

# AIR QUALITY AND COMFORT IN AIRLINER CABINS

NIREN L. NAGDA  
EDITOR

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# ***Air Quality and Comfort in Airliner Cabins***

*Niren L. Nagda, editor*

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# Foreword

This publication, *Air Quality and Comfort in Airliner Cabins*, contains papers presented at the symposium of the same name held in New Orleans, Louisiana on 27–28 October 1999. The symposium was sponsored by ASTM Committee D22 on Sampling and Analysis of Atmosphere, and its Subcommittee D22.05 on Indoor Air. The symposium chairman was Niren L. Nagda, ENERGEN Consulting, Inc.

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# Air Quality and Comfort in Cabins: Overview

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Cabin environmental issues have been a subject of interest to parties such as aircraft manufacturers, airlines, flight attendants, passengers, regulators, and researchers for a number of decades. Despite these varied interests, there has not been any comprehensive or systematic treatment of this topic since 1986, when a report was published by the National Academy of Sciences Committee on Air Quality. Among the important issues is proper characterization of the airliner cabin environment and its effects on the occupants. Without adequate characterization, one can only speculate about potential causes of various types of discomfort that seem to be commonly reported by the occupants, and attempts to improve the situation may be misguided.

For these reasons, a Symposium on Air Quality and Comfort in Airliner Cabins was convened in October 1999 in New Orleans, LA. The symposium was sponsored and organized by ASTM Committee D22 on Sampling and Analysis of Atmospheres, and brought together more than 80 professionals representing public and private interests in the United States, Canada, and numerous countries overseas. The primary aim of the symposium was to provide a platform for sharing state-of-the-art information on various aspects of cabin air quality with all parties interested in the topic.

The keynote address for the symposium was given by Russell Rayman, M.D., Executive Director of the Aerospace Medical Association, Alexandria, VA. Dr. Rayman began his address by presenting a hypothesis that the presence of contaminants or indicators such as carbon dioxide, carbon monoxide, particles, ozone, and volatile organic chemicals in the aircraft cabin can cause symptoms such as headaches, nausea, or respiratory irritation. Based on the results of various monitoring studies that have been conducted, a conclusion can be drawn that levels of contaminants found in airliner cabins are not likely to cause adverse health effects. Nonetheless, complaints of discomfort or health symptoms, especially from flight attendants, appear to be real. Thus, other factors associated with air travel, such as barometric pressure, hypoxia, vibration, temperature/humidity, fatigue, and jet lag, need to be considered as potential causative factors and investigated in greater depth.

Dr. Rayman concluded that future research needs to address areas such as viruses in the cabin environment and redefining acceptable cabin altitude standards. He also stressed that studies need to go beyond the examination of physical factors in the cabin environment, to include health-based surveys of passengers and flight attendants with attention to the various factors mentioned above. Further, the research needs to involve all interested parties, including flight attendants, passengers, airlines, aircraft manufacturers, and appropriate governmental agencies, to ensure that the greatest benefit can be achieved for all concerned parties.

The symposium was organized into six sessions covering the following topical areas:

- Cabin Air Quality Measurements
- Chemicals, Toxicity, and Effects
- Standards
- Modeling and Control of Cabin Air Quality
- Cabin Air Quality and Emerging Issues/Research
- Relationships between Cabin Environment Factors and Comfort and Health Responses

The remainder of this overview provides summaries and highlights of the papers in each of these sessions. All papers presented at the symposium are included in the main body of this STP. In this overview, topics of discussion that followed each paper are highlighted; the actual questions or comments and authors' closures are given after each paper in this STP.

### Cabin Air Quality Measurements

**Dumyahn et al.** present a comparison of air quality in different types of transportation environments, based on the results of two surveys conducted in 1994 and 1996. In the 1994 survey, 22 domestic U.S. flight segments were monitored. These segments ranged from 2 to 5 hours in duration and included a variety of standard- and wide-body aircraft. For the 1996 survey, 6 flight segments (all with Boeing 777 aircraft) were monitored in addition to 6 train segments, 7 interstate bus segments, and 8 subway segments.

All modes of transportation had CO<sub>2</sub> concentrations averaging above 1,000 ppm. The average concentrations were similar across environments but highest for aircraft (during boarding) and lowest for subways. However, aircraft while in the air had the lowest CO<sub>2</sub> levels except for subways. Average CO concentrations were highest on buses (2.4 ppm) and lowest on aircraft (0.7 ppm). Average NO<sub>2</sub> levels were highest on subways (121 ppb) and lowest on aircraft (36 ppb). All modes of ground transport had higher particle concentrations than aircraft. Ozone levels were uniformly low—below the lower detection limit (LDL) in all cases but one (even that case was within 20 % of the LDL). Noise levels were highest on aircraft (75–90 dbA), followed by subways (70–90 dbA), buses (70–80 dbA), and trains (65–75 dbA). Humidity levels were lowest on aircraft.

Fungal concentrations were not significantly different across environments, but frequently were lowest on aircraft. House dust-mite allergens and cat allergens were lowest on subways and for all environments generally were similar to levels measured in Boston-area living rooms. VOC concentrations were similar to those found in office buildings and residences without obvious sources such as new furnishings or products and materials used in remodeling. Ethanol, 2-propanol, acetone, and butanone were present in almost every sample. Acetone and ethanol are common human bioeffluents and, along with butanone, also are emitted from distilled spirits and cleaning products. Aircraft had the highest concentrations of ethanol and acetone. VOCs indicative of fuel exhaust were higher for the ground-transportation segments.

