ESTIMATION OF EFFECT OF ENVIRONMENTAL TOBACCO SMOKE ON AIR QUALITY WITHIN PASSENGER CABINS OF COMMERCIAL AIRCRAFT. II.

G.B. Oldaker III*[1], M.W. Stancill[1], F.W. Conrad, Jr.[1], B.B. Collie[1], R.A. Fenner[2], J.O. Lephardt[2], P.G. Baker[2], J. Lyons-Hart[2] and M.E. Parrish[2]

[1]Research and Development Department, Bowman Gray Technical Center, R.J. Reynolds Tobacco Company, Winston-Salem, North Carolina 28102, U.S.A.

[2]Research and Development, Phillip Morris USA, P.O. Box 26583, Richmond, Virginia 23261, U.S.A.

ABSTRACT

To assess exposures to environmental tobacco smoke (ETS), concentrations of nicotine, respirable suspended particles (RSP), and ultraviolet particulate matter (UVPM) were determined in passenger cabins of commercial aircraft. Arithmetic mean concentrations of nicotine, RSP, and UVPM in nonsmoking sections were 2.3, 15, and 7 $\mu g\ m^{-3}$, respectively; corresponding arithmetic mean concentrations in smoking sections were 10.6, 39, and 26 $\mu g\ m^{-3}$, respectively. The effect of smoker segregation on ETS was shown by statistically significant differences ($P < 0.05$) between concentrations of nicotine, RSP, and UVPM measured in nonsmoking and smoking sections of the aircraft.

INTRODUCTION

The earlier report in this series (1) addressed results from measurements of vapor phase nicotine in passenger cabins of narrow-bodied B727-200, B737-200, and B737-300 aircraft on U.S. domestic flights. Vapor phase nicotine was employed as the indicator of environmental tobacco smoke (ETS) because it is specific to ETS and because experiments have shown that approximately 95% of the nicotine associated with ETS exists in the vapor phase (2, 3). Results of this earlier investigation showed that smoker segregation significantly reduces exposure of passengers in non-smoking sections of these aircraft to ETS and that the design and operation of the aircraft heating, ventilating, and air conditioning (HVAC) systems could account for such reduction.

Since the promulgation of U.S. regulations restricting smoking (4), no investigation of ETS in wide-bodied aircraft has been reported. Results from measurements of ETS performed in narrow-bodied aircraft are not expected to be representative of ETS in wide-bodied aircraft because of differences in the design and operation of heating, ventilating, and air conditioning (HVAC) systems, seating patterns, passenger loads, and lengths of flights. To assess more completely the effect of cigarette smoking on air quality in passenger cabins of commercial aircraft, we conducted investigations in wide-bodied aircraft during long flights. Compared to earlier surveys, these investigations used more sophisticated sampling equipment capable of determining ETS constituents in addition to nicotine. For the investigations reported here, sampling was conducted throughout passengers cabins in both smoking and non-smoking sections and in all classes of service on board B747 aircraft.

EXPERIMENTAL

Aircraft

Investigations were performed during December 1987 in one B747LR-100 and three B747LR-200s on non-stop, regularly scheduled, week-day flights connecting New York (Kennedy), Tokyo (Narita), and Hong Kong (Kai Tak). B747LR-100s and B747LR-200s have seating capacities of 292 and 352 revenue passengers, respectively.

Although constructed at different times ranging from May 1970 to June 1983, the Boeing 747LR-100 and -200 aircraft studied have HVAC systems of the same design (5). Each system has three air conditioning units feeding into a common plenum chamber. Air from the plenum chamber flows to five air conditioning zones. Zone 1 includes the cockpit; zones 2, 3, and 4, the passenger cabin on the main level; and zone 5, the passenger cabin on the upper deck. Air can be recirculated within a given zone, but is never recirculated between the cabin and the plenum chamber.

Within the passenger cabin, air enters from outlets high on the side walls, flows toward the center of the cabin where it converges, and then flows down and back along the floor to the walls. At the walls the air divides, one portion exiting through the side vents into the lower cargo compartment and the other rising to join the incoming air from ceiling-level ducts.

