7837

CABIN AIR QUALITY

Cabin Air Quality

Boeing Engineer taking relative humidity measurements

David Space
Senior Engineer
Environmental
Control Systems
747/767 Division

Cabin air quality is a complex function of many parameters including ambient air quality, the design of the cabin volume, the design of the ventilation and pressurization systems, the way the systems are operated and maintained, and the presence of sources of contaminants and the strength of such sources.

INTRODUCTION

The purpose of this article is to provide the latest information available on cabin air quality aboard Boeing commercial airplanes, obtained from independent scientific investigations and investigations conducted by Boeing. Additionally, this article addresses some of the conflicting information that has recently been written on this subject and provides insight on the design approach and philosophy taken by Boeing to insure satisfactory cabin air quality.

The news media has on occasion attrributed fatigue, dizziness, nausea, headaches, eye and nose irritation and respiratory problems to low fresh air ventilation and the use of recirculated cabin air. These claims are not supported by credible scientific investigations conducted by the National Academy of Sciences, Department of Transportation (DOT) based on data taken on 92 randomly selected revenue flights, independent research groups or Boeing (see References for list of corresponding studies). It is more likely that the above symptoms are caused by interaction between stressors: the individual's health, overeating, alcohol consumption, smoking, motion sickness, inactivity, stress, normal cabin altitude, low relative humidity and high particulate levels in the smoking section(s) on flights that allow smoking.

Furthermore, it has been written that jet lag is caused by high CO_2 concentrations in the passenger cabin. Boeing has not been able to corroborate this from any published literature, governmental or private, nor is it agreed that cabin CO_2 levels are excessive. Boeing and DOT have conducted studies of cabin air quality on many revenue flights during which CO_2 was measured and deemed to be well within norms. The main cause of jet lag is traveling to a different time zone without giving the body a chance to adjust to new night - day cycles (Circadian Rhythm Upset).

CONTAMINANTS AND OTHER PARAMETERS OF THE AIRPLANE CABIN

Airflow

The total volume of air is exchanged approximately every two and one half to three minutes in a wide-body airplane and every two to three minutes on a standard-body airplane. The airflow per unit length of the airplane for the first class and business class sections is not increased over the economy class section. The reason economy class has lower airflow per passenger is due to an increased seating density compared to first class and business class seating densities. A high air exchange rate and sufficient quantity of fresh air must be supplied to each cabin zone to maintain air quality, control temperature gradients, prevent stagnant cold areas and dissipate smoke and odors in the cabin. The flight deck is provided higher airflow per person than the cabin in order to positively pressurize the cockpit to prevent smoke ingress from adjacent areas (abnormal condition), provide cooling for electrical equipment, account for increased solar loads and night heat loss through airplane skin and windows and to minimize temperature gradients.

Current-production Boeing airplanes provide approximately 50% conditioned (fresh) and 50% recirculated air to the passenger cabin on a continuous basis.

The recirculated air is cleaned (filtered) by drawing through high efficiency recirculation filters; the filters cannot be bypassed. The air distribution system is designed to provide approximately 10 cubic feet per minute (cfm) fresh and 10 cfm recirculated air per passenger. Fully loaded all tourist class passenger airplanes (worst case - maximum seating density throughout airplane) can have a fresh air quantity per passenger of 6.5 cfm (standard-body) to 8 cfm (wide-body). Fresh air ventilation rates of 5 to 7 cfm per person have been established as providing satisfactory air quality for other types of vehicular travel that have nonsmoking sections, including passenger and commuter trains and subways. It should be noted that the large majority of airplanes currently flying are not of an all tourist class seating density configuration.

Increasing the quantity of fresh air beyond 50% to the cabin is not necessary. If done, it would lower the cabin CO_2 concentration slightly, but would also increase the potential cabin ozone concentration and lower the cabin relative humidity. Consequently, an airplane's Environmental Control Systems are thoroughly scrutinized throughout the design, analysis and testing phases to fully optimize the systems to first supply the correct amount of air to the passengers for health and comfort, and second, to minimize fuel consumption. Figure 1 provides a schematic of the Environmental Control Systems for the Boeing 767 airplane.

The fresh air quantity supplied to some models of Boeing airplanes can be lowered by shutting off one Air Conditioning Pack. The availability of Pack controls to the flight crew is to provide flexibility to deal with system failure or special use of the airplane. Boeing recommends full operation of the Packs when passengers are onboard.

