Air quality, ventilation, temperature and humidity in aircraft

These four parameters were measured on 45 flights and compared with existing comfort regulations

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The increasing number of air travelers in recent years has increased the concern of air quality in aircraft. Hence, it is vitally important that the health and comfort of passengers are ensured.

The health and comfort of air travelers depends on the complex interplay of several factors. Some important factors are: the adequacy of the ventilation system to allow fresh air in the occupied zone; the concentration of contaminants; the temperature; and relative humidity.

The purpose of our study was to measure these parameters, compare them with existing regulations and comfort recommendations, and then evaluate the health and comfort in passenger airplanes.

Testing environment & strategy

The tests were conducted on 45 flights from seven identical aircraft of the same airline. The average flight duration was between 30 minutes and one hour; all were non-smoking flights.

The aircraft had a seating capacity of 101 passengers, with five-member crews. One or both of the aircraft conditioning units (hot air packs) were functioning on all flights, as selected by the flight crew.

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Measurements were taken at two locations in the aircrafts' economy section: on the right side (when facing forward), in front of the first row; and on the left side, in front of the last row. The sampling strategy and methodology employed are summarized in *Table 1*.

The sampling and analysis of the chemical and gas contaminants were performed according to the National Institute of Occupational Safety and Health Guidelines (NIOSH 1977) and IRSST methods. The only exception was formaldehyde, which was sampled and analyzed using McGill University methods (an American Industrial Hygiene Association approved lab).

The quantity of fresh air was measured using the sulfur hexafluoride (SF_6) tracer gas method. A quantity of 1 ppm of SF_6 was injected along the aisle of the cabin. Air samples were taken 15 minutes following the SF_6 injection, every 3 to 5 minutes up to one hour. Air sampling started approximately 10 minutes after take-off. The SF_6 concentrations were

Table 1. Summary of Sampling Methodology and Strategy

Contaminant/ Parameters	Measurement Techniques	Detection Limits	Sampling Frequency
Carbon monoxide	Direct reading electrochemical cell monitor	1 ppm	Every 5 min. during each flight
Carbon dioxide	Direct reading infrared monitor	10 ppm	Every 3-5 min. during each flight
Nitrogen dioxide	Direct reading electrochemical cell monitor	0.05 ppm	Twice per flight
Formaldehyde	Passive sampler analyzed by gas chromatography	17 ppm	Integrated sample taken in the test aircrafts' day schedule (6 to 8 hours)
Volatile organic compounds	Activated charcoal tube analyzed by gas chromatography	25 μg	Tube sampled at 0.5 liters per minute over the duration of the test aircrafts' day schedule (6 to 8 hours)
Total particulates	Polyvinyl chloride filter 37 mm diameter; 0.8 μm pore size gravimetric analysis	25 μg	Filter sampled at 1.5 liters per minute over the duration of the test aircrafts' day schedule (6 to 8 hours)
Temperature	Passive logger (resistor-thermistor series)	1°C	Data recorded every 2 min. over the duration of each flight
Relative humidity	Passive logger (resistor-thermistor series)	1%	Data recorded every 2 min. over the duration of each flight
Outdoor air supply	60 cc syringe analyzed by gas chromatography	5 ppb	Gas decay sampled with vacutainer tubes monitored up to every 5 min. for up to one hour successfully on 33 flights

measured by gas chromatography with electron capture detection.

The calculation of fresh air change is related to the logarithmic degradation of the tracer gas concentration with respect to time. The slope of the curve is the rate of fresh air-change.

The calculation is performed using the following equations:

$$\ln C/C_1 = -(Q/V) * T$$
$$\ln C/C_1 = -I * T$$

where, C_1 = the initial tracer gas concentration (uniformly mixed) (ppm)

- C = tracer gas concentration after time T (ppm)
- Q = rate of fresh-air change of the aircraft (m^3/hour)
- V = the cabin volume (m^3)
- T = the time in hours
- I = the rate of fresh air-change per hour

Air temperature (which is controlled by the flight crew) and humidity (which originates from the passengers) were measured with four loggers. The two loggers were placed in the seating area behind each first class section and at the rear of each economy section.