The major exhaust route is through outflow valves located in the aft ventral area of the fuselage. Air from the passenger cabin reaches these valves by flowing into the side-wall grilles near the cabin floor and moving aft through the lower cargo compartment. When all three air conditioning packs are in operation, air is exhausted at about 220 m^3 min^{-1} by this route. Another vent system, which serves the lavatories, galleys and staircase, exhausts about 30 m^3 min^{-1}. Lastly, a small amount of air leaves the cabin through minor leaks, occurring primarily at door seals. During the investigation, all three air conditioning packs operated automatically at full rate throughout every flight. Based on the exhaust flow rates identified above, a maximum flow rate of 250 m^3 min^{-1} through the cabin is presumed.

Because the aircraft design causes air to be taken in somewhat more rapidly by the floor-level grilles in the aft sections than by the floor-level grilles in the forward sections, there is a slight tendency for the general air movement in the cabin to be from front to rear. Thus, the general direction of air flow through the cabin is a diagonal movement from ceiling to floor with a small velocity from the front of the cabin to the rear.

Sampling Locations

Ten sampling locations were randomly selected for each of the four flights. The distribution of sampling locations was two in first class and four in each of the business and economy classes with equal numbers in smoking and non-smoking sections of each class. Window and bulkhead seats were not chosen because of the possibility that wall effects (6) would lead to biased estimates of exposure.

Two samples were collected at each location on flights between New York and Tokyo. Collection of the first sample began after the aircraft doors were closed and ended about mid way into the flight, when collection of the second sample started. Collection of the second sample ended when the aircraft doors were opened upon arrival at the gate. On flights between Tokyo and Hong Kong, only one sample was collected at each location.

Flight crews were informed of the investigation before each departure. Flight data were obtained and cigarette butts were collected at the end of each flight. Aircraft were cleaned by maintenance personnel before the sampling team boarded each flight.

Sampling methods and procedure

Portable air sampling systems (PAS
of vapor phase nicotine, RSP, and U
pressure. The PASS is an area sam
appear as an ordinary briefcase.
noise it makes is imperceptible in
off switch positioned under the
diametrically at the corners. Ad
briefcase hardware. The above fe
sampling will influence the smokin

The PASS was tested to ensure th
Test results showed that the P
specifications.

For sampling in the aircraft, ea
secured with a seat belt fastened
as close as possible to the breat
one member of the sampling team t
measurement began and ended on ti

The method used to sample nicotin
the sampling system include a so
Four, PA) connected by rubber
operated at 1 L min^{-1}. Particulate
by Conner et al. (9); this metho
at 3.5 µm, a filter assembly cont
size of 1.0 µm (Milipore, Corp.,
Inc.) operated at 2 L min^{-1}. Pum
with a film flow meter. Sam
deviations from average flow gre

CO monitoring systems were dev
sensors to operate with sampl
Gainesville, GA) are fitted with
NJ) and provided with a voltage-
sampling. The detector is inter
Logan, UT) programmed to recor
cassette tape and then to a pers
calibrated with gaseous standar

Analytical Procedure

Nicotine was quantified with
collected on XAD-4 resin is
triethylamine, which neutrali
Analyses are performed with a
selective detector (Hewlett-Pa
X 0.53 mm inside diameter, fus
of DB-5 (5% phenyl methylpoly
is employed as an internal st
XAD-4 resin are analyzed s
Desorption efficiency was qu
Institute of Occupational Saf
collaboratively tested (12).

RSP was quantified gravimetr
Filters with and without samp
humidity for at least 12 hour
filters and samples under an
Products Co., El Monte, CA)

Sampling methods and procedure

Portable air sampling systems (PASS's) (7, 8) were used to collect integrated samples of vapor phase nicotine, RSP, and UV-PM and to monitor CO, temperature, and barometric pressure. The PASS is an area sampling device, powered by batteries and designed to appear as an ordinary briefcase. During operation, the PASS remains closed and the noise it makes is imperceptible in the cabin. The briefcase exterior includes an on-off switch positioned under the handle and inlet and exhaust ports positioned diametrically at the corners. Added hardware is brass selected to match the normal briefcase hardware. The above features are intended to reduce the possibility that sampling will influence the smoking behavior of passengers.

The PASS was tested to ensure that its operation would not interfere with avionics. Test results showed that the PASS conforms with Federal Aviation Administration specifications.

