GUIDELINE

ASHRAE Guideline 28-2016
(Supersedes ASHRAE Guideline 28-2012)
Includes ASHRAE addenda listed in Appendix C

Air Quality within Commercial Aircraft

See Appendix C for dates of approval by the ASHRAE Standards Committee and the ASHRAE Board of Directors.

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NOTE

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(This foreword is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

FOREWORD

This guideline is intended to serve as a companion to ANSI/ASHRAE Standard 161-2007, Air Quality within Commercial Aircraft. *Standard 161 provides an air quality standard that addresses the unique characteristics of the aircraft cabin environment and aircraft operations. In the process of developing this standard, the project committee gathered and organized a considerable amount of research and other supporting information related to assuring good air quality within the aircraft cabin. In order to keep the standard document reasonably concise, much of this information was not included in Standard 161. Guideline 28, which carries the same title as the standard, utilizes this information to provide additional guidance that can be used for assessing and assuring cabin air quality.*

1. PURPOSE

This guideline serves as a companion to ASHRAE Standard 161 (ASHRAE 2007) and provides supplemental information on air quality in air-carrier aircraft and on measurement and testing related to aircraft air quality.

2. SCOPE

2.1 This guideline applies to commercial passenger air-carrier aircraft carrying 20 or more passengers and certified under Title 14 CFR Part 25 (FAA 2008b).

2.2 This guideline considers chemical, physical, and biological contaminants as well as, but not limited to, factors such as moisture, temperature, and pressure that may affect air quality.

3. DEFINITIONS

air, ambient: the outside air surrounding the aircraft.

air, engine bleed: air extracted from the compressor stages of gas turbine propulsion engines and auxiliary power units.

air, outside: the fraction of supply air that has not been recirculated in the cabin. As used in this guideline, the term usually refers to ambient air that is compressed in either the aircraft engines or APU, conditioned in the ECS, and supplied to the aircraft cabin. During ground operations, this term can also refer to ambient air that is conditioned by the ECS, ground cart, or airport conditioner, and delivered to the cabin.

air, recirculated: air from the aircraft passenger cabin that is reused as part of the supply air.

air, supply: air delivered to the aircraft cabin and used for pressurization, ventilation, temperature control, and humidity control.

air-conditioning system (packs): a part of the environmental control system, typically pneumatically powered, that provides cooling and heating for aircraft cabin temperature control.

aircraft, commercial: aircraft engaged in common carriage per FAA 8300.10 (FAA 2006).

alveolar partial pressure: the partial pressure of oxygen at the interface between the lungs and the blood.

auxiliary power unit (APU): a gas-turbine powered unit that provides electrical power and compressed air to operate aircraft systems independent of the aircraft propulsion engines.

blood oxygen saturation: the level of oxygen dissolved in the blood as compared to the maximum level of oxygen capable of being carried by the blood.

cabin: a term applied to any spaces in the aircraft occupied by passengers or crew members.

cabin altitude: the effective altitude to which the aircraft cabin is pressurized.

cabin pressure control system (CPCS): part of the environmental control system that regulates cabin altitude.

contaminant: an airborne constituent that may reduce acceptability of the air.

cockpit: see *flight deck*.

emergency cabin depressurization: loss of cabin pressure in an environment where supplemental oxygen is required to sustain human life.

environmental control system (ECS): the equipment in an aircraft used to pressurize, ventilate, air condition, dehumidify, or humidify the aircraft cabin. It includes cabin-supply airflow control, pressure control, temperature control, distribution, recirculation, and air cleaning.

flight: a term used in this guideline to describe the status of the aircraft anytime it is not in contact with the ground. (This definition is not necessarily consistent with the FAA definition of "flight operations.")

flight deck: the portion of the aircraft occupied by the pilots for the purpose of aircraft operation (also referred to as the *cockpit*).

flight management computer: aircraft system that controls navigation. It may also include fuel management and flight planning functions.

ground operations: a term used in this guideline to describe the status of the aircraft anytime it is in contact with the ground and is occupied by at least one crew member.

high-altitude operations: aircraft flight in an outside environment incapable of sustaining human life.

high-performance liquid chromatography (HPLC): a test for determining the different contaminants in a chemical sample and their respective ratios in the sample; in this method, a sample is dissolved in a solvent and analyzed using a chromatograph.

hypoxia: any state in which the oxygen in the lung, blood, and/or tissues is abnormally low compared with that of a normal resting person breathing air at sea level.

nondispersive infrared (NDIR) analysis: a test for determining contaminants in a chemical sample. In this method, a gas sample is analyzed using an infrared spectral detector.

outflow valve: a part of the cabin pressure control system that opens or closes to maintain the cabin pressure.

ozone converter: a part of the environmental control system or air-conditioning system used to reduce the ozone present in the outside air supply to acceptable levels for cabin occupant respiration.

personal airflow outlet (PAO): an adjustable air supply nozzle located at the passenger-seat overhead console or crew station that is individually controlled by the passenger or crew member. It is also commonly known as a *gasper* or an *individual outlet*.

pressure relief valves: valves used to protect the aircraft structure from excessive positive or negative differential pressure.

quick-donning oxygen mask: a supplemental oxygen mask provided to cockpit crew specifically designed to be applied over the nose and mouth very rapidly in case of emergency cabin depressurization.

respirable particulate matter (RPM): liquid and particulate matter suspended in the air that can reach the lower region of the lungs.

supplemental oxygen: oxygen supplied to the passengers and crew to prevent hypoxia.

UV absorption photometry: a test for measuring contaminant levels in an airstream by monitoring absorption of ultraviolet (UV) light by the contaminants.

ventilation: the process of supplying air to or removing it from a space for the purpose of controlling air contaminant levels, cabin pressure, humidity, airflow patterns, and temperature within the space.

volumetric airflow: the volume of air that flows through a space in a given amount of time.

4. CONVERSION FACTORS

4.1 Contaminant Concentrations. The concentrations of gaseous contaminants are often expressed in terms of volume fractions, mole fractions, and mass densities. Numerically, volume fractions and mole fractions are identical for ideal gases. The gases in aircraft cabins behave as ideal gases. Volume or mole fractions are normally expressed as parts per million (ppm), and mass densities are normally expressed as micrograms per cubic metre (μg/m^3). Although it is customary to convert between these two forms of expression using standard conditions of 77°F (25°C) and one atmosphere (1 atm) of pressure, 14.696 psi (101.33 kPa), for some aircraft types, the cabin altitude can be as high as 8000 ft (2440 m), resulting in cabin pressure as low as 0.74 atm, or 10.91 psi (75.2 kPa). Consequently, the conversion between volume or mole fraction and mass density depends on cabin pressure.

TABLE 4.1.1 Conversion Factors for Concentration Calculations

Cabin Altitude,		Cabin Pressure,			1000 *P/RT*,
ft	m	atm	psi	kPa	mol/m^3
0	0	1.0	14.696	101.33	40.9
1000	305	0.965	14.175	97.74	39.4
2000	610	0.930	13.664	94.21	38.0
3000	914	0.896	13.173	90.83	36.6
4000	1219	0.863	12.682	87.44	35.3
5000	1524	0.832	12.230	84.33	34.0
6000	1829	0.801	11.778	81.21	32.8
7000	2134	0.772	11.341	78.20	31.6
8000	2438	0.743	10.914	75.25	30.4
9000	2743	0.715	10.506	72.44	29.2
10,000	3048	0.688	10.108	69.70	28.1

The relationship between volume or mole fraction and mass density for a contaminant in air is expressed by the following equations:

$$C_i = [D_i / M_i] / [1000P / (RT)] \quad (4\text{-}1)$$

or

$$D_i = C_i M_i [1000P / (RT)] \quad (4\text{-}2)$$

where

C_i = volume or mole fraction of contaminant *i* in the air, ppm
D_i = mass density of contaminant *i* in the air, μg/m^3
M_i = molecular weight of contaminant *i*, kg/kmol
P = pressure of the air in the cabin, kPa
R = universal gas constant, 8314 J/kmol·K
T = absolute temperature of the air, K

Equations 4-1 and 4-2 are accurate if the concentration of the contaminant is small (i.e., $C < 10{,}000$ ppm). Table 4.1.1 presents the value of the term 1000 $P/(RT)$ at 77°F (25°C) for various cabin altitudes or cabin pressures.

The conversion factors between volume or mole fraction and mass density presented in Table 4.1.1 describe only the physical equivalents for the two expressions of concentration at a given cabin pressure. They do not describe the equivalence of concentrations at different cabin pressures in terms of the impact on the occupants.

TABLE 4.2.1 Conversion Factors for Concentration Calculations

Cabin Altitude,		Pressure,	Conversion Factor,	
ft	m	atm	cfm/(lb_m/min)	(L/s)/(kg/min)
0	0	1.0	13.53	14.07
1000	305	0.965	14.02	14.58
2000	610	0.930	14.54	15.13
3000	914	0.896	15.10	15.71
4000	1219	0.863	15.67	16.31
5000	1524	0.832	16.26	16.92
6000	1829	0.801	16.89	17.57
7000	2134	0.772	17.52	18.23
8000	2438	0.743	18.20	18.94
9000	2743	0.715	18.92	19.68
10,000	3048	0.688	19.67	20.46

Two example calculations follow.

Example 1: Carbon monoxide is present at the concentration of 10,000 μg/m^3 and the cabin altitude is 6000 ft. The volume concentration is then calculated as follows:

$$C_{CO} = [10{,}000 / 28.011] / 32.8 = 10.9 \text{ ppm}$$

where 28.011 is the molecular weight of carbon monoxide and 32.8 is from Table 4.1.1.

Example 2: Sulfur dioxide is present at a concentration of 0.15 ppm and the cabin altitude is 8000 ft. The mass concentration is then calculated as follows:

$$D_{SO2} = 0.15 \times 64.06 \times 30.4 = 292 \text{ μg/m}^3$$

where 64.06 is the molecular weight of sulfur dioxide and 30.4 is from Table 4.1.1.

4.2 Airflow Rates. Airflow rates may be expressed in terms of volume flow rates or in terms of mass flow rates, cfm (L/s) or lbm/min (kg/min). The relationship between the volume flow rate and the mass flow rate depends on the density of the air, which in turn depends on the pressure and temperature of the air. Table 4.2.1 presents the conversion factors between volume and mass flow rates for air at 77°F (25°C) at various cabin altitudes.

The conversion factors in Table 4.2.1 are valid for dry air, 0% relative humidity (RH). Humidity in the air increases the conversion factors slightly, with a maximum increase of about 3% at 100% RH.

Two example calculations follow:

Example 1: An airflow of 0.55 lb_m/min at a cabin altitude of 8000 ft is as follows:

$$0.55 \times 18.20 = 10.0 \text{ cfm}$$

Example 2: An airflow of 5.0 L/s with a sea level (0 ft) cabin altitude is as follows:

$$5.0 / 14.07 = 0.36 \text{ kg/min}$$

Volumetric airflows are also sometimes expressed as a sea-level equivalent. The sea-level equivalent flow is the volume flow rate at sea level that would be required to generate the same mass flow as the flow in question. Two example calculations follow.

A flow rate of 7.5 cfm sea level equivalent is, at a cabin altitude of 6000 ft, a volume flow rate of

$$7.5 \times 16.89 / 13.53 = 9.4 \text{ cfm}$$

The sea-level equivalent of a flow rate of 10.0 cfm at a cabin altitude of 8000 ft is

$$10.0 \times 13.53 / 18.20 = 7.5 \text{ cfm}$$

5. SYSTEMS AND EQUIPMENT

While ASHRAE Standard 161 (ASHRAE 2007) is intended to be independent of specific aircraft systems and equipment, a basic understanding of typical aircraft environmental control systems is essential in applying the standard. The systems and equipment described in this section are typical but not universal. There are considerable variations between aircraft makes and models. More detailed descriptions may be found in the *ASHRAE Handbook—HVAC Applications* (ASHRAE 2011).

In flight at typical cruise altitudes, an aircraft flies in an outside environment that is hostile to human survival. The outside temperature may be –60°F (–50°C) or colder, and the atmospheric pressure may be less than 0.25 atm. Human survival in these conditions is measured in minutes. To protect against these conditions, the environmental control system (ECS) has two critical functions in flight: to pressurize the cabin and to control the thermal environment at conditions appropriate for human occupation. In addition, the ECS must ventilate the cabin and control contaminant concentrations to acceptable levels.

Pressurization is not required on the ground, but the other functions remain. Appropriately conditioned ventilation air is available from ground-based systems at many airports. However, these ground sources are not always available, and the aircraft ECS must be able to provide the necessary thermal conditions and ventilation on the ground at any location where the aircraft operates. Many commercial aircraft are required to be able to operate throughout the world, from polar to equatorial regions and from desert to rain-forest regions.

The aircraft fuselage, along with bulkheads at the front and rear, forms an essentially airtight vessel that is pressurized during flight. Any outside air supplied to the cabin in flight must first be pressurized. Thus, all outside ventilation air must be compressed to the required pressure. The amount of air supplied to the aircraft is the greater of the amount needed for ventilation or the amount needed to maintain pressurization. The source of air for aircraft pressurization and ventilation for

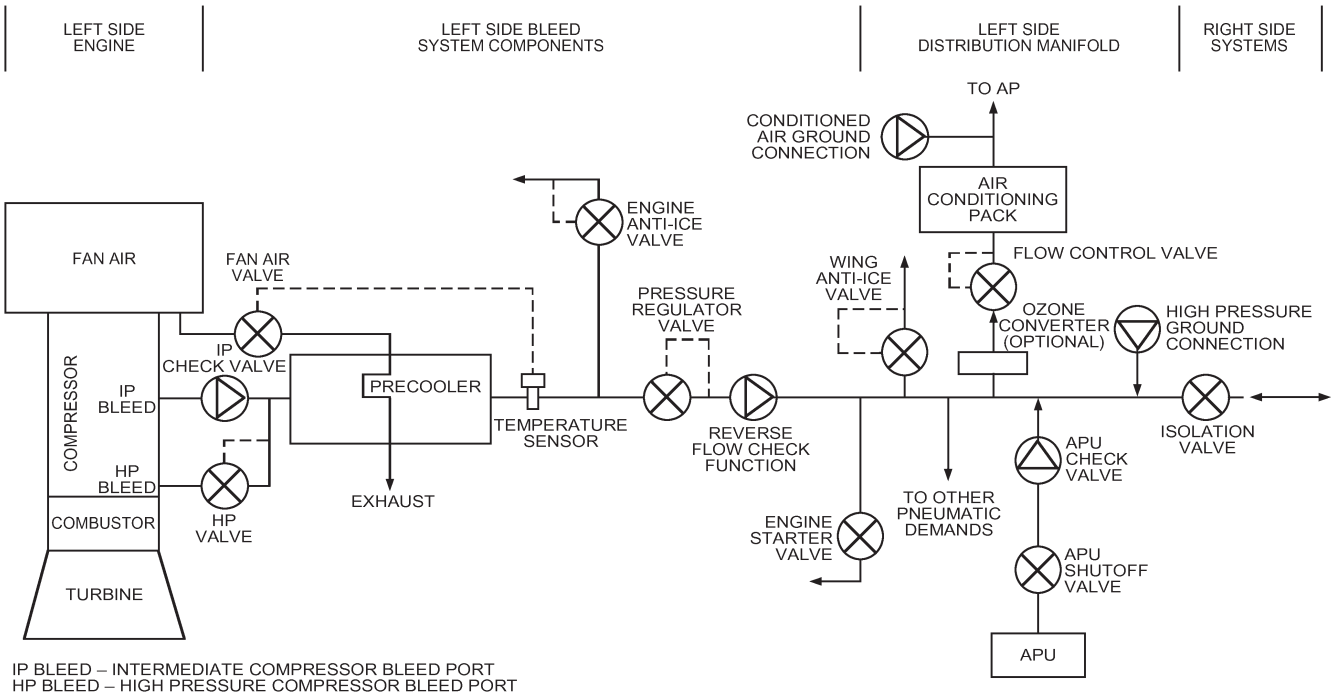

Figure 5-1 Bleed air system (SAE 2007c).

most aircraft is bleed air extracted from the aircraft engine compressors. Figure 5-1 shows a simplified diagram of a bleed-air supply system. The bleed air is used for several functions on the aircraft in addition to supplying the ECS. The bleed air coming from the engine compressor is hot, typically 340°F to 660°F (170°C to 350°C), and pressurized at between 2 to 10 atm of pressure. This air is cooled by ambient air to a maximum of about 350°F (175°C) before it is supplied to the ECS.

The bleed air is further cooled in an air-conditioning pack before it is supplied to the aircraft cabin. Figure 5-2 shows a simplified diagram of a typical modern air-conditioning pack. The pack utilizes rotating air-cycle machinery to cool the bleed air. The motive power for operating the air-cycle machinery is the pressurized bleed air supplied to it. At typical cruise altitudes, it may be possible to cool the bleed air sufficiently with ambient air, and so the bleed air may bypass the rotating machinery. In warm environments on the ground or at low altitudes, the air-cycle system is required to adequately cool the air supplied to the cabin. Reliability, light weight, and compactness are critical considerations in air-conditioning pack design.