The authors concluded that the air quality measurements in their surveys indicate that conditions in these public transportation modes are comparable and do not, in themselves, pose a health risk. At the same time, it was acknowledged that the number of monitored travel segments was limited and that many compounds of potential interest were not measured.

One attendee at the conference questioned whether measurements taken at a passenger seat location would be indicative of exposures of a flight attendant spending a majority of time in the galley. Another asked about major temporal and spatial variations in aircraft environmental quality, and a third commented on the relatively high uncertainty of relative humidity measurements at the low end of the scale.

**Arnold et al.** present an analysis of the effect of recirculation on aircraft cabin air quality, based primarily on a simulation model but supplemented with monitoring results for the purpose of model verification. In their dynamic simulation model, the partial pressures of oxygen and relative humidity and the concentrations of CO<sub>2</sub> are computed by performing a mole balance on each constituent. Results are computed separately for the flight deck and cabin because they have different air sources. Initial conditions for molar gas concentrations are based on the total cabin volume and the constituent gas concentrations on the ground. Perfect mixing is assumed within each of the modeled compartments, and air entering these compartments is assumed to be completely dry. That is, all humidity is assumed to be due to human respiration and perspiration.

The model has been configured for a variety of aircraft types. Flight parameters that can be changed between simulations are the number of passengers, number of flight-deck crew, cabin temperature setting, flight profile (including ambient pressure and altitude), flight duration, and the air recirculation rate. To verify the modeling results, the authors conducted monitoring of partial pressure of oxygen, concentrations of ozone, CO<sub>2</sub> and CO, and temperature, pressure and humidity on



three types of aircraft. They also used the model to examine what-if scenarios related to alternative recirculation rates.

The authors conclude that the model can reliably predict trends in behavior of air quality parameters in a closed environment. The best correspondence between modeled and measured values was at cruise, the longest portion of most flights. Poorer predictions for ascent or descent were thought to be related to transient sensor response in a varying pressure environment, coupled with limited ascent/descent data on which to base model inputs. Oxygen partial pressure is stated to be primarily a function of cabin pressure, and passenger loads are considered to have the greatest influence on humidity levels. The model could be used to test the impact of new technologies before they are introduced, or as an aid to setting target concentration values for breathing-gas constituents.

One attendee asked whether pilots operating the test flights were aware that air quality testing was being conducted. Another pointed out that the practicality of using recirculation airflow to control humidity needs to be evaluated.

**Lee et al.** present results of air quality measurements for 16 commercial-aircraft flights in Hong Kong. The project included flights on three different types of wide-body aircraft with durations ranging from 3 to 13 hours (ten of the flights were more than 10 hours long). A few sampling points were used in the business-class area on each flight, subject to availability. Relative humidity, temperature, CO<sub>2</sub>, and RSP were monitored continuously, at 5-minute intervals. Time-integrated samples were collected for SO<sub>2</sub>, NO<sub>2</sub>, ozone, and microbiological organisms.

In aircraft carrying more than 74 passengers, measured CO<sub>2</sub> levels generally exceeded 1,000 ppm and tended to peak during boarding and de-boarding periods. Humidity levels generally decreased with increasing flight duration. The distribution of humidity was not uniform in the aircraft cabin, due to sources such as food preparation and lavatory water separators (in addition to passenger respiration and perspiration). The measured temperature levels were considered to be relatively stable compared to other comfort parameters. There was a major difference in RSP levels between smoking and non-smoking flights, with a maximum level of 264  $\mu\text{g}/\text{m}^3$  on a smoking flight as compared to 17  $\mu\text{g}/\text{m}^3$  on a non-smoking flight. All ozone measurements were below 25 percent of the limits allowed by FAA regulations. Concentrations of CO were higher on smoking flights but well within regulation limits in all cases. Bacteria and fungi levels (measured on 3 flights) were relatively low, but slightly higher near the beginning and end of flights due to passenger activities.

The authors conclude that the aircraft air quality was satisfactory, but noted that the CO<sub>2</sub> concentration was not uniform—higher in economy class and passenger areas, and lower in first class and toilet areas. The vertical temperature profile was considered to be uniform. It was noted that increasing the fresh-air supply lowers the levels of both CO<sub>2</sub> (desirable) and relative humidity (undesirable). Thus, the optimum ventilation rate should strike a balance between these two comfort factors.

One attendee noted that a distinction between maximum and time-weighted-average levels needs to be included when comparing measurements and standards. Another questioned whether it was appropriate to compare measurements taken in smoking sections on smoking flights with those from non-smoking sections on non-smoking flights, and pointed out that RSP measurements with optical sensors are highly sensitive to the type of aerosol used for calibration. A third commented that certain ozone measurements appeared lower than expected for the type of aircraft and flight route, and a fourth asked why humidity levels apparently decreased with increasing flight duration.