For sampling in the aircraft, each PASS was placed upright in its assigned seat and secured with a seat belt fastened through its handle. In this position the PASS sampled as close as possible to the breathing zones of passengers. Each PASS was attended by one member of the sampling team to prevent its being disturbed and to assure that each measurement began and ended on time.

The method used to sample nicotine has been described before (1). Major components of the sampling system include a sorbent tube containing XAD-4 resin (SKC Inc., Eighty-Four, PA) connected by rubber tubing to a constant-flow sampling pump (SKC Inc.) operated at 1 L min^{-1}. Particulate matter samples were collected by the method described by Conner et al. (9); this method employs a system comprising an impactor separating at 3.5 μm, a filter assembly containing a 37-mm Fluoropore membrane filter with a pore size of 1.0 μm (Milipore, Corp., Bedford, MA), and a constant-flow sampling pump (SKC Inc.) operated at 2 L min^{-1}. Pumps were calibrated before and after sample collection with a film flow meter. Samples were invalidated if calibration checks showed deviations from average flow greater than 10%.

CO monitoring systems were developed by modifying commercially available, passive sensors to operate with sampling pumps (7, 8). CO detectors (Neotronics, N.A., Gainesville, GA) are fitted with sampling lines and sampling pumps (Gilian, Inc., Wayne, NJ) and provided with a voltage-regulated power supply to maintain constant flow during sampling. The detector is interfaced to a 21X Micrologger (Campbell Scientific, Inc., Logan, UT) programmed to record data each minute. Recorded data were transferred to cassette tape and then to a personal computer for analysis. CO monitoring systems were calibrated with gaseous standards before and after sample collection.

Analytical Procedure

Nicotine was quantified with the method described by Ogden et al. (10). Nicotine collected on XAD-4 resin is desorbed in 2 mL ethyl acetate containing 0.01% (v/v) triethylamine, which neutralizes acidic sites on surfaces of analytical glassware. Analyses are performed with a Model 5880A gas chromatograph equipped with a nitrogen-selective detector (Hewlett-Packard, Avondale, PA). Chromatography is done on a 30 m X 0.53 mm inside diameter, fused silica capillary column coated with a 1.5 micron film of DB-5 (5% phenyl methylpolysiloxane) (J&W Scientific, Inc., Folsom, CA). Quinoline is employed as an internal standard. For each sample, the front and rear segments of XAD-4 resin are analyzed separately to assess breakthrough; none was observed. Desorption efficiency was quantified by the method described by the U.S. National Institute of Occupational Safety and Health (NIOSH) (11). The nicotine method has been collaboratively tested (12).

RSP was quantified gravimetrically according to method described Conner et al. (9). Filters with and without samples are conditioned at room temperature and 50% relative humidity for at least 12 hours before weighing. Static charges are removed by holding filters and samples under an anti-static device (Staticmaster, Model No. 2V500, Nuclear Products Co., El Monte, CA) for at least one minute before each weighing. Weights are measured with a balance having a readability of one microgram (Mettler M3, Mettler Instrument Corp., Highstown, NJ) and having an anti-static device attached to the interior wall. Each gravimetric result is the average of at least five separate weighings.

UVPM was quantified as described by Conner et al. (9). After RSP is determined, the sample and filter are extracted with 4 mL methanol and a 50-μL aliquot of the extract is injected into a columnless liquid chromatographic system equipped with an ultraviolet detector measuring adsorption at 325 nm. Masses of UVPM are computed from a standard calibration curve derived from a series of ETS concentrations prepared in an environmental chamber (13). For the work reported here, methanolic solutions of 2,2′,4,4′- tetrahydroxybenzophenone (Aldrich, Milwaukee, WI) were used as secondary standards (9). Ingebrethsen et al. (9, 14) have shown that results from RSP and UVPM methods are unbiased relative to results from piezoelectric balances.

RESULTS AND DISCUSSION

Table I presents results from determinations of concentrations of nicotine, RSP, and UVPM in nonsmoking (NS) and smoking sections (S). Classes of service are: first class, FClass; executive, Exec; and economy, Econ. Flights are identified as follows: flight 1, Tokyo to Hong Kong; flight 2, Hong Kong to Tokyo; flight 5, New York to Tokyo; and flight 8, Tokyo to New York. Data invalidated because of calibration results are designated not available (NA).