The air coming out of the pack can be quite cold, even below freezing. To provide air at a suitable temperature to be supplied to the cabin, this cold air is mixed with recirculated air from the cabin in the mix manifold as shown in Figure 5-2. The total supply airflow, recirculated air plus conditioned bleed (outside) air, must be sufficient to provide adequate air distribution and circulation in the cabin. Trim air, which is bleed air that bypasses the air-conditioning pack, is mixed with the supply air for fine temperature control in each temperature control zone. Most commercial aircraft have two or more air-conditioning packs that connect to a single mix manifold supplying the entire aircraft.

Supply air from the mix manifold is introduced into the cabin through linear diffusers that typically run the full length of the cabin. The dominant circulation pattern in the cabin is perpendicular to the longitudinal axis of the aircraft, as shown in Figure 5-3. Air exits the cabin through exhaust ports in the cabin side wall just above the floor. This air coming from the cabin may circulate in the spaces above the cabin ceiling and below the cabin floor, but not the cargo hold. Recirculation fans pull a portion of this air through filters and supply it to the mix manifold as shown in Figure 5-2. The remainder is exhausted overboard through the outflow valve. The outflow valve controls aircraft pressurization by regulating the amount of air flowing overboard.

Air extracted from the lavatories and galleys is ducted directly to the outflow valve so that it does not mix with the recirculation air.

When conditioned air from ground sources is supplied to the aircraft, it is supplied through a connection to the mix manifold. At some locations, high-pressure air, analogous to bleed air, is supplied on the ground. In this case, the ground source air supply connects ahead of the air-conditioning pack and is cooled, if necessary, by the air-conditioning pack before it is supplied to the aircraft.

Commercial aircraft are also equipped with an auxiliary power unit (APU). The APU is a small gas turbine unit that provides electrical power and hot compressed air, similar to bleed air, to the aircraft when the engines are not operating. The APU allows operation of the aircraft ECS on the ground when ground sources of air are not available. Hot, compressed air from the APU is supplied to the air-conditioning packs, and

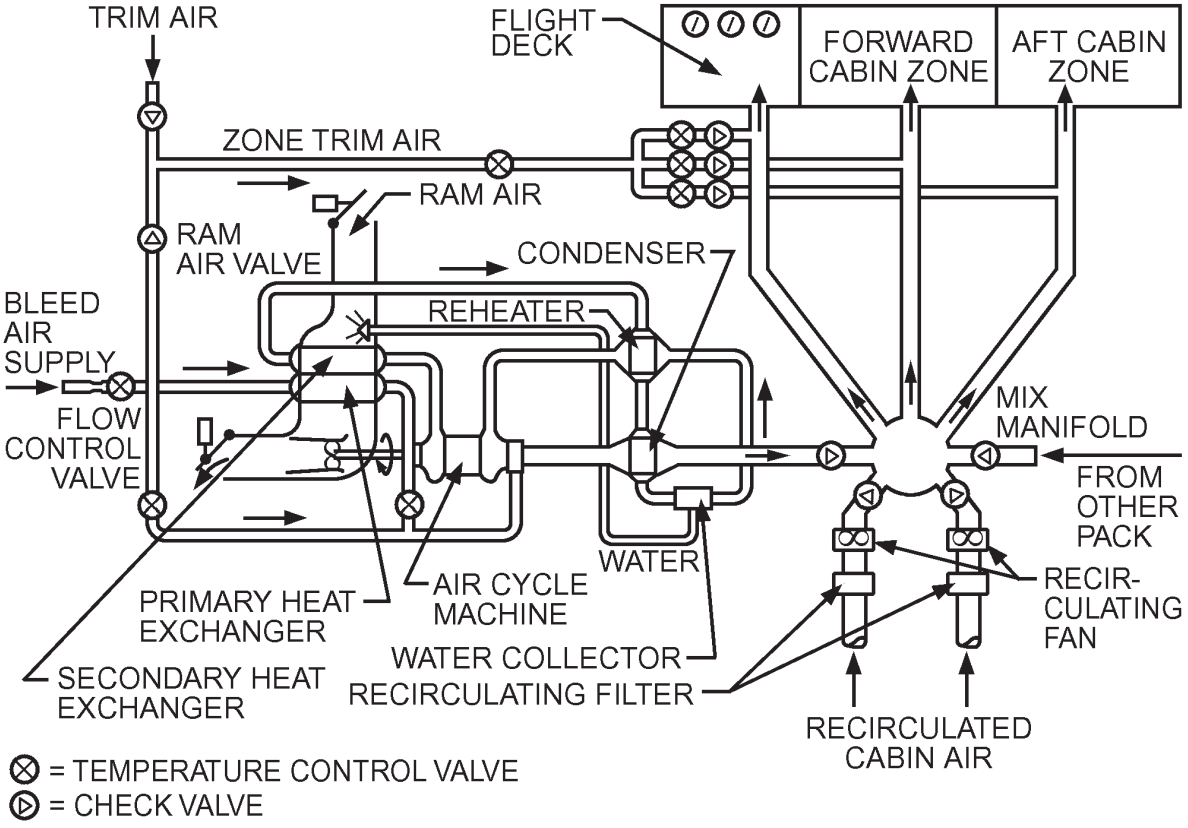

Figure 5-2 Air-conditioning pack and air distribution (ASHRAE 2011).

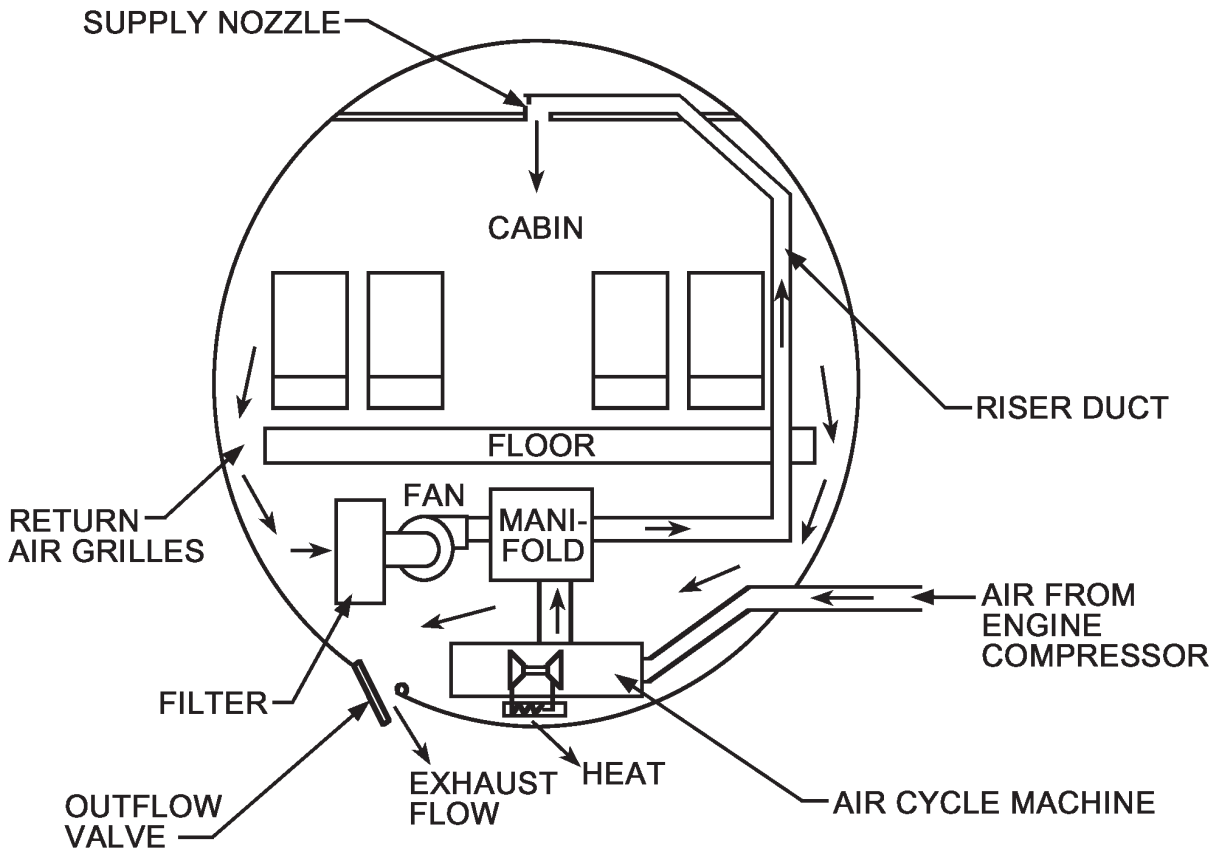

Figure 5-3 Air circulation in the aircraft cabin (ASHRAE 2011).

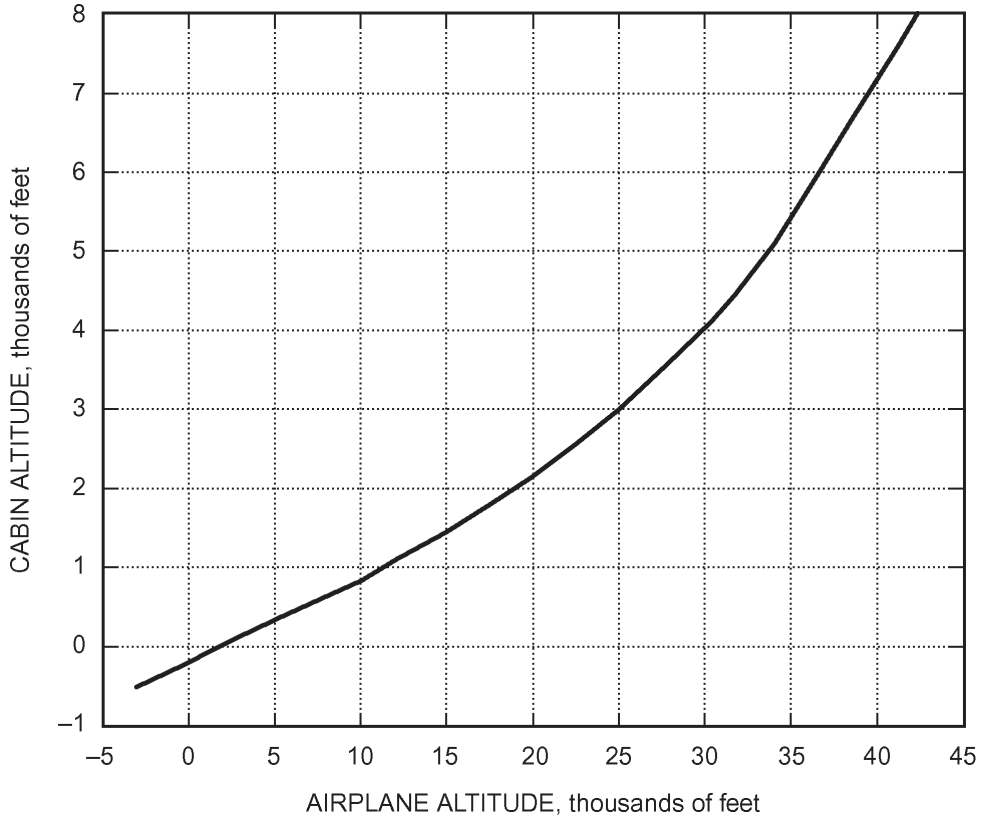

Figure 6-1 Typical aircraft cabin pressure schedule (Hunt et al. 1995).

they work in the same manner as when supplied with bleed air from the engines.

One aircraft design uses electrically driven compressors to provide compressed outside air to power the air-conditioning packs in lieu of bleed air from the engines or APU.

6. CABIN PRESSURE

Aircraft cabins are pressurized to allow the occupants to breathe normally without the need for supplemental oxygen. While the aircraft outside environment varies from near sea-level barometric pressure to extreme low pressure at cruise altitudes such as 43,000 ft (13,000 m), the cabin must be pressurized to levels that provide sufficient oxygen partial pressure to sustain normal body function. Maintaining cabin pressure at ground-level pressure is impractical because of aircraft fuselage structural design requirements that are a function of cabin-to-ambient differential pressure. Therefore, the cabin is controlled to a pressure lower than ground pressure (see Figure 6-1).

Cabin pressure is normally expressed in terms of the equivalent cabin altitude. During the aircraft certification process, manufacturers must demonstrate that the cabin pressure altitude do not exceed 8000 ft (2440 m) under normal operating conditions. This requirement is stipulated as an airworthiness requirement in U.S. Federal Aviation Regulation 14 CFR 25.841(a). An aircraft is designed to realize the 8000 ft (2440 m) cabin pressure altitude when operated at its maximum certified cruise altitude. At 8000 ft (2440 m), the partial pressure of oxygen is 4.6 in. Hg (118 mm Hg) (74% of the 6.3 in. Hg [160 mm Hg] available at sea level). This 8000 ft (2440 m) design standard for cabin altitude was first issued in 1957 by the U.S. Civil Aeronautical Board (CAB 1957) and recodified as 14 CFR Part 25 Section 841.a in November 3, 1964). However, no regulatory authority has issued an explicit operating standard for cabin altitude. The cabin pressure control system, however, and corresponding cabin altitude control schedule must be certified by the Federal Aviation Administration (FAA) prior to airplane service.

The flight altitude schedule (i.e., the change in flight altitude as a function of flight time) depends on the size of the aircraft and the duration of the flight. For example, wide-body aircraft on longer flights gain altitude according to a step progression, flying highest towards the end of each flight after consuming the majority of their heavy fuel load. Typically, wide-body long-duration flights fly with a cabin altitude in the 5500 to 7000 ft range, only reaching the higher cabin altitude at the end of the flight after fuel has been burned off. In contrast, narrow-body and commuter aircraft are typically operated at or near their maximum flight altitude, resulting in a cabin altitude in the range of 7000 to 8000 ft for a greater proportion of their flight, although the flight is typically much shorter than for wide-body aircraft. Additional factors are weather, quantity of remaining fuel, pilot judgment, and airline policy. A typical short-duration flight profile and corresponding cabin pressure profile is provided in Figure 6-2.

At lower cruise altitudes, the systems are designed to maintain a lower cabin pressure altitude, based on the

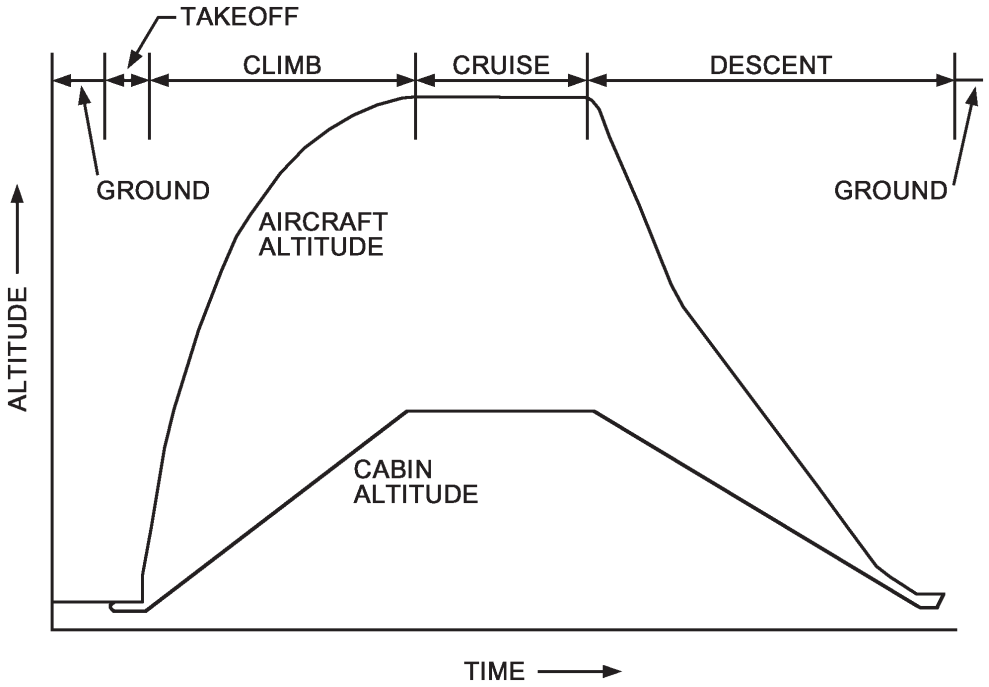

Figure 6-2 Typical aircraft cabin pressure schedule (SAE 2006c).

controlled differential pressure between the pressurized cabin and the ambient air under normal operating conditions. There are some normal operating conditions, such as landing at an airport greater than 8000 ft (2440 m) altitude, where the cabin pressure altitude will be higher.

This section of the guideline provides background information on cabin pressurization, technical aspects of the aircraft pressurization systems, related occupant health considerations, including hypoxia and ear discomfort, and relative humidity.

6.1 Cabin Pressurization—Background. It is necessary to pressurize the cabin and flight deck because, during typical flights, the partial pressure of oxygen in the ambient outside air is too low to support life. The introduction of compressed air into the aircraft cabin ensures that the internal cabin pressure (and the corresponding partial pressure of oxygen) is substantially higher than the outside air pressure at flight altitude.

Typically, manufacturers calculate and publish curves that define the necessary inflow of outside air, as a function of flight altitude, to maintain a cabin altitude less than 8000 ft (2440 m) at the maximum flight altitude, both for new aircraft with tight door and window seals and for older aircraft with anticipated seal wear. If a new aircraft is operated below its maximum certified altitude, the cabin altitude should not reach 8000 ft (2440 m) under normal operating conditions (assuming the departure and arrival airports are below 8000 ft). However, if an air-conditioning system malfunction results in reduced cabin air inflow that does not maintain the scheduled cabin pressure, then the cabin altitude can exceed 8000 ft (2440 m). The cabin altitude can also exceed 8000 ft (2440 m) if an aircraft develops unusually high external leakage that exceeds the cabin air inflow, or if an aircraft is operated above its maximum certified altitude.