## Chemicals, Toxicity, and Effects

A paper by **van Netten** reports on small-chamber tests to examine pyrolytic breakdown products from two jet lubricating oils and a hydraulic fluid, and implications for aircraft air quality. The constituents or breakdown products of such products may enter the cabin air if jet oil or hydraulic fluid should leak into bleed air used for ventilation.

Samples of each tested oil or fluid were placed on a piece of aluminum foil on top of a ceramic hot plate. The general behavior of each sample was investigated by heating the hot plate to 525 °C at a rate of about 10 °C /min. Generation of volatile components at 525 °C was investigated by heating the hot plate to that temperature in a small, open stainless-steel chamber. The foil was then placed on top of the hot plate, the chamber lid closed, and the temperature maintained for one additional minute. Direct-reading instruments were used to monitor NO<sub>2</sub>, O<sub>2</sub>, CO, CO<sub>2</sub>, lower explosive limit, temperature and humidity. A midjet impinger was used to sample for other airborne constituents.

The various fluids tested began to generate white smoke at temperatures ranging from 220 to 265 °C. Hydraulic fluid was found to be more volatile than the engine oils and, in general, appeared to evaporate rather than pyrolyze. The lubricating oils showed a significant release of CO, indicating the breakdown of their constituents. The neurotoxin trimethyl propane phosphate (TMPP) was not found in any of the samples tested, nor was the tri-orthocresyl phosphate (TOCP) isomer. However, the presence of five of the ten possible tricresyl phosphate (TCP) isomers was demonstrated.

The authors speculate that certain symptoms associated with the central nervous system might be caused by such isomers. At times when there is an oil/fluid seal failure causing visible smoke in the cabin, the isomers might condense onto smoke particles and be transported into the cabin air through the ventilation system. Potential CO exposure is another concern, in the case of engine oil.

One attendee commented that the recirculation filter possibly could be used to get an indication of the level of non-volatile pollutants following a serious incident of engine or hydraulic ingress into the cabin. Another indicated that it might be instructive to compare flight attendant reports of symptoms with pilot reports on aircraft work needed or mechanic reports of repair/maintenance. A third raised the caution that symptoms should not be assigned to causes without factual information. Another comment by one attendee concerned determination of possible isomers of TCP in jet oil, as there are too many isomers present and standards have never been synthesized for most of them.

**Hollick and Sangiovanni** describe a proposed air quality metric for the combined effects of gaseous contaminants, based on exposure limits for health and comfort. They suggest that such a metric should be based on objective, quantifiable parameters that can be measured by instrumentation, so that IAQ assessments are independent of evaluator bias. Ideally, such a metric would account for both health and comfort, and further should recognize that some compounds are harmful at very low levels whereas others can be tolerated at much higher levels.

The metric is calculated by first computing a tolerance index for each contaminant, defined as the ratio of the measured concentration for that contaminant to its allowable limit, or acceptable concentration. The allowable limit for a contaminant is taken to be the lowest value of the following: 0.1\*TLV (threshold limit value), SMAC (Spacecraft Maximum Allowable Concentration), 0.03\*RD<sub>50</sub> (exposure level causing a 50% decrease in respiration), and geometric mean odor threshold. Next, the ratios are summed across contaminants to obtain a total tolerance index. A total tolerance index of less than 1.0 is considered to indicate acceptable air quality.

Applications of the proposed metric to airliner cabin air quality and to public office buildings are illustrated in the paper. The authors acknowledged that, while the concept of a tolerance index is sound, allowable limits used in this paper will need further work, especially incorporating organ- or end-point-based tolerance indexes as well as levels of health concerns that relate to public rather than occupational exposure and health effects.

One attendee argued that the authors have attempted to provide a simple answer to a complex problem, without adequate toxicological advice or consideration of differences in data quality and purposes of databases used for reference values. Another stated that there is no scientific basis for the proposed metric, because the authors dismissed the established principle that chemical agents acting on a given target organ are considered additive whereas those acting on different target organs are not. A third commented that the metric is too conservative and will lead to an undue burden for testing and control of contaminants. A fourth expressed concerns about using criteria for occupational exposure when criteria developed to protect public health may be more appropriate.

## Standards

A presentation by **Persily** describes the rationale for ventilation rate requirements in ASHRAE Standard 62-1999 and potential revisions to the standard. Ideally, the ventilation rate should be sufficient to keep specific contaminants below target concentrations. However, data are limited both on contaminant source strengths and on concentration guidelines for non-industrial buildings. The ventilation rate necessary to maintain oxygen at 19.5 percent is less than 1 cfm per person, lower than would be expected in any residential or commercial building. The ventilation rate required by building codes and ventilation standards generally is in the range of 5 to 20 cfm per person, with higher rates for certain situations such as gymnasiums or art studios.

A table in Standard 62 lists ventilation requirements for 82 space types, with a minimum rate of 15 cfm per person. The experimental basis for the minimum rate is tied to perception of body odors—80 percent of adapted occupants are satisfied with odor at 5 cfm/person, and 80 percent of unadapted visitors at 15 cfm/person. Studies in office buildings indicate that ventilation rates below 20 cfm/person correlate with increased Sick Building Syndrome and perception of poor air quality. About 80 percent of unadapted visitors would be satisfied with body odor when the indoor CO<sub>2</sub> level is 700 ppm above that outdoors. At steady-state, a ventilation rate of 15 cfm/person corresponds to 700 ppm, yielding an indoor CO<sub>2</sub> concentration near 1000 ppm for a typical outdoor level around 350 ppm.

