD) calculated using flow rate and total time pump was running from personal air samples.
^{D}Values were not adjusted to take into account estimated exposure while working in the tank and therefore may be underestimated for some of the high exposure group workers.

chemicals (i.e., gasoline vapors, degreasers or other cleaners) were considered and excluded from final models if the variables were not significant predictors or were determined to be surrogates for other reported variables. Smoking status was not a significant predictor of analytes in air and was excluded from the final models, a result that was expected given that the air pump was removed whenever participants smoked a cigarette. An example of the model used can be described as follows:

$$Y_{ijk} = \ln(X_{ijk}) = \beta_0 + \beta_{1k}\text{EXPGRP}_{ik} + b_i + \varepsilon_{ijk}$$

where X_{ijk} represents the inhalation exposure level of the ith participant on the jth day, and Y_{ijk} is the natural logarithm of measurement X_{ijk}. The β is the fixed effect for the covariate, such that for the *a priori* exposure group variable (EXPGRP) k = (high, moderate, low). The b_i represents the random effect for each subject, and ε represents the error. Models for the mean were compared using the percent of between-worker variability explained by the fixed-effects model as well as Akaike's Information Criteria (AIC) values (AIC values were obtained using maximum likelihood estimation). A compound symmetric covariance structure was used to fit the models, and the final models were fit using restricted maximum likelihood estimation.

For workers who entered the fuel tank (entrants), the in-tank air samples and NIOSH assigned protection factor (APF) of 50[24] for a full-face, continuous flow supplied-air respirator equipped with a tight-fitting face piece were used to adjust personal air levels, taking into account estimated exposure while working in the tank. The APF 50 adjusted personal air data were used for the scatter plots, correlation coefficients, and regression models. The personal air levels were also adjusted assuming that the participant did not wear the respirator while inside the tank.

RESULTS

The study population included 21 (87.5%) males, 21 (87.5%) participants who described themselves as white, and 7 (29.2%) current smokers. The group averaged 27.7 ± 6.8 years of age and had spent on average 7.0 ± 6.6 years in the Air Force.

Table I presents the summary statistics for THC, BTEX, and naphthalene in personal air samples by exposure group. The geometric mean concentrations for all analytes decreased from the high to low exposure groups. In univariate regression models assessing study day (1–3) as a categorical predictor of the air levels, THC, BTEX, and naphthalene varied significantly by day in the high exposure group ($p < 0.0001$–0.01), whereas ethylbenzene, *m*-/*p*-xylene, *o*–xylene, and naphthalene varied significantly in the moderate exposure group ($p = 0.004$–0.01). The levels did not vary by day in the low exposure group.

The overall within- and between-worker variability (with standard error) for each analyte are as follows: THC: 0.65 (0.14), 1.53 (0.52); benzene: 0.90 (0.19), 0.66 (0.30); toluene: 0.92 (0.20), 0.71 (0.32); ethylbenzene: 0.86 (0.18), 2.49 (0.83); *m*-/*p*-xylene: 0.91 (0.19), 2.89 (0.95); *o*-xylene: 0.84 (0.18), 2.81 (0.92); and naphthalene: 0.24 (0.05), 0.43 (0.15). The