TABLE I. Results from Determinations of Nicotine, RSP, and UVPM Concentrations in B747 Aircraft

					Concentration, μg m^{-3}		
No.	Class	Section	Flight	Sample	Nicotine	RSP	UVPM
1	Econ	S	1		25.7	119	88
2	Exec	S	1		NA	102	102
3	Exec	S	1		NA	50	47
4	Econ	S	1		31.4	59	59
5	FClass	S	1		11.4	33	20
6	Exec	NS	1		3.3	3	3
7	FClass	NS	1		NA	3	3
8	Econ	NS	1		0.1	3	3
9	Econ	NS	1		12.4	98	30
10	Exec	NS	1		2.9	3	3
11	FClass	S	2		9.0	5	5
12	Econ	S	2		42.7	185	113
13	Exec	S	2		9.4	5	5
14	Econ	S	2		NA	31	31
15	Exec	S	2		14.9	NA	NA
16	Exec	NS	2		2.9	63	14
17	FClass	NS	2		6.1	21	19
18	Econ	NS	2		4.6	35	18
19	Exec	NS	2		2.7	48	13
20	Econ	NS	2		NA	5	5
21	FClass	S	5	1	10.6	21	21
22	Exec	S	5	1	7.6	55	15
23	Exec	S	5	1	1.8	22	5
24	Econ	S	5	1	NA	35	35
25	Econ	S	5	1	NA	32	19

TABLE I. Results from Det
in B747 Aircraf

No.	Class	Section	Flight
26	Econ	NS	5
27	Exec	NS	5
28	Exec	NS	5
29	FClass	NS	5
30	Econ	NS	5
31	Econ	S	5
32	Exec	S	5
33	FClass	S	5
34	Exec	S	5
35	Econ	S	5
36	Econ	NS	5
37	FClass	NS	5
38	Exec	NS	5
39	Econ	NS	5
40	Exec	NS	5
41	Exec	S	8
42	Exec	S	8
43	Econ	S	8
44	Econ	S	8
45	FClass	S	8
46	Exec	NS	8
47	FClass	NS	8
48	Econ	NS	8
49	Exec	NS	8
50	Econ	NS	8
51	Exec	S	8
52	Econ	S	8
53	Exec	S	8
54	Econ	S	8
55	FClass	S	8
56	Exec	NS	8
57	Econ	NS	8
58	Exec	NS	8
59	FClass	NS	8
60	Econ	NS	8

The CO monitoring systems provi
showed that low relative humid
substantially shorten the worki
been obtained, it might have be
annoyance from exposure to ETS.

Goodness of fit tests were used
indicate that the log normal d
distribution. Table II prov
arithmetic and geometric means,

TABLE I. Results from Determinations of Nicotine, RSP, and UVPM Concentrations in B747 Aircraft (continued)

					Concentration, $\mu g\ m^{-3}$		
No.	Class	Section	Flight	Sample	Nicotine	RSP	UVPM
26	Econ	NS	5	1	NA	2	2
27	Exec	NS	5	1	0.8	6	6
28	Exec	NS	5	1	0.7	26	4
29	FClass	NS	5	1	0.1	11	3
30	Econ	NS	5	1	3.8	2	2
31	Econ	S	5	2	NA	3	3
32	Exec	S	5	2	2.1	3	3
33	FClass	S	5	2	4.7	47	15
34	Exec	S	5	2	8.8	42	4
35	Econ	S	5	2	NA	23	23
36	Econ	NS	5	2	NA	24	22
37	FClass	NS	5	2	0.1	5	3
38	Exec	NS	5	2	0.7	8	4
39	Econ	NS	5	2	3.7	7	7
40	Exec	NS	5	2	0.6	24	9
41	Exec	S	8	1	13.9	28	28
42	Exec	S	8	1	7.3	26	22
43	Econ	S	8	1	3.9	26	9
44	Econ	S	8	1	4.3	3	3
45	FClass	S	8	1	NA	55	20
46	Exec	NS	8	1	1.1	NA	NA
47	FClass	NS	8	1	0.3	3	3
48	Econ	NS	8	1	4.6	3	3
49	Exec	NS	8	1	1.0	3	3
50	Econ	NS	8	1	NA	8	8
51	Exec	S	8	2	5.9	63	21
52	Econ	S	8	2	1.8	30	6
53	Exec	S	8	2	3.5	19	14
54	Econ	S	8	2	1.8	3	3
55	FClass	S	8	2	NA	3	3
56	Exec	NS	8	2	0.6	NA	NA
57	Econ	NS	8	2	2.2	9	9
58	Exec	NS	8	2	0.5	3	3
59	FClass	NS	8	2	0.1	3	3
60	Econ	NS	8	2	NA	2	2