The 8000 ft (2440 m) design standard for cabin altitude and the desired maximum flight altitude define the required cabin-to-ambient differential pressure that the manufacturer must design the aircraft skin to withstand under normal operating conditions for the anticipated number of pressure cycles during the lifetime of the aircraft. On commercial aircraft, the cabin-to-ambient differential pressure is typically between 7 to 9 psi (48 to 62 kPa), depending on the maximum flight altitude for which that the aircraft is designed. The aircraft model is certified for this maximum flight altitude (e.g., see aircraft-specific U.S. FAA Type Certificate Data Sheets), and this limit is incorporated into the flight operations manual.

A typical cabin-to-ambient differential pressure schedule design for commercial aircraft is provided in Figure 5-1. Increasing the cabin-to-ambient differential pressure may impose a weight penalty because of necessary structural additions, or it may reduce the number of pressure cycles allowable over the life of the aircraft. One benefit of increasing the cabin-to-ambient differential pressure is that the design cabin altitude can be reduced for added cabin comfort. Many business jets, for example, are designed with a pressure differential across the skin that provides a cabin altitude of 6000 to 6500 ft (1830 to 2130 m). This is achieved by having a smaller fuselage, with stress being a function of the radius of the fuselage and the lower number of flight cycles. The use of different materials may also reduce fatigue and allow a reduced cabin pressure.

Aviation authorities have established rules for the use of supplemental oxygen for in-flight first aid, high-altitude operations, and emergency cabin depressurizations. According to the FAA, when an aircraft is operated between 25,000 ft

(7620 m) and 41,000 ft (12,500 m), each pilot must have ready access to a quick-donning oxygen mask. When operated above 41,000 ft (12,500 m), or when alone in the flight deck above 25,000 ft (12,500 m), a pilot must wear an oxygen mask at all times. When operated above 25,000 ft (12,500 m), flight attendants must have ready access to masks distributed throughout the cabin, and passengers must be briefed in advance on how to use the oxygen masks. In the event of an emergency depressurization, the flight crew must don their oxygen masks when the cabin altitude reaches 10,000 ft (3050 m). The masks in the cabin must be deployed when the cabin altitude reaches 14,000 ft (4270 m), and the flow of oxygen through these masks must be maintained until the aircraft has safely descended to an altitude of 10,000 ft (3050 m) or less.

6.2 Cabin Pressurization—Technology. Modulating the airflow discharged from the pressurized cabin through one or more cabin outflow valves controls cabin pressure. The cabin pressure control system includes the outflow valves, controller, selector panel, and positive-pressure relief valves. Provisions for negative pressure relief are incorporated in the relief valves and/or included in the aircraft structure (door). The system controls the cabin ascent and descent rates to acceptable comfort levels and maintains cabin pressure altitude in accordance with cabin-to-ambient differential pressure schedules. Modern systems require minimal input from flight crew and provide maximum comfort by monitoring aircraft flight via the flight management system and the air-data computer to minimize the cabin pressure altitude and rate of change.

The cabin pressure control system outflow valves (cabin pressure modulating valves) and safety valves (positive pressure relief valves) are located either on the aircraft skin (in the case of large commercial aircraft) or on the fuselage pressure bulkhead (in the case of commuter, business, and military aircraft). Locating the outflow valves on the aircraft skin precludes the handling of large airflow in the unpressurized tailcone or nose areas and provides some thrust recovery; however, these double gate valves are more complex than the butterfly valves or poppet-type valves used for bulkhead installations. The safety valves are poppet-type valves for either installation. Most modern commercial aircraft systems use electronic controllers that are located in the electronic equipment bay. The cabin pressure selector panel is located in the flight deck.

The automatic scheduling of the cabin pressure during flight uses available information from other aircraft systems, such as the air data and flight management computers. Some or all of the following information may be available: ambient pressure, planned cruise altitude, planned landing field altitude, estimated time to climb, and estimated time to descend. Using this information, the cabin pressure is optimally scheduled to provide the lowest cabin altitude and lowest rates of change consistent with the flight profile, while avoiding the risk of over- or underpressurization. In the event that some or all of the above information is unavailable, or unexpected changes occur during the flight, alternate reconfiguration logic must be available to reschedule the cabin pressure.

Critical parameters are displayed in order to inform the flight crew of the operational status of the system, including cabin altitude, cabin altitude rate of change, cabin-to-ambient differential pressure, and outflow valve position. They can be displayed either by separate analog instruments or, in modern aircraft, by the "glass flight deck" display.

The following safety functions are provided and are independent of the basic control functions:

1. Overpressure relief can be provided by independent overpressure relief valves that can handle the maximum cabin inflow. Typically these are pneumatically self-powered poppet-type valves.
2. A reverse or negative pressure relief function is also provided by an independent valve that can provide enough inflow to prevent the cabin negative pressure from exceeding its specified value with no cabin inflow at a given aircraft descent rate and altitude.
3. Automated pressure scheduling and control algorithms contain safety algorithms to prevent, for example, a runaway valve from depressurizing the cabin.
4. Manual control can be provided as a final override to allow the crew to directly position the outflow valve(s).

6.3 Cabin Pressurization—Occupant Health Considerations

6.3.1 Hypoxia. As altitude increases, the ambient air pressure and corresponding partial pressure of oxygen decrease (see Figure 6-3). At 6000 ft (1830 m), for example, the partial pressure of oxygen is 5.0 in. Hg (128 mm Hg) (80% of 6.3 in. Hg [160 mm Hg] at sea level) compared to 4.6 in. Hg (118 mm Hg) (74% of 6.3 in. Hg [160 mm Hg] at sea level) at 8000 ft (2440 m).

Hypoxia is a condition in which insufficient oxygen is present in the blood to meet the needs of the body's systems—that is, demand for oxygen is greater than the supply. The symptoms and prognosis of hypoxia are a function of the extent and duration of oxygen deprivation. Impaired night vision, prolonged reaction time for novel tasks, fatigue, and impaired judgment are classic signs of hypoxia. Other symptoms can be mild (e.g., headache, nausea, light-headedness) or more serious (e.g., numbness, euphoria, fainting).

Hypoxia can contribute to abnormal heartbeat (ventricular or atrial fibrillation) and can trigger or exacerbate lymphedema.

Within a limited range, the body compensates for an increased demand by increasing the breathing rate and depth of breathing. For example, the job duties of a flight attendant that require physical exertion (e.g., pushing a 230 lb [105 kg] cart up an incline, walking, bending, and carrying) increases oxygen demand and respiration rate (see Section 6.4). Similarly, the respiration rate of infants and pregnant women are elevated.

There are two physiological measures to assess the body's oxygen supply: (1) the partial pressure of oxygen at the interface between the lungs and the blood (called *alveolar partial pressure*) and (2) the percentage of hemoglobin—the molecule in the red blood cells that transports oxygen to the

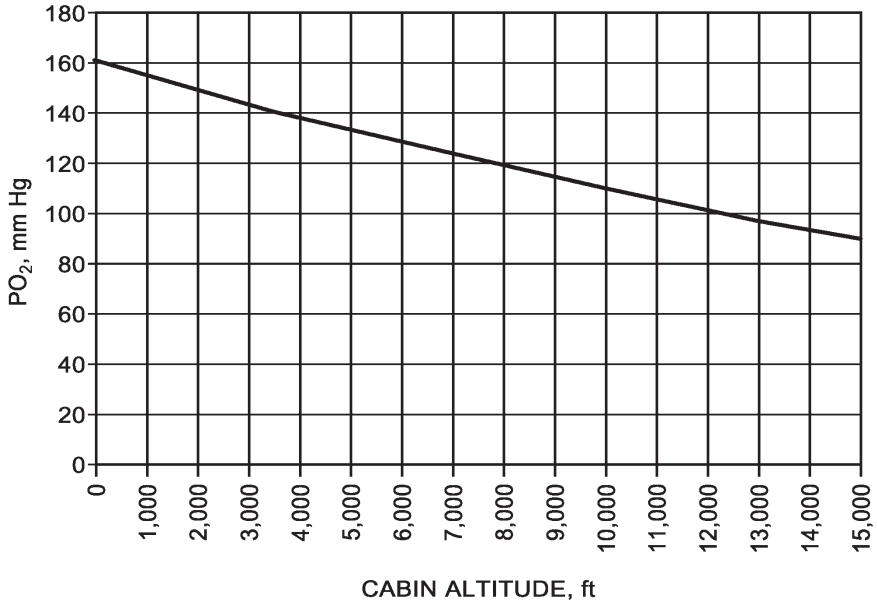

Figure 6-3 Partial pressure of oxygen as a function of altitude above sea level (DeHart 1985, Table 5-10 data).

tissues—that is saturated with oxygen (called blood oxygen saturation).

The alveolar partial pressure of oxygen is primarily a function of available oxygen but cannot be predicted precisely because it varies according to respiration rate, pulmonary disease, and age. Limited data are available in the literature as a function of altitude, but historically, they primarily reflect the physical characteristics of young military men.

Blood oxygen saturation (SaO_2) is primarily a function of the alveolar partial pressure of oxygen but cannot be predicted precisely because many factors can reduce the efficacy of the blood oxygen transport system, thereby increasing the onset and severity of hypoxia. Figure 6-4 illustrates the relationship between blood oxygen saturation and altitude for a young, healthy individual. The shape of the curve illustrates the rapid drop in blood oxygen saturation above 10,000 ft (3050 m) and the sensitivity of the blood transport system between 8000 ft (2440 m) and 10,000 ft (3050 m). Pulmonary disease, cardiovascular disease, anemia, pregnancy, young or advanced age, smoking, and consumption of alcohol or certain medications can facilitate a leftward shift of the curve in Figure 6-4, reducing the altitude tolerances of the oxygen transport system. To this end, when the 8000 ft (2440 m) design limit was introduced in 1957, it was recognized as the altitude that "corresponded with the maximal acceptable degree of hypoxia in passenger aircraft" based on studies of sedentary pilots in the 1940s (NRC 2002). Further, it was recommended that "under routine operating conditions, cabin pressure altitude should not exceed 5000 to 6000 ft."

Operating with a cabin altitude at or below 6000 ft (1830 m) instead of 8000 ft (2440 m), for example, would increase operating costs as well as oxygen levels because it would require the following measures: (1) structural changes to new and current aircraft to increase the cabin-to-ambient pressure differential tolerated across the skin, (2) operation of the current fleet below their maximum certified flight altitudes, (3) reduced aircraft design life, or (4) some combination thereof.

6.3.2 Ear Discomfort. Since the human ear is very sensitive to large changes in pressure, the rate of cabin pressure change must be closely controlled. Small changes in cabin pressure can be made at any rate without causing ear discomfort, but as the amplitude of the change increases, the rate of change becomes more important. The current regulatory threshold for rate control is a change in cabin pressure of 0.132 psi (0.91 kPa). This is equivalent to 250 ft (76 m) at sea level. The cabin pressure rate of change can be expressed as psi/min (kPa/min) or, in terms of the cabin altitude equivalent, sea level ft/min (sea level m/min), a measure that is expressed as slfpm (slmpm). The generally accepted cabin rates for comfort are 500 slfpm (152 slmpm) for decreasing pressure (increasing altitude), and 300 slfpm (91 slmpm) for increasing pressure (decreasing altitude), as shown in Figure 6-5.

The ear is essentially an air-filled closed cavity that can equalize pressure only when the Eustachian tube is open. Near the middle ear cavity, the Eustachian tube is surrounded by bone and remains open. The membranous tissue at the rear of the nasal passage normally closes the Eustachian tube.

The foremost cause of ear discomfort during pressurized flight is a pressure differential across the eardrum that causes the ear bones to press against the inner ear. The discomfort level as a function of this pressure differential is illustrated in Figure 6-6. The physiological reason for difference in the comfort levels for climb and descent is that air can more easily escape from the inside of the ear through the tiny Eustachian tube than it can enter.

The Eustachian tube opens occasionally by involuntary contraction of the Eustachian tube dilator muscles. This muscle action equalizes pressure across the eardrum. Voluntary opening of the Eustachian tube can be accomplished by swallowing, yawning, or by learned contraction of the dilator

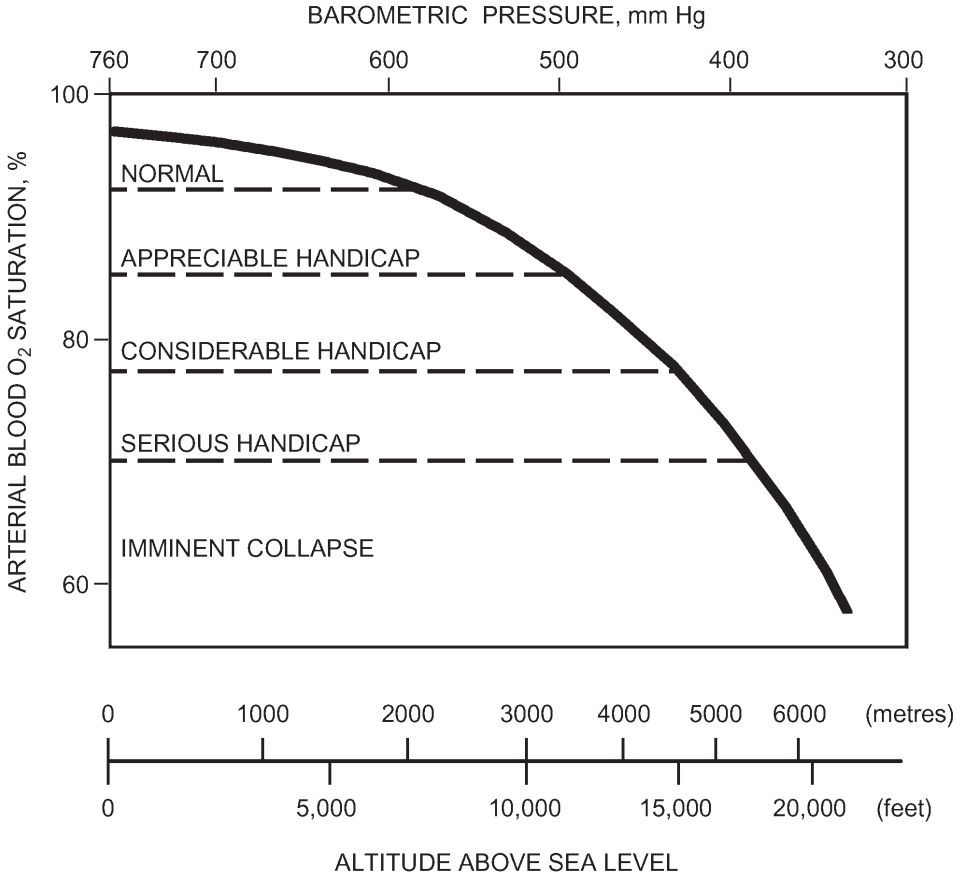

Figure 6-4 Typical arterial blood oxygen saturation of a healthy individual as a function of altitude above sea level (Ganong 1973).

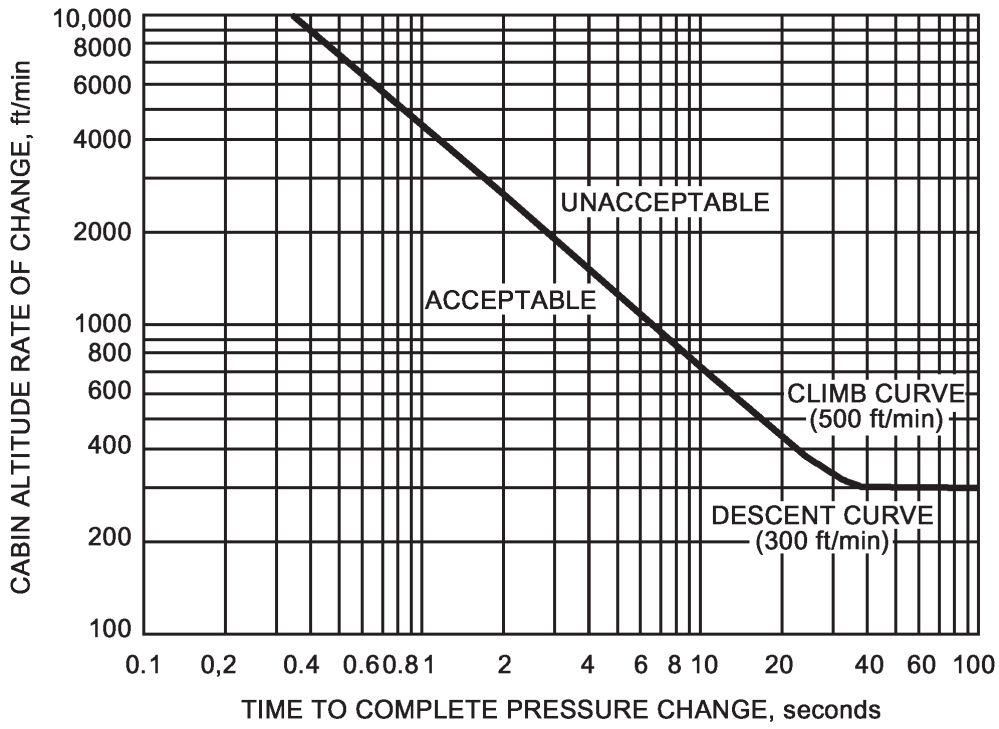

Figure 6-5 Design limits for short duration pressure changes based on the threshold of detection in humans (SAE 2006c).