Air temperature was measured at three levels: the floor; above the ankle; and at head height. This was approximately 0 in. (0 cm), 4 in. (10 cm), and 4.5 ft (140 cm) above the floor-level, respectively. Measurements were recorded every four minutes.

Regulations & standards

The U.S. Federal Aviation Administration (FAA) applies limits for three contaminants: carbon monoxide, carbon dioxide and ozone. For ventilation, the FAA regulations state that the crew compartment should receive 10 cfm/person to enable crew members to perform their duties without undue discomfort or fatigue and that the passenger compartment "must be suitably ventilated." There are no specific limits for outdoor supply air.

The Aviation and Occupational Safety and Health Regulations of the Canadian Labour Code (CLC) use the American Conference of Governmental Industrial Hygienists (ACGIH) 1986-87 threshold limit values (TLV) in determining contaminant control limits. The concentration limits placed by the regulations are for health risk concerns (see *Table 2* for a summary of the regulations).

ASHRAE *Standard 62-1989* provides standards for outdoor supply air in transportation vehicles, and carbon dioxide levels and recommendations for comfort. Other standards (see *Tables 2* and *3*) are also used as comfort guidelines. All are usually used in evaluating comfort in the office environment.

In comparing the contaminant concentrations and comfort parameters to the standards, the most severe standards were used for the purpose of this study (see *Table 3* for a summary of the comfort and ventilation standards).

Results & discussion

The measured values of chemical and gas contaminants are given in *Table 4*.

Table 2. Health Regulations and Comfort Standards for Aircraft

Contaminant	Canadian Labor Code	Federal Aviation Administration	ASHRAE 62-1989	Environmental Protection Agency	Exposure Guidelines/ Residential IAQ
Carbon dioxide (ppm)	30,000 15 min. 5,000 8 hrs.	30,000 continuous	1,000 continuous		< 3,500 continuous
Carbon monoxide (ppm)	400 15 min. 50 ppm 8 hrs.	50 continuous		35 1 hr. 9 8 hrs.	< 25 1 hr. < 11 8 hrs.
Nitrogen dioxide (ppm)	5 15 min. 3 8 hrs.			0.05 1 yr.	0.25 1 hr. 0.05 continuous
Formaldehyde ($\mu g/m^3$)	3,000 15 min. 1,500 8 hrs.				120 continuous
Ozone ($\mu g/m^3$)	600 15 min. 200 8 hrs.	20 above 27,000 ft 3 hrs. 490 above 32,000 ft continuous		235 1 hr.	< 240 1 hr.
Total dust ($\mu g/m^3$)	10,000 8 hrs.				75 1 yr. 260 24 hrs.

Table 3. Ventilation and Comfort Standards

Parameters	ASHRAE 62-1989	ASHRAE 55-1989	ISO 7730	EGRIAQ	Manufacturer Recomm.
Outdoor air supply rate cfm/person	15				10
Temperature, °F (°C)		66-73 (19-23) winter 73-79 (23-26) summer	Vertical temp. diff. between ankles and head 3° Floor temperature 66-79 (19-26)		
Relative humidity (%)		20 (minimum)		30	

The temperature and humidity results are shown in *Table 5*.

Ozone is prevalent at high altitude and during high latitude flights. Ozone enters the cabin from the outdoor supply air. The major acute and chronic health risk from inhalation exposure to this gas is irritation of the respiratory tract and lung tissue. Ozone was measured to be 26 percent of the limits allowed by the FAA health regulations and 2.3 percent of the EPA limit for 1 hour.

Carbon monoxide is a chemical asphyxiant, while nitrogen dioxide can cause irritation to the lung tissues. The major source of these contaminant gases is from the combustion of the engine fuel. Both gases were found to be substantially below the limits allowed by the regulations and comfort standards.