The basis for ventilation requirements in proposed addendum 62n is control of both body odor and non-occupant sources. For body odor control, the minimum requirement is 5 cfm/person. For non-occupant sources, the requirement is in units of cfm/ft<sup>2</sup> of floor area. Thus, the total required ventilation would be equal to the sum of (number of people times the people rate for a space type) plus (floor area times the “building” rate for the space type). The arguments for this additive approach include experimental evidence of the additivity of odor and irritation considerations, coupled with elimination of some prior problems of over- and under-ventilation in low and high occupancy spaces.

One attendee felt that, in arriving at a ventilation rate requirement of 5 cfm/person, the loading of the space (i.e., number of individuals relative to volume) was not addressed; this individual further contended that only fresh air (as opposed to recirculation) would address the problem. A second questioned whether 15–20 cfm/person is more appropriate than 5 cfm/person for aircraft. A third noted that the 80 percent of adapted occupants satisfied with air quality, as noted in some past studies, probably is based on sedentary individuals; by comparison, flight attendants typically are moving about the aircraft.

A presentation by **Holcomb** describes the purpose and the status of a proposed ASHRAE standard for cabin air quality (161P). The purpose of the standard is to define requirements for air quality in commercial aircraft carrying 19 or more passengers and to specify measurement methods and compliance requirements. The standard covers chemical, physical, and biological contaminants and physical cabin environment parameters, such as temperature, relative humidity, and pressure. A draft standard and informative appendix are under preparation by the committee.

There were numerous comments at the meeting concerning this presentation. One attendee contended that the standard should specify the mean acceptable ventilation rate rather than the minimum acceptable level. Another noted that the basis for the proposed minimum level was studies by Cain and Leaderer in the early 1980s, and that Cain has since stated that ventilation rates should not be based on acceptability to adapted occupants (since contaminant sources can move, occupants can move, and new sources can appear). A third commented that flight attendants would be asked to work in an environment with 1/3 the fresh-air rate per person that is recommended for office workers. A fourth questioned whether there were any published studies on ventilation efficiency in aircraft that used actual measurements rather than modeling.

Most other comments were related to a recommendation in the standard that relative humidity (RH) be less than 25 percent. One attendee asked whether published data demonstrate that RH levels above 25 percent in commercial aircraft are truly a safety hazard (as opposed to below 25 percent being a

design feature desired by manufacturers), and whether it is feasible to propose a single standard for all flights regardless of length. Several individuals felt that no limit should be given for humidity (e.g., such a limit may discourage innovation). Another attendee asked whether it would be more appropriate in the standard to say that low RH has the potential for adverse health effects. A further suggestion was made that it might be more appropriate to specify recommendations for temperature and humidity simultaneously.

### Modeling and Control of Cabin Air Quality

**Baker et al.** describe an approach for predicting the distribution of air ventilation in aircraft cabins using computational fluid dynamics (CFD). An example of previous use of CFD is in the design of gasper systems used on some aircraft models. Because the airline industry is reaching out to new markets such as business aircraft, there are many new entries in the design phase. Such entries may have significantly different interior design features, such as absence of overhead storage bins that influence the design of gasper systems or additional electronic amusement/business gear with accompanying heat loads.

Measures of comfort include (1) Predicted Mean Vote (ISO Standard 7730.1994(E)), dependent on mean temperature, radiant temperature, air velocity, humidity, heat flux, metabolism, and clothing, and (2) Predicted Draft rating, dependent on temperature, air velocity and turbulence level. For air quality, the concept of Age of Air is related to the ventilation rate and ventilation distribution effectiveness. The authors state that these quantities could be predicted if there was sufficient knowledge of the flow field in the airliner cabin, which conceivably can be predicted using CFD analysis.

The two fundamental challenges, in the authors' opinion, are that the computer code must be operationally robust (stable and sufficiently convergent) and that the underlying mathematical approximation theory must rigorously control artificial dissipation (which can totally mask the genuine physical diffusion processes that are present). They further state some practical aspects for a candidate CFD theory/code system, and express the opinion that some available codes meet these requirements to varying extents. Using one such system, a computational experiment was conducted to predict the flow field at cruise in the business conference section of a business jet. The exercise (with no validation) indicated that a table in this section significantly disrupts flow-field evenness, to the point that an exhaust plenum effectively becomes a supply.

The authors conclude that CFD methodology possesses the attributes necessary to quantify comfort and eventually IAQ in an indoor environment. Although the procedures require significant labor resources and computing power, an obvious benefit is the ability to evaluate candidate designs before they are introduced. The existence of validation data for comparison with CFD results would be critical to obtaining acceptance for the methodology.

One attendee asked whether or how certain parameters were incorporated in the CFD model, such as inner surface temperature, passenger loading, cabin pressure, and air density. Another stated that CFD results need to be validated with measurement data, but also noted that model results could be used in the future to determine where experimental measurements should be made.

**Hall et al.** describe an approach to contaminant removal from airliner cabins using air purifiers, with a design based on ultraviolet (UV) light illumination of a photoactive semiconductor. The authors state that this technology is effective both in converting harmful VOCs to generally non-toxic compounds and in killing bioaerosols. As an aid to evaluating alternative approaches, they define a tolerance index as the sum (across various contaminants of interest) of the ratio of each contaminant's steady-state concentration to its maximum allowable concentration.