The CO monitoring systems provided no valid data. Experiments done after the study showed that low relative humidity levels, such as existed in the aircraft cabins, substantially shorten the working life of the CO sensor used by the PASS. Had CO data been obtained, it might have been possible to address issues regarding irritation and annoyance from exposure to ETS.

Goodness of fit tests were used to assess the form of the concentration data. Results indicate that the log normal distribution describes the data better than the normal distribution. Table II provides, by section, summary statistics including the arithmetic and geometric means, maximum and minimum values, and number of samples.

Table II. Summary of Results from Samples Collected in Non-Smoking (NS) and Smoking (S) Sections of B747LR-100 and B747LR-200 Aircraft

	Concentration, $\mu g\ m^{-3}$					
	Nicotine		RSP		UV-PM	
	NS	S	NS	S	NS	S
Mean						
arithmetic	2.3	10.6	15	39	7	26
geometric	1.1	7.1	8	23	5	14
Max	12.4	42.7	98	185	30	113
Min	0.1	1.8	3	3	2	3
N	24	21	28	29	28	29

Statistical analyses employing ANOVA were done to test for differences between mean concentrations (both arithmetic and geometric) of nicotine, RSP, and UV-PM measured in sections and classes of service. Results indicate no statistically significant difference ($P > 0.05$) in concentrations of ETS indicators between classes of service. Class-by-section interactions (Class * Section) also were found not to be significant ($P > 0.05$) for the three indicators. Statistically significant differences are shown between smoking and non-smoking sections for nicotine, RSP, and UVPM. P-values for analyses of the log transformed results are as follows: nicotine, $P = 0.0001$; RSP, $P = 0.0019$; and UVPM, $P = 0.0007$. P-values for the non-transformed results are similar: nicotine, $P = 0.0009$; RSP, 0.0166; and UVPM, 0.0086.

The finding that smoker segregation reduces exposure of passengers seated in non-smoking sections is consistent with results from investigations performed in narrow-bodied aircraft (1, 15, 16, 17). Additionally, this finding is in line with the design and operation of ventilation systems for B747LR-100 and -200 aircraft which are designed to provide more than 17 air changes per hour.

Class-by-section interaction statistics can indicate trends in ETS concentrations going from first class to economy class. The absence of significant class-by-section interaction also is consistent with the design of the ventilation system: air is intended to be uniformly distributed throughout the cabin with flow being predominantly from ceiling to floor with little fore to aft movement.

Nicotine results agree with those previously reported in connection with aircraft cabins. Muramatsu et al. (15, 16) used personal sampling devices to collect nicotine. They reported arithmetic mean concentrations of 13.5 and 5.3 $\mu g\ m^{-1}$ at smoking seats and non-smoking seats, respectively. The mean nicotine concentrations for the two sections were statistically different ($p \leq 0.01$) (17). Our earlier investigation (1) of B727-200, B737-200, and B737-300 aircraft reported geometric mean nicotine concentrations of 9.2 $\mu g\ m^{-3}$ in smoking sections and 5.5 $\mu g\ m^{-3}$ in non-smoking sections. Additionally, statistical analyses showed that the difference between nicotine concentrations measured in the sections was significant.

RSP results for smoking sections are similar to those jointly reported by the U.S. Department of Health, Education and Welfare (DHEW) and U.S. Department of Transportation (DOT) (18). For that investigation, RSP concentrations ranged from none detected to 120 $\mu g\ m^{-3}$ with an arithmetic mean of 40 $\mu g\ m^{-3}$. Such similarity might be expected because the DHEW/DOT investigated wide-bodied aircraft. However, these investigations were performed in 1971 when smoking demographics were different and before the promulgation of regulations segregating smokers; thus, the basis for comparison is limited.

Mean concentrations of RSP and UV-P
of the absence of significant sourc
with the exception of ETS. The di
UVPM and RSP measured in smoking
concentrations of RSP in the absen

Results reported for measurements
no smoking conditions. On several c
in non-smoking sections were obser
nicotine, RSP, and UVPM found in n
situation.

