

Aircraft Cabin Air Quality Trends Relative to Ground Level Standards

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Abstract Aircraft cabin air quality has attracted much attention, summarized recently by a detailed examination and commentary by a U.S. National Academy of Sciences Committee. Ventilation of aircraft has several significant variables that require control measures that are seldom of concern for occupied space at ground level. The principal of these special requirements are the need to compensate for the substantial difference between cabin

and outside pressures, the much lower available space per occupant in aircraft cabins, and the need for coping with more extreme external temperatures than are common at ground level. The breadth of these concerns is of interest in the policies and regulatory aspects of a number of agencies which are briefly described, and their roles and areas of potential interest outlined. Types of possible contaminants are listed, and the limits which have been set by several of these agencies for many of these potential contaminants are tabulated. In addition recent measured aircraft cabin concentrations of several key contaminants are listed. This chapter provides an overview of the general air quality variables affecting enclosed space to enable these to be related to the special needs of some of the less common enclosed spaces described in the following chapters.

Keywords Air contaminants · Gases · Vapors · Aerosols · Particulates · Physical parameters · Infective agents

Abbreviations

ACGIH	American conference of governmental industrial hygienists
ASHRAE	American society for heating, refrigeration and air conditioning engineers
CFU	colony-forming unit
ECS	environmental control system
EPA	U.S. environmental protection agency
FAA	federal aviation act
FAR	federal aviation regulation
HEPA	high efficiency particulate air [filter]
MSDS	manufacturer(s) safety data sheet
NAAQS	national ambient air quality standard
NAS	national academy of sciences
NACOSH	national advisory committee on occupational safety and health
NASA	national aeronautics and space administration
NRC	national research council
OSHA	US occupational safety and health act
PEL	permissible exposure limits
SARS	severe acute respiratory syndrome
SEALS	submarine escape action levels
SMACs	spacecraft maximum allowable concentrations
STEL	short term exposure level
TLV	threshold limit value
TWA	time weighted average
VOC	volatile organic compounds

1

Introduction

Significant concerns have been raised regarding the impact of the cabin air environment on the health and safety of passengers and crew. The combination of high occupant density, relatively low ventilation rates, and varying but potentially long occupancy periods up to 18 hours on some intercontinen-

tal flights create the potential for adverse health impacts. Aircraft cabins are a uniquely challenging environment. As Hocking has noted, aircraft cabins have the smallest available airspace per person of any current social environment, and occupants of a fully loaded aircraft typically have about 35–70 ft³ (1–2 m³) of available airspace per person, approximately 1/10th that of a typical office worker or a spectator in an auditorium [1].

In 2003, the US National Academy of Sciences [2] (NAS) released its latest report, funded by the Federal Aviation Administration. The NAS report, most importantly, recommends that air quality in commercial aircraft be monitored with routine surveillance of air-quality characteristics such as ozone, carbon monoxide, carbon dioxide, fine particulate matter, cabin pressure, relative humidity, and temperature. In addition, it called for a detailed research program to be launched to investigate specific questions about the possible association between air contaminants and observed or reported health effects.

As noted by the NAS report, since passage of the Federal Aviation Act in 1958, the Federal Aviation Agency maintains authority over the regulations related to operation and safety of civil aircraft (Public Law 85–726). The Occupational Safety and Health Act (OSHA) was adopted in 1970 to regulate health and safety provisions for workers (Public Law 91–516). Exemptions from OSHA coverage included workers in industries regulated by other agencies such as the Airlines (FAA), Railroads (Federal Railway Administration), maritime workers, and federal, state and local government workers. The FAA exercised its option to regulate the safety and health of airline cabin workers beginning in 1975 (40 FR 29114, DOT 1975). Federal Aviation Regulations (FARs) that have been subsequently promulgated by the FAA to govern air quality in commercial aircraft so far include O₃, CO, carbon dioxide (CO₂), ventilation, and cabin pressure (14 CFR 21, 14 CFR 25, 14 CFR 121, and 14 CFR 125). Similarly, the European Joint Airworthiness Authority (JAA) regulates European cabin air through Joint Aviation Regulations.

The National Academy of Sciences (NAS) report [2] concluded that the current design standard for the minimum amount of outside air circulated into cabins is about half the ventilation rate often required for building environments. Reduced ventilation rates in buildings have been linked to increased reports of health symptoms and sick leave, but whether building ventilation standards are appropriate for airplanes has not been determined. Studies of transmission of infectious airborne diseases such as tuberculosis during flights suggest that the spread of infectious agents during flights does not appear to be facilitated by aircraft ventilation systems, but rather by the high density of people, the committee concluded. An aircraft's environmental control system itself can be a source of contamination during abnormal operations when engine oil, hydraulic fluids, or de-icing solutions enter the cabin through the air-supply system in what is called "bleed air". Many crews and passengers have reported "air quality incidents" involving smoke or odors

within cabins. The NAS committee said FAA should study the need for and feasibility of installing equipment to remove vapors and particles from air supplied by the environmental control system on all flights.