Environmental Tobacco Smoke (ETS)

Environmental tobacco smoke (ETS) generated from cigarette smoking, is a complex mixture of gas and particulate-phase contaminants made up of more than 3,800 compounds.

A cabin crew survey conducted by a European airline indicates that smoky air caused by ETS is their number one complaint.

Currently, there are no direct governmental, occupational or ambient standards for ETS in any environment. An indirect method to control ETS in the cabin is to control the concentration of Carbon Monoxide (CO) and Respirable Suspended Particulates (RSP) which are tracer constituents of ETS and for which standards do exist. This method does not take into account other constituents present in ETS. Measured CO levels in the smoking section(s) of airplanes during peak smoking are well within acceptable standard limits. RSP concentrations in the smoking sections can exceed recommended RSP levels during peak smoking; this is true

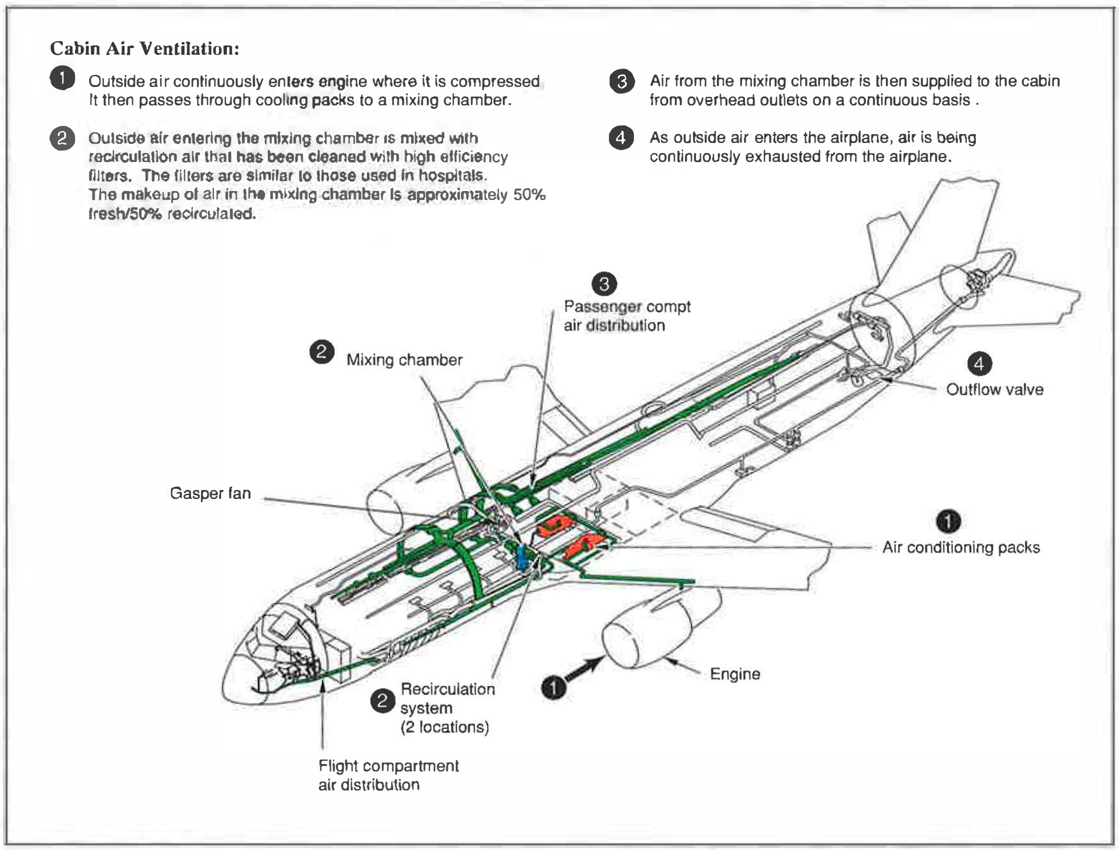


Figure 1. This illustration of a Model 767, shows the typical components and system layout for the Environmental Control Systems.

of most heavy smoking areas, e.g. restaurants, bowling alleys, etc.

The National Academy of Sciences recommended banning smoking on U.S. Domestic flights in 1986 to eliminate the possibility of fires caused by cigarettes, lessen irritation and discomfort to passengers and crew and reduce potential health hazards associated with ETS by bringing the cabin air quality of the smoking section into line with established standards regarding air particulate limits (ASHRAE (Canada) limit for RSP is 100 µg/m3). Average RSP values of 40 µg/m3 and 175 µg/m3 were measured in the nonsmoking and smoking sections respectively, of the 92 airplanes tested in a DOT sponsored study. Smoking was initially banned on U.S. Domestic flights in 1988 for flights of less than two hours; smoking was banned on all domestic flights of less than six hours in duration in 1990.