Table III gives information on nu
flights. Smoking rates are fai
passenger^{-1} h^{-1}. It was desired to g
passenger^{-1} h^{-1}; however, occurrence
computations. From data reported
and 0.6 cigarette passenger^{-1}
transcontinental flights involvin
of 0.735 cigarette passenger^{-1} h^{-1} i
and Starrett (19). These rates (1
investigation, as might be expecte
occurred since these earlier meas

Table III. Smoking Rate Data and

flight	average sampling time, min
New York to Tokyo	787
Tokyo to Hong Kong	294
Hong Kong to Tokyo	203
Tokyo to New York	767

The RSP and nicotine data reveal
used to evaluate results (20). F
of 7:1 to estimate RSP concent
aircraft cabins. Data for the p
both terms of the ratio can expl
the RSP term of the RSP to nicoti
ETS, because RSP does not apporti
concentrations of RSP in airc
consequently, the RSP term of th
the ratio should tend to be le
density of smokers is similar.

Lastly, an appreciable backgrour
from walls and fabrics might exi
other researchers have investig
et al. (22) found a background
having an adjoining bar. Highe
aircraft cabins compared to gro
because aircraft cabins have a
continuously and a greater surf

Mean concentrations of RSP and UV-PM agree closely. This agreement is expected in view of the absence of significant sources of RSP either within or outside of the aircraft, with the exception of ETS. The differences between geometric mean concentrations of UVPM and RSP measured in smoking and non-smoking sections suggest that background concentrations of RSP in the absence of ETS range between 3 and 9 $\mu g\ m^{-3}$.

Results reported for measurements conducted in non-smoking sections do not represent no smoking conditions. On several occasions during the investigation, passengers seated in non-smoking sections were observed smoking. Indeed, the highest concentrations of nicotine, RSP, and UVPM found in non-smoking sections are associated with just such a situation.

Table III gives information on numbers of passengers and smoking rates for the four flights. Smoking rates are fairly uniform, ranging from 0.25 to 0.37 cigarette passenger^{-1} h^{-1}. It was desired to quantify smoking rates in terms of cigarettes smoking passenger^{-1} h^{-1}; however, occurrence of smoking in non-smoking sections precluded such computations. From data reported by the DHEW/DOT (18) in 1971, smoking rates of 0.4 and 0.6 cigarette passenger^{-1} h^{-1} are computed for domestic flights and for transcontinental flights involving military personnel, respectively. A smoking rate of 0.735 cigarette passenger^{-1} h^{-1} is calculated from data reported in 1961 by Halfpenny and Starrett (19). These rates (18, 19) are higher than those measured for the present investigation, as might be expected, owing to changes in smoking demographics that have occurred since these earlier measurements were reported.

Table III. Smoking Rate Data and Results

flight	average sampling time, min	total no. passengers	no. cigarettes	smoking rate, cigt passenger^{-1} h^{-1}
New York to Tokyo	787	170	619	0.28
Tokyo to Hong Kong	294	252	304	0.25
Hong Kong to Tokyo	203	287	357	0.37
Tokyo to New York	767	96	306	0.25

The RSP and nicotine data reveal one of the limitations of RSP to nicotine ratios when used to evaluate results (20). Repace and Lowrey (21) assume an RSP to nicotine ratio of 7:1 to estimate RSP concentrations from concentrations of nicotine measured in aircraft cabins. Data for the present study give a ratio of 4:1. Factors affecting both terms of the ratio can explain this difference. For ground level environments, the RSP term of the RSP to nicotine ratio generally will be biased high, overestimating ETS, because RSP does not apportion for ETS. In contrast to ground level environments, concentrations of RSP in aircraft cabins are affected less by non-ETS sources; consequently, the RSP term of the RSP to nicotine ratio should better indicate ETS and the ratio should tend to be less than that for ground level environments where the density of smokers is similar.

Lastly, an appreciable background concentration attributable to desorption of nicotine from walls and fabrics might exist within the aircraft cabins. Although neither we nor other researchers have investigated the nicotine background in aircraft cabins, Eudy et al. (22) found a background concentration of approximately 1 ug m^{-3} in a restaurant having an adjoining bar. Higher background concentrations of nicotine might exist in aircraft cabins compared to ground level environments such as offices and restaurants because aircraft cabins have a greater density of smokers where smoking can occur continuously and a greater surface to volume ratio.