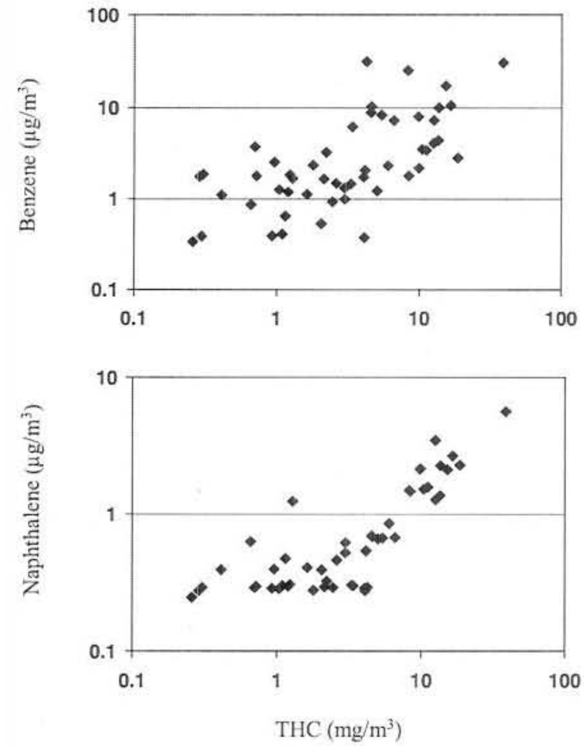

FIGURE 1. Scatterplots of THC with benzene and naphthalene for the high and moderate exposure groups combined (presented on the log scale)

ratio of within- to between-worker variability is generally less than one (except for benzene and toluene), indicating that there is more between-worker variability than within-worker variability overall. However, there is generally more within-worker variability than between-worker variability within each *a priori* exposure group. For example, the within- and between-worker variability (with standard error) for THC in the high exposure group are 0.70 (0.14) and 0.45 (0.36), and in the moderate exposure group are 1.05 (0.37) and 0.29 (0.38).

THC was moderately to strongly correlated with all analytes (Table II). Correlations among all other analytes were generally strong, although naphthalene and benzene were moderately correlated. Correlations were generally stronger in

TABLE II. Correlation Coefficients for All Analytes for the High and Moderate Exposure Groups Combined (thc: Mg/M³, BTEX and Naphthalene: μg/m³)

	Benzene	Toluene	Ethylbenzene	*m*-/*p*-Xylene	*o*-Xylene	Naphthalene
THC	0.66	0.86	0.91	0.91	0.92	0.81
Benzene		0.84	0.75	0.75	0.72	0.59
Toluene			0.97	0.97	0.95	0.73
Ethylbenzene				1.00	1.00	0.80
m-/*p*-Xylene					1.00	0.79
o-Xylene						0.80

TABLE III. Results of Final Models Evaluating Inhalation Exposure for All Participants (24 workers, n = 69 worker-days)

	THC		Benzene		Toluene		Ethylbenzene		*m*-/*p*-Xylene		*o*-Xylene		Naphthalene	
Parameters	**β(SE)**	**P-values**	**β(SE)**	**P-values**	**β(SE)**	**P-values**	**β(SE)**	**P-values**	**β(SE)**	**P-values**	**β(SE)**	**P-values**	**β(SE)**	**P-values**
Model I														
Intercept	−0.95 (0.34)		−0.46 (0.28)		0.75 (0.30)		−1.19 (0.42)		−0.31 (0.44)		−0.94 (0.44)		−1.10 (0.25)	
Reported JP8 Exposure		<0.0001		<0.0001		0.0001		<0.0001		<0.0001		<0.0001		0.02
Yes	2.11 (0.41)		1.38 (0.34)		1.39 (0.36)		2.69 (0.50)		2.95 (0.52)		2.88 (0.52)		0.67 (0.29)	
No	0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)	
Model II														
Intercept	−1.16 (0.29)		−0.66 (0.28)		0.61 (0.29)		−1.51 (0.36)		−0.68 (0.38)		−1.29 (0.37)		−1.20 (0.20)	
Exposure Group		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001
High	2.84 (0.38)		1.71 (0.37)		1.86 (0.38)		3.58 (0.47)		3.87 (0.49)		3.81 (0.48)		1.22 (0.26)	
Moderate	1.72 (0.38)		1.44 (0.37)		1.11 (0.37)		2.37 (0.47)		2.68 (0.49)		2.55 (0.48)		0.32 (0.26)	
Low	0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)	
Model III														
Intercept	−1.16 (0.16)		−0.66 (0.22)		0.61 (0.17)		−1.51 (0.18)		−0.68 (0.21)		−1.29 (0.18)		−1.20 (0.13)	
Task Group		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001
Fuel Systems Hangar	3.21 (0.23)		1.97 (0.30)		2.18 (0.24)		3.97 (0.25)		4.27 (0.29)		4.22 (0.25)		1.43 (0.18)	
Refueling Maintenance	3.01 (0.35)		2.63 (0.46)		2.53 (0.37)		4.23 (0.40)		4.56 (0.45)		4.46 (0.39)		1.15 (0.28)	
Fuel Systems Office	1.63 (0.32)		0.84 (0.43)		0.86 (0.34)		2.27 (0.36)		2.56 (0.41)		2.45 (0.36)		0.48 (0.26)	
Fuel Handling	1.37 (0.22)		1.13 (0.29)		0.74 (0.23)		1.86 (0.25)		2.17 (0.28)		2.03 (0.24)		0.09 (0.18)	
Clinic	0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)		0 (Ref)	