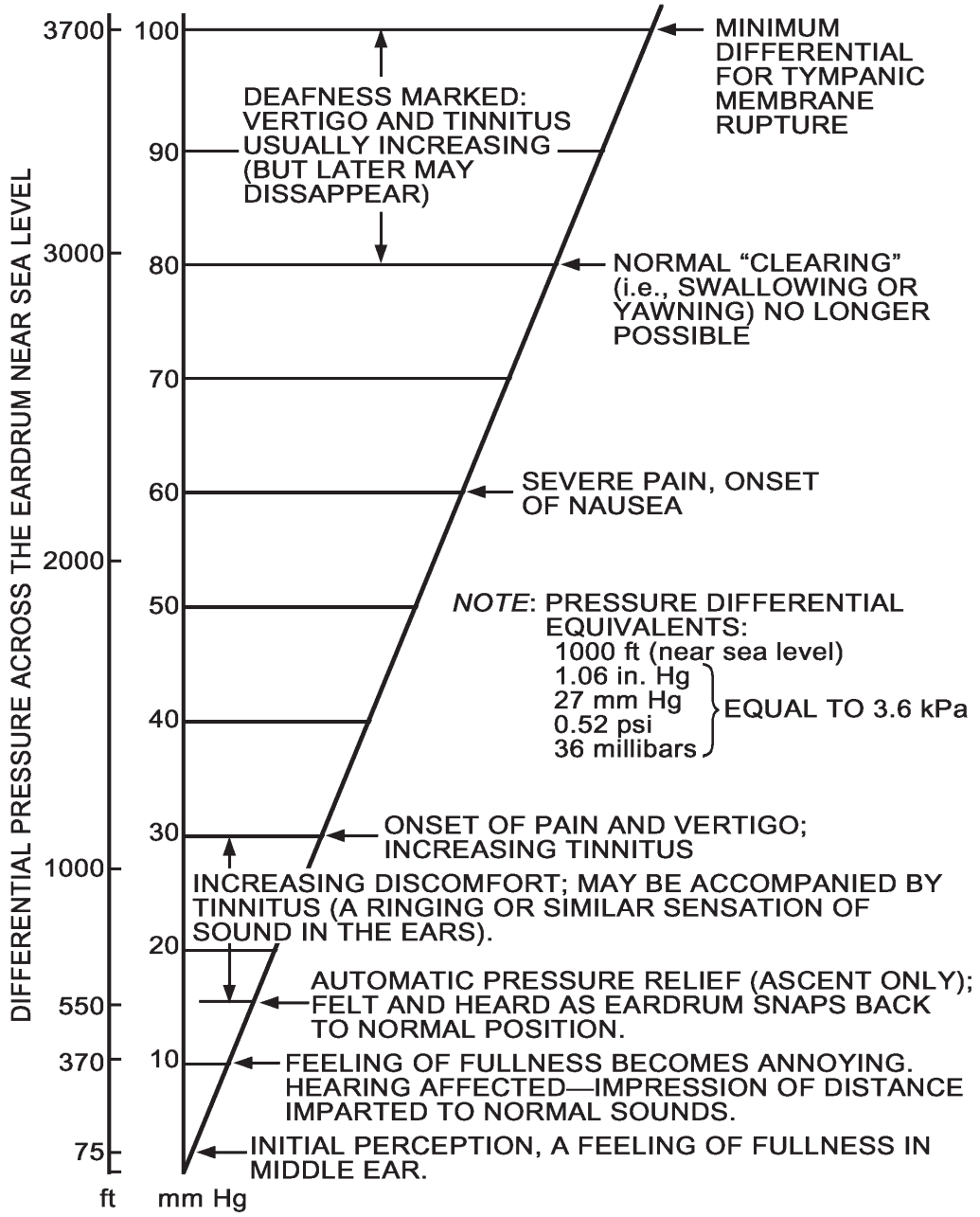

Figure 6-6 Physiological effects of pressure differential on the normal human ear for increasing pressure (SAE 2006c).

muscles. This contraction can be accomplished by suppressing a simulated yawn. A roaring in the ears indicates when the effort is successful.

Commercial airline flights often include passengers who are unable to ventilate the middle ear properly during descent. These are (1) sleeping passengers (swallowing at decreased intervals); (2) children; (3) passengers with colds, sinus congestion, or abnormal ear passages; and/or (4) passengers who are unaware of the techniques for equalization of pressure in the middle ear. The average person swallows involuntarily every 60 to 75 seconds. A rate of climb or descent of 200 slfpm (60 slmpm) usually causes no discomfort; a 500 slfpm (150 slmpm) ascent or a 300 slfpm (90 slmpm) descent causes only slight discomfort even though no effort is made to ventilate the middle ear artificially. However, a passenger with a restricted middle ear passage (such as might occur from a head cold) can experience pain, while the passenger with normal passages would experience no discomfort at these rates of change. A sudden and dramatic reduction in cabin pressure (i.e., rapid decompression) can cause the eardrum to rupture.

6.4 Cabin Pressurization—Altitude Adjustment Based on the Effects of Cabin Altitude on Respiratory Rates. Requirements for altitude adjustment of ventilation minima were considered for inclusion in ASHRAE Standard 161 but in the end were not included. The principles for altitude adjustments are discussed in the following section for background information.

6.4.1 Summary. As an aircraft ascends from sea level to 8000 feet (2440 m), the atmospheric pressure decreases from 29.92 in. Hg (760 mm Hg) to 22.20 in. Hg (564 mm Hg). Correspondingly, the partial pressure of the oxygen in the air drops from 6.26 in. Hg (159 mm Hg) to 4.65 in. Hg (118 mm Hg). Both of these pressure decreases are over 25%. The respiration rate does increase in response to this change but by much lesser amounts; surprisingly, the rate increases by only 5% with 2.0 met and 11% with 1.0 met activity level.

6.4.2 Background. The respiratory rate, V_r, which is an important factor in determining the effective exposure to many contaminants, is defined as the average volume flow rate at which air is inspired. It is the product of the tidal volume and the respiratory frequency. A description of how the respiratory rate responds to altitude follows.

Under current aircraft certification standards, cabin altitudes range from sea level to 8000 ft (2440 m) under normal conditions. A simple model of respiration using published information on respiratory rate regulation that estimates the effects of altitudes in this range is presented in the remainder of this section.

The effect of altitude on respiration rate is a function of the relationship between the oxygen and carbon dioxide partial pressures in the lung and the ambient atmospheric conditions, the metabolic activity level, and the respiration rate.

6.4.3 Mass Flows and Partial Pressures in the Lungs. The amount of air reaching the deep lung is given by

$$V_r' = V_r(1 - f) \tag{6-1}$$

where

V_r' = effective ventilation rate to the deep lungs, cfm (L/min)
V_r = ventilation rate, cfm (L/min)
f = fraction of inspired air that is effectively shunted back out, dimensionless

The oxygen partial pressure of the air entering the deep lung is then

$$P_{O2}' = P_{O2}(P_{atm} - P_{sat})/P_{atm} \tag{6-2}$$

where

P_{O2}' = oxygen partial pressure of the air entering the deep lung, in. Hg (mm Hg)
P_{O2} = oxygen partial pressure of the ambient air if no moisture were present, in. Hg (mm Hg)
P_{atm} = ambient atmospheric pressure, in. Hg (mm Hg)
P_{sat} = water vapor saturation pressure at body temperature, in. Hg (mm Hg)

Since deep body temperature is approximately constant, P_{sat} can be treated as a constant of approximately 1.85 in. Hg (47 mm Hg).

Oxygen consumption, V_{O2}, and carbon dioxide production, V_{CO2}, are normally expressed in terms of the sea-level equivalent volume flows,

$$V_{O2}^* = V_{O2}P_{atm}/P_{atm}^* \tag{6-3}$$

and

$$V_{CO2}^* = V_{CO2}P_{atm}/P_{atm}^* \tag{6-4}$$

where

V_{O2} = volume flow rate of oxygen consumed at actual ambient conditions, cfm (L/min)
V_{CO2} = volume flow rate of carbon dioxide generated at actual ambient conditions, cfm (L/min)
V_{O2}^* = volume flow rate for the same mass of oxygen at sea level pressure, cfm (L/min)
V_{CO2}^* = volume flow rate for the same mass of oxygen at sea level pressure (L/min)
P_{atm} = actual ambient pressure, in. Hg (mm Hg)
P_{atm}^* = atmospheric pressure at sea level, in. Hg (mm Hg)

In the deep lung, the air is considered to be well mixed, and so an oxygen mass balance can be written:

$$V_r'P_{O2}'/RT - V_r'P_{aO2}/RT - V_{O2}P_{atm}/RT = 0 \tag{6-5}$$

where

P_{aO2} = partial pressure in the deep lung, alveolar pressure, in. Hg (mm Hg)
R = universal gas constant, in. Hg ft^3/mol·R (mm Hg m^3/mole·K)
T = absolute temperature, R (K)

Simplifying Equation 6-5 and introducing the relationships in Equations 6-1 through 6-4 yields the following:

$$V_r(1 - f)(P_{O2}(P_{atm} - P_{sat})/P_{atm} - P_{aO2}) = V_{O2}^*P_{atm}^* \tag{6-6}$$

Solving for P_{aO2} yields the following:

$$P_{aO2} = P_{O2}(P_{atm} - P_{sat})/P_{atm} - V_{O2}^*P_{atm}^*/(V_r(1 - f)) \tag{6-7}$$

A similar mass balance can be written for carbon dioxide:

$$V_r'P_{CO2}'/RT - V_r'P_{aCO2}/RT + V_{CO2}P_{atm}/RT = 0 \tag{6-8}$$

where

P_{CO2}' = carbon dioxide partial pressure of the air entering the deep lung, in. Hg (mm Hg)
P_{aCO2} = carbon dioxide partial pressure in the deep lung, alveolar pressure, in. Hg (mm Hg)

The oxygen consumed and the carbon dioxide generated are related according to the respiratory quotient (RQ).

$$RQ = V_{CO2}^*/V_{O2}^* \tag{6-9}$$

Also, the partial pressure of the carbon dioxide in inspired air is generally very close to zero, and the P_{CO2}' term in Equa-

TABLE 6.4.4a Calculation Results for 1.0 met Activity Level

Estimated V_r, L/min	Resulting P_{aO2}, mm Hg	Resulting P_{aCO2}, mm Hg	$V_r P_{aO2}$ (P_{aCO2}), L/min	$V_r P_{aCO2}$ (P_{aO2}), L/min
7.5	58.8	40.0	11.5	11.5
8.0	61.9	37.5	9.0	9.3
8.5	64.5	35.3	7.7	7.8
8.3 (result)	63.5	36.1	8.3	8.4

TABLE 6.4.4b Calculation Results for 2.0 met Activity Level

Estimated V_r, L/min	Resulting P_{aO2}, mm Hg	Resulting P_{aCO2}, mm Hg	$V_r P_{aO2}$ (P_{aCO2}), L/min	$V_r P_{aCO2}$ (P_{aO2}), L/min
15	58.9	45.0	25	20
16	61.9	42.2	14.5	14.3
15.5	60.5	43.5	17.3	17.0
15.7 (result)	61.1	43.0	15.7	15.8

tion 6-8 can be neglected. The carbon dioxide mass balance then reduces to

$$\mathrm{RQ}V_{O2}{}^{*}P_{atm}{}^{*} = (1-f)V_r P_{aCO2} \quad (6\text{-}10)$$

Solving for P_{aCO2} gives

$$P_{aCO2} = P_{atm}{}^{*}\mathrm{RQ}V_{O2}{}^{*}/(V_r(1-f)) \quad (6\text{-}11)$$

If we know the ventilation rate, V_r, the ambient oxygen partial pressure, P_{O2}, the ambient atmospheric pressure, P_{atm}, and the amount of oxygen consumed, V_{O2}*, we can use Equations 6-7 and 6-11 to calculate the partial pressures of oxygen and carbon dioxide in the lungs.

The rate of oxygen consumption is directly related to the metabolic activity level. For a 1.0 met activity level (sedentary), it is approximately 0.010 cfm (0.29 l/min), and for a 2.0 met activity level (moderate activity level) it is double, or 0.020 cfm (0.58 l/min) at sea-level pressure. These two activity levels are representative of passengers and cabin crew, respectively. The short-term activity level of cabin crew may be much higher during certain activities (e.g., pushing a cart uphill from one end of the cabin to the other), and these higher levels may be very important for determining acceptable limits on cabin altitude. For evaluating the respiratory rate as it relates to contaminant exposure, time-averaged respiration rate, and thus time-averaged metabolic rate, is what is important. A 2.0 met activity level should be representative of the activity level of a typical flight attendant on a flight with a sustained, busy, workload.

The ambient oxygen partial pressure can be calculated directly from the total atmospheric pressure:

$$P_{O2} = 0.2095P_{atm} \quad (6\text{-}12)$$

and tables relating P_{atm} to altitude (or cabin altitude) are readily available.

6.4.4 Evaluating the Effect of Altitude. It is necessary to evaluate the parameters RQ and $(1-f)$ for each activity level because they could change with metabolic activity and respiration rate. Equation 6-7 can be used to estimate the value of the bypass fraction, f. Based on data from Ward et. al. (2000), we can expect P_{aO2} to be close to 3.9 in. Hg (100 mHg) at sea level, independent of activity level. The total atmospheric pressure at sea level, P_{atm}, is 29.92 in. Hg (760 mm Hg) and the oxygen partial pressure is 6.26 in. Hg (159 mm Hg). The respiratory rate at sea level for 1.0 met of activity is approximately 0.26 cfm (7.5 L/min) and is 0.53 cfm (15.0 L/min) at 2.0 met.

Substituting into Equation 6-7 for 1.0 met using SI units, we obtain

$$100 = 159(760-47)/760 - 0.29 \times 760/(7.5(1-f))$$

Solving for $(1-f)$ gives

$$(1-f) = 0.598$$

The values for 2.0 met are

$$100 = 159\,(760-47)/760 - 0.58 \times 760/[7.5\,(1-f)]$$

and the result is the same

$$(1-f) = 0.598$$

The term $(1-f)$ may be considered the volumetric efficiency of the lung. While no data are readily available for validation of this calculation, a volumetric efficiency of 60% is certainly a plausible value.

We can now use Equation 6-11 and Table 6.4.4a to evaluate RQ. At sea level, with a 1.0 met activity level, the respiratory rate is 0.26 cfm (7.5 L/min) and the deep-lung oxygen partial pressure is 3.9 in. Hg (100 mm Hg), as discussed previously. From Table 6.4.4b, the P_{aCO2} value needed to generate this respiratory rate with this oxygen partial pressure is 1.6 in.

Hg (40 mm Hg). Substituting into Equation 5-11 using SI units gives

$$40 = 760\ RQ\ 0.29/(7.5 \times 0.598)$$

$$RQ = 0.81$$

With a 2.0 met activity at sea level, the respiratory rate is 0.53 cfm (15 L/min) and the corresponding P_{aCO2} value from Figure 6-7 is 1.8 in. Hg (45 mm Hg). Substituting into Equation 6-11 using SI units gives

$$45 = 760\ RQ\ 0.58/(15 \times 0.598)$$

$$RQ = 0.91$$

These values are right in line with values that would be expected for these activity levels (ASHRAE 2009), which supports the assumption that the equations and control functions are accurate.

For simplicity, the altitude adjustment calculations are performed only for a cabin altitude of 8000 ft (2440 m) at the two metabolic activity levels. The trial-and-error solution procedure is as follows. First, an estimate is made for the value of the resulting respiratory rate. Next, the values of P_{aO2} and P_{aCO2} are calculated using this respiratory rate. Then, the respiratory rate that results from Tables 6.4.4a and 6.4.4b using the above values of P_{aO2} and P_{aCO2} are determined. If these values are greater than the estimated value, then the estimated rate is too low, and if the values are lower than the estimated value, then the estimated rate is too high. The estimate is then adjusted based on these results and the process is repeated until there is negligible difference between the estimated respiration rate and the two values indicated by the chart.

Table 6.4.4a shows the results of the trial-and-error calculations for the 1.0 met activity level, and Table 6.4.4b contains the results for the 2.0 met activity level. The respiration rate increases from 0.26 cfm to 0.29 cfm (7.5 l/min to 8.3 l/m) for 1.0 met activity when going from sea level to a cabin altitude of 8000 ft (2440 m), an 11% increase. The respiration rate increases from 0.53 cfm to 0.55 cfm (15.0 l/min to 15.7 l/min) for the same altitude change with the 2.0 met activity, a 5% increase.

7. TEMPERATURE AND RELATIVE HUMIDITY

7.1 Temperature. During ground operations, additional capacity for cooling and heating may be necessary to effectively manage heat loads that are less predictable and more variable than those which occur in-flight. These include

- supply air temperature and humidity that vary according to destination and season;
- heat absorbed by the fuselage while sitting on a hot tarmac, especially in the sun; and
- open doors that introduce the ambient air into sections of the cabin.

It may also be necessary to provide additional cooling during ground operations to counter the anticipated increase in occupants' metabolic rate as they move through the cabin and stow or retrieve their luggage. In effect, the upper and lower limits of the acceptable in-flight temperature range typically shift downward during ground operations. Another consideration for ground operations is that it may not be feasible to maintain a narrow range of temperature within the vicinity of an open door if conditions outside that door are much hotter or colder than the acceptable temperature range in the cabin or flight deck.