According to the authors, when the photoactive semiconductor titania is irradiated by UV light in the wavelength of 200–400 nanometers, an electron-hole pair is created. The hole can react with adsorbed water vapor to create hydroxyl radicals, which attack and adsorb contaminants on the titania

surface, reducing them to carbon dioxide and water. Titania-coated honeycomb monoliths were found to offer good illuminated surface-to-volume ratios with minimal pressure drop and weight. The efficiency of the process is maximized by the low-humidity environment characteristic of aircraft cabins. The air purification process attacks practically all gaseous species of interest; it is most effective for trace contaminants at levels on the order of one ppm or less. With this technology, killing doses of UV-C radiation can be directly delivered to airborne aerosols, obviating the need for a filter.

Life-cycle costs are presented in the paper for the air purifier using UV germicidal irradiation and photocatalytic oxidation (PCO), in comparison to one using HEPA filtration and activated carbon (AC) absorption. For determination of these costs, the two types of air purifier were designed to deliver the same total tolerance index at each of several fresh airflow rates. The authors indicate that the prototype UV/PCO system is superior to the HEPA/AC system in all features essential to airliner operations. For example, at a 5 cfm fresh-ventilation airflow, the UV/PCO system is predicted to be 1/4 the volume, 1/5 the weight, and half the life cycle cost of the HEPA/AC system.

Two of the attendees questioned the efficiency of the air purifier under low-humidity conditions in aircraft. Another asked about purification efficiency and reaction rates for chlorinated or unsaturated compounds. A concern was expressed whether byproducts from purification of chlorinated compounds could themselves be toxic. Another attendee questioned whether the claimed reduction for infectious agents would be adequate in the aircraft cabin environment, and others asked whether the unit could handle active pathogens or spills of oil/hydraulic fluids.

Fox reported on a case study that involved air quality testing aboard a commuter aircraft to identify possible contaminants entering the aircraft and to identify other factors that could affect the comfort of the aircraft occupants. Parameters that were monitored included volatile and semivolatile compounds, aldehydes, CO, CO<sub>2</sub>, O<sub>2</sub>, relative humidity, temperature and air flow. Testing was performed with and without revenue passengers, and with recirculated air adjusted from zero to 50 percent. One objective, addressed through ground testing, was to determine whether there was a safety issue associated with a pack burnout, a cleaning operation designed to volatilize hydrocarbons while the cabin is empty. A second objective was to determine the air quality impact of using a charcoal filter at the end of its service life. Other objectives included evaluations of relative humidity, temperature, airflow and contaminant levels for the case of full fresh air versus 40 percent recirculation.

The monitoring results indicated that full hydrocarbon clean out of the ECS system never occurred on the tested aircraft. New filters did not result in a reduction of measured contaminant levels but did reduce the detection of odors. Outlet flows were highest at the forward three rows of the cabin and were considerably higher near windows than in the aisle.

Temperature and oxygen levels appeared very stable throughout all flights, regardless of passenger loads. The relative humidity level was less than 5 percent with a full passenger load when full fresh air was used, compared to 9–13 percent with 40 percent recirculated air. Carbon dioxide levels were elevated only in the aft galley where dry ice was present. Formaldehyde levels in the cabin during pack burnout were deemed unsafe, but levels during flight were minimal. No isomers of tricresylphosphate were detected, but tri-*n*-butyl phosphate was detected. Odors in the supply air were below air thresholds, but not water mixture thresholds in the cockpit during flight conditions with old charcoal filters.

The author concludes that pack burnouts appear to reduce the number of odor complaints when performed on a daily basis, but also caution that mechanics should spend minimal time on board during this process due to unsafe formaldehyde levels. Findings indicate that hydrocarbons break through the filter as it ages, and heating up the air-conditioning system likely reduces the filter life. The author states that a method of assessing filter life needs to be developed. Odors were detected in the cabin on the flight that had filters with over 1000 hours of service; changing filters eliminated odors on takeoff. Based on improvement in humidity levels and reduction in organic contaminants while operating in a recirculation mode, the author recommends that aircraft be operated in this mode.

One attendee noted that it is not practical to recover SVOCs from charcoal filters, because most are

irreversibly sorbed, and asked whether potential losses/contamination were evaluated when using long sample lines to transfer cabin air samples to SUMMA polished canisters. Another commented that sampling on non-revenue flights might not yield representative results.

### Cabin Air Quality and Emerging Issues/Research

**Space et al.** summarize past, present and future research on cabin air quality and the airplane cabin environment. The authors begin by describing the history of cabin environmental issues, going back to early complaints in the 1930s—mainly dizziness and nausea related to motion sickness. The history is taken through the 1990s, concluding with establishment in 1995 of an ASHRAE Aviation Standards Committee to develop an air quality standard unique to airplanes. In that same year, the ASHRAE Transportation Committee established an Aviation Research Subcommittee charged with identifying and implementing research central to the issues of aircraft cabin environment air quality.