Boeing airplanes are within recommended guidelines for air particulate concentrations in the nonsmoking sections of the airplanes.

Ozone

Ozone is present in the atmosphere as a consequence of the photochemical conversion of oxygen by solar ultraviolet radiation. A marked and progressive increase in ozone concentration occurs within the flight altitude of commercial airplanes.

The mean ambient ozone concentration increases with increasing latitude, is maximal during Spring (Fall season for Southern latitude), and often varies with weather systems to result in high ozone plumes descending down to lower altitudes.

Residual cabin ozone concentration is a function of the ambient concentration, the design of the air distribution system and how it's operated and maintained and whether or not catalytic ozone converters are installed.

Cabin ozone limits are set by FAR 121.578 and FAR 25.832. The use of catalytic ozone converters is generally required on airplanes flying mission profiles where the cabin ozone levels can be predicted to exceed these FAR limits (refer to the FAA Code of Federal Regulations for other compliance methods).

Cabin ozone measurements were well below FAA limits on all 92 randomly selected flights tested in the DOT air quality study and on flights tested by Boeing.

Microbial Aerosols

Biologically derived particles that are known to become airborne include viruses, bacteria, actinomycetes, fungal spores and hyphae, arthropod fragments and droppings, and animal and human dander.

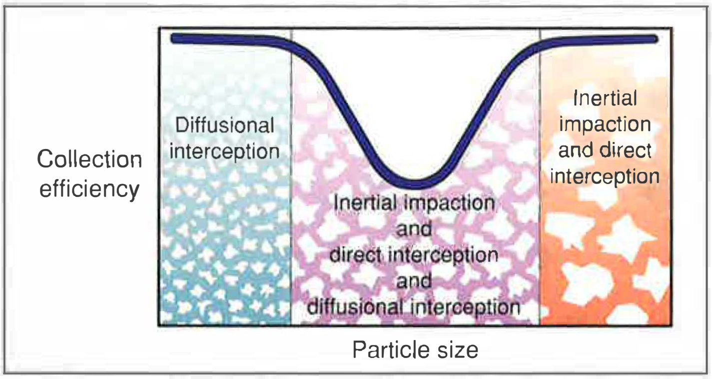
Some articles imply that it is highly likely that if someone on a flight has an active case of an infectious disease like influenza, then other people on board will also have the disease by the end of the flight. Only one study has clearly documented the occurrence of an outbreak of infectious disease related to airplane use. In 1977, because of an engine malfunction, an airliner with 54 persons on board was delayed on the ground for 3 hours, during which the airplane ventilation system was reportedly turned off. Within 3 days of the incident, 72% of the passengers became ill with influenza. One passenger (the index case) was ill while the airplane was delayed. Documentation of this outbreak was assisted by the fact that all the passengers traveled to one small town and were treated by the same local physician.

By shutting off the airplane ventilation system (airplane had 100% fresh air system), an abnormal situation occurred which likely resulted in increasingly high concentrations of microbial aerosols, CO_2 and high temperatures in the airplane cabin. With the ventilation system shutoff, there was no fresh air being introduced into the cabin to displace microbial aerosols and CO_2 or control cabin temperatures. Boeing believes that had the ventilation system been operating during the delay, the possibility of other passengers becoming ill would have been minimal.

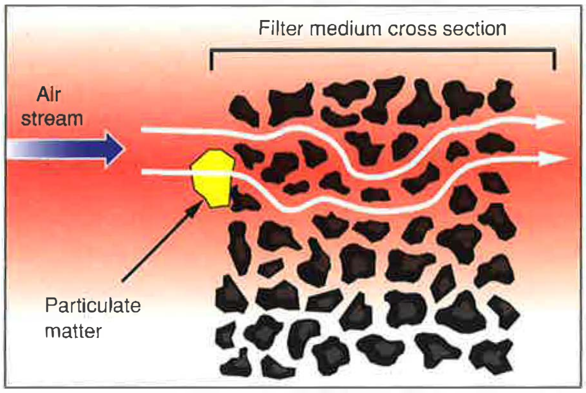
Whether on the ground or in flight, Boeing does not recommend shutting off the airplane ventilation system when passengers are on board; an exception to this is for no Pack takeoffs in which the air distribution Packs are shutoff for a short duration on takeoff only, but not the recirculation fans.

