MEASUREMENTS OF INDOOR AIR QUALITY ON COMMERCIAL TRANSPORT AIRCRAFT

MA Waters*, TF Bloom, B Grajewski and J Deddens

National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Cincinnati, OH, USA

ABSTRACT
Exposures to cabin environmental contaminants were measured on 36 commercial transport aircraft. The objectives were to characterize levels of contaminants and evaluate the relationship between flight factors such as aircraft size, occupancy, ventilation, and flight length, and environmental parameters. Monitoring was conducted at two coach locations for the duration of the flight for VOCs, nitrogen oxides, CO, CO_2, O_3, temperature, relative humidity, total particulates, and barometric pressure. Five-minute average concentration ranges were: CO_2 515-4902 ppm; O_3 <0.05-0.24 ppm; CO <0.2-2.9 ppm; nitrogen oxides <0.05-2.0 ppm; and total particulates <0.028-0.197 mg/m^3. Gate-to-gate average concentrations of VOCs were: toluene <3-130 ppb, limonene <3-12 ppb, and ethanol <0.8-2.4 ppb. Carbon dioxide exposures were highest on shorter and high-occupancy flights, aircraft with greater recirculated-to-fresh-air ratio, and narrow-bodied aircraft. In general contaminant levels were low compared to standards. Carbon dioxide levels indicated lower ventilation rates per occupant than most other indoor environments.

INDEX TERMS
Cabin air quality, Aircraft, Ventilation, Carbon dioxide, Relative humidity

INTRODUCTION
Much scientific and public interest has focused on cabin air quality in aircraft, which is the workplace of approximately 198,000 flight personnel in the US (Air Transport Association, 2000). Cabin air contaminants may include carbon dioxide, products of combustion such as carbon monoxide, nitrogen oxides, particulates and aldehydes, organic hydrocarbons from engine oil, fuel, hydraulic fluids, de-icing agents, cleaning products, allergens and infectious agents such as viruses and bacteria.

Engine compressor bleed air is pre-conditioned, sent to the air conditioning packs, and delivered to the cabin through a manifold that permits mixing with recirculated cabin air. Outside air is not filtered but the recirculation system incorporates air filtration; types and efficiency of filters vary by aircraft. Recirculation maintains air supply rate and minimizes use of more costly bleed air. While outside supply air at aircraft altitudes is generally very clean, it may become contaminated with engine oil, fuel, and hydraulic fluids aloft. During ground operations hydrocarbon vapors from refueling and other outdoor pollutants may enter the ventilation system (van Netten and Leung, 2000). Ozone may enter the cabin when an aircraft flies through the ozone layer. Although aircraft are equipped with catalytic converters to destroy ozone in bleed air, catalyst age may degrade efficacy.

* Contact author email: mwaters@cdc.gov

In general the outside fresh air ventilation rates in commercial transport aircraft have decreased over the last thirty years to as little as 6.3 ft^3/min per person (Hocking, 2000). Commercial aircraft are not required by the Federal Aviation Administration to meet performance criteria with respect to provision of either outside or recirculated air. Federal regulations require design specifications to provide at least 0.55 lb/min per occupant of fresh air which is approximately 10 ft^3/min per occupant at 8000 ft pressure (Federal Air Regulation, 1996). These are average ventilation rates per person over all occupied compartments.

Previous measurement studies of cabin air quality on commercial aircraft have been reviewed recently (Nagda, Rector, Zhidong *et al*., 2001). Most studies have addressed specific aircraft models or parameters such as environmental tobacco smoke and data on aircraft contaminants are few. The objectives for this study were to characterize cabin environmental quality parameters and to the extent possible evaluate the relationship between aircraft type and environmental parameters. This work is part of an exposure assessment for NIOSH health studies of flight crew. Reported here are levels and variability of cabin environmental quality measures including ozone, carbon dioxide, carbon monoxide, nitrogen oxides, volatile organic hydrocarbons, particulates, temperature, relative humidity, pressure, and on smoking-permitted flights environmental tobacco smoke, and the relationship between carbon dioxide and aircraft type.