Other countries have also convened reviews of airline cabin air quality, including the British House of Lords [3] and the Australian Parliament [4].

Rep. John Mica (R-FL), the Chairman of the U.S. House Subcommittee on Aviation, stated in a June 5, 2003 hearing, "Flight crews and passengers have continued to raise concerns about the cabin air quality in commercial aircraft. There have also been questions about the possible transmission of contagious diseases in-flight. Most recently, the focus has been severe acute respiratory syndrome, or "SARS". Often those who fly complain of headaches, fatigue, fever, and respiratory difficulties. The unanswered question is whether these complaints are due to poor cabin air quality or to other factors inherent when flying for a long period of time in a confined space with other people".

Patricia Friend, President, Association of Flight Attendants, noted in the same hearing the following issues related to airline cabin air quality that are currently unresolved:

- Inadequate ventilation and standards for aircraft;
- Polluted air supply on the ground from exhaust fumes and heated deicing fluids;
- Exposure to heated oils and hydraulic fluids that can leak or spill into air supply systems;
- Reduced oxygen in the ambient air during flights which is generally equivalent to altitudes of 6000 to 8000 feet;
- Inadequate attention to the thermal environment;
- Exposure to ozone gas which can result in respiratory distress and increase susceptibility to infection;
- Exposure to potentially high concentrations of pesticides that are sprayed in planes on some international flights.

Unless adequate solutions are found to the above problems, these concerns will tend to increase with the growth of air traffic, the tendency for airlines to seek greater fuel efficiency, and the trend toward future generations of aircraft providing less fresh air ventilation and more recirculation of air in aircraft cabins. Despite the above concerns, and the work of several active committees tasked with such standard development for over the past 10 years, there are currently no accepted International, North American or European standards for the air/environmental quality within aircraft cabins. In light of these developments, and in particular, the worldwide SARS epidemic of 2003, U.S. Senator Dianne Feinstein (D-Calif.) has called for a national standard for airplane cabin air quality [5]. The absence of US regulations addressing a wider range of additional cabin air contaminants and environmental factors is the source of significant concern on the part of airline industry workers, unions and the flying public. Particularly in light of current economic stressors on

major sectors of the airline industry, these problems may be exacerbated in the future.

This chapter will address the following questions:

1. What are the existing ground level air quality standards of potential relevance to the airline cabin environment?
2. What are relevant measured levels of airborne contaminants of concern aboard aircraft?
3. What are potential actions and policy options for development of airline cabin air quality standards in the future?

Standards are reference values to which something can be compared. If properly developed and maintained they represent the combined knowledge of designers, manufacturers, and consumers and are useful as benchmarks for industry, providing a way to insure compatibility, comparability, enabling mass production and a means of measuring and testing of products [6]. Common weaknesses of standards include failure to prevent contamination due to conflict of interest in standards setting organizations, failure of standards setting bodies to update standards with new information or changes in technology, and failure of enforcement.

Federal regulatory agencies other than the US FAA (with its limited set of airline cabin environmental standards), such as the U.S. Occupational Safety and Health Administration (OSHA) and the U.S. Environmental Protection Agency (EPA) have not established exposure limits for the unique environment of aircraft, nor are their existing standards necessarily appropriate for this environment. What are the agency standards and standard-setting processes that currently exist that might be appropriate as a starting point for considering development of a more comprehensive set of airline cabin air standards?

2

Candidate Ground Level Standards and Standard-setting Agencies

2.1

US Occupational Safety and Health Administration

The US Occupational Safety and Health Administration (OSHA) was established in 1970 as an administrative agency in the US Department of Labor. OSHA is the primary federal agency responsible for maintaining minimal standards for indoor air of workplaces. The setting of standards for workers would have spill-over benefits in terms of potentially protecting passengers and the general public, although workplace standards are often significantly less stringent compared with standards for the environment of the general public, including potentially more susceptible populations. The National Ad-

visory Committee on Occupational Safety and Health (NACOSH) has noted “since consensus standards were first adopted in the two years after the passage of the Occupational Safety and Health Act, a relatively small number of standards have been promulgated. Further, standards such as Permissible Exposure Limits (PEL) have not been successfully updated. The average time to develop and promulgate a standard is ten years During the time these important standards were under consideration, hundreds of workers continued to be killed or seriously injured annually by these hazards”. NACOSH made recommendations for streamlining and speeding up the standard setting process. However, underlying problems causing the ineffectiveness of OSHA standard setting, including lack of political will in administrations fundamentally opposed to regulation and the increasing weakness of unions compared with corporate interests, were not addressed. Some states that opt to have state OSHA plans have had more success in updating and adopting standards. This is permitted as long as they adopt standards that are at least as effective as the federal standards. Even in the best states, however, there is a relative lack of systematic scientific or worker input into the standard setting process, resulting in the tendency toward wholesale and uncritical adoption of industry “consensus” standards such as the American Conference of Governmental Industrial Hygienists’ Threshold Limit Values.