Notes: Units: THC (LN(mg/m^3), BTEX, and naphthalene (LN($\mu g/m^3$)).

TABLE IV. Results of Univariate Analyses Evaluating Inhalation Exposure Among Fuel Systems Maintenance Workers (9 workers, n = 25 worker-days)

	THC (LN(mg/m^3))	
Parameters	β(SE)	P-values
Time in hangar		0.0002
Hours	0.30 (0.08)	
Distance from tank (during tank work)^A		<0.0001
Inside	2.00 (0.38)	
<25 ft	0.58 (0.41)	
>25 ft	0 (Ref)	
Job		0.008
Entrant	1.24 (0.49)	
Attendant/runner/fireguard	0.17 (0.54)	
Other (outside hangar)	0 (Ref)	
Searched for leak		0.02
Yes	1.09 (0.46)	
No	0 (Ref)	
Repaired leak		0.7
Yes	0.16 (0.38)	
No	0 (Ref)	
Removed bolts from tank door		0.2
Yes	0.62 (0.48)	
No	0 (Ref)	
Removed tank door		0.1
Yes	0.65 (0.43)	
No	0 (Ref)	
Depuddled		0.1
Yes	1.06 (0.69)	
No	0 (Ref)	
Held ventilation in place		0.09
Yes	0.86 (0.50)	
No	0 (Ref)	
Handed tools to entrant		1.0
Yes	0.01 (0.39)	
No	0 (Ref)	

^{A}n = 24 due to missing value of independent variable.

the high exposure group compared to the moderate exposure group (results not presented). Scatterplots of THC with benzene and naphthalene are presented in Figure 1.

The mean air levels measured inside the fuel tank were 402 ± 288 mg/m^3 for THC, 78.8 ± 71.9 μg/m^3 for benzene, 755 ± 484 μg/m^3 for toluene, 764 ± 514 μg/m^3 for ethylbenzene, 2400 ± 1604 μg/m^3 for *m-/p*-xylene, 1260 ± 831 μg/m^3 for *o*-xylene, and 77.5 ± 52.7 μg/m^3 for naphthalene.

Exposure Metrics — All Exposure Groups

Table III presents parameter estimates and p-values for three regression models evaluating exposure metrics as predictors of inhalation exposure for all study participants. The results of Model 1 indicate that self-reported JP8 exposure was a significant predictor of THC exposure such that levels were approximately eight times higher (exponentiated β from the model) among workers who reported JP8 exposure. The fixed-effects model explained 61% of the between-worker variability (AIC value of 203.1) but none of the within-worker variability, given that self-reported JP8 exposure did not change over time. Self-reported JP8 exposure was a significant predictor of all other analytes as well.

The results of Model 2 indicate that *a priori* assigned exposure group was a significant predictor of THC exposure such that levels in the high group were 17 times higher than the low group, while levels in the moderate group were six times higher than the low group, reflective of the results presented in Table I. The fixed-effects model explained 81% of the between-worker variability (AIC value of 193.3). *A priori* assigned exposure group was a significant predictor of all other analytes as well.