METHODS

The study design included 36 commercial transport flight segments on eleven different aircraft. Flight segments were selected to obtain a range of flight durations and latitudes. Flight duration is relevant for pollutants such as carbon dioxide which build up during longer flights and was stratified into three categories: short (<2 hr), medium (2-8 hr), and long (>8 hr). About half of the flights were polar flights (some portion of the flight greater than 50 degrees latitude). Atmospheric ozone levels are higher at high latitudes where the ozone layer can penetrate down to aircraft altitudes. Six smoking-permitted flight segments were included. The cabin environment measurement parameters, sampling and analysis methods, and direct-reading data logging (DRDLI) instruments are summarized in Table 1.

Table 1. Environmental parameters monitored and sampling and analysis methods

Parameter	Sample type	Detection/analysis method
O_3, CO, nitrogen oxides	DRDLI, passive sampling	electrochemical
CO_2	DRDLI, active sampling	non-dispersive infrared
VOCs semiquantitative	integrative, thermal desorption tube	GC/MS[1] (NMAM 2549)[2]
Aldehydes	integrative, coated porous polymer	GC/FID/MS (NMAM 2539)
Ethanol	integrative, charcoal	GC FID (NMAM 1400)
aliphatic hydrocarbons	integrative, charcoal	GC FID (NMAM 1500)
aromatic hydrocarbons	integrative, charcoal	GC FID (NMAM 1501)
inhalable particulates	integrative, 25 mm 5 μm PVC	gravimetric
total particulates	integrative, 37 mm 5 μm PVC	gravimetric (NMAM 500)
respirable particulates	integrative, 37 mm 5 μm PVC	gravimetric (NMAM 600)
Nicotine	integrative, porous polymer	gravimetric (NMAM 2551)

[1]NMAM = NIOSH Manual of Analytical Methods (NIOSH, 1998)
[2]GC = gas chromatography, FID = flame ionization detector, MS = mass spectrometry

Environmental tobacco smoke and respirable particulates were collected on smoking-permitted flights only. In addition to the contaminants, temperature, relative humidity, and barometric pressure were continuously monitored. Monitoring was performed in the coach compartment in two sampling locations in coach, forward and rear. Sampling probes were clipped on the aisle seat backs above the breathing zone. Sampling was performed continuously from (at minimum) gate departure to gate arrival or "gate-to-gate". Additional samples were collected in other locations for nicotine (smoking flights only). Flight crew provided ventilation air pack usage, airflow schedule settings and passenger counts. For the DRDLI the sampling interval was 5 minutes. Field blanks for analytes sampled on integrative media were collected on each flight segment. Direct-reading data logging instruments (DRDLI) were calibrated before and after each field campaign using span gases (CO and NO_x) and chemical methods (O_3). Pressure correction factors were applied to air sample measurements.

RESULTS

The gate-to-gate times for the flight segments ranged from 42 to 863 minutes, with approximately equal allocation to short, medium, and long duration categories. Passenger occupancy ranged from 34-100% of capacity in coach.

Gases

Carbon monoxide full-flight average levels were generally less than 1 ppm, with 5-minute averages occasionally ranging as high as 9.4 ppm. No differences between front and rear coach location levels or trends by aircraft type were identifiable. Nitrogen oxides averaged 0.57 ppm (sd 0.56 ppm); no significant relationship between concentrations and aircraft type or route or between front and rear coach locations was found. Ozone gate-to-gate average levels ranged from < 0.05 to 0.24 ppm, with the highest five-minute average during a flight averaging 0.17 ppm (n=22). All aircraft were equipped with catalytic ozone converters to reduce in-cabin concentrations. No discernible trend by altitude or by polar/non-polar route was observed. None of the gate-to-gate average ozone levels exceeded the 0.25 ppm Federal Air Regulation (1996) applicable to flights over 32,000 ft.