2.2

American Conference of Governmental Industrial Hygienists

The American Conference of Governmental Industrial Hygienists (ACGIH) establishes industry standards through a “Threshold Limit Values (TLV) Committee”. This effort started in 1946. The membership of ACGIH represents industry, government, academia and to a diminishing extent, labor organizations and was drawn from four disciplines: industrial hygiene, toxicology, occupational medicine and occupational epidemiology. The TLV Committee sets guidelines and recommendations, not regulations, and they publish an annual booklet of recommended limits for chemical substances and physical agents, primarily for use by industrial hygienists. According to the preface of the TLV booklet, TLVs “are health-based recommendations derived from assessment of the available published scientific information from studies in exposed humans and from studies in experimental animals” [7]. Criticism of the TLV development process has focused on the lack of adequate documentation of the committee’s decision-making processes, lack of an effective means of preventing conflicts of interest from tainting committee decisions [8], and lack of explicit scientific rationale or health basis [9] for many of the TLV’s that have been developed. Nevertheless, the TLV’s tend to be more protective than current Federal OSHA regulations, and are more frequently updated. As Peter Montague has noted, “During the 20 years that OSHA spent setting 12 new PELs, the ACGIH TLV Committee revised 234

TLVs downward, making them more protective (and stricter than the corresponding PELs which had been adopted in 1970 but never revised), and adopted 168 new TLVs for which there were no PELs” [10].

2.3

US Environmental Protection Agency

The Environmental Protection Agency is responsible for setting ambient air quality standards for the general public, including sectors of the population that may be most vulnerable. Since airlines serve the same general public, and include passengers that are in the vulnerable groups, EPA’s ambient air quality standards could serve as a starting point for aircraft cabin air standards. The EPA national ambient air quality standards mandated by the 1991 Clean Air Act cover “criteria air pollutants” with a focus on those associated with smog: ground level ozone, carbon monoxide and particulates, volatile organic compounds and 189 specific “hazardous air pollutants”. Many, but not all of these overlap with chemical contaminants of concern in aircraft cabins.

2.4

American Society for Heating, Refrigeration and Air Conditioning Engineers

The American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) establishes standards for many aspects of building ventilation. One standard in particular is most applicable to ventilation of airline cabins: Standard 62–2001. The purpose of ASHRAE Standard 62, as defined in Sect. 1, is to “specify minimum ventilation rates and indoor air quality that will be acceptable to human occupants and are intended to minimize the potential for adverse health effects”. The scope of Standard 62 “applies to all indoor or enclosed spaces that people may occupy, except where other applicable standards and requirements dictate larger amounts of ventilation than this standard”. This guideline is voluntary, and has not been adopted by the FAA. Most useful for aircraft environments may be the standard for comfort (odor) criteria with respect to human bioeffluents. In addition, ASHRAE recommends that indoor CO₂ concentrations be maintained less than 700 ppm above the outdoor air concentration [11], Table 4. As the NAS 2002 report has pointed out, ASHRAE Standard 62–1999 is also generally more restrictive than FAA’s FAR 25 with respect to both O₃ and CO [12]. In addition, it states that [13] “Assuming that the cabin temperature and pressure apply, and not the outside conditions, it is seen that ASHRAE Standard 62–1999 would require 50–100% more outside air than the current requirement in FAR 25”.

Temperature and humidity guidelines are also provided by another ASHRAE Standard (55–1992, *Thermal Environmental Conditions for Human Occupancy* ASHRAE 1992), that proposes voluntary ranges of temperature

and humidity that are generally found comfortable related to activity level and clothing.

2.5

Society of Automotive Engineers

The Society of Automotive Engineers has published a recommended practice guideline, *Procedure for Sampling and Measurement of Engine Generated Contaminants in Bleed Air Supplies from Aircraft Engines Under Normal Operating Conditions*, ARP4418 (SAE 1995), that includes a table from AIR4766, *Air Quality for Aircraft Cabins* that specifies the maximal concentrations of contaminants in engine bleed air. Multiple other guidelines relevant to airline cabins have been prepared by SAE, for example, *Testing of Airplane Installed Environmental Control Systems (ECS)* ARP217 March 1999.

2.6

European Community

The European Commission Directive 2000/39/EC of 8 June 2000 established a first list of indicative occupational exposure limit values in implementation of Council Directive 98/24/EC on the protection of the health and safety of workers from the risks related to chemical agents at work [14]. Unfortunately, the amount of overlap between the regulated occupational exposures listed and those likely to be of concern in airline cabins is small (Table 1).