ACKNOWLEDGEMENTS

We gratefully acknowledge the cooperation and participation of Japan Air Lines. We also express appreciation for statistical assistance provided by Walter Morgan and Dallas Johnson and for technical assistance provided by the Boeing Commercial Airplane Company and by John Drake. Finally, the authors thank Mr. Douglas Abbey for his assistance in collecting samples.

LITERATURE CITED

(1) G.B. Oldaker III and F.W. Conrad, Jr., Environ. Sci. Technol., 21, 994-999 (1987).

(2) L.W. Eudy, F.A. Thome, D.L. Heavner, C.R. Green, and B.J. Ingebrethsen, Proceedings of the 79th Annual Meeting of the Air Pollution Control Association, paper 86-38.7, Minneapolis, MN, June 1986.

(3) D.J. Eatough, C. Benner, R.L. Mooney, D.L. Bartholomew, D.S. Steiner, L.D. Hansen, J.D. Lamb, E.A. Lewis, and N.L. Eatough, Proceedings of the 79th Annual Meeting of the Air Pollution Control Association, paper 86-68.5, Minneapolis, MN, June 1986.

(4) Fed. Regis. 1973, 38, 19146.

(5) Boeing Commercial Airplane Company, Maintenance Manual for B747 Aircraft.

(6) N. Nagda and H. Rector, Guidelines for Monitoring Indoor Air Quality, EPA-600/4-83-046, September 1983.

(7) J.R. Carson, and C.A. Erikson, Environ. Technol. Lett., 9, 501-508 (1988).

(8) B.C. McConnell, G.B. Oldaker III, and R.F. Walsh, United States Patent No. 4,786,472, November 22, 1988.

(9) J.M. Conner, G.B. Oldaker III, and J.J. Murphy, Environ. Technol. Lett., accepted for publication.

(10) M.W. Ogden, L.W. Eudy, D.L. Heavner, F.W. Conrad, Jr., and C.R. Green, Analyst, 114, 1005-1008 (1989).

(11) National Institute for Occupational Safety and Health, Manual of Analytical Methods, Part II, Vol. 3, Method No. S293, Cincinnati, OH, 1977.

(12) M.W. Ogden, J. Assoc. Off. Anal. Chem., 72, 1002-1006 (1989).

(13) D.L. Heavner, F.A. Thome, L.W. Eudy, B.J. Ingebrethsen, and C.R. Green, Proceedings of the 79th Annual Meeting of the Air Pollution Control Association, paper 86-37.9, Minneapolis, MN, June 1986.

(14) B.J. Ingebrethsen, D.L. Heavner, A.L. Angel, J.M. Conner, T.J. Steichen, and C.R. Green, J. Air Pollut. Control Assoc., 78, 413-417 (1988).

(15) M. Muramatsu, S. Umemura, T. Okada, and H. Tomita, Environ. Res., 35, 218-227 (1984).

(16) M. Muramatsu, S. Umemura, J. Fukui, T. Arai, and S. Kira, Int. Arch. Occup. Environ. Health, 59, 545-550 (1987).

(17) G.B. Oldaker III, Environ. Sci. Technol., 22, 1238-1240 (1988).

(18) U.S. Department of Health, Education, and Welfare and U.S. Department of Transportation, Health Aspects of Smoking in Transport Aircraft U.S. Government Printing Office, Washington, DC, 1971.

(19) P.F. Halfpenny and P.S. Starrett, ASHRAE J., 3, 39-44 (1961).

(20) G.B. Oldaker III, W.E. Crouse, and R.M. DePinto, Excerpta Medica International Congress Series pp. 287-290 (1989).

(21) J.L. Repace and A.H. Lowrey, Environ. Sci. Technol., 22, 1238 (1988).

(22) L.W. Eudy, D.J. Heavner, M.W. Stancill, J.S. Simmons, and B.C. McConnell, Proceedings 4th International Conference on Indoor Air and Climate, Vol. 2, pp. 126-130, B. Seifert, H. Esdorn, M. Fischer, H. Ruden, and S. Wegner, Eds., Berlin, August 1987.