During flight operations, occupants have reported thermal dissatisfaction as follows: (1) cold drafts at ankle level when working in galleys or cold drafts when sitting adjacent to one or more doors; (2) stagnant, warm air in the upper section of the galleys, especially when ovens are operating; and (3) highly variable temperatures either between or within zones on some aircraft types.

The temperature recommendations for aircraft in this guideline are intended to mirror those established in ASHRAE Standard 55 (2010), with some necessary aircraft-specific modification. The corresponding comfort criteria defined in Section 5.2.1.1 of Standard 55 are intended to satisfy at least 80% of occupants with an activity level described as "light, primarily sedentary." This activity level is consistent with that of passengers during a flight but not with that of passengers during boarding and deplaning, and that of cabin crew throughout much of the flight.

Standard 55 does not explicitly recognize that it may be necessary to apply different operative temperature limits during a given occupancy. Presumably, RH and activity level are expected to be relatively constant in a building environment, but on aircraft, activity levels and ambient RH changes considerably during a flight cycle—the former as a function of flight phase and occupant type and the latter as a function of flight phase (boarding/deplaning versus cruise) and ambient environmental conditions (ground versus flight). To this end, aircraft requirements must define different acceptable ranges of operative temperatures according to the flight phase (e.g., boarding/deplaning versus in-flight). Also, installing operational personal airflow outlets (PAOs) in flight attendant work areas help to accommodate the increased activity level of the cabin crew throughout the flight by providing some control over the crew's thermal environment.

On aircraft, consistent with Standard 55, it is necessary to address the vertical and horizontal temperature differentials that are created by radiant cooling and heating as well as from cooled air that can leak from "sweeping" door seals during a flight. The maximum allowable airspeed in Standard 55 depends on turbulence intensity and is only defined for the comfort temperature range. Anecdotally, the temperature of the air in the vicinity of the doors is below the lower temperature limit defined in Standard 55 (68°F), so the maximum mean air speed for comfort can only be estimated and depends on the turbulence intensity. To ensure that the adjacent areas are within the acceptable range of operative temperatures, a means to heat the ambient air (e.g., a door heater at floor level) is likely necessary. Similarly, the provision of personal control nozzles in galleys should control the discomfort caused by radiant heat sources, such as oven doors.

TABLE 8.1.1 Subset of Contaminants that Could Be Present in the Aircraft Cabin Environment

Contaminant or Group of Contaminants	Possible Sources*	Examples
Carbon monoxide	A, B, D, E	
Carbon dioxide	G, H	
Ozone	J	
Ultra fine PM	A, B, C, E, G	
$PM_{2.5}$	C,H, B, E	
PM_{10}	C, H	
Aldehydes	A, B, E, F,H	Formaldehyde, acetaldehyde, acrolein, valeraldehyde, butyraldehyde, benzaldehyde, crotonaldehyde, hexaldehyde, propionaldehyde, nonanaldehyde
Organophosphates	B, E, I	All tricresylphosphate isomers, tributyl phosphate
Carboxylic acids	B, F	Pentanoic acid, heptanoic acid, octanoic acid
Aromatics	A, B, F, I	Benzene, toluene, ethylbenzene, xylene, styrene, naphthalene, etc.
Alkanes	A, F, I, B, E	Heptane, hexane, octane, nonane, decane, 3-methylpentane, 2-methyl hexane, 3-methylhexane, 1-methylcyclohexane
Amines	B, F, E	N-phenyl-1-napthylamine
Ketones	B, H	Methylethylketone, acetone
Esters	B, E	ethyl acetate, butyl acetate
Pyrethroids	I	Permethrin/phenothrin
Alcohols	A, D, H	Ethylene glycol, propylene glycol, ethanol, methanol

* Possible sources: A = fuel, B = oil, C = equipment wear, D = deicing fluid, E = hydraulic fluid, F = anticorrosion coating, G = galley, H = occupants, I = pesticides, J = outside air (Outside air is a possible source for most contaminants, particularly when on the ground or at low altitudes.)

7.2 Relative Humidity. Considerations of comfort, health and safety provide a basis for RH recommendations for the aircraft cabin. Comfort-based recommendations for RH in ground-based environments are included in ASHRAE Standard 55 (ASHRAE 2010). For the aircraft cabin environment, an upper limit for RH is dictated by safety considerations related to the protection of the aircraft fuselage from the possible condensation of water vapor on structural elements. Literature shows that low humidity is not discernible to humans and further shows that it does not cause significant adverse effects (Andersen et al. 1974; Stroud et al. 1992). However, research has also shown that modest increases in humidity in relatively dry ground-based environments reduce symptoms such as irritation to the eyes, skin, and upper airways; headache; and fatigue (Reinikainen et al. 1992; Wyon 1992; Nordstrom et al. 1994). In these studies, RH was increased with active humidification systems. On aircraft, RH may be increased by reducing the flow of outside air or by installing a humidification system. Increasing RH by 5% to 10% in the aircraft cabin environment may have similar beneficial effects but experimental data are not available (Nagda and Hodgson 2001), and the impact of the accompanying reduction in outside airflow would need to be evaluated.

8. TRACE CONTAMINANTS

Except for industrial workplaces and certain specialized environments, such as spacecraft, indoor air quality standards do not exist for most indoor or confined environments, including aircraft cabins. Nevertheless, contaminants such as volatile organic compounds (VOCs), carbon monoxide, ozone, and respirable particulate matter, including biological aerosols, can occur in any indoor environment and cause discomfort and adverse health effects (SAE 2006b). In the aircraft, these contaminants can emanate from occupants; aircraft materials; products brought on board; dust and fleecy materials, such as carpets and seating; cleaning products; and processes and accumulations of water or damp materials (SAE 2007b). Such problems can be exacerbated by low per-person ventilation and circulation rates, tight seating arrangements, high occupancies, dirty and dusty seats and carpets, and by thermal, noise, and vibration discomfort (SAE 2007a).

8.1 Rationale for Looking at Trace Contaminants. Table 8.1.1 presents a list of some contaminants that could be present in the aircraft cabin environment.

8.1.1 General Effects from Exposure to Airborne Contaminants. People can be exposed to contaminants in the environment in many ways. Contaminants can be inhaled, ingested, or taken in through the skin. Adverse health effects can take place at the initial epithelial barrier, which is either

the respiratory tract, the gastrointestinal tract, or the skin, or they can occur in other organ systems after penetration and translocation by diffusion or transport by blood, lymph, etc. (Lippmann 1992). While total human exposure is essential to consider in the context of environmental hazards, this guideline focuses on exposure to airborne contaminants only.

Airborne contaminants may be released into the aircraft cabin and can then be inhaled or can be deposited on surfaces and then transferred to people when they touch the contaminated surfaces. Problems with exposure to airborne contaminants in the aircraft cabin may range from discomfort and nuisance due to the presence of odors to adverse health effects due to exposure to short-term peak air concentrations or sustained air concentrations at lower levels under certain conditions.

The limited published aircraft sampling data suggest that a large number of these compounds are present at typical indoor concentrations. Above-average levels of some contaminants (e.g., ozone, ethanol, and carbon dioxide) and below-average levels of others (e.g., $PM_{2.5}$ and formaldehyde) have also been identified. See Table 8.2.4 for a more detailed look at average concentrations of various contaminants in aircraft and other occupied spaces. Contaminant concentrations during nonroutine conditions (e.g., bleed air contamination) have not been fully examined.

Cognizant authorities have studied the health significance of exposure to many different chemical compounds, but the source of these data is largely ground-based environments. These studies typically do not consider the possible effects of altitude.

This guideline does not mandate any contaminant exposure standard to be used for an evaluation but rather provides information on typical published indoor levels and available standards and guidelines in Table 8.2.2. Measurement methods are listed in Table 8.2.3. The user is advised to seek appropriate guidance in interpreting contaminant measurement data.

Some contaminants and groups of contaminants have been identified as marker compounds for sources. Tables of potential contaminants are provided for major sources on commercial aircraft and are listed in Table 8.2.1. Odor thresholds are identified where available for these contaminants in Tables 8.2.5 and 8.2.6. In addition, arithmetic means and ranges of published data for aircraft and for other sources, such as buildings, are listed in Table 8.2.4 to provide users with comparative data with which to evaluate the quality of air in their aircraft.

The summation principle may apply in certain instances, such as for odor (for comfort) and for health (irritancy, neurological, pathogenicity, and toxicity). In situations where several chemicals may have similar effects on an organ or system, the user should be aware that there may be synergism between contaminants, even though individual chemical concentration values may be less than published threshold values.

8.1.2 Rationale for Inclusion of Various Contaminants and Their Markers. Table 8.2.1 provides a subset of compounds or groups of compounds that could be present in the aircraft cabin environment. In addition, it provides the underlying rationale for inclusion of the compounds and their possible sources and provides examples of the compounds. The list of potential sources and markers are included to provide information as to the possible source of the compounds.

Following is a discussion of the rationale for inclusion of these compounds in the various categories below. Any contaminant sensor shall be validated for use on aircraft and to ensure that it meets its intended function.

8.1.2.1 Carbon Monoxide (CO). CO may be produced as a byproduct of incomplete combustion. CO can enter the aircraft from the outside (e.g., exhaust fumes). CO may also be generated due to thermal decomposition of contaminants entering the bleed air supply system, such as oil from a malfunctioning (leaking) engine seal, ingested hydraulic fluid, ingested fuel vapors, or ingested deicing fluid. The CO concentration generated is dependent on many factors, such as airflow, the quantity of the contaminant, and the temperature of the bleed air and surfaces in contact with the contaminant.

CO may also be created by an accidental fire associated with electrical part failures. Trace levels of CO are generated by occupants, even on nonsmoking flights (NASA 1999). Higher levels can be present on smoking flights.

The 2002 National Research Council committee recommended that the FAA require operators to continuously monitor CO and establish standard operating procedures for pilots to respond to elevated levels of CO because of the risk to flight safety (NRC 2002). The least-costly method for monitoring of carbon monoxide is by solid-state or electrochemical sensors. These sensors may be subject to interference from other compounds, including various organic compounds. Low levels of RH in the cabin may also affect response during flight. More precision in monitoring is available through the use of nondispersive infrared (NDIR) analysis, but there is an increase in cost and power consumption associated with this type of detector.

8.1.2.2 Carbon Dioxide (CO_2). Outside air contains carbon dioxide (CO_2) at levels typically ranging from around 648 mg/m^3 (360 ppm) at altitudes of 30,000 ft (9000 m) to ground-level ranges of 360 to 500 ppm (648 mg/m^3 to 900 mg/m^3), depending on the airport environment where the measurement is being taken. Levels well above this range may be observed near sources of combustion. The primary source for indoor CO_2 is from the respiration of the aircraft occupants. A secondary source of CO_2 is dry ice used for refrigerating meals aboard aircraft. Carbon dioxide generated by thermal decomposition of oil or hydraulic fluid is very small compared to these sources. Carbon dioxide constitutes approximately 5% of jet exhaust. It is possible to have elevated levels of CO_2 in the bleed air when the aircraft is ingesting exhaust by an engine or an APU. The level ingested is dependent on the percentage of air entering the core of the engine versus the amount bypassed, as well as environmental factors surrounding the ingestion event.

The 2002 National Research Council report recommended that CO_2 measurements be part of an ongoing surveillance project (NRC 2002). If there are no other CO_2 sources in the aircraft and the cabin, CO_2 measurements can be used as a surrogate for the average outside air ventilation rate per

person. The most common method of analysis for CO_2 is the use of real-time NDIR monitors.

8.1.2.3 Ozone (O_3). The source of ozone is the environment the aircraft is operated in. During the certification process, new aircraft must meet 14 CFR 25.832. Aircraft that do not have ozone removal equipment shall utilize procedural means as described in the FAA Advisory Circular 120-38 (FAA 1980).

Ozone, if present in the air, may cause symptoms such as eye and nose irritation, coughing, and chest pain. The discomfort and ill effects depend upon the O_3 concentration, exposure time, and an individual's sensitivity to O_3. Ozone may react with other chemicals and form other potentially more irritating compounds (NRC 2002).

Natural O_3 is primarily formed in the upper atmosphere as a result of the action of ultraviolet light on oxygen (O_2) molecules. At high altitudes and latitudes, high levels of O_3 can be present in the atmosphere. This air is ingested in the propulsion engines, where it is compressed, and a portion is extracted as the source for cabin ventilation and pressurization. During this process, O_3 dissociation occurs as a result of heat and surface contact.

The ratio of cabin O_3 concentration to outside O_3 concentration on an unoccupied aircraft without an ozone converter is known as the *retention factor* or *retention ratio*, *R*. Factors affecting the retention factor include bleed air operating temperature and pressure, use of recirculated air, cabin materials, and air distribution system components. The FAA accepts an assumed retention factor of 0.7 when computing cabin O_3 concentration if a retention factor has not been measured for the aircraft being analyzed (FAA 1980); see also 14 CFR 121.578 (FAA 2008a).

Instrumentation for real-time monitoring of O_3 is based on UV absorption photometry and electrochemical sensing principles. The UV absorption technology is the most reliable and provides adequate minimum detection limits for low concentrations. It is recommended that measurement equipment have adequate precision and be capable of resolving the O_3 concentration to a value not greater than 1/10 of the limit values specified in the Federal Aviation Regulation (14 CFR 25.832 [FAA 2008b]; SAE 2002).

8.1.2.4 Respirable Particulate Matter (RPM). Respirable particulate matter consists of solid or liquid particles that, with diameters less than 10 μm, are easily suspended in air and inhaled by exposed persons. RPM on aircraft can be generated from a variety of sources. The relative contribution of different sources to RPM on aircraft is currently not known. A major source of RPM is the airplane occupants. Pollutants generated by occupants are distinct from other types of particle sources in that the emissions occur where an individual is located and the occupant is not always stationary, but rather can move around. Occupants can generate RPM that may contain viruses or bacteria that are suspended in mucus generated from coughing or sneezing and that are found in organic and inorganic compounds carried by larger particles such as skin flakes or clothing fiber. Another source of RPM on airplanes is accumulated dust, which is resuspended in the air by occupants as they move around the aircraft cabin. This dust could contain allergenic material such as endotoxins and mycotoxins, as well as other irritating and potentially toxic chemicals such as pesticides. Other sources of RPM include galley operations, episodic introduction of fluids such as fuel and oil via the ventilation system, spraying of pesticides and cleaners, and equipment operation. Fleecy materials (e.g., carpet, seating) can be sources of RPM as a result of occupant movement (SAE 2006a).

Particle diameter, chemical composition, airborne concentrations, duration of exposure to RPM, and individual sensitivity all play a part in the impact particles have on aircraft occupants. A recent study showed that during normal operations, the highest concentrations of particulate matter were present during boarding and deplaning (Dumyahn et al. 2000). At the same time, a number of studies, including ASHRAE Research Projects 957 (RP-957) (Pierce et al. 1999) and 959 (RP-959) (Nagda et al. 2001) have shown that mass concentrations of particles during cruise are very low during normal conditions, often in the range of 10 $\mu g/m^3$. In a typical aircraft ventilation system, air that is recirculated is usually passed through high-efficiency particulate arresting (HEPA) filters, removing particles with great efficiency (HEPA filter efficiency rating is 99.97% at 0.3 μm). Outside air typically passes through the system without filtration but is not of concern as a source of particles since there are very few particles at altitude.

The U.S. Environmental Protection Agency (EPA) has developed National Ambient Air Quality Standards (NAAQS) for PM2.5 (particulate matter with aerodynamic diameter <2.5 μm). PM2.5 is not regulated by the federal aviation regulations (FARs). They are included in this guideline because PM2.5 has been documented to cause adverse chronic health effects upon exposure and because particles in this size range have the ability to penetrate into the deepest areas of the human lung upon inhalation. The NAAQS maximums for PM2.5 are 15 $\mu g/m^3$ annual arithmetic mean (three-year average) and 65 $\mu g/m^3$ over 24 hours (three-year average of the 98th percentile of 24-hour concentrations). Canadian Exposure Guidelines place a limit of <100 $\mu g/m^3$ for a one-hour interval for particles having <2.5 μm mass median aerodynamic diameter.

The U.S. EPA has also developed NAAQS for PM10 (particulate matter with aerodynamic diameter <10 μm). PM10 is not regulated by the FARs. They are included in this guideline because of their irritancy potential, although they are large enough that they will not penetrate to the deepest areas of the human lung when inhaled. The NAAQS for PM10 are 50 $\mu g/m^3$ annual arithmetic mean and 150 $\mu g/m^3$ over 24 hours.