The sources of volatile organic compounds and formaldehyde can be from adhesives, lubricants, elastomers, sealing compounds, coatings, cleaning products, carpets and upholstery inside the aircraft cabin. The concentration of these contaminants is closely related to the amount of off-gassing of chemicals from these materials or from the volatization of the irresidual solvents.

Exposure to high concentrations of these chemicals affects the nervous system and respiratory tract. Volatile organic compounds were not detected, and formaldehyde compounds were found to be significantly less than the regulation health limits. Formaldehyde was measured at 20 percent of the level allowed by the most severe comfort standard.

The particulates are derived from the passengers' clothing and belongings, and from the activity on the runway during embarkment onto and disembarkment from the aircraft. The total particulate contents were measured to be substantially below regulation (1 percent) and 1.4 times that allowed by the most severe comfort standard.

An increase in ambient carbon dioxide in the aircraft results from the metabolism of the passengers released by exhalation. An increase in the number of passengers raises the carbon dioxide concentration in the aircraft.

Uncomfortable levels such as 50,000 ppm can cause headaches, dizziness and visual distortions. Symptoms relating to fatigue, headaches and stuffiness can be associated with levels between 500 and 3,200 ppm (FPA Committee 1987).

The measured concentrations did not exceed the FAA regulation limit of 30,000 ppm. However, in an aircraft carrying more than 74 passengers, the average carbon dioxide concentration was measured to exceed the ASHRAE *Standard 62-1989* limit of 1,000 ppm.

The general trend of carbon dioxide concentrations with respect to time (indicated by four flights on one excursion) is shown in *Figure 1*. The carbon dioxide concentration tends to peak at the beginning and at the end of each flight. This is taken as evidence that the fresh air supply level set by the aircrew is low during take-off and before landing.

The outdoor supply air contains outside air from the compressors in the engine and recirculated air from the cabin and storage areas. The quantity of outside air is regulated by a flow-control valve, controlled by the crew manually or automatically. Only one of the two air-packs can be functioning because of energy conservation (the pilot's decision is based on the number of passengers on-board).

From the compressors, the air passes through the heat exchangers where it is cooled or heated to the required comfort temperature. The supply air enters the cabin through the grilles situated on the sidewalls below the storage bins. The air is exhausted through the floor level grilles

Table 4. Contaminants Measured in Aircraft Cabin

Contaminant	Mean	Mini.	Maxi.	Standard Deviation	Most Severe Health Regulation	Most Severe Comfort Standard
Carbon dioxide (ppm)	719	330	2,170	233	< 5,000 CLC	< 1,000 ASHRAE
Carbon monoxide (ppm)	1.6	1	4	1.4	< 50 FAA continuous CLC 3 hrs.	9 8 hrs. EPA
Nitrogen dioxide (ppm)	< 0.1	< 0.1	< 0.1	0	3 8 hrs. CLC	0.25 1 hr. EGRIAQ (regarding detectability)
Ozone ($\mu g/m^3$)	5.3	5.3	5.3	0	20 continuous above 27,000 ft altitude (FAA)	235 1 hr. EPA
Formaldehyde ($\mu g/m^3$)	25	17	82	20	1,500 8 hrs. CLC	120 continuous EGRIAQ
Volatile organic compounds ($\mu g/m^3$)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total particulates ($\mu g/m^3$)	105	25	200	68	10,000 8 hrs. CLC	75 1 yr. EPA

Table 5. Temperature and Humidity Results

	Mean	Minimum	Maximum	Standard Deviation	Standard
Temperature, °F (°C)	74 (23.4)	56 (13.2)	95 (35.1)	1.6	67-73 (19.5-23) winter 73-79 (23-26) summer ASHRAE 55-1981
Vertical temperature between ankles and head, °F (°C)	2 (1.1)	0 (0)	4.3 (2.4)	1.3	5.4 (3) ISO
Floor temperature, °F (°C)	75 (24)	61 (16)	84 (29)	2.3	66-79 (19-26) ISO
Humidity (%)	18.5	4.6	48.5	3.8	30 EGRIAQ

that run alongside the wall and lead to the outflow valves. The amount of air exhausted is controlled as a function of the desired cabin pressure.