The results of Model 3 indicate that job task group was a significant predictor of THC exposure such that levels were ranked as follows: fuel systems hangar (25-fold higher than the clinic) > refueling maintenance (20-fold higher than the clinic) > fuel systems office (5-fold higher than the clinic) > fuel handling (4-fold higher than the clinic). The fixed-effects model explained 100% of the between-worker variability (AIC value of 166.7) but none of the within-worker variability, given that task groups did not change over time. Task group was a significant predictor for all other analytes and generally followed the THC task ranking, with a few slight differences.

In the *post hoc* sensitivity analyses, including the one outlier sample, all models remained statistically significant. However, the order of the task groups was impacted in Model 3 such that THC and naphthalene exposure was higher in refueling maintenance than the fuel systems hangar task group.

Job-Related Predictors of Exposure — High Exposure Group

Table IV presents parameter estimates and p-values for univariate regression models evaluating predictors of inhalation exposure to THC for fuel systems maintenance workers (high exposure group, n = 9) over the 3-day study period. Inhalation exposure to THC, as well as BTEX and naphthalene (results not presented), was found to significantly increase with increasing time spent in the hangar during the work shift. Distance from the fuel tank was also a significant predictor of inhalation exposure to THC, as well as all other analytes except benzene, with exposure generally increasing the closer the participant was to the fuel tank.

The participant's job activity was a significant predictor of inhalation exposure to THC, as well as all other analytes except benzene, and generally was ordered as follows: entrants > attendant/runner/fireguard > jobs outside the hangar. The job task of searching for fuel tank leaks was a significant predictor of inhalation exposure to THC, as well as all other analytes, such that exposures were consistently higher among workers whose job tasks involved searching for leaks compared with those that did not.

Removing bolts from the tank door, removing the tank door, depuddling, and holding ventilation in place were not significant predictors of inhalation exposure to THC but were significant for some other analytes. Repairing a leak and handing tools to the entrant were not significant predictors of inhalation exposure. While statistical significance varied, the results of these models consistently indicated that performing these various job tasks led to higher inhalation exposure.

Respirator Protection Adjustments

The geometric mean for the APF 50 adjusted THC data for the tank entrants (7 workers, 11 worker-days) was 8.7 ± 2.3 mg/m^3(range: 1.6–38.8 mg/m^3), while the geometric mean when assuming that the entrant did not wear a respirator inside of the fuel tank was almost 10 times higher (82.6 ± 2.1 mg/m^3, range: 29.5–262 mg/m^3). The relationship between the APF 50 adjusted levels and those assuming that the entrant did not wear a respirator are similar for the other analytes assessed. The mean time spent in the fuel tank was 86 ± 48 min, ranging from 30 to 165 min.

DISCUSSION

Overall, we found that personal exposure levels generally varied over the study days, supporting the statement JP8 exposure varies over time. The utility of the surrogate JP8 exposure metrics increased from self-reported JP8 exposure, to *a priori* assigned exposure group, to job task group being the most informative, suggesting that task-based information provides the most useful surrogate for JP8 exposure. Several job-related predictors of JP8 exposure among fuel systems maintenance workers (*a priori* high exposure group) were also found, indicating that increased time in the hangar, working close to the fuel tank, and performing various job tasks near the fuel tank resulted in higher JP8 exposure. Personal exposure levels for the entrants were higher when assuming the worker did not wear a respirator while working inside the fuel tank, thus highlighting the importance of wearing a respirator while working inside the fuel tank, as exposure levels may exceed 200 mg/m^3(the Air Force-recommended OEL) if the respirator is not worn.

Personal Air Concentrations

All personal exposure levels for THC were below the Air Force-recommended OEL. Similarly, exposures to other analytes were below NIOSH recommended exposure limits (REL). The QA/QC data for naphthalene showed that recovery was low (15%) and likely due to the use of a sorbent that was too strong for naphthalene's higher molecular weight. However, the extraction efficiency for naphthalene was likely reduced in a fairly consistent manner, since naphthalene was highly correlated with THC (87% recovery) in the high and moderate exposure groups combined, and naphthalene was still found to differ significantly by exposure group.