To meet the NAAQS for PM2.5 and PM10, particulate matter is collected on filter media using certified air-sampling instrumentation and gravimetrically analyzed. The EPA recommends gravimetric determination of mass concentrations by collecting particulate matter on filters using certified air-sampling instrumentation since NAAQS are based on health effects studies that predominantly used gravimetric methods to characterize particular matter. In addition to mass concentrations, particle diameter and number concentrations are also very important parameters for describing airborne particulate matter. Particle deposition in the lungs upon inha-

TABLE 8.1.2.6.1 Approximate Amounts of Total TCP and Its Ortho Isomers in Oil (Mackerer and Ladov 1999)

	Concentrations of Ortho Isomers in Total Tricresylphosphate (TCP) by Weight Fraction, ppm	Concentrations of Tricresylphosphate (TCP) and its Ortho Isomers in Oil by Weight Fraction, ppm
Total TCP		30,000 (3%)
MOCP	3070	92
DOCP	6	1.8
TOCP	0.005	0.00015

Note: TCP CAS Number 1330-78-5

lation is a strong function of particle size. Optical-laser particle counters (OPCs) are commonly used instruments that count the number of particles in sampled air as a function of particle diameter and time. However, very few of the health standards are based on characterization of particulate matter using optical particle counters. Typically OPCs measure particles in the size range 0.1 to >10 μm, depending on the instrument and how it is calibrated. Particles smaller than 0.1 μm diameter are typically referred to as ultrafine particulate matter. Ultrafine particles are currently measured using condensation particles counters (CPC), which increase the diameter of the particle by using it as condensation nuclei until it is large enough to be detected optically by a laser. CPCs only provide total number of particles as a function of time and do not provide any sizing information. To size particles smaller than 0.1 μm, a CPC is usually coupled to an electrostatic classifier, which uses electrostatic forces to separate the particles according to size (Baron and Willeke 2001). Aerodynamic sizing instruments are also in common use. These instruments allow real-time measurement of aerodynamic diameter based on acceleration and time-of-flight principles (Baron and Willeke 2001). Typically these instruments can measure particle diameters from about 0.5 to 100 μm.

8.1.2.5 Aldehydes and Ketones. Aldehydes entering an aircraft cabin may be generated from the thermal decomposition of fuel; from synthetic oil, hydraulic fluid, deicing fluid, or anticorrosion coatings; or even from the occupants themselves. Aldehydes of primary health concern are those with one-to-six carbon atoms (C1 to C6) (see Tables 8.2.5 and 8.2.6). Longer-chain aldehydes are not of as great concern from an irritancy perspective but may be of concern from an odor perspective. For example, acrolein can cause mucous membrane or nasal irritation at 0.11 mg/m^3 (0.05 ppm) (ACGIH 2010). Title 14CFR does not regulate aldehydes.

A variety of aldehydes at very low concentrations (e.g., measured average concentrations for acetaldehydes in the range below 0.018 $\mu g/m^3$ [10 ppb]) are measured in air supplied to the cabin. The EPA-preferred method of measurement is to sample air on two adsorbent cartridges connected in series. The first cartridge removes ozone from the sampled air and the second chemically converts the aldehydes to a more stable compound for concentration. Instead of using two cartridges, one may obtain a cartridge that contains both media beds. The concentrated sample is then analyzed in a laboratory using high-performance liquid chromatography (HPLC).

Ketones may have a variety of sources of origination. They may be created by the combustion of fuel, by the thermal decomposition of oil, or even by aircraft occupants or maintenance or disinsection (solvents). For example, methyl ethyl ketone is fuel generated, whereas acetone could be occupant or decomposition related. Rancid galley odors can also indicate the presence of ketones. Methods of sampling and analysis include sampling on adsorbent media, such as that used for aldehydes, and sampling by evacuated cylinders followed by gas chromatography/mass spectroscopy (GC/MS) analysis.

8.1.2.6 Organophosphates. Organophosphates have a variety of potential sources. Tricresylphosphates (TCPs) are used in turbine engine oils and some hydraulic fluids, typically 1% to 5% TCP by weight. Although the orthoisomer of TCP—triorthocresyl phosphate (TOCP)—has often been studied in the past, there are a total of 10 different isomers; the three monoorthocresyl phosphates (MOCPs) and the two diorthocresyl phosphates (DOCPs), are respectively 5 and 10 times more toxic than TOCP (Mackerer et al. 1999; Henschler and Bayer 1958). The MOCP and DOCP isomers may be present in the turbine oils in concentrations sufficient to be of concern for health and are reported to be in many synthetic jet engine oils in significantly higher concentrations than TOCP. A commercial aircraft oil manufacturer advised the Australian Senate in 2000 that MOCP was in the TCP at 3070 ppm, DOCP at 6 ppm, and TOCP at 5 ppb (Mackerer and Ladov 1999). For example, Table 8.1.2.6.1 lists the approximate amounts of these isomers for one oil blend at a given condition. Depending on the method of analysis of semivolatile compounds, isomers may be difficult to distinguish from one another (Henschler and Bayer 1958). Typical commercial-grade TCP is a complex mixture of different isomers, all of which are neurotoxicants, with some more potent than others. There is also evidence that when heated to temperatures above 480°F (250°C) in a laboratory, TCPs can react with trimethyl propane esters of carboxylic acids present in the base stock of some engine lubricants and form the potent neurotoxin trimethylol propane phosphate (TMPP) (Wright 1996).These are not regulated by Title 14 CFRs, and the only occupational health guideline available is for TOCP.

Tributyl phosphate (TBP) isomers come predominantly from hydraulic fluid since these isomers are the primary constituent of this fluid. By evaluating test data, the observer can determine whether the most likely source of the organophosphate is oil or hydraulic fluid. As an example, the EPA method for sampling for organophosphates is by drawing air

through adsorbent cartridges and/or filters consisting of polyurethane foam and solid adsorbent medium. In the EPA method, the sampled mass is solvent desorbed and then analyzed with GC-MS.

Based on current analytical methodologies, a sample volume of at least 20 ft^3 (500 L) should be adequate to address a target concentration of 0.01 mg/m^3 TCP isomers. However, in order to achieve sample results above the detection limits, researchers have found that it is often necessary to collect a substantially larger sample volume (e.g., several cubic metres). This cannot typically be achieved in a short period of time without the use of high-volume samplers, which occupy 0.05 to 0.1 m^3 (2 to 4 ft^3) of space and may be noisy.

8.1.2.7 Carboxylic Acids. Carboxylic acids originate predominantly from the thermal decomposition and hydrolysis of synthetic turbine oil. This decomposition occurs in air-conditioning systems if oil residue and moisture are present. These acids have very low odor thresholds and can be irritating to the observer. Carboxylic acids have a smell characteristic of dirty socks. They are not specifically regulated by the FARs.

The most common method of analysis is by adsorption onto thermal desorption tubes, followed by GC/MS analysis. Evacuated canister analysis has not been found to be an effective method of sampling for these compounds, especially the heavier acids.

8.1.2.8 Alkenes, Alkanes, Aryl Compounds

8.1.2.8.1 Alkenes and Alkanes. Alkenes and alkanes are generated by the decomposition of fuel or synthetic turbine oil. Alkenes such as benzene, ethylbenzene, xylene isomers, and styrene can come from fuel thermal decomposition or combustion. Toluene has been observed to be a thermal decomposition product from both fuel and oil. Evacuated canisters and adsorbent tubes both are effective sampling methods. GC/MS is the typical separation and analysis method.

8.1.2.8.2 Aromatics (Aryl Compounds). Benzene, ethylbenzene, and xylene are present in fuel and in solvents used in pesticide sprays. Aryl compounds may come from unburned fuel or from solvents in pesticide sprays.

8.1.2.9 Amines. Some amine-type compounds are used in low quantities (1% to 2% of blend) as antioxidants in synthetic turbine oil and possibly in some anticorrosion coatings. Due to their chemical properties, amine compounds are typically sampled on a (treated) solid sorbent and analyzed either by gas chromatography with a nitrogen phosphorous detector or by HPLC. These instruments are preferred over GC/FID because they are more sensitive for amines.

8.1.2.10 Esters. Esters are used in the base stocks of synthetic turbine oil and are combined with carboxylic acids during the synthesis process. Thermal decomposition causes turbine oil to revert back to esters and carboxylic acids. Acetate compounds such as ethyl acetate may be present in materials such as solvents used during maintenance. The EPA measurement method is to sample on solid adsorbents or evacuated canisters followed by GC/MS analysis. Use of high-volume sampling techniques recommended for organophosphates will also improve detection limits in the analysis of esters.

8.1.2.11 Pyrethroid Pesticides. The U.S. EPA does not approve any insecticides for spray application in the aircraft cabin or cockpit, whether occupied or unoccupied. Despite this, maintenance workers are sometimes instructed to spray insecticides (e.g., pyrethrum and piperonyl butoxide) in the aircraft cabin, both in response to insect sightings and for routine control of cockroaches and other insects. Until at least the late-1970s, DDT was sprayed on particular domestic flights in the U.S. for seasonal insect control. Currently, 47 countries enforce quarantine laws that require incoming aircraft to be sprayed with insecticides, typically pyrethroids, either upon or prior to arrival in order to protect against importing insects that may damage public health, agriculture, or plants (ICAO 2004). Both the in-flight and residual sprays contain multiple solvents, and the in-flight sprays contain a propellant (typically HFCs). The application method influences the exposure potential. Some countries require cabin crews to spray an aerosol product containing 2% d-phenothrin over the passengers' heads either in-flight or upon arrival. Other countries require unoccupied aircraft to have been sprayed with a 2% solution of permethrin on all surfaces of the cabin and cockpit before crew and passengers board prior to departure for a country with spraying rules, every 56 days. Pyrethroid application is endorsed by the World Health Organization (WHO) and described as safe and necessary, "if carried out with the recommended precautions" (WHO 2003). However, WHO-recommended spray volume limits can be exceeded, and they are not enforceable. Furthermore, there are no control measures to ensure that treated surfaces have dried before crew and passengers board.

Many reported incidents have centered on improper/excessive application of the insecticide and on inadequate time between application and boarding, as well as on in-flight applications during which it is impossible for passengers and/or crew to avoid exposure. An independent investigation concluded that residual disinsection poses a health hazard to cabin crew, that current assumptions about the human health impacts of residual disinsection underestimate the risks, and that the relative efficacy of aircraft disinsection in preventing vector-borne disease are not adequately researched (Sutton et al. 2007). Pyrethroid insecticides have been associated with a wide variety of symptoms, including headache, nausea, respiratory distress, chest tightness, generalized weakness, irritation, skin rash, anaphylaxis, and immune system effects (WHO 2003; Sutton et al. 2007; Zaleska et al. 2001; Altenkirch 2000; Muller-Mohnssen 1999; He et al. 1988, 1989). Both airborne and dermal exposure need to be assessed, and the most common analytical method for airborne sampling analysis is HPLC. The International Civil Aviation Organization (ICAO) recently reported its intent to coordinate with WHO and countries with spraying requirements to evaluate nonchemical approaches to aircraft disinsection (ICAO 2004). The WHO also enlarged its definition of disinsection to include procedures that control (not just kill) insects (WHO 2005).

8.1.2.12 Bioaerosols. Bioaerosols are airborne organisms and other biologically derived particles. Bioaerosols

include bacteria; fungi, their spores, and fragments thereof (including associated chemical toxins); and viruses. Exposure to bioaerosols can be responsible for infection, allergic reactions, or irritancy. In flight, bioaerosols in aircraft cabins arise mainly from inside sources such as passengers, arthropods (fliers, spiders, etc.), pets and service animals, and settled dust. When an aircraft is on the ground, an additional source of bioaerosols is the outside air. With the number of passengers that are transported in aircraft each year, concerns regarding human exposure to bioaerosols have been raised. Exposure to bioaerosols is increased when passengers are confined in a cabin without adequate ventilation and system operation (NRC 2002). The proper design, operation, and maintenance of an aircraft ventilation system can reduce but not eliminate the transmission of infectious agents and exposure to bioaerosols on aircraft. A person's risk of acquiring an infection on an aircraft is dependent on multiple factors, including the presence of an infectious person and release of infectious agents by that person, the ventilation rate in the cabin and mixing of cabin air, the amount of cabin air that is recirculated and how it is treated, proximity to the source person, duration of exposure, and susceptibility to the specific infectious agents (NRC 2002).

The major allergens of concern in aircraft cabins are those associated with dust mites and cockroaches, cats, dogs, other small animals; *Alternaria* species and other fungi; and pollen (IOM 2000). Cat and dog allergens are present everywhere as a result of allergen being carried on people's clothing. Hypersensitivity responses have also been documented on aircraft with exposure to peanut allergens (Sicherer et al. 1999).

The reservoirs for infectious agents in aircraft cabins are the people on board (virus, bacteria, and fungi carried in and on their bodies) and other vectors (such as arthropods). The infectious agents of concern are those transmitted by person-to-person droplet contact and airborne transmission of droplet nuclei (i.e., droplets that are small enough to remain airborne for long periods of time). Investigations of potential infectious disease transmission on aircraft have been summarized (NRC 2002). Infectious agents that are known or suspected to have been transmitted in aircraft include influenza, measles, tuberculosis, meningococcal disease, acute respiratory infections, and severe acute respiratory syndrome (SARS) (Olsen et al. 2003; NRC 2002). Influenza and measles viruses and tuberculosis bacteria are spread from person-to-person primarily via the airborne route after coughs and sneezes. In one case, *Legionella* was found in reservoirs on aircraft (NRC 2002), emphasizing the need to prevent such occurrences during system design and during the operation of active humidification systems.

Extensive monitoring has been conducted of bioaerosol loadings in residences and typical office buildings and other occupational settings, such as the agriculture industry. Few measurements have been made on commercial aircraft. Summaries of the available data have been published (NRC 2002; Hernandez and Swartz 2000). In general, available case studies indicate that the levels of bioaerosols in aircraft cabins are below those found in other indoor environments, are proportional to passenger loading, and are not likely to cause adverse health effects. Given the small number of studies and the limitations of the studies (use of a single assay, such as culturing; use of grab samples; small number of observations), conclusions based on these case studies regarding the bioaerosol loading in the general commercial airline fleet are limited; more data need to be collected (Hernandez and Swartz 2000).

Because of the wide range of organisms studied in bioaerosol investigations, few official exposure guidelines have been published. It has not been established if such exposure guidelines are applicable in commercial aircraft. In the U.S., while there are currently no guidelines, organizations such as the American Industrial Hygiene Association (AIHA) and the American Conference on Governmental Industrial Hygienists (ACGIH) are considering proposing guidelines. Health Canada provides numerical limits for fungi in office buildings only: more than 50 colony-forming units (CFU)/m^3 of a single species other than *Cladosporium* or *Alternaria* is cause for concern. Up to 150 CFU/m^3 is acceptable if there is a mixture of species reflective of outside samples, and up to 500 CFU/m^3 is acceptable in summer if the species are primarily phylloplane (i.e., leaf fungi) (Health Canada 1995; Dillon et al. 1996). Canada also recommends that the persistent presence of significant numbers of toxigenic fungi (e.g., *Stachybotrys chartarum, toxigenic Aspergillus, Penicillium,* and *Fusarium* species) require action. In the U.S., the state of New York has issued guidelines for the rapid remediation of mold contamination (all species of fungi) of building components (walls, ventilation systems, support beams, etc.) that are chronically moist or water damaged. In Europe, the Commission of the European Communities (CEN) is considering standardization of bioaerosol sampling methods. The interim air quality guidelines for Hong Kong contain a numerical action level of 1000 CFU/m^3, and this limit has been cited as appropriate for commercial airliners in Hong Kong (Lee et al. 1999). In the Russian Federation, the maximum allowable concentration for biological contamination ranges between 1000 and 10,000 cells/m^3, depending on the species (Hernandez and Swartz 2000).

A few bioaerosol researchers have recommended various limits and sampling protocol for biological investigations. Reponen et al. (1992) reports that >500 CFU/m^3 in the winter is abnormal. Reynolds et al. (1990) reports that indoor sources are the predominant sources if the indoor levels are greater than the outside levels.

8.1.2.12.1 Measurements. The objective of bioaerosol sampling is to collect bioaerosol from sampled airflow without changing the physical characteristics or viability of the organism. Important parameters include sampling efficiency (how efficiently the organisms are brought into the sampler), collection efficiency (how efficiently the organisms are collected into/onto the media within the sampler, for example, agar or liquid), and biological efficiency (how the metabolic or physical state or the organisms is changed upon sampling). There are four main categories of samplers. An inertial impactor uses an organism's own inertia to remove it from the sampler-accelerated airstream and deposit it on collection media (typically agar or filters). Impingers use particle inertia and diffusion to impact/wash the organism into a collection fluid. Filtration uses impaction, diffusion, and interception to collect particles onto filter media (glass fibers,

fluorocarbon, etc.). Centrifugal samplers use centrifugal forces to impact particles onto sidewalls of sampler.

Liquid-capture samplers, while difficult to transport, offer the greatest recovery factors and highest yields for bioaerosol data acquisition. High-volume and research-grade samplers are becoming more portable and economical and may be suitable for studies of bioaerosol on commercial aircraft in the near future. Note that, because the capture efficiency is unknown, no bioaerosol samplers are adequate for quantification of airborne viruses except filters.

In addition to sampling the air, dust reservoirs are sampled and analyzed for biocontaminants such as allergen and dust mites. Dust reservoirs on aircraft include carpeting and seat cushions. Typically, dust is collected from specified areas for a constant duration using vacuums. The vacuums must be able to collect the dust onto a filter or into a special container and must be efficient collectors and not stir up the dust into the air.