The results illustrated in *Figure 2* indicate that, generally, the quantity of outdoor air varies for each flight. When the number of passengers exceeds 34, the average quantity of outdoor air does not satisfy the manufacturers' standard of 10 cfm per person. When the number of passengers exceeds 13, the ASHRAE *Standard 62-1989* recommendation of 15 cfm per person is generally not met.

It was found that 18 out of the 33 flights evaluated did not comply with the aircraft manufacturer's recommendation (10 cfm) and 24 out of 33 flights did not satisfy the ASHRAE standard (15 cfm) for comfort.

In comparing *Figure 1* with *Figure 2*, it is evident that an increase in the carbon dioxide concentration does not necessarily correspond to a relatively low quantity of fresh air per person. Although it was noted that when the carbon dioxide concentration was above 1,000 ppm, the quantity of outdoor air per person generally averaged only 3 cfm per person.

Conversely, an acceptable concentration of carbon dioxide does not necessarily guarantee an acceptable quantity of outdoor air per person (as measured for flights 4, 6, 7, 8, 10, 12, 13, 16, 19, and 20 through 27). The results do not indicate a significant difference in the quantity of outdoor supply air or carbon dioxide concentrations between both sampling sites.

Temperature is controlled by the flight crew. The heat exchanger valve is used to establish the required cold temperature, whereas, when hot temperature is required, a zone reheating system exists to warm the air. The mean measured ambient air temperature of 73°F (23°C) is comfortable in relation to the recommended ASHRAE standard for the summer and winter seasons. The average vertical air temperature difference in the areas between the ankles and head is less than 5.4°F (3°C), and the average floor temperature is between the the recommended 66°F (19°C) and 78°F (26°C). Both are acceptable according to the ISO standards (see *Table 5* for the results).

The humidity in the aircraft depends on the respiratory and perspiratory vapor given off by the passengers and crew. No other sources are supplied, other than those from the food preparation and lavatory areas. Humidity is removed by mechanical water separators before entering the engine turbine and cabin air supply duct.

The relative humidity in the cabin varies inversely with the quantity of outdoor air. The results indicate low humidity, about 10 percent below the comfort recommendations (see *Table 5* for the results).

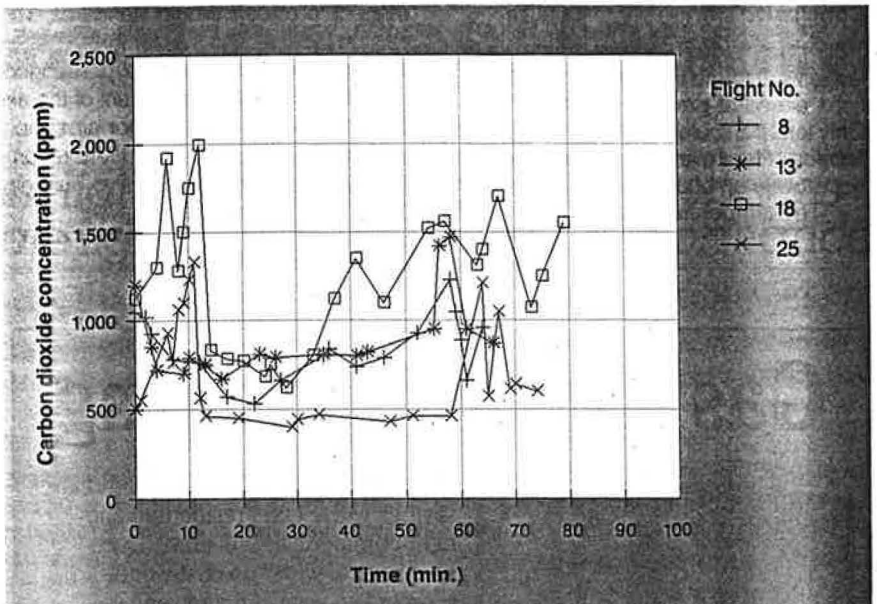

Figure 1. Carbon dioxide concentration compared to time.