2.7

Spacecraft Guidelines

The National Aeronautics and Space Administration (NASA) requested that the National Research Council (NRC) develop spacecraft maximum allowable concentrations (SMACs) for airborne contaminants. A subcommittee was established and four [17] reports of its findings have been published to date, including recommendations by NASA scientists and contractors on 35 substances of concern. Recognizing that differences exist regarding conditions aboard spacecraft compared with airline cabins, most notably duration of trips, weightless conditions, and unique contaminants that each environment may face, nevertheless, the spacecraft air guidelines may be a useful starting point for considering possible similar standards for airlines. The 1 hour and 24 hour SMACs, however, are clearly intended for emergencies, and may result in some mild mucosal irritation symptoms. They are not intended for protecting the general public, especially susceptible populations. These are further discussed in other sections of this volume.

Table 1 Limits on contaminants that may be found in aircraft cabin air (adapted from NAS 2002, reprinted with permission) [37]

Contaminants	FAA	ASHRAE ^a	EPA NAAQS ^b	OSHA PEL ^c	ACGIH TLV ^d	NAS SMACS
Ozone ^{e,f}	0.1 ppm 0.25 ppm	0.05 ppm	0.12 ppm (1 h) 0.08 ppm (8 h)	0.1 ppm	0.05 ppm (TWA) (heavy work), 0.08 ppm (moderate work), 0.1 ppm (light work)	
Carbon dioxide	5000 ppm	700 ppm above ambient ^g	–	5000 ppm	5000 ppm (TWA), 30 000 ppm (STEL)	
Carbon monoxide	50 ppm 35 ppm (1 h)	9 ppm (8 h) 9 ppm (8 h)	35 ppm (1 h)	50 ppm	25 ppm (TWA)	
Nitrogen dioxide	–	0.055 ppm (ann avg)	0.05 ppm (annual average)	5 ppm	3 ppm (TWA), 5 ppm (STEL)	

^aASHRAE 62–1999.^bEPA NAAQS, 40 CFR 50.^cPEL = OSHA permissible exposure limit.^dTWA = time-weighted average concentration in a normal 8-h workday and a 40-h workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect (ACGIH 1999). STEL = short-term exposure level is a 15-min TWA exposure that should not be exceeded at any time during the workday (ACGIH 1999).^eFAA airworthiness standards (14 CFR 25) for ozone: “0.25 parts per million by volume, sea level equivalent, at any time above 32 000 ft; and 0.1 parts per million by volume, sea level equivalent, time-weighted average during any 3-h interval”.^fNational Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) not to be exceeded at any time for O₃ is 0.10 ppm (NIOSH 1997); California Air Resources Board California ambient air-quality standard (CAAQS) for O₃ is 0.09 ppm for 1-h exposure (CARB 1999); and World Health Organization guideline for O₃ is 0.06 ppm for 8-h exposure (WHO 2000).^gApplies to use of carbon dioxide as a proxy for odors from bioeffluents; not a limit on exposure to carbon dioxide.

Table 1 (continued)

Contaminants	FAA	ASHRAE ^a	EPA NAAQS ^b	OSHA PEL ^c	ACGIH TLV ^d	NAS SMACs
PM ₁₀ ^h	-	-	150 µg/m ³ (24 h)	-	-	-
PM _{2.5} ^h	-	-	65 µg/m ³ (24 h)	-	-	-
Formaldehyde	-	-	-	0.75 ppm (TWA) 2 ppm (STEL)	0.3 ppm (ceiling)	-
Freon 113	-	-	-	1000 ppm	1000 ppm	1 hour 50 ppm 24 hour 50 ppm
Acetic acid	-	-	-	10 ppm	10 ppm (TWA) 15 ppm (STEL)	-
Acetone	-	-	-	-	500 ppm (TWA), 750 ppm (STEL)	-
Acetylaldehyde	-	-	-	200 ppm (TWA)	25 ppm (ceiling)	1 hour 10 ppm, 24 hour 6 ppm
Acrolein	-	-	-	0.1 ppm	0.1 ppm (ceiling)	1 hour 0.075 ppm, 24 hour 0.035 ppm
Benzene	-	-	-	1 ppm	0.5 ppm (TWA) 2.5 ppm (STEL)	1 hour 10 ppm, 24 hour 3 ppm
Temperature	-	ASHRAE_55-1996 ⁱ	-	-	-	-

^aASHRAE 62-1999.

^bEPA NAAQS, 40 CFR 50.

^cPEL = OSHA permissible exposure limit.

^dTWA = time-weighted average concentration in a normal 8-h workday and a 40-h workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect (ACGIH 1999).

^eSTEL = short-term exposure level is a 15-min TWA exposure that should not be exceeded at any time during the workday (ACGIH 1999).