The objective of bioaerosol analyses is to quantify the level and/or state of collected organisms. There are five main techniques used to quantify bioaerosol levels. Culture of colony-forming units (CFUs) is probably the most commonly used analysis and consists of plating organisms onto an appropriate agar, incubating the sample, and then counting the number of colonies that grow from the plated sample. Culturing gives an indication of the most probable number of airborne organisms that retain the ability to reproduce (i.e., this is the definition of infectious). Direct microscopy consists of staining collected organisms with fluorescent stains and then counting them under a microscope. This method provides an estimate of total bioaerosol "loads" without culturing bias. Samples can also be stained for specific attributes such as activity. Genetic amplification techniques, such as polymerase chain reaction (PCR), are a promising forensic technique that has been quantitatively successful in small-scale studies. These techniques are specific and extremely sensitive. Immunochemical techniques are used to determine the mass of common allergens associated with airborne particulate matter. Finally, other chemical analyses have been used to quantify organic compounds associated with and liberated by microorganisms (GC/MS).

8.1.2.13 Total Volatile Organic Compounds Created by Contaminants. As noted earlier, VOCs include several hundred individual organic compounds. Thus, measuring VOCs is a complex task. Instead of measuring individual VOCs, the concept of total volatile organic compounds (TVOCs), which involves the use of a single parameter (i.e., the sum of individual VOC concentrations), has been used in the past. This approach could be useful in physically isolating a major source but has a number of disadvantages in terms of interpreting air quality. These points are described in more detail below.

The TVOC concept was originally conceived to be the sum of all VOCs with boiling points ranging between 50°C and 260°C (120°F and 500°F) (Mølhave 1991). This original definition specifically excluded very potent irritants and was related strictly to sensory irritation, odor, and the complex symptoms associated with sick building syndrome (SBS) (as opposed to human health concerns associated with long-term exposure). Monitoring techniques include nonspeciated or blind summation using direct-reading, nonspecific analyzers, as well as more difficult speciated or functional summation based on chemical-specific laboratory analysis (Nagda and Rector 2000). While nonspeciated measurements are easier to implement, speciated measurements are preferred based on both analytical and interpretation grounds because this method makes it possible to report simplified results without losing the identity of individual compounds (Wolkoff 1995; Mølhave et al. 1997).

The TVOC concept has fallen into disuse as the sole indicator of SBS-type health effects for a number of reasons. First, the data comparability between blind summation and functional summation is poor. Second, Wolkoff (1995) found that TVOC as a marker for SBS should be replaced with more specific air concentration parameters. Further, a peer review of the scientific literature has judged the use of TVOC as a risk index for health/comfort effects to be inconclusive (Andersson et al. 1997). Finally, the TVOC indicator (regardless of the basis for measurement) fails to represent chemical-specific potency (Mølhave et al. 1997). This last point, indicating that TVOC measurements can produce misleading results, is particularly important. For example, if fairly innocuous compounds dominated VOCs, then an elevated TVOC value would indicate unacceptable air quality even though human response would indicate otherwise. Conversely, a low TVOC value could be produced from a mixture of very strong sensory irritants at relatively low concentrations, and such a condition could cause adverse reactions while being labeled as indicative of acceptable air quality. To determine whether there could be a VOC problem in an environment, individual VOC concentrations and their comparison to individual VOC indoor air norms is required. Due to these limitations, TVOC measurements alone for characterizing cabin or bleed air quality is not recommended without considering individual VOC data as well. Their use should be restricted to basic troubleshooting and source identification. Measurements of TVOC are useful for locating strong sources of organic compounds within the aircraft.

Additional information on application of TVOC measurements may be found in Anderson et al. (1997), Mølhave (1991), Mølhave et al. (1997), Nagda and Rector (2000), and Wolkoff (1995).

8.1.2.14 Flame Retardants. Halogenated flame retardants, such as polybrominated diphenyl ethers (PBDEs) and chlorinated tris (TDCPP), are organobromine and organochlorine compounds, widely used as flame retardants in foams, fabrics, carpets, electronics, molded plastics, and resins. They are used in residential and occupational environments, as well as in transportation vehicles, including aircraft. Flame retardant compounds can be released from treated compounds during the product's life cycle.

Many halogenated flame retardants are known to bioaccumulate. Published studies have identified them as disrupting hormones, interfering with reproduction and thyroid function and impairing the development of the nervous system (Chevrier 2010; Harley 2010; Herbstman 2010; Schreiber 2010; Darenud 2008; Herbstman 2008; Turyk 2008; Chao et al. 2007; Costa et al. 2007; Main et al. 2007; Hardell 2006). In

2009, the Environmental Protection Agency committed to summarize PBDE exposure hazards and outline the health risks and specific actions (EPA 2009b).

Concentrations of flame retardants in the aircraft cabin air have yet to be adequately quantified. To date, only two small exploratory studies have investigated potential PBDE exposure in aircraft cabins, and none have investigated exposure to other types of flame retardants, such as, for example, TDCPP. One of these exploratory studies reported the presence of PBDEs in aircraft cabin dust (Christiansson 2008). That study also identified a small increase in the PBDE serum level of nine passengers after a round trip flight, although this increase cannot necessarily be attributed to exposure in the aircraft because of the opportunity of those passengers to have been exposed to nonaircraft sources between flights. In contrast, blood serum analyses of two frequent flyers did not show elevated PBDE levels as compared to the general population. The second study (Schecter 2010) measured some PBDEs in the blood of nine flight attendants and one pilot. The authors reported that PBDE blood levels of the subjects were comparable to those of the general public, although the presence of other flame retardants was not investigated.

Aircraft and interiors must meet regulatory standards intended to prevent the spread of fire on aircraft. The FAA has issued a performance standard for cabin materials that an ignited source must self-extinguish per requirements of 14 CFR Part 25 Appendix F, but it neither prescribes nor proscribes the use of any particular fire retardant.

8.2 Guidelines, Methods, and Published Data. Table 8.2.2 lists health, safety, and comfort-related guidelines for exposure to various chemicals. There are currently no federal regulations governing levels of exposure to chemicals measured in aircraft cabin air other than those for carbon dioxide, carbon monoxide, and ozone. The table provides a way for users to compare their measurements with standards that have been adopted by various agencies and organizations. Most of these guidelines were developed for ground-based applications. They do not apply to the general public (ACGIH 2010) and do not account for the fact that crewmembers often work duty days of 14 hours or more. Also, they do not account for extremes in temperature or RH (ACGIH 2010), and chemical exposures at these levels may not protect against impairment to high-level cognitive functions, although such functions must be maintained by pilots in particular throughout flight (Singh 2005). However, this information gives users some comparative information to determine whether their measurements are low enough to not be of immediate concern or high enough to require immediate action. Meeting levels stated in these guidelines may not ensure a healthy, safe, and comfortable environment for all occupants in aircraft.

Table 8.2.3 is included to provide a cross reference for several methods that are accepted for measuring the various classes of compounds. Surface sampling may also be necessary to assess potential sources of airborne exposure. In addition, dermal exposure assessment may be necessary, depending on the compound. The final method chosen will depend upon the equipment available for analysis.

Tables 8.2.4a and 8.2.4b are provided to give the user additional information on ranges of measurements of chemicals in other studies. This is intended to aid users in the evaluation of their data to make a determination whether levels are low or high when compared to other published measurements. Users could capture ranges of measurements in their database for quality assurance purposes.

Table 8.2.4c provides a summary of available TCP sampling data collected on military and commercial aircraft.

Table 8.2.5 provides the user with a quick reference of the specified levels of selected chemicals found in several standards. While these standards currently have not been adopted for use in airline cabins, they are useful to show relative magnitudes for limits of exposure to several compounds. For application of these values and a potential method of analysis to derive acceptable concentrations for individual chemicals in the cabin environment, the reader is referred to ASTM D7034 (ASTM 2004).

Table 8.2.6 is provided to help identify potential sources of contamination based on the odor characteristics of the air. In addition, one may obtain a relative idea of the amount of a substance that must be present to be observed by individuals with an acute sense of smell. The references cited may be useful to the observer when evaluating data to determine whether reported compounds could be responsible for observed odors. Much study is still being done to understand odor observation. It is believed that the odor of various contaminants is additive, i.e., even though various compounds individually may not be present in amounts to individually be sensed, when combined their mixture may be detectable and have its own character.

8.3 Measurements and Contaminant Identification. Measurements of cabin air quality generally fall into three categories:

- ***episodic event:*** an event in which passengers and/or flight crew experience an odor or irritation that is not commonly experienced. The event may be associated with a particular aircraft or a type of aircraft, phase of flight, or flight path, but is not common to all aircraft at any given time. The episodic events may or may not cause noticeable health effects for passengers and/or crew. The basic difficulty with measurements during episodic events is that of not knowing when, where, and what to measure for an event that is potentially of short duration.
- ***nonepisodic measurements or measurements on routine flights:*** measurements taken on flights operating under routine conditions. Concentrations, often at low levels, of a number of substances and compounds are anticipated during routine operations. A typical goal of such measurements is to characterize the cabin environment.
- ***trend monitoring:*** a series of measurements of an individual chemical or a group of chemicals that shows a time-related change in contaminant levels. For example, the NRC (2002) committee has recommended that such monitoring be routinely conducted for carbon monoxide and ozone.

TABLE 8.2.2 Health, Safety, and Comfort-Related Guidelines for Exposures to Contaminants

Guideline[a]	Background	Approximate Number of Compounds	Issues Related to Airplane Applicability[b]
Integrated Risk Information System (EPA 2010)	IRIS is the United States EPA official repository of consensus information on potential adverse human health effects from chronic or lifetime exposure. It provides values for reference concentration (RfC), NOAELs, and LOAELs for each chemical, as available.	500 to 600	The RfC values are for lifetime exposures.
Minimal Risk Levels for Hazardous Substances (ATSDR 2009)	Minimal risk levels (MRLs) are estimates of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse non-cancer health effects over specified duration of exposures. Developed by the Agency for Toxic Substances and Disease Registry (ATSDR) and used in screening contaminants and potential health effects at hazardous waste sites. Guideline values for acute (exposure duration of 1 to 14 days), intermediate (15 to 364 days), and chronic (>1 year) inhalation exposures are available for some chemicals.	300	Acute and intermediate level guidelines may be appropriate for consideration.
National Ambient Air Quality Standards (EPA 1990a)	Standards tied to the Clean Air Act, intended to protect public health and welfare for carbon monoxide, lead, nitrogen dioxide, ozone, sulfur dioxide, and particulate matter.	10	
Airworthiness Standards: Transport Category Airplanes	Design standard for airplanes developed by the Federal Aviation Administration. Located in Code of Federal Regulations, Title 14, Part 25 (14CFR25). Available @ http://www.fedworld.gov.	3	Does not specify hazardous quantities of smoke or fumes.
Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants (NASA 2000)	NASA/NRC guidelines, 1 hour to 180 days, and toxicology profiles.	45	Not applicable to general population.
Threshold Limit Values and Biological Exposure Indices (ACGIH 2010)	A listing of threshold limit values (TLVs), short-term exposure limits (STELs), and ceiling limits (C). Published annually by ACGIH, it gives 8-hour, 15-minute time-weighted-average occupational threshold limits as well as limits not to be exceeded.	2000	Not applicable to general population.
Odor Threshold for Chemicals with Established Occupational Health Standards (AIHA 1989)	Published by AIHA to eliminate wide variations in odor threshold data reported in existing literature. A major table in the AIHA report presents the best estimate and range of detection and recognition odor threshold along with qualitative descriptions of odor character, threshold limit values, chemical formula, and molecular weight.	110	Odor is not an indication of hazard, but can serve as an exposure indicator/warning for some people if sensed prior to olfactory fatigue.
Permissible Exposure Limits (OSHA 2010)	OSHA standards on 8-hour time-weighted average (TWA) occupational exposure limits.	700	Not applicable to general population.
Air Quality Guidelines for Europe (WHO 2000)	Developed by the World Health Organization (WHO) to help reduce human exposure to harmful levels of air pollutants. Document includes numerical guideline values that were developed based on noncancer effects (including sensory irritation) and risk estimates for carcinogens.	35	
Exposure Guidelines for Residential Indoor Air Quality (Health Canada 1987)	Developed by Health Canada, these guidelines take into account the sensitivity of groups at special risks. Document includes two types of exposure limits for compounds with noncarcinogenic effects (acceptable long-term exposure ranges [ALTERs]; acceptable short-term exposure ranges) and action levels for those with carcinogenic effects.	12	

Note a: Almost all of these databases state that their applicability to uses other than those cited specifically in the databases is not recommended.
Note b: None of the guidelines in this table consider the effects of cabin altitude.

Acronyms and Abbreviations

RfC = Reference concentration, which is an estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleteri lifetime. It can be derived from a NOAEL, LOAEL, or benchmark concentration, with uncertainty factors generally applied to reflect limitations of the data used. Generally used in EPA's noncancer health assessments.

NOAEL = No-observed-adverse-effect level. This is the greatest concentration or amount of a chemical found by experiment or observation that causes no detectable adverse alteration of morphology, functional capacity, growth, development, or life span of the target is a level that should be considered safe and requires no application of a safety factor to determine a safe intake, based on the most sensitive subgroup.

LOAEL = Lowest-observed-adverse-effect level. This is a level that should NOT be considered safe for everyone and may require the application of a safety factor to calculate a safe intake.

TABLE 8.2.3 Measurement Methods for a Subset of Contaminants that Could Be Present in the Aircraft Cabin Environment

	Toxic Organic Compendium (EPA 2009a)						TO-10A	TO-11A	TO-13A	TO-14A	TO-15	TO-17
	ASTM Standard:						D4861 (ASTM 2011)	D5197 (ASTM 2009a)		D5466 (ASTM 2007)	D5466 (ASTM 2007)	D6196 (ASTM 2009b)
	Collection:	Filter Media	Real Time	Real Time	Real Time	Real Time	PUF Tube	DNPH Tube	PUF/XAD Tube	Passivated Canister	Passivated Canister	Thermal Desorption Tube
	Analysis:	Gravimetric Analysis	Optical Particle Counter/ Aerodynamic Particle Sizing (OPC)	Condensation Particle Counter (CPC)	Flame Ionization Detector (FID)	Chemiluminescence Detector (CLD)	Multiple Analytical Methods	High-Performance Liquid Chromatography (HPLC)	Gas Chromatography/ Mass Spectroscopy (GC/MS)	GC/MS	GC/MS	GC/MS
Chemical Abstract Service Reference Number (CASRN)	Chemical						Semivolatile Organic Compounds (SVOC)	Aldehydes	SVOC	Volatile Organic Compounds (VOC)	VOC	VOC
75-07-0	Acetaldehyde (Ethanal)							▲				▲
67-64-1	Acetone (Note a)							▲		▲	▲	▲
107-02-8	Acrolein (Note b)							▲			▲	▲
71-43-2	Benzene									▲	▲	▲
100-41-4	Ethyl benzene									▲	▲	▲
64175	Ethyl Alcohol (Ethanol, Ethanole)									▲	▲	▲
50000	Formaldehyde							▲				
110543	n-Hexane									▲	▲	▲
75-09-2	Methylene Chloride									▲	▲	
123-38-6	Propionaldehyde							▲		▲		▲
127-18-4	Tetrachloroethene									▲		▲
6163-58-2	Tricresylphosphate Isomers (TCP)						▲		▲			
108883	Toluene									▲	▲	▲
1330-20-7	Xylene Isomers									▲	▲	▲

Notes:
(a) High background levels of acetone on DNPH tubes for method TO-11A suggest that an alternative method (e.g., TO-15 or TO-17) would be more appropriate in view of the fact that TO-15 and TO-17 are for low levels.
(b) ASTM D5197 (ASTM 2009a) specifically states that this method (TO-11A) is not to be used for accurate determinations of acrolein levels. In addition, there is an addendum to this effect on the EPA website. EPA method TO-15 references acrolein.
(c) Carbon monoxide and carbon dioxide may both be monitored by real-time instrumentation. See ASTM D3162 (ASTM 2012a) and ASTM D6245 (ASTM 2012b).
(d) Exposure to permethrin or phenothrin during residual or in-flight application will be airborne and dermal. Dermal exposure assessment methods are outside the scope of this guideline, but dermal exposure should be assessed.

TABLE 8.2.3 Measurement Methods for a Subset of Contaminants that Could Be Present in the Aircraft Cabin Environment *(Continued)*

	Toxic Organic Compendium (EPA 2009a)						**TO-10A**	**TO-11A**	**TO-13A**	**TO-14A**	**TO-15**	**TO-17**
	ASTM Standard:						**D4861 (ASTM 2011)**	**D5197 (ASTM 2009a)**		**D5466 (ASTM 2007)**	**D5466 (ASTM 2007)**	**D6196 (ASTM 2009b)**
	Collection:	**Filter Media**	**Real Time**	**Real Time**	**Real Time**	**Real Time**	**PUF Tube**	**DNPH Tube**	**PUF/XAD Tube**	**Passivated Canister**	**Passivated Canister**	**Thermal Desorption Tube**
	Analysis:	**Gravimetric Analysis**	**Optical Particle Counter/ Aerodynamic Particle Sizing (OPC)**	**Condensation Particle Counter (CPC)**	**Flame Ionization Detector (FID)**	**Chemiluminescence Detector (CLD)**	**Multiple Analytical Methods**	**High-Performance Liquid Chromatography (HPLC)**	**Gas Chromatography/ Mass Spectroscopy (GC/MS)**	**GC/MS**	**GC/MS**	**GC/MS**
Chemical Abstract Service Reference Number (CASRN)	**Chemical**						**Semivolatile Organic Compounds (SVOC)**	**Aldehydes**	**SVOC**	**Volatile Organic Compounds (VOC)**	**VOC**	**VOC**
124-38-9	Carbon Dioxide (Note c)											
630-08-0	Carbon Monoxide (Note c)											
10028-15-6	Ozone					▲						
	Total Volatile Organic Compounds (TVOC)				▲					▲	▲	
	Ultrafine Particulate Matter (Ultrafine PM)			▲								
	PM2.5	▲	▲									
	PM10	▲	▲									
126-73-8	Tributyl Phosphate						▲					
526-45-53-1	Permethrin (Note d)						▲					
26002-80-2	Phenothrin (Note d)						▲					

Notes:
(a) High background levels of acetone on DNPH tubes for method TO-11A suggest that an alternative method (e.g., TO-15 or TO-17) would be more appropriate in view of the fact that TO-15 and TO-17 are for low levels.
(b) ASTM D5197 (ASTM 2009a) specifically states that this method (TO-11A) is not to be used for accurate determinations of acrolein levels. In addition, there is an addendum to this effect on the EPA website. EPA method TO-15 references acrolein.
(c) Carbon monoxide and carbon dioxide may both be monitored by real-time instrumentation. See ASTM D3162 (ASTM 2012a) and ASTM D6245 (ASTM 2012b).
(d) Exposure to permethrin or phenothrin during residual or in-flight application will be airborne and dermal. Dermal exposure assessment methods are outside the scope of this guideline, but dermal exposure should be assessed.