The THC exposure levels in our high and moderate exposure groups were generally lower than those reported previously. Carlton and Smith[10] reported full-shift mean JP8 (THC) levels of 14.2 mg/m^3 during fuel tank entry and repair, activities that should be comparable to our high exposure group. Puhala et al.[12] reported full-shift mean naphtha levels of 1.33 ppm (10 mg/m^3) for aircraft maintenance workers (a category consistent with our high exposure group) and levels of 0.607 ppm (4.5 mg/m^3) for fuel-handling workers (a category consistent with our moderate exposure group).

The benzene exposure levels in our high, moderate, and low exposure groups were also lower than those reported previously. Egeghy et al.[7] reported median benzene levels of 252 μg/m^3, 7.4 μg/m^3, and 3.1 μg/m^3 in similar exposure groups (collected over approximately 4 hr). Puhala et al.[12] reported full-shift mean benzene levels 0.00690 ppm (22 μg/m^3) for aircraft maintenance workers and levels of 0.00573 ppm (18 μg/m^3) for fuel-handling workers.

Within the high exposure group, we expected that personal air exposure levels would be lower than in previous studies, since participants in other studies wore air monitors during tank entry while wearing their respirators,[7] whereas we removed the air monitoring pumps. Our adjusted personal air exposure levels showed much higher levels when assuming that the entrants did not wear a respirator. As mentioned by Puhala et al.,[12] exposure levels would also be expected to vary by base, which may depend on variations in fuel composition, job tasks, work practices, level of work activity, and if the aircraft being worked on contains fire suppressant foam,[7] which would likely result in higher exposure levels.[10]

The adjustment of personal air exposure levels, assuming the entrants did not wear a respirator while working inside the fuel tank, was instructive because, although the measured personal air exposure levels were below the OELs for all analytes, THC exposure levels would have exceeded the Air Force-recommended OEL of 200 mg/m^{3}for one worker-day if this participant had not worn respiratory protection. Similarly, THC exposure levels would have exceeded 100 mg/m^3 on 5 worker-days if the proper respiratory protection had not been worn.

Tank Air Concentrations

As with personal air levels, fuel tank air levels in this study were generally lower than those reported previously. Pleil et al.[11] reported air levels collected inside the fuel tanks (comparable to our interior fuel tank area), with a mean air level for benzene of 2987 ppbv (9543 μg/m^3). The over 100-fold difference between the interior fuel tank area levels measured in this study compared with those reported by Pleil et al.[11] may be due to the lack of fire-suppressant foam used on the aircraft in the present study, differences in the length of time the fuel tank was ventilated prior to sample collection, and differences in the formulation of the JP8 used.

Predictors of Inhalation Exposure

Participants reporting JP8 exposure had significantly increased exposure levels, implying that workers' self-reported JP8 exposure may be a useful surrogate for inhalation exposure. A more informative predictor of exposure (based on the between-worker variability explained and AIC values) was the *a priori* assigned exposure group based on general job level categorization. However, additional analyses examining exposure levels according to job task group revealed that refueling maintenance workers (part of the *a priori* moderate exposure group and performed maintenance activities on fuel distribution trucks) had higher exposure than fuel systems office workers (part of the *a priori* high exposure group and worked primarily in an office attached to the hangar). The explained between-worker variability of 100% for this model is likely due to the small sample size, and though the use of job task-based categories may reduce the potential for exposure misclassification, it would not eliminate this possibility. The existing potential for exposure misclassification is important to consider given that surrogate categorization schema are often employed in epidemiologic studies to examine relationships between exposure and health outcomes.

The examination of task groups revealed that THC and naphthalene levels were highest among those who worked primarily in the fuel systems hangar, followed by those who worked in refueling maintenance. However, for BTEX, the order of these task groups was reversed, suggesting that exposure to BTEX, at least in the moderate exposure group, may have come from other sources in addition to JP8 (e.g., degreasers or gasoline). Benzene, which had the weakest correlation with THC in the high and moderate group, may have come from other sources (e.g., degreasers or gasoline) in both groups.