The authors present a schematic called “Airplane Cabin Environment Wheel” with three groups that can influence cabin environment comfort and health: manufacturers; airlines; and occupants. The issue is complicated by the fact that multiple factors or combinations of factors can cause the same symptoms. For example, the symptom of a stuffy nose could be caused by low relative humidity, temperature, or air contaminants, and can be influenced by individual health status and flight duration.

Low relative humidity levels in the airplane cabin may lead to a feeling of dryness and thirst, but also can inhibit fungal and bacterial growth. Designing for cabin relative humidity levels above 25 percent is limited due to the effects of condensation, corrosion, and fatigue on the airplane structure. Increasing the filtered recirculation air within boundaries to increase relative humidity may be beneficial, as ozone levels would decrease and microbial levels (with high filtration) would not increase. Reported average cabin air temperatures are in the same range as normally encountered in office buildings, but the cabin environment has notable differences along such lines as air density, relative humidity, and occupant density. Due to the increased activity levels of flight attendants, their thermal requirements are likely to be different from those of sedentary passengers.

The percentage of oxygen in cabin air remains virtually unchanged by occupant breathing as it is replaced in far larger quantities, through outside air changes, than the human consumption rate at all flight altitudes compared to sea level. However, the partial pressure of oxygen decreases with increasing altitude. It is believed that the increase in cabin altitude, combined with longer flight duration, can lead to low grade hypoxia (reduced tissue oxygen levels) in certain segments of the population, causing symptoms such as headaches, fatigue, and stress.

Flight attendant studies show that their work can be fatiguing and stressful. Possible related factors include a highly variable work schedule, disruption of circadian rhythm, and the physical working environment. Frequently reported health symptoms include swelling of stomach and legs, stomach complaints, colds, blocked nose, cough, eye irritation, and ear complaints. A recent passenger comfort survey indicates that, for flights less than 2 hours, seats were the predominant factor affecting comfort and health (back/joint pain). For flights over 4 hours, humidity-related symptoms of dry/stuffy nose and irritated eyes were the predominant health symptoms.

According to the authors, future research will need to include (1) chamber studies designed to evaluate tradeoffs between recirculation rates, relative humidity, air velocities, and temperature, and (2) in-flight studies utilizing questionnaires and objective measurements to evaluate effects of multiple factors on passenger and flight attendant comfort and health. Research on bleed-air contaminants, their potential health effects, and the effects of age and maintenance practices also should be considered.

One attendee suggested that effects of a cabin altitude of 5,000 to 8,000 feet should be evaluated under realistic conditions, and that reduction in hypobaric oxygen saturation may explain complaints such as giddiness, light-headedness, and fatigue. Another questioned why humidity seems to be receiving attention when flight attendant illness reports more often cite lack of air or oxygen. A third

suggested that future research on cabin air quality requirements should account for proximity of people when establishing acceptable levels, and that risk assessments should account for the effectiveness of ventilation and/or purification on contaminant levels.

**Nagda et al.** provide a review of past studies concerning cabin air quality, based on nine studies conducted since 1985 that have reported primary measurement data. Aspects of the review include study design (e.g., representativeness of results), measurement methods, quality control and assurance methods (e.g., precision and accuracy), and benchmarks used for comparison or interpretation of measured concentrations.

Designs of the selected studies ranged from one modest effort involving a few flights to extensive efforts involving about 100 flights. Only two of studies had a sample size greater than 40 flights and utilized random sampling techniques. Approaches to quality assurance differed greatly across the studies, ranging from poorly chronicled to fairly complete. A very limited number of studies gave sufficient information to assess data quality. Standards or guidelines used as benchmarks for comparison have included FAA Airworthiness Standards, National Ambient Air Quality Standards (NAAQS), NASA Spacecraft Maximum Allowable Concentrations (SMACs), and workplace standards or guidelines developed by OSHA and ACGIH. However, as noted by the authors, occupational standards often have been applied to public health situations without acknowledging differences in population characteristics, exposure conditions, or protection goals.

Results of cabin air quality studies show that the measured levels of pollutants in the airliner cabin generally are low, and the studies do not appear to uncover conditions that would cause overwhelming concern. Although there are no quantitative guidelines for levels of bacteria and fungi in the cabin environment, results of four studies show that the average levels did not approach the 1000 CFU m<sup>-3</sup> level commonly used to judge acceptability for ground environments. Low concentrations were routinely encountered for CO in the aircraft cabin. The technology for CO measurements is adequate, and a high degree of confidence can therefore be placed in the reported concentrations. Although the reported levels of O<sub>3</sub> are lower than FAA standards, there is a fair degree of uncertainty in those measurements, because reliable and portable instruments for measuring O<sub>3</sub> in the cabin environment are not available.

Reported levels of particulate matter have shown the greatest variability, and there are three factors that complicate the issue. First, light-scattering optically-based monitors give readings that are highly variable since size/mass distributions of aerosols in the field may be quite different from those used for calibration. Second, more reliable methods of collecting particles on filters for gravimetric analysis generally cannot be used in cabin air quality studies because the sampling time typically is not adequate to collect sufficient mass for quantitative analysis. Third, the NAAQS are defined for PM<sub>10</sub> and PM<sub>2.5</sub> but the monitoring equipment may measure other size ranges, or "total" particulate matter.