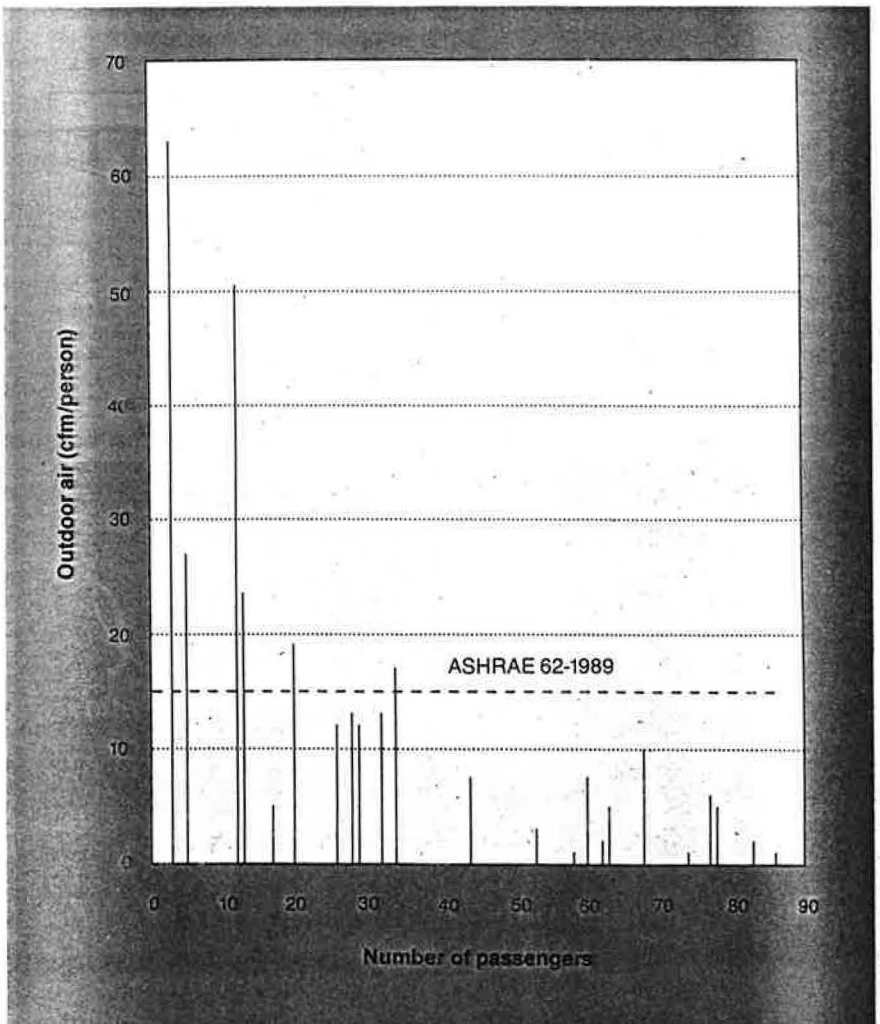

Figure 2. Quantity of outdoor air per passenger.

Conclusion

The measured chemical contaminant levels were found to be within the regulations aimed at preventing a health risk. Only total particulate levels exceeded the comfort criteria even though smoking was not allowed on board.

The temperature results agree with respect to office building standards. The carbon dioxide concentrations were generally high when the number of passengers reached more than 68 percent of the aircraft occupancy. The outdoor air supply was generally below the ASHRAE recommended comfort level. Relative humidity could reach uncomfortable levels.

For improved comfort, the outdoor air supply should be increased on flights carrying more than 13 passengers. The desired increase in outdoor air supply should result in cabin concentrations of carbon dioxide below 1,000 ppm. Well-maintained air filters in the recirculating ventilation system would decrease the concentration of total particulates to a more comfortable level. Different options should be studied to attain an acceptable percentage of relative humidity. ■

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