VOCs and aldehydes

The predominant VOC was ethanol, followed by toluene and limonene. Toluene levels ranged from <3 to 130 ppb, limonene from <3-12 ppb, and ethanol from <0.8-2.4 ppm. Levels (ppb) of hexane (<0.004), ethyl acetate (<0.02), formaldehyde (<0.07)and acrolein (<0.2) were detectable but too low to be quantified. Using the semi-quantitative thermal desorption tube method (NIOSH, 1998) trace levels of propylene glycol monomethyl ether acetate , siloxane, tributylphosphate, perchlorethylene, butyl cellosolve, methyl pyrollidine, benzene, and 1-methoxy-2-propanol were found.

Particulates and nicotine

Full-flight average inhalable particulates averaged 0.12 μg/L and ranged from 0.038 to 0.3 μg/L. Total particulates averaged 0.086 μg/L. Concentrations of both total and inhalable particulates were higher in the rear of coach than the front ($p<0.05$). The ratio of inhalable-to-total particulate averaged 1.4, indicating that the majority (71%) of the mass distribution was comprised of particles smaller than 30 μm. The mean concentration of inhalable particulate did not differ for smoking (0.119 μg/L) versus non-smoking flights (0.123 μg/L). The mean concentration of total particulate were somewhat higher on smoking flights (0.11 μg/L) than on non-smoking flights (0.08 μg/L).

Respirable particulates (RSP) and nicotine were sampled on six smoking-permitted flights in non-smoking areas of the aircraft. Levels of RSP ranged from 19.9 to 153 $\mu g/m^3$. Nicotine levels ranged from 0.38 to 24.1 $\mu g/m^3$. Coach rear levels were substantially higher than coach front levels for both respirable particulates and nicotine, as expected due to proximity of the rear sampling station to the designated smoking rows in the rear of coach.

Carbon dioxide

Carbon dioxide concentrations in coach averaged over both front and rear locations and over the entire flight period ranged from 874-2328 ppm (mean 1387 ppm, sd=351 ppm). The lowest 5-minute TWAs over the duration of the flight averaged 1021 ppm. Some flights never had CO_2 concentrations lower than 1556 ppm. The highest gate-to-gate 5-minute TWAs averaged 2216 ppm, with single values at one location ranging as high as 4902 ppm CO_2. The 5-minute TWAs were also parsed into three periods (boarding, midflight, and deboarding) by examining each plot of front plus rear coach average concentrations versus time and developing a cutoff point based on the CO_2 levels. The mean CO_2 concentrations in ppm during these periods were: 1522 (range=784-3284) during boarding, 1317 (range=751-2217) during midflight, and 1150 (range=818-2439) during deboarding. Geometric standard deviations for each of these distributions were so low (<= 1.4) that it was not possible to distinguish between fit to a normal or lognormal distribution using the Shapiro-Wilk test.

The correlation between several flight factors and carbon dioxide levels was evaluated both parametrically (Spearman) and nonparametrically (Pearson). Two surrogates for aircraft size were used: coach capacity (number of seats) as a continuous discrete variable and narrow body single-aisle aircraft versus wide-body double-aisle aircraft as a dichotomous variable. Occupancy in coach expressed as a percentage of capacity, the flight length in minutes, and the number of air changes per hour for the aircraft were also evaluated. The only significantly correlated factor identified was the occupancy, showing CO_2 levels were highly dependent on passenger load ($p<0.01$). The analysis of the effect of air changes per hour on carbon dioxide levels was hindered by the fact that ventilation rates available were averages based on volume of the entire aircraft including the cargo, business class and first class compartments and were not specific to the coach compartment where the CO_2 levels were measured. Despite lack of statistical significance, several relationships were evident. CO_2 levels were higher on aircraft with recirculation (1352 ppm versus 1144 ppm) and slightly higher on smaller aircraft on short flights (1388 ppm vs. 1256 ppm). CO_2 levels were not statistically significantly correlated with flight length or surrogates for aircraft size.