CO<sub>2</sub> is the one monitored pollutant that routinely has approached and exceeded the level (1000 ppm) commonly used to judge acceptability in ground-based settings, based on ASHRAE standard 62-89. However, interpretation of the significance of CO<sub>2</sub> levels has been refined in recent years. For example, according to ASTM Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation (D6245), it is appropriate to use the CO<sub>2</sub> level as indicator of comfort in terms of body odor (i.e., for a visitor walking into space), but it cannot be considered a comprehensive indicator of air quality. Thus, in an environment with a high density of people such as the aircraft cabin, CO<sub>2</sub> levels would be expected to be higher without many of the health concerns that might be associated with other environments.

Concentrations of VOCs were measured with various techniques but the reported data are inadequate for developing firm conclusions. Only two studies used techniques that are appropriate for quantitating individual VOCs, but both included a small number of flights. The concentrations of ethyl alcohol accounted for 80 to 85 percent of the total VOCs measured in the two studies. Because some studies have measured aldehydes using methods with insufficiently low detection limits, and

others using more appropriate methods have been limited in sample size, the representativeness of results to date is limited. No measurements of SVOCs in the cabin environment have been reported.

The authors conclude that reported levels of all contaminants measured to date have been below levels of concern for public exposure and that representative, reliable measurements have been reported for bioaerosols, CO, and CO<sub>2</sub>. Some questions remain, however, for particulates and ozone, due to limitations of methods used to date. Levels of formaldehyde, VOCs, SVOCs, and viruses are considered to be major unknowns.

One attendee cited previous experience suggesting that small-volume canisters for VOCs do not collect adequate sample volumes for the cabin environment. Another noted that ASTM and EPA have published reliable measurement standards for many organic compounds, classified according to vapor pressure. A third remarked that, although bioaerosols were listed in the presentation as being well measured, virus measurements are rare due to the expense of the method. A fourth questioned whether any reviewed studies addressed aircraft air quality under upset conditions such as a spill of hydraulic fluid/oil, and a fifth suggested that a check interval for air quality needs to be established that is compatible with reasonable maintenance costs and trouble-shooting procedures.

### **Relationships between Cabin Environment Factors and Comfort/Health Responses**

A paper by **de Ree et al.** examines ozone and relative humidity in airliner cabins on polar routes. According to the authors, certain symptoms such as dry eyes, dry throat, or respiratory discomfort may be due to low relative humidity or due to elevated ozone levels. The 24 polar flights in the study included measurement of relative humidity and ozone on the flight deck and a physical-symptoms questionnaire (presence/intensity) completed by cabin and flight crew both before and near the end of each flight. The monitored flights were evenly distributed between two airlines, with similar departure times and flight lengths. The aircraft for one of the airlines had no catalytic converters and were fitted with flight deck humidifiers, whereas for the other airline the same type of aircraft had catalytic converters but no humidifiers. The extent of relationship between ozone levels or relative humidity and reported symptoms was examined using correlation coefficients.

Valid ozone and relative humidity data were collected only for a subset of study flights. For the airline without catalytic converters, ozone data were collected on two outbound and five return flights, and relative humidity was measured on a total of seven flights. For the airline with catalytic converters, ozone data were collected on one outbound and nine return flights, and relative humidity on a total of eleven flights. For days with paired measurements, ozone levels were lower on aircraft with converters in all cases. Relative humidity, on the other hand, was equally likely to be higher or lower on the aircraft fitted with deck humidifiers. The authors speculate that there may have been operational or equipment-servicing deficiencies with the humidifiers.

The percentage of crew reporting symptoms was somewhat higher on aircraft with converters and no humidifiers, but the difference was not statistically different. For both airlines, the number of reported symptoms was higher near the end than before the flight. The percentage of crewmembers who reported impairment in ozone-related symptoms did not differ significantly between the two airlines, and measured ozone levels did not correlate significantly with changes in reported symptoms. Similarly, there was no significant correlation between measured relative humidity and symptom changes. The authors note that the results must be treated with some caution due to several study limitations, including questionable reliability/validity for the symptoms questionnaire and lack of control over study conditions. These factors are in addition to incomplete ozone and relative humidity data and possible deficiencies with humidifiers, as noted above.

One attendee questioned whether certain symptoms on the questionnaire were specific to ozone, as claimed by the authors. Another commented that ozone's reactions with other chemicals or indoor sinks may lead to spatial variations in ozone concentrations. A third noted the experience of an air-



line whereby, after installing an ozone converter for long-range flights, there were no further reports on the typical odor associated with ozone.

**Lee et al.** report on a questionnaire survey designed to evaluate the health and comfort of cabin crew. The study included 16 flights on wide-body aircraft with flight times ranging from 1.5 to 18 hours. In total, cabin crew on these flights completed 185 questionnaires. The questionnaires were used to evaluate the crew's perception of cabin lighting, noise, humidity, cigarette smoke, air odor, air movement, and temperature.

Almost all crewmembers were satisfied with cabin lighting, and most crew (71 percent) rated the cabin temperature as satisfactory. A large majority (88 percent) of the crew rated the humidity level as uncomfortable. About half the crew felt that there was a distinct, unpleasant odor in the cabin, although the source could not be identified. About half the crew thought the overall comfort was satisfactory or comfortable. More than half the crew received complaints from passengers concerning aircraft air quality, with temperature, humidity, odor, and noise cited most frequently.