^hPM₁₀ = particulate matter less than 10 microns in diameter; PM_{2.5} = particulate matter less than 2.5 microns in diameter.

ⁱThermal Environmental Conditions for Human Occupancy.

Table 1 (continued)

Contaminants	FAA	ASHRAE ^a	EPA NAAQS ^b	OSHA PEL ^c	ACGIH TLV ^d	NAS SMACs
Ethanol	-	-	-	1000 ppm	1000 ppm (TWA)	-
Ethylene glycol	-	-	-	50 ppm (ceiling)	39.4 ppm (ceiling)	-
2-ethoxy ethanol	-	-	-	200 ppm	5 ppm	1 hour 10 ppm 24 hour 10 ppm
Hydrazine	-	-	-	1 ppm	0.01 ppm	1 hour 4 ppm 24 hour 0.3 ppm
Hydrogen sulfide	-	-	1 hour 0.1 ppm 24 hour 0.005 ppm (PA) [15]	50 ppm	10 ppm	15 ppm (Submarines [16])
Methylene chloride	-	-	-	500 ppm	50 ppm	1 hour 100 ppm 24 hour 35 ppm
Toluene	-	-	-	200 ppm	50 ppm (TWA)	-
Xylene	-	-	-	100 ppm	100 ppm (TWA) 150 ppm (STEL)	-
Pyrethrum	-	-	-	5 mg/m ³	5 mg/m ³	-
Vinyl chloride	-	-	-	1 ppm	5 ppm	1 hour 130 ppm 24 hour 30 ppm

^aASHRAE 62-1999.^bEPA NAAQS, 40 CFR 50.^cPEL = OSHA permissible exposure limit.^dTWA = time-weighted average concentration in a normal 8-h workday and a 40-h workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect (ACGIH 1999). STEL = short-term exposure level is a 15-min TWA exposure that should not be exceeded at any time during the workday (ACGIH 1999).

2.8

Submarine Guidelines

The US Navy has proposed Submarine Escape Action Levels (SEALS) that are intended to be protective of the health of personnel in a disabled submarine. U.S. Navy Health Research Center's Toxicology Detachment proposed two exposure levels, called submarine escape action level (SEAL) 1 and SEAL 2, for each gas. SEAL 1 was defined as the "maximum concentration of a gas in a disabled submarine below which healthy submariners can be exposed for up to 10 days without experiencing irreversible health effects". SEAL 2 is defined as the "maximum concentration of a gas in a disabled submarine below which healthy submariners can be exposed for up to 24 hours without experiencing irreversible health effects". These were reviewed by the NAS and found to be adequate with the exception of chlorine [16]. They are similarly not intended for protecting the general public, especially susceptible populations and thus are not likely to be useful with regard to development of airline cabin air quality standards. These are further discussed in other sections of this volume.

3

Types of Contaminants and their Regulation

Specific standards for pollutants and physical environmental characteristics potentially found in aircraft cabins are listed in Table 1. Some are commonly found in other indoor or transportation environments, and others are relatively unique to the aircraft cabin. Chapters 10 to 12 of this volume address these contaminants in detail. Measurement of levels of contaminants is particularly a problem in difficult to predict intermittent cabin air quality "incidents".

The US FAA ventilation standard specifies that the air of the cockpit and cabin must be free of harmful or hazardous concentrations of gases or vapors (14 CFR 25, Section 831). For example, according to the standard, CO concentrations in excess of 1 part in 20 000 parts of air (50 ppm) are considered hazardous, and CO₂ concentrations during flight may not exceed 0.5% by volume (sea-level) or 5000 ppm.

3.1

Other Specific Contaminants of Concern

Spengler [18] reported a wide range of sources of potential contaminants in cabin air: Volatile Organic Compounds (VOCs), including; fuel exhaust (toluene, xylenes, benzene, decane, undecane, hexane pentadiene), distilled spirits and human bioeffluents (propan-2-ol, ethanol, acetone), air fresheners

and cosmetics (limonene, toluene), dry cleaning agent (tetrachloroethene), refrigerants (dichlorodifluoromethane), solvents (butan-2-one, toluene, 1,1,1-trichloroethane, xylenes) and plastic resin (vinyl acetate).

Table 2 lists existing data on measured air contaminants aboard aircraft from recent studies. Additional studies in the future will expand this information, particularly if the NAS recommendations for additional sampling are followed.

3.2

Specific Classes of Compounds, by Use Type

3.2.1

Pesticides

Pesticides used on aircraft include 2% phenothrin aerosol or residual spraying using a permethrin emulsion. In a study analyzing contents of aerosol sprays, VOCs were found in all preparations including ethyl benzene and xylene isomers along with phenothrin. Residual sprays contained cis-, and trans-permethrins, palmidrol, and occasionally naphthalene [19]. There are currently no US or European standards designed to control pesticide exposures aboard aircraft. US OSHA standards exist for some of the “inert” ingredients such as xylene and ethyl benzene.