Relative humidity, temperature and pressure

Relative humidity ranged vary widely, with gate-to-gate averages ranging from 10.1 to 45.6% (mean=19.8%, sd=6.7%, n=36). Front and rear coach levels were not significantly different. The longest flights had the lowest gate-to-gate averages; some had extended periods around 6-8%RH. Over 50% of the flights had RH averages below 20%, generally the lower cutoff for ASHRAE comfort criteria, dependent on temperature (ASHRAE, 1999). Temperatures ranged between 19-29.5°C (5-minute TWA). The lowest pressures attained on each flight ranged from 574-680 mm Hg (1-minute TWA), with duration-of-flight averages from 609-726 mm HG.

DISCUSSION

Carbon monoxide and nitrogen oxides air concentrations found in this study were largely comparable to values reported in other aircraft studies (Spengler, Burge, Dumyahn, *et al.*, 1997; Pierce WM, Janczewski JN, Roethlisberger B, *et al.,* 1999). Carbon monoxide levels on the B-777 were reported as averaging 0.7 ppm (range 0.8-1.3, n=3) (Spengler *et al*., 1997). Spengler *et al*. (1997) found nitrogen dioxide levels on the B-777 averaging 36 ppb (range 23-60, n=4); these results are not directly comparable since we measured nitrogen oxides.

Ozone levels in aircraft reported by Nagda, Fortmann, Koontz, *et al*. (1989) averaged 22 ppb on non-smoking flights and 10 ppb on smoking flights. Spengler, Burge, Dumyahn, *et al.* (1997) reported ozone levels on the B-777 to be all below the detection limit which varied from 1.8-9.8 ppb. De Ree, Bagshaw, Simons, *et al*. (2000) found mean levels ranging from 2-28.4 ppb on aircraft with catalytic converters (n=19) and from 43-177 ppb on aircraft without catalytic converters (n=12). They also reported maximums (30 second averaging interval) of 8-159 ppb and 158-383 ppb for aircraft with and without converters, respectively. In this study flight mean levels ranged from <50 to 240 ppb (all on aircraft with converters). The large variation in levels determined between each of these studies is likely a reflection of the difficulty of accurate ozone measurement using portable instrumentation and the difficulty of maintaining calibrations in the field.

VOC levels were low or non-detectable in this study and the profile observed was not atypical for indoor environments. Since these measurements were collected integratively, it was not possible to discern time trends in levels over the course of the flight. However, bioeffluents would likely track the time trends throughout flight of carbon dioxide since both are related to metabolic rate. VOCs associated with meal service, especially ethanol, are likely higher during meal service. VOCs originating from cleaning agents or furnishings would be expected to follow a time course related to ventilation rate, which is lowest during periods when power is needed for thrust, such as take-off and the early ascent phase. Future characterization efforts in the aircraft cabin should use more sensitive VOC methods than used here and include measurement of semi-volatile organic compounds, although the aircraft cabin, with space and power source constraints, poses sampling difficulties not easily overcome. Pesticides, typically pyrethroids, are applied regularly inside aircraft cabins using a method sufficient to leave a residual for six weeks. Yet no pesticide quantitation studies, either of surface contamination or air concentrations, have been performed.

CONCLUSIONS AND IMPLICATIONS

In general contaminant levels measured here were low compared to standards. Carbon dioxide levels, while not related to any health effects at the levels found here, are indicative of lower ventilation rates per occupant than most other indoor environments. ASHRAE is currently in the process of setting an air quality standard for commercial transport aircraft.