The examination of the fuel systems maintenance workers (*a priori* high exposure group) revealed that several job-related factors resulted in increased exposure. Time spent in the hangar during the work shift, distance from the fuel tank, job activity, and searching for fuel tank leaks were all generally significant predictors of the analytes. Although participants wore respirators when entering the fuel tank, entrants likely had higher inhalation exposure compared with the other job activities due to additional time spent outside the tank without a respirator. Searching for fuel tank leaks could have occurred inside (while wearing a respirator) or outside the fuel tank and could be associated with higher inhalation exposure for similar reasons. Our results are generally consistent with those of Egeghy et al.[7] who also found that job (entrant, attendant, other); purpose of maintenance activity (inspect, find leak, repair, other); and distance of the worker from the fuel tank (>3 m, <3 m, inside) were significant predictors of exposure to naphthalene levels in personal air.

Strengths and Limitations

We used a repeated measures study design, collecting samples over 3 consecutive workdays, allowing for a comprehensive characterization of JP8 exposure. This design was important because personal air exposure varied over the study days. Inhalation exposure was measured throughout the work shift, excluding while the worker was wearing a respirator or smoking, thus reducing confounding by these factors. This study also adds to the previous jet fuel literature because JP8 exposure varies by base and time due to variations in job tasks, characteristics, and fuel composition.

Although measured, dermal exposure could not be quantified due to the low percentage of samples with concentrations above detection limits. In spite of this, these findings are important to document because this information could be useful in informing the design of future JP8 exposure and health effects studies. The QA/QC data for THC, ethylbenzene, *m-/p*-xylene, *o*-xylene, and naphthalene showed acceptable recovery, although the recovery of the lower molecular weight compounds (benzene and toluene) was low (<30%), which may have been due to volatilization during sample preparation. Therefore, laboratory methodology was sufficient for all of the analytes except benzene and toluene

One explanation for the low detection is that dermal exposures were simply lower in this study than in previous studies that have used this method, as other studies involved examination of fuel systems maintenance workers who had to remove fire suppressant foam from the fuel tanks as part of their work tasks.[5] Another explanation is that the time period between exposure and tape stripping was too long in our study (increased penetration or volatilization time), which may reduce the analyte levels in the upper layers of the skin.[5] A previous study that measured dermal exposure to JP8 did so after a 4-hr work shift, as compared to our full shift, and also measured three exposed body regions with potential for JP8 exposure.[5,6]

Dermal absorption has been shown to be a major route of exposure to JP8,[5–8] and it is important to note that these findings do not reflect a lack of potential for dermal exposure but an inability to capture this exposure at the end of a full work shift using this tape stripping method in this worker population.

The modest sample size (24 workers, 69 worker-days) limited our ability to model personal air exposure levels with multiple parameters. Data for this study came from a single Air Force base, and since exposure scenarios are likely to vary across bases, it is important for future studies to collect data from more than one base to improve generalizability. While adjusting personal air exposure levels among the entrants using the assigned protection factor of 50 is more realistic than assuming 100% respirator protection while inside the fuel tank, in future jet fuel exposure studies it would be more useful to measure the actual exposure levels inside the respirator. We also likely underestimated the naphthalene levels in personal air. For future studies we recommend sample collection procedures using a weaker sorbent that is better suited for determining lower level exposures to a chemical with the molecular weight of naphthalene.

CONCLUSIONS

Exposure levels varied throughout the workweek and were lower than those reported in previous studies, which further supports the idea that exposure levels vary considerably over time and by Air Force base. While self-reported JP8 exposure and the *a priori* assigned exposure groups were useful in significantly distinguishing JP8 exposure levels among our participants, task-based categories may provide further reduction in potential exposure misclassification when used in epidemiologic studies.

Naphthalene was strongly correlated with THC in the high and moderate exposure groups combined, suggesting that naphthalene may be an appropriate surrogate of exposure to JP8. Finally, our results underscore the importance of wearing respirators at all times while working inside the fuel tank, as the potential exists for exposure levels to exceed the Air Force-recommended OEL if the respirator is not worn.

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