3.2.2

Jet Fuels

Jet fuels are complex mixtures of hydrocarbon components and performance additives. JP-8 is one common military jet fuel containing naphthalenes while Jet A and A-1 are among the most common sources of nonmilitary occupational chemical exposure. Jet fuel varies by airplane and engine type. Combustion of jet fuel results in CO₂, H₂O, CO, various carbon-containing particles, NO_x, and a large number of complex organic compounds. OSHA as well as EPA standards exist for various components of jet fuels and their combustion byproducts.

3.2.3

Jet Oils

A recent review summarized the hazards of jet oils: “Jet oils are specialized synthetic oils used in high-performance jet engines. They have an appreciable hazard due to toxic ingredients, but are safe in use provided that maintenance personnel follow appropriate safety precautions and the oil stays in the engine. Aircraft engines that leak oil may expose others to the oils through uncontrolled exposure. Airplanes that use engines as a source of air for cabin

Table 2 Contaminant concentrations reported in published studies (from NAS, 2002, reprinted with permission)

Contaminants or Characteristic	Study and number of flights								
	Nagda et al. 1989 ^a 92	CSS 1994 35	Dechow 1996 x	Spengler et al. 1997 6	ASHRAE/ CSS 1999 8	Haghighat et al. 1999 43	Lee et al. 1999 ^a 16	Waters et al. 2001 37	Nagda et al. 2001 ^b 10
Ozone, ppb									
mean	22±23			na	51±15		na	200±180	
min	na			2	< 20		0	< 50	
max	78			10	122		90	1000	
Carbon dioxide, ppm									
mean	1756±660	1162		1400	1469±225	386-1091 ^c	683-1557 ^c	1387±351	1380
min	765	na		1200	924	293	423	664	na
max	3157	na		1800	1959	2013	2900	4238	1755
Carbon monoxide, ppm									
mean	0.6			0.7	na		1.9-2.39 ^c	0.87±0.65	0.2
min	na			0.8	< 0.1		1.0	< 0.2	na
max	1.3			1.3	7		4.0	9.4	0.8
Nitrogen oxides, ppb									
mean				36			4.5-49.6 ^f	580±700	
min				23			na	< 200	
max				60			na	3100	
Particulate matter, µg/m ³									
mean	37 (PM _{3.5})	176 (PM ₁₀)		na (total particles)			1-17 ^{c,d}	na (PM ₁₀)	< 10 (PM _{2.5} & PM ₁₀)
min	na	140		3			na	30	
max	199 ^e	200		10			1980	380	

Table 2 (continued)

Contaminants or Characteristic	Nagda et al. 1989 ^a	CSS 1994	Dechow 1996	Spengler et al. 1997	Study and number of flights			Waters et al. 2001	Nagda et al. 2001 ^b
					ASHRAE/ CSS 1999	Haghighat et al. 1999	Lee et al. 1999 ^a		
	92	35	x	6	8	43	16	37	10
VOC, µg/m ³ , with ethanol									
mean		na	na	3171 ^e	900 ± 450				
min		na	na	608	380				
max		2200 (ppb)	2200 ^e (ppb)	1805 ^e	1500				
Formaldehyde, ppb									
mean			7		2.9 ± 1.7		na	na	7.2 (µg/m ³)
min			3		< 0.6		0	na	na
max			26		4.9		< 0.07	13 (µg/m ³)	13 (µg/m ³)
Bacteria, CFU/m ³									
mean	131.1 ± 123.4	na	na	201 ^f	na		na		
min	na	0	20	na	39		44		
max	642	360	1700	na	244		93		
Fungi, CFU/m ³									
mean	9.0 ± 12.7	na			na		na		na
min	na	0			< 1		17		17
max	61	110			37		107		107

Table 2 (continued)

Contaminants or Characteristic	Nagda et al. 1989 ^a	CSS 1994	Dechow 1996	Spengler et al. 1997	Study and number of flights			Waters et al. 2001	Nagda et al. 2001 ^b
					CSS 1999	ASHRAE/ CSS 1999	Haghighat et al. 1999		
92	35	x	6	8	43	16	37	10	
Temperature, °C									
mean	24.1 ± 1.6	24.4	23.0	23 ± 1.7	20.3–23.8 ^c	21.3–25.3 ^c			
min	21.0	na	22.2	17.8	19	17.8		23	
max	27.2	na	25.6	26.1	27	26.3		26	
Relative humidity, %									
mean	21.5 ± 5.1	16.8	18	14 ± 3.2	x	10.0–42.6 ^c		10.5	
min	9.9	na	17	8.8	1.8	4.9		na	
max	30.8	na	19	27.8	nba	55.5		34.3	
Cabin-pressure altitude, ft									
mean	4344		na	na				5500	
min	2415		5500	na				8000 ^g	
max	7212		6900	6950					

^aData from non-smoking flights.