To remove microbial aerosols, dust, lint, etc. from the cabin environment, filter assemblies installed on all current Boeing airplanes contain a High Efficiency Particulate Air Filter (HEPA) that has a minimum efficiency of 91% to 99.9% D.O.P. as measured by MIL-STD-282. A HEPA filter is rated at approximately the most difficult particle size to filter, which is about 0.3 microns in diameter. A filter's efficiency increases over time and due to the overlap of capture mechanisms within a filter (see Figure 2), also increases for particles smaller and larger than 0.3 microns. The efficiency of a HEPA filter to remove 0.01 micron particles from the air is in excess of 99+%. A HEPA filter's efficiency does drop as the particle size approaches that of a gas molecule.

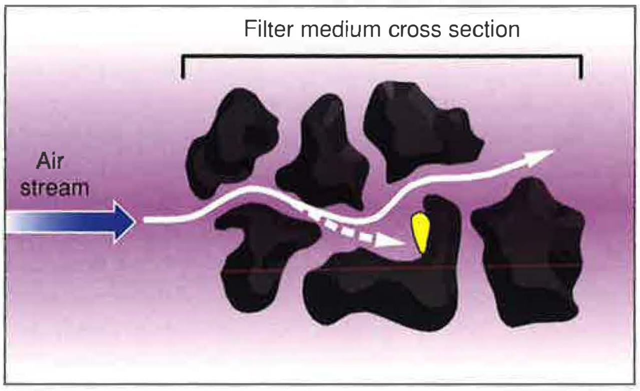
Many bacteria (99% exceed 1 micron in size) are attached to larger particles such as human skin flakes. Viruses generally occur in clusters or in and on other particles (viruses range from .003 to .05 microns). A biology lab at Boeing has analyzed HEPA filters for organic



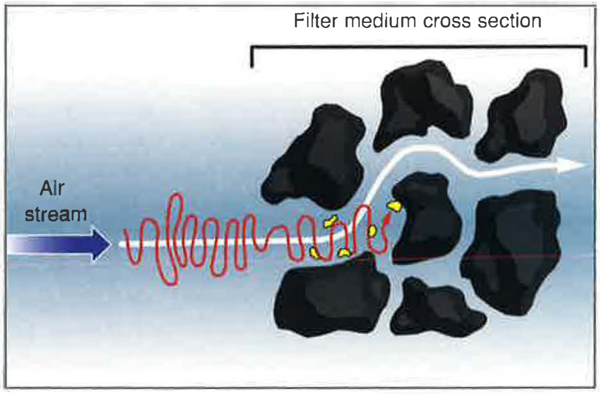
1. Airplane filters are able to remove particles down to the size of viruses. 0.01 µm and below. Filters must also remove particles of tobacco smoke, bacteria and particulate matter spanning the range up to 10 µm. To achieve this, several mechanisms of filtration are involved.



2. Direct Interception
Filters consist of matrices with defined pores. If the particles are larger than the pores, they are removed by direct interception.



3. Inertial Impaction
Filters remove particles smaller than the pore size by inertial impaction. Particles of higher density than air deviate from the air flow path and impact on the solid surfaces or walls of the pores, where they adhere.Particles larger than about 0.5µm and up to approximately 10 µm will impact and adhere. Particles less than 0.3 µm will not impact.



4. Diffusional Interception
For very small particles such as viruses, Brownian motion causes particles to be collected on the individual fibres and pore walls. Particles in the range 0.1µm and below are efficiently removed by this mechanism. Airplane filters are designed with media which provide a high efficiency, even for the most penetrating particle size. Passenger and crew protection is assured.

Figure 2. These illustrations show a High Efficiency Particulate Air Filter's (HEPA) capture mechanisms.

Above illustrations courtesy of Pall Land & Marine Corporation

particulate content. Of the filters tested, virtually all organic material was on the surface of the filter and an insignificant amount penetrated into the center of the filter. The medical community uses a similar type of filter to keep the air clean in hospitals.

A study sponsored by the DOT conducted on 92 randomly selected flights, showed levels of bacteria and fungi that were relatively low on all monitored flights. *The levels and genera measured in the cabin environment were similar to or lower than those commonly encountered in indoor environments characterized as normal.*

Volatile Organic Compounds

Volatile organic compounds (VOC) can be emitted by materials used in furnishing the cabin, pesticides, disinfectants and cleaning agents.