Although symptom and health effect studies have been conducted in non-transportation indoor environments, little symptomatology research has been performed among aircrew (Lee, Poon, Li, *et al.,* 2000). One study comparing aircrew perception of cabin air quality with office workers showed cabin crew complaints about air quality were greater than office workers (Lindgren, Norback, Andersson, *et al.,* 2000), and a survey of passengers concluded that passengers' assessment of cabin air quality was an important determinant of comfort and health-related symptoms (Rankin, Space, and Nagda, 2000). Additional research is needed to investigate the relationship between health effects, symptoms and cabin air quality.

ACKNOWLEDGEMENTS

We thank the Civil Aeromedical Institute, US Federal Aviation Administration (CAMI-FAA), the airline companies, unions, and the flight and cabin crews for their support and assistance during this study. This study was funded in part by the CAMI-FAA, Interagency Agreement DTFA0197F80353.

REFERENCES

Air Transport Association. 2000. The Annual Report of the U.S. Scheduled Airline Industry. Air Transport Association, Washington DC.

ASHRAE. 1999. ANSI/ASHRAE Standard 62-1999. Ventilation for Acceptable Indoor Air Quality, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

De Ree H, Bagshaw M, Simons R, *et al.* 2000. Ozone and relative humidity in airline cabins. In *Air Quality and Comfort in Airline Cabins*, ASTM STP 1393, NL Nagda, ed. West Conshohocken PA: American Society of Testing Materials, pp 243-258.

Federal Air Regulation (FAR). 1996. Title 14 Code of Federal Regulations, Chapter I–Federal Aviation Administration, Department of Transportation, Part 25–Airworthiness Standards: Transport Category Airplanes, Section 831: Ventilation, as amended June 5, 1996.

Hocking MB. 2002. Passenger aircraft cabin air quality: trends, effects, societal costs, proposals. *Chemosphere*. Vol. 41(4), pp 603-15.

Lee SC, Poon CS, Li XD, *et al.* 2000. Questionnaire survey to evaluate the health and comfort of cabin crew. In *Air Quality and Comfort in Airline Cabins*, ASTM STP 1393, NL Nagda, ed. West Conshohocken PA: American Society of Testing Materials, pp 259-268.

Lindgren T, Norback D, Andersson K, *et al.* 2000. Cabin environment and perception of cabin air quality among commercial aircrew. *Aviation Space & Environmental Medicine*. Vol. 71(8), pp 774-82.

Nagda NL, Fortmann RC, Koontz MD, *et al.* 1989. *Airliner Cabin Environment: Contaminant Measurements, Health Risks, and Mitigation Options*. US Department of Transportation, Report No. DOT-P-15-89-5. Washington, DC: Govt Printing Office.

Nagda NL, Rector HE, Zhidong L *et al.* 2000. Aircraft cabin air quality: A critical review of past studies. In *Air Quality and Comfort in Airline Cabins*, ASTM STP 1393, NL Nagda, ed. West Conshohocken PA: American Society of Testing Materials, pp 215-235.

NIOSH. 1998. Methods 500, 600, 1400, 1500, 1501, 2539, 2549, 2551. In *NIOSH Manual of Analytical Methods (NMAM)*, 4th ed, Eller PM, Cassinelli ME, eds. Cincinnati OH, DHHS Publication 98-119.

Pierce WM, Janczewski JN, Roethlisberger B, *et al.* 1999. Air quality on commercial aircraft. *ASHRAE Journal*. Vol. 41, pp 26-34.

Rankin WL, Space DR, and Nagda NL. 2000. Passenger comfort and the effect of air quality. In *Air Quality and Comfort in Airline Cabins*, ASTM STP 1393, NL Nagda, ed. West Conshohocken PA: American Society of Testing Materials, pp 269-289.

Spengler J, Burge H, Dumyahn T, *et al.* 1997. Environmental Survey on Aircraft and Ground-based Commercial Transportation Vehicles. Report of May 31, 1997, Boston MA, Harvard School of Public Health.

van Netten C, Leung V. 2001. Hydraulic fluids and jet engine oil: pyrolysis and aircraft air quality. Archives of Environmental Health. 56(2), pp181-186.