^bValues represent those in cabin during cruise.

^cRange of means.

^dParticle size range measured was not specified.

^eValues from Space DR, Johnson RA, Rankin WL, Nagda NL (2000) The airplane cabin environment: past, present and future research. pp. 189–214 in Air Quality and Comfort in Air Cabins, Nagda NL (ed), ASTM STP 1393. West Conshohocken: American Society for Testing Materials.

^fGeometric mean.

^gRange varied depending on aircraft type. For B767 and B747, cabin-pressure altitude was 5,500–6,500 ft. during cruise, for B737, approximately 8,000 ft.

pressurization may have this source contaminated by the oil if an engine leaks. Examination of the ingredients of the oil indicates that at least two ingredients are hazardous: N-phenyl-1-naphthylamine (a skin sensitizer) and tricresyl phosphate (a neurotoxicant, if ortho-cresyl isomers are present). Publicly available information such as labels and MSDS understates the hazards of such ingredients and in the case of ortho-cresyl phosphates by several orders of magnitude.” [20] Applicable standards: Airborne Exposure Limit for Tri-orthocresyl Phosphate (TOCP): OSHA Permissible Exposure Limit (PEL) is 0.1 mg/m^3 (TWA) and the ACGIH Threshold Limit Value (TLV) is 0.1 mg/m^3 (TWA).

3.2.4

Hydraulic Fluids

Hydraulic fluids used in commercial aircraft include, for example, Skydrol 500B-4. This is a fire resistant hydraulic fluid including a proprietary phosphate ester mixture composed principally of dibutyl phenyl phosphate and tributyl phosphate [21]. Hydraulic fluids may similarly enter the airline cabin if air used for ventilation is contaminated. The existing standards for tributyl phosphate: OSHA General Industry PEL – 5.0 mg/m^3 and the ACGIH TLV: 0.2 ppm , 2.2 mg/m^3 TWA.

3.2.5

Carbonyl-containing Compounds

Carbonyl compounds (e.g. formaldehyde, acetaldehyde, acetone, and acrolein) may be found in airline cabin environments at low levels [22]. OSHA standards exist for each of these compounds.

3.2.6

Dusts and Particulates

Existing standards for dusts and particulates of concern in airline cabin air such as dander and cat allergens, food particles such as peanuts, and surface dusts and dust mite allergens consist primarily of OSHA’s nuisance dust standard of 5 micrograms/m^3 , a level that is not appropriate for indoor transportation environments.

The US EPA has established standards for ultrafine particles ($\text{PM}_{10 \mu\text{m}}$ and $\text{PM}_{2.5 \mu\text{m}}$) in ambient air. Particles in the ultrafine, and more generally, in the submicron ranges are produced mainly from combustion, gas to particle conversion, nucleation processes or photochemical processes, with some of them emitted directly by the source and some formed in the air from the precursors emitted by the sources [23]. These constitute the largest number of particles in ambient air. Cigarette smoke was a major source of respirable suspended

particulates in cabin air until smoking was progressively controlled and then finally banned from all US domestic and international flights in the year 2000 (see Sect. 3.2.9 below).

3.2.7

Physical Parameters

Standards for physical parameters of cabin environment affecting cabin air quality including temperature, relative humidity and cabin air pressure have been set by the US FAA. However, existing standards will require extensive review: For example, the FAA requirement for cabin air pressure was set in 1964 “without any rationale”, according to Eileen Abt, a National Academy of Science staff director who worked on their recent panel on cabin air quality. “It has never been revisited”. Cabin air velocity/mixing is a more recent concern. Air flow patterns and air velocity have significant effects on thermal environment and air quality around passengers [24]. Air distribution inside aircraft cabins is a key factor affecting comfort as well as potentially affecting disease transmission. Cabin altitude – average during cruise, maximum rate of change during ascent, descent, tilt of take-off and landing all are potential concerns.

3.2.8

Infectious Disease Transmission

Infectious diseases of concern in airline cabin environments include bacteria, e.g., *Mycobacterium tuberculosis* (M. tb) and bacterial byproducts such as endotoxin, viruses, such as influenza, measles, mumps and chicken pox and corona viruses such as is associated with Severe Acute Respiratory Syndrome (SARS). The risk of transmission of infectious agents that are aerosolized such as M. tb from an infectious person to passengers or crew on an aircraft appears to be highest on long flights (8 hours or more) [25] and among those working or sitting closest to the infectious person. There are no currently applicable standards for microorganisms in ground environments, although there have been attempts to set an OSHA standard for tuberculosis that have been unsuccessful to date. Guidelines from the US Centers for Disease Control and Prevention [26] have been used by US state OSHA enforcement units for control of tuberculosis in health care workplaces but not aircraft cabin environments. The World Health Organization has also developed guidelines to prevent tuberculosis transmission aboard aircraft [27].