In-flight air quality testing was conducted by Boeing on 19 revenue flights. Samples were sent to the University of Washington Department of Environmental Health for analysis by gas chromatography (gas chromatography can dissociate complicated chemical solutions allowing a wide range of air constituents to be isolated and identified).

The gas chromatography studies detected only trace quantities of VOCs at less than quantifiable and identifiable amounts. The low VOC measurements are due to the high cabin air exchange rates (three to five times greater than in a typical office building) and stringent material off-gassing limits for an airplane cabin.

CARBON DIOXIDE

Carbon dioxide ($C0_2$) is the product of normal human metabolism, which is the predominant source in airplane cabins. The $C0_2$ concentration in the cabin varies with fresh air rate, the number of people present, and their individual rates of $C0_2$ production which vary with activity and (to a smaller degree) with diet and health. $C0_2$ has been widely used as an indicator of indoor air quality, typically serving the function of a surrogate.

$C0_2$ alone is not a health issue even at the highest levels likely to be encountered in a cabin environment. The FAA regulation and industry standards for $C0_2$ limits are shown in Table 1.

Per DOT sponsored study, measured cabin $C0_2$ values of 92 randomly selected smoking and nonsmoking flights averaged 1,500 PPM.

A $C0_2$ limit for health factors is provided by the American Conference of Governmental Industrial Hygienists (ACGIH). The Environmental Exposure Limit adopted in 1984-1985 by ACGIH gives 5,000 PPM as the time-weighted average (TWA) limit for $C0_2$; this value corresponds to a fresh air ventilation rate of 2.3 cfm per person. The TWA is the concentration, for a normal 8 hour workday and a 40 hour workweek, to which nearly all workers can be repeatedly exposed, day after day, without adverse effects. Boeing airplane cabin $C0_2$ concentrations are well below the ACGIH TWA limit for $C0_2$ concentration, and this appears to be the most appropriate standard.

The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) defines acceptable indoor air quality as *air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction.* The ASHRAE standard is set to satisfy comfort and health requirements, with comfort driving the standard.

The ASHRAE (62-1981) standard provides a hard limit for $C0_2$ itself to satisfy comfort. This standard indicates an adequate limit for $C0_2$ is 5,000 PPM; however, a $C0_2$ limit of 2,500 PPM was chosen by ASHRAE to allow for a factor of safety in accounting for health variations and some increased activity levels. The minimum corresponding fresh air ventilation rate to meet this $C0_2$ limit is 5 cfm per person. The recommended CO_2 value specified in the new ASHRAE (62-1989) standard of 1,000 PPM serves as a surrogate for odor and control of other contaminants (odor being the driver), and is not a CO_2 specific requirement in itself. It is set to satisfy the odor perception of 80% or more of visitors entering an occupied space.

The new ASHRAE (62-1989) standard for CO_2 does not realistically apply to an airplane environment per se, since it was derived as a surrogate to satisfy visitors entering an environment on a perceived odor basis. In airplanes, passengers enter and stay for long periods and are therefore considered occupants. ASHRAE's reference studies indicate that a much larger quantity of fresh air is required to satisfy 80% of visitors compared to satisfying 80% of acclimated occupants. In the airplane cabin, all known contaminants are controlled to lower than harmful concentrations and an over abundance of high quality fresh air is supplied for passenger comfort.

Humidity

Relative humidity is the ratio of the amount of water vapor in the air at a given temperature to the capacity of the air at that temperature.

The relative humidity in the airplanes tested in the DOT sponsored study ranged from approximately 5% to 35% with an average of 15% to 20%. The humidity is mainly made up of moisture from passengers and will increase with more passengers and decrease with increased fresh airflow. A major benefit of recirculated air supplied to the passenger cabin is an increase in cabin humidity compared to airplanes with

STANDARD/ REGULATION	CONCENTRATION LIMIT (PPM)	COMMENT
FAR 25.831	30,000	requirement for aircraft
ACGIH/OSHA	5,000	8 hour time weighted average
GOV. OF CANADA	3,500	long term exposure range
ASHRAE (1981)	2,500	* 5 cfm/person; hard limit
ASHRAE (1989)	1,000	* 15 cfm/person; surrogate (odor)

FAR - Federal Aviation Regulation
ACGIH - American Conference of Governmental Industrial Hygienist
OSHA - Occupational Safety and Health Administration
ASHRAE - American Society of Heating, Refrigeration and Air Conditioning Engineers
PPM - Parts Per Million by volume

* Corresponding fresh air ventilation rate to meet CO_2 concentration limit

Table 1. FAA regulation and industy standards for CO_2 limits.

solely fresh air supplied.