The three symptoms experienced most frequently were dry or irritated eyes, dry or stuffy nose, and skin dryness or irritation. Crew also indicated that odors were more serious in the summer and on older aircraft, and that air quality was best in first class and poorest in economy class.

Air quality measurements also were taken on the study flights, but these were not the focus of the paper. The authors did not comment on possible relationships between air quality measurements and crew perceptions of air quality or the frequency of symptoms.

One attendee questioned the difference between acceptable and adequate air quality (both responses were used for the study questionnaire). Two others felt the authors' conclusion that "overall cabin air quality is good" seemed to be an overstatement, given that 20 percent of the flight crew classified air quality as "poor" and another 30 percent classified it as "adequate" (or less than "acceptable" with the scale used in the study).

A passenger survey reported by **Rankin et al.** was designed to evaluate factors affecting passenger comfort, the level of comfort and extent of symptoms experienced by passengers, and whether passenger comfort is related to percent of bleed air versus filtered, recirculated air, standard- versus wide-body aircraft, or flight length. Data were collected from 3,630 passengers on 71 flights, in three distance categories—1086 to 1464 miles (nominal duration of 2-3 hours), 3452 to 3784 miles (6-7 hours), and 5457 to 6427 miles (10-12 hours). Six types of aircraft were used in the flight—three wide-body (accounting for about two-thirds of completed questionnaires) and three standard-body. The respective design values for the aircraft ranged from 0 to 50 percent recirculated air.

Comfort was measured on a 7-point scale ranging from 1 (very poor) to 7 (excellent). The average passenger rating for overall comfort was 4.71, with 57 percent giving a high rating (above 4). Among the higher ranked aspects of comfort were cabin appearance and air odor. The aspects ranked at the low end all were related to seats. From the standpoint of temperature and air movement, passenger discomfort was more pronounced before takeoff than during flight. Seat comfort was the best predictor of overall flight comfort. All standard-body aircraft had lower average ratings than the wide-body aircraft.

Passenger ratings for health during the flight generally were quite high. The two health symptoms experienced most by passengers, as in the paper by Lee et al. on their questionnaire survey, were back/joint/muscle pain and dry or stuffy nose. Baseline health (prior to the flight) had by far the strongest correlation with passenger health during the flights, and the symptoms most strongly correlated with passengers' self-assessed state of health during flights were sinus problems and headaches.

There was no consistent pattern for passenger comfort, health, or symptoms in relation to the aircraft recirculation rate. There was a consistent trend of poorer passenger ratings with progressively longer flights, most notably in going from short to medium distances. Most symptoms with greater differences between medium and long flights were apparent reflections of a low-humidity cabin environment. Based on the results, the authors make the following conclusions: that seat comfort, flight

smoothness, and air quality are the three most important determinants of comfort and health in the aircraft cabin environment; that the percent of recirculated air had no impact on passenger comfort ratings or reported health symptoms; that longer flight duration contributes to decreased overall comfort and increased health symptoms; and that seat discomfort on longer flights becomes noticeable to passengers sooner than irritation due to low relative humidity.

One attendee commented that it would be useful to disaggregate the data (e.g., by seat location, class of service, proximity to aisle or window, proximity to galley or lavatory) in an attempt to obtain further insights.

### **General Comments**

In general discussion toward the end of the symposium, some comments were offered that were specific to airlines or to the medical profession. Dr. Eranava of British Airways Health Services noted that the airline carries out a disinfection process, using synthetic pyrethroids, on arrival/departure at certain stations to comply with public health requirements. Passengers are advised that they may experience some irritation of mucous membranes. Mr. De Ree of KLM stated that it is certainly desirable to raise humidity to satisfy passengers and crewmembers, but the airline is now fitting zonal dryers for their MD-11 aircraft because insulation blankets are getting very wet.

Dr. Simon of the Netherlands Aeromedical Institute offered suggestions both for airlines and for physicians. Airlines should collaborate on data collection and "events" (trip reports) so as to achieve a larger cohort of "patients" and, thus, more meaningful results. Physicians should work on developing uniform methods to objectively describe symptoms, describing and characterizing them in a more scientifically useful way.

### **Concluding Remarks**

One of the aims of the symposium was to identify needs in the area of standards development. Four candidate topics for standards were introduced during the symposium. The topics, and the individual for each who may have first identified the need at the symposium, are as follows:

- Protocol for cabin air quality measurements during episodic conditions (Bill Needelman, Pall Corporation.);
- Practice for air quality measurement on aircraft, including specifications for sampling media, sampling lines, and other accessories (Bob Lewis, U.S. Environmental Protection Agency);
- Uniform methods and criteria for reporting and categorizing symptoms (M. Simons, Netherlands Aeromedical Institute); and
- Practice for defining adequate check interval for measuring cabin air quality on aircraft (or frequency of measurement to obtain representative data) (Kirsten Behnke, Lufthansa).

The papers presented at the symposium collectively focus on characterization of the aircraft cabin environment and effects on the occupants. Through the presentations and the vigorous discussions that followed, participants gained broad perspectives and valuable insights into issues and challenges associated with the aircraft cabin environment. Such an outcome would not have been achievable without the cooperative efforts of the authors and the attendees.

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