3.2.9

Tobacco Smoke

The difficulties in regulating indoor air aboard aircraft are illustrated by the case of tobacco smoke. A petition was first submitted in 1969 to the US FAA to request federal action to control tobacco smoking aboard aircraft [28]. The FAA did not act on the petition, taking the position that tobacco smoke was not likely to be a health problem for those exposed to second-hand smoke aboard aircraft. The US Civil Aeronautics Board was more receptive and beginning in 1973 began regulating smoking aboard aircraft primarily through establishing no-smoking zones in the cabin and separating cigar and pipe smokers. A series of federal reports were published in 1986 summarizing the mounting scientific evidence for harmful health effects of passive smoking, including *The health consequences of involuntary smoking*, by the US Surgeon General [29], and the US National Academy of Sciences report, *Environmental tobacco smoke: measuring exposures and assessing health effects* [30]. In addition, the US National Academy of Sciences published, in the same year, *The airliner cabin environment*, its first report on Cabin Air Quality [31] that proposed banning smoking from all flights within the US. Despite the efforts of the tobacco industry, in 1988, a law to ban smoking aboard US domestic flights of less than two hours went into effect. In 1990, Congress made the ban on smoking on domestic flights permanent and expanded it to include all domestic flights of six hours or less [32]. Most international airlines banned smoking in the 1990s. Finally, smoking was banned from all domestic and international flights to and from the US in 2000. A few airlines internationally continue to allow smoking on flights [33].

4

Effects of Aircraft Environmental Systems

4.1

Environmental Control Systems

The primary purpose of the ECS is to maintain cabin pressure in a range from a maximum of 101 kPa (14.7 psi) on the ground at sea level to a minimum of 75 kPa (10.9 psi) in flight regardless of the altitude at which the aircraft flies. A Congressional Aviation Subcommittee memorandum has summarized air supplied to various aircraft types: “Older model airplanes, such as the DC-9, the B-727, and half of the DC-10’s, provide 100% fresh air to the aircraft cabin. Newer models of jet aircraft, including the MD-80, DC-10, B-737, 747, 757, and A-300, 320 and 310, provide up to 50% re-circulated air. The recycled air system allows newer model aircraft to conserve fuel. The effectiveness of these filtration systems is often the focus of debate on cabin air quality” [34].

4.2

Filtration Systems

Recirculated air in aircraft cabins is used to reduce the cost of compressing outside air and maintain air circulation. Current practice is to filter recirculated air with particle filters. Filter efficiency varies from 40% on MD-80 aircraft to 99.97% (High Efficiency Particulate Air – HEPA – for 0.3 micron particles) on most recently manufactured aircraft. [35] Filter changes occur most often at scheduled maintenance checks, usually at 4000 to 12 000 flight hours [36]. Although these filters remove various sized particles from recirculated air depending on the filter efficiency, including bacteria and viruses when HEPA filters are used, they do nothing to remove chemical contaminants in the form of gases. Optional activated charcoal filters may be used on some aircraft to remove organic chemical contaminants, but these are uncommon.

4.3

Distribution of Air and Temperature Control in the Cabin

In a typical aircraft, air is supplied in amounts sufficient to maintain thermal uniformity throughout the cabin and exhausted along the whole length of the cabin. Air distribution is accomplished by single (narrow body aircraft) or multiple diffusers (wide body aircraft) located in the middle of the ceiling in the aisles, above the windows, or near the overhead baggage compartments. The NAS has noted that “Adequate temperature control in the cabin requires that conditioned air be supplied to the cabin at about 0.65 kg/min (1.4 lb/min) per person to maintain a comfortable temperature. This requirement is more than twice the FAR 25 requirement of 0.25 kg/min per person for outside air”.

5

Conclusions and Recommendations

Existing ground level standards may be used as a starting point for development of airline cabin air quality standards, but as they exist currently, none can be simply adopted as appropriate without careful review by a panel of independent experts. Possible policy and action options for the future include:

1. Implementation of NAS recommendations for additional sampling and research. This will provide a better scientific basis for future standard setting activities.
2. It is the role of FAA to promulgate appropriate cabin environmental standards for the wide range of contaminants and other environmental quality parameters potentially impacting crew and passengers.

3. If the FAA fails to exercise its preemption and promulgate such standards in a timely fashion, US Federal OSHA could develop appropriate emergency temporary cabin air quality standards covering cabin crew.
4. Similar efforts are needed at the level of the European Union and United Nations to establish worldwide cabin air quality standards.

A new sense of urgency is needed among the responsible agencies to increase the likelihood that appropriate airline cabin air standards will be established in the near future.

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