After three or four hours of exposure to relative humidity in the 5-10% range, some passengers may experience discomfort, such as dryness of the eyes, nose and throat. However, there is no evidence of extensive or serious adverse health effects of low relative humidity on the flying population. In fact, many people live in areas where the relative humidity is in the range experienced in an airplane cabin environment (e.g. Southwestern United States).

Cabin Pressure/Oxygen

At a normal airplane cruise altitude, the air outside the airplane does not contain a sufficient partial pressure of oxygen to sustain normal body function. Consequently, airplane cabins are pressurized to a maximum cabin altitude of 8,000 ft (to compress the ambient air to a form that is physiologically acceptable). The National Academy of Sciences study concluded that *current pressurization criteria and regulations are generally adequate to protect the traveling public.* The Academy also noted that the normal maximum rates of change of cabin pressure (approximately 500 ft/min in increasing altitude and 300 ft/min in decreasing altitude) are such that they do not pose a problem for the typical passenger.

However, pressurization of the cabin to equivalent altitudes of up to 8,000 ft, as well as changes in the normal rates of pressure during climb and descent, might create discomfort for some segments of the population such as persons suffering from upper respiratory or sinus infections, obstructive pulmonary diseases, anemias or certain cardiovascular conditions. Supplemental oxygen may be recommended for people suffering from existing medical conditions as mentioned above. Children and infants might experience some discomfort or pain because of pressure changes during climb and descent. Injury to the middle ear can occur in susceptible people, but is rare.

It has been stated in various articles and reports that substandard conditions exist in airplane cabins due to a lack of oxygen. It has been reported that this condition is exacerbated by reduced fresh air ventilation rates or through the use of recirculated air. These arguments imply that the oxygen content of cabin air is depleted through the consumption by occupants. Humans at rest breathe at a rate of approximately 0.32 cfm while consuming oxygen at a rate of 0.015 cfm. The percent oxygen makeup of the supply air remains at approximately 21% at cruise altitude. A person receiving 10 cfm of fresh air and no recirculation air would therefore receive approximately 2.1 cfm of oxygen. Consequently, the content of oxygen in cabin air is little affected by breathing as it is replaced in sufficient quantities compared to the human consumption rate.

Although the percentage of oxygen in cabin air remains virtually unchanged (21%) at all normal flight altitudes, the partial pressure of oxygen decreases with increasing altitude, which decreases the amount of oxygen held by the blood's hemoglobin. It is believed that the increase in cabin altitude can lead to low grade hypoxia (reduced tissue oxygen levels) in certain segments of the population and that the main cause of passenger fainting and fatigue is low grade hypoxia in combination with other stressors discussed earlier. However, the National Academy of Sciences concluded that *pressurization of the cabin to an equivalent altitude of 5,000 to 8,000 ft is physiologically safe - no supplemental oxygen is needed to maintain sufficient arterial oxygen saturation.*

SUMMARY

Boeing airplanes exceed all applicable regulatory and industry health standards for air quality in the passenger cabin. Recent government, academic and industry studies have concluded that the airplane cabin environment does not pose a health threat to the traveling public. These studies were conducted on airplanes which use the current 50% recirculation type systems as well as older airplanes with 100% fresh air systems.

Boeing believes that the more frequent complaints associated with cabin air quality, nausea, headaches, eye and nose irritation, etc., are due to complex interactions of combinations of stressors, i.e.: ETS, low relative humidity, motion sickness, cabin altitude, etc.

Boeing will continue to look at new technologies and new ideas and will cooperate fully with the U.S. government in studies on cabin air quality, as has been done in the past, to continuously improve our products.

REFERENCES

a. National Academy Press, The Airliner Cabin Environment: Air Quality and Safety, 1986.
b. Report No. DOT-P-15-89-5, Airliner Cabin Environment: Contaminant Measurements, Health Risks, and Mitigation Options, December, 1989.
c. ASHRAE Journal, April 1991, Air Quality, Ventilation, Temperature and Humidity in Aircraft.
d. Boeing Service Letter M-7230-1445, Air Circulation and Air Quality in the Passenger Cabin of 737-300 Airplanes, dated June 10, 1988.