TABLE 8.2.4a Published Measurements of Various Contaminants Reported on Noncomplaint Aircraft and in Buildings (data corrected to normal temperature and pressure conditions: 25°C and 760 torr [77°F and 14.7 psia])

	Cabin Air Measurements, ppm (numbers in parentheses on a weight basis)				Bleed Air Measurements, ppm (numbers in parentheses on a weight basis)				Building Measurements, ppm (office and residential)			
Chemical Name (Measurement Location)	**Ref. No.**	**No. Flights**	**Maximum Measured**	**Arithemetic Mean**	**Ref. No.**	**No. Flights**	**Maximum Measured**	**Arithmetic Mean**	**Ref. No.**	**No. Bldg. Measurements**	**Maximum Measured**	**Arithmetic Mean**
Carbon dioxide												
(Aft galley, cruise)	1	26	1488	734								
(Forward galley, cruise)	1	26	1406	637								
(Aft galley, noncruise)	1	26	3686	1656								
(For. galley, noncruise)	1	26	2490	1232								
(Aft galley)	6	8	1547	2840								
(Aft galley)	6	8	4915	1469	2	6	969-board	680-board				
(Aft galley)	2	4	1547	N/A	2	6	408-ascent	402-ascent	14	98	2920	1171
(Aft galley)	3	37	4238	1387	2	6	390-cruise	340-cruise				
(Aft galley)	4	43	1800	1300	2	6	368-descent	359-descent				
(Smoking)	5	3	4900	1000								
(Smoking)	8	69	1910	1568								
(Nonsmoking)	5	13	1800	1000								
(Nonsmoking)	8	23	N/A	1746								
Carbon monoxide												
(Various)	6	8	7.0	<0.01								
(Various)	2	4	1.7	0.5								
(Various)	3	37	9.4	0.87	2	6	0.9-board	0.5 board				
(Various)	4	27	1.3	0.7	2	6	0.3-ascent	0.1-ascent	14	98	28	2.4
(Smoking)	5	3	5	3	2	6	0.3-cruise	0.1-cruise				
(Smoking)	8	69	3.4	1.4	2	6	0.7-descent	0.3-descent				
(Nonsmoking)	5	13	4	2								
(Nonsmoking)	8	23	1.3	0.6								
Ozone												
(Aft galley)	1	26	0.034 (66.1)	0.007 (13.7)								
Flight deck)	1	26	0.039 (76.1)	0.013 (26. 3)								
(Overall)	6	8	N/A	0.051								
(Various)	3	37	0.122	0.2								
(Smoking)	8	69	1.0	0.01								
(Nonsmoking)	8	23	N/A	0.02								

Table Abbreviations: N/A = Not Applicable; N/D = Not Detected; N/R = Not Reported

Table References (see Section 9 for full references): 1 = Lindgren and Norback2002; 2 = Nagda et al. 2001; 3 = Waters et al. 2001; 4 = Dumyahn et al. 2000; 5 = Lee et al. 2000; 6 = Pierce et al. 1999; 7 = Dechow et al. 1997; 8 = Nagda et al. 1992; 9 = Tucker 2001; 10 = Shields et al. 1996; 11 = Brown et al. 1994; 12 = Shah and Singh 1988; 13 = Larson et al. 2004; 14 = Miller et al. 2009. References 2, 4, 5, 6, 7, and 9 to 11 are summarized and discussed in Nagda et al. 2003.

TABLE 8.2.4a Published Measurements of Various Contaminants Reported on Noncomplaint Aircraft and in Buildings (data corrected to normal temperature and pressure conditions: 25°C and 760 torr [77°F and 14.7 psia]) *(Continued)*

	Cabin Air Measurements, ppm (numbers in parentheses on a weight basis)				Bleed Air Measurements, ppm (numbers in parentheses on a weight basis)				Building Measurements, ppm (office and residential)			
Chemical Name (Measurement Location)	**Ref. No.**	**No. Flights**	**Maximum Measured**	**Arithemetic Mean**	**Ref. No.**	**No. Flights**	**Maximum Measured**	**Arithmetic Mean**	**Ref. No.**	**No. Bldg. Measurements**	**Maximum Measured**	**Arithmetic Mean**
Particulate matter (PM)									13	161	65	10
Various	2	6	(660)-PM_{10} (645)-$PM_{2.5}$						($PM_{2.5}$)	98	119	27.2
									14 ($PM_{2.5}$)			
Various	7	N/R	4×10^8 particles/m^3									
	3	37										
Various	4	27	(380)									
Cruise			(3)									
Boarding	4	27										
nonsmoking			(90)	(2)								
nonsmoking	6	8										
nonsmoking	5	5	N/A	(<0.010)								
smoking	8	23	(<100)	(<100)								
smoking	5	3	(18)	(10)								
	8	69	(3300)	(200)								
			(355)	(177)								
Acetaldehyde (ethanal)	2	10	0.039	N/A	2	3	0.017	0.009	9	41		0.0039
	7	N/R	>1.78	0. 593								
Acetic acid	7	N/R	0.011	0.006					11	5		
Acetone	7	N/R	0.236	0.024	2	3	0.013	0.004	11	86	0.038	
		4							12	4		0.0080
	2	42	0.055 (130)									
	4		0.063 (150)	0.043 (103)								
Benzene	4	16	0.002 (6)	0.001 (3)	2	3	0.002		9	41		0.0018
									11	2171	71	0.0052
									12	2128		0.0052
2-Butanone	2	4	0.003 (9.4)		2	3	0.002 (6.1)		9	41		0.00064
	4	42	0.005 (16)	0.003 (8)					10	50		
									11	1867	0.013	
									12	2278		0.0029
Carbon disulfide	2	4	0.003 (9. 2)		2	3	0.0007 (2. 2)		11	39		
Chloromethane	2	4	N/D	0.017 (3.5)	2	3	0.010 (21)		9	41		0.011
	4	27	0.002 (4)						12	315		0.049

Table Abbreviations: N/A = Not Applicable; N/D = Not Detected; N/R = Not Reported

Table References (see Section 9 for full references): 1 = Lindgren and Norback2002; 2 = Nagda et al. 2001; 3 = Waters et al. 2001; 4 = Dumyahn et al. 2000; 5 = Lee et al. 2000; 6 = Pierce et al. 1999; 7 = Dechow et al. 1997; 8 = Nagda et al. 1992; 9 = Tucker 2001; 10 = Shields et al. 1996; 11 = Brown et al. 1994; 12 = Shah and Singh 1988; 13 = Larson et al. 2004; 14 = Miller et al. 2009. References 2, 4, 5, 6, 7, and 9 to 11 are summarized and discussed in Nagda et al. 2003.

TABLE 8.2.4a Published Measurements of Various Contaminants Reported on Noncomplaint Aircraft and in Buildings (data corrected to normal temperature and pressure conditions: 25°C and 760 torr [77°F and 14.7 psia]) *(Continued)*

	Cabin Air Measurements, ppm (numbers in parentheses on a weight basis)				Bleed Air Measurements, ppm (numbers in parentheses on a weight basis)				Building Measurements, ppm (office and residential)			
Chemical Name (Measurement Location)	**Ref. No.**	**No. Flights**	**Maximum Measured**	**Arithemetic Mean**	**Ref. No.**	**No. Flights**	**Maximum Measured**	**Arithmetic Mean**	**Ref. No.**	**No. Bldg. Measurements**	**Maximum Measured**	**Arithmetic Mean**
Ethylbenzene	2	140	N/D		2	3	0.002		11	656	0.029	
Ethyl alcohol (ethanol)					2	3	0.159	0.019	9	41		0.0011
Formaldehyde	1 6 7 3	26 8 N/R 37	<0.004 (<5) 0. 0049 0.00002 (0.026) N/D	0.012 (15) N/A 0.00001 (0.007)	2	3	0.003	0.002				
N-Hexane	4	27	0.006 (20)	0.003 (10)	2	3	2.27	1.13				
Methylene chloride	2			0.206 (714)	2	3	0.003	0.002	12	2195	0.0031	
Methyl *tert*-butyl ether	2 4	4 27	N/D N/D		2	3	0.014 (52)		9 10 11 12	41 50 792 220	 0.078 0.0074	0.0076
Nitrogen dioxide (NO_2) (Aft galley) (Flight deck) (Overall) (Various)	 1 1 1 3	 26 26 26 37	 0.02 (37) 3.1	 0.007 (14.1) 0.004 (7.0) 0.58					11	891	0.011	
Propionaldehyde	2	4	0.006 (13.7)		2	3		0.003	10 11	50 1587	0.025	
Tetrachloroethene	2 4	4 42	0.002 (12) 0.004 (28)		2	3	0.0003 (2)	0.0002				
Toluene	7 2 4	N/R 4 42	0.135 (0.51) 0.006 (21) 0.008 (29)	0.00 (0.018)	2	3	0.012 (45)	0.001				
Trichloroethene	2	4	N/D		2	3	0.0006 (3.4)		9	41		0.0039
o-Xylene	2 4	4 42	N/D 0.00069 (3)		2	3	0.0018 (7.8)	0.0009	11	5		
m,p-Xylenes	4	42	0.0018 (8)	0.0008 (3. 5)	2	3	0.0064 (2 8)	0.001	11 12	86 4	0.038	0.0080

Table Abbreviations: N/A = Not Applicable; N/D = Not Detected; N/R = Not Reported

Table References (see Section 9 for full references): 1 = Lindgren and Norback2002; 2 = Nagda et al. 2001; 3 = Waters et al. 2001; 4 = Dumyahn et al. 2000; 5 = Lee et al. 2000; 6 = Pierce et al. 1999; 7 = Dechow et al. 1997; 8 = Nagda et al. 1992; 9 = Tucker 2001; 10 = Shields et al. 1996; 11 = Brown et al. 1994; 12 = Shah and Singh 1988; 13 = Larson et al. 2004; 14 = Miller et al. 2009. References 2, 4, 5, 6, 7, and 9 to 11 are summarized and discussed in Nagda et al. 2003.

TABLE 8.2.4b Contaminant Concentrations Reported in Published Studies (Reprinted with Permission from National Research Council 2002, Table 1-2 pp. 26–27)

Contaminant or Cabin Characteristic		Nagda et al. (1989)	CSS (1994)	Dechow (1996)	Spengler et al. (1997)	Pierce et al. (1999)	Haghighat et al. (1999)	Lee et al. (1999[a])	Waters et al. (2001)	Nagda et al. (2001[b])
		Number of Flights								
		92	35	x	6	8	43	16	37	10
Ozone, ppb	mean	22 ± 23			x	51 ± 15		x	200 ± 180	
	min; max	X; 78			2; 10	<20; 122		0; 90	<50; 1000	
Carbon dioxide, ppm	mean	1756 ± 660	1162		1400	1469 ± 225	386-1091[c]	683-1557[c]	1387 ± 351	1380
	min; max	765; 3157	x; x		1200; 1800	942; 1959	293; 2013	423; 2900	664; 4238	x; 1755
Carbon monoxide, ppm	mean	0.6			0.7	x		1.9-2.39[c]	0.87 ± 0.65	0.2
	min; max	x; 1.3			0.8; 1.3	<0.1; 7		1.0; 4.0	<0.2; 9.4	X; 0.8
Nitrogen oxides, ppb	mean				36			4.5-49.6[f]	580 ± 700	
	min; max				23; 60			x; x	<200; 3100	
Particulate matter, $\mu g/m^3$	mean	37($PM_{3.5}$)	176 (PM_{10})		x (total particles)			1-17[c,d]	x (PM_{10})	<10 ($PM_{2.5}$ & PM_{10})
	min; max	x; 199[e]	140; 200		3; 10			nd; 1980	30; 380	
VOC, μ/m^3, with ethanol	mean		x	x	3171[e]	900 ± 450				
	min; max		x; 2200 (ppb)	x; 2200[e] (ppb)	608; 1805[e]	380; 1500				
Formaldehyde, ppb	mean			7		2.9 ± 1.7			x	7.2 ($\mu g/m^3$)
	min; max			3; 26		<0.6; 4.9			0; <0.07	x; 13 ($\mu g/m^3$)
Bacteria, CFU/m^3	mean	131.1 ± 123.4	x	x	201[f]	x		x		
	min; max	x; 642	0; 360	20; 1700	x; x	39; 244		44; 93		
Fungi, CFU/m^3	mean	9.0 ± 12.7	x			x		x		
	min; max	x; 61	0; 110			<1; 37		17; 107		
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; max	21.0; 27.2	x; x		22.2; 25.6	17.8; 26.1	19; 27	17.8; 26.3		23; 26
Relative humidity, %	mean	21.5 ± 5.1	16.8		18	14 ± 3.2	x	10.0 – 42.6[c]		10.5
	min; max	9.9; 30.8	x; x		17; 19	8.8; 27.8	1.8; x	4.9; 55.5		x; 34.3
Cabin-pressure altitude, ft	mean	4344			x	x				
	min; max	2415; 7212			5500; 6900	x; 6950				5500; 8000[g]

Table Abbreviations:
X = data not provided
CFU = colony-forming units.

Table Notes:
(a) Data from nonsmoking flights
(b) Values represent those in cabin during cruise
(c) Range of means
(d) Particle size range measured was not specified.
(e) Values from Space et al. 2000
(f) Geometric mean
(g) Range varied depending on aircraft type. For B767 and B747, cabin-pressure altitude was 5500 to 6500 ft during cruise, and for B737, approximately 8000 ft.

TABLE 8.2.4c Aircraft Sampling Data for Tricresylphosphate Isomers (TCP) and Tributylphosphate Isomers (TBP)

Source (see Note a)	Sampling Methodology
Muir et al. (2008)	Concentrations were reported as a 10–18 minute average based on approximately 1.2 L of air/sample. Ground operations: TBPs: <2–42 μg/m^3; oil fumes: 11–14 μg/m^3; TCPs: 0.6–1.3 μg/m^3. In-flight, transient oil fume event was reported in flight deck on B757. Oil odor noticeable for one minute and ultrafine particle levels increased for two minutes. Exposure was reported as an 18-minute average, so the peak TCP/oil exposures during this sample period could be underestimated by a factor of 10 (p. 71). Oil fumes: 5 μg/m^3; TCPs: 0.04 μg/m^3.
van Netten (2005)	Qualitative GC-MS analysis of a flight deck roof filter, recirculated air prefilter, HEPA filter, lavatory ceiling filter, flight deck wall, and pilot's trousers all tested positive for at least one TCP isomer.
Hanhela et al. (2005)	The authors conducted a Royal Australian Air Force investigation into cockpit air contamination in military aircraft (N=59). Sampling identified TCP oil additives, phenyl-α-naphthylamine and dioctyldiphenylamine (jet engine oil) and trialkylphosphates (hydraulic fluid). The majority of TCP samples were <4 μg/m^3 with two exceptions (22 μg/m^3, 49 μg/m^3). The authors recommended that total TCPs be kept below 1 μg/m^3.
CAA (2004)	As part of an investigation into pilot incapacitation, a U.K. regulator sampled duct linings on two commercial aircraft and identified TCP oil additives ranging from 24.7 to 73.5 μg TCP/g oil in ducts. See Chapter 2, Appendix A, Table 1.
Fox (2000a) as referenced in (Michaelis 2007)	In response to a request from its airline customer, Honeywell replaced the engine on a BAe146 with a reported oil fume event where the captain had been incapacitated in flight and conducted engine bleed air monitoring on the incident aircraft with the new engine. Honeywell measured oil-based contaminants in the bleed air supplied by that engine. TOCP was < DL, other TCP isomers (CASRN 1330-78-5) were detected at a maximum concentration of 4.9 μg/m^3, and TPP isomers were identified at a maximum concentration of 20 μg/m^3.
Fox (2000b) as referenced in (Michaelis 2007)	In response to a request from its airline customer, Honeywell removed the engine from a BAe146 with a reported oil fume event where the captain had been incapacitated in flight. Honeywell measured the oil-based contaminants in the bleed air supplied by that engine. TOCP was < DL, other TCP isomers (CAS 1330-78-5) were detected at a maximum concentration of 22 μg/m^3, and TPP isomers were identified at a maximum concentration of 8 μg/m^3.
Kelso et al. (1988)	The authors identified oil vapor and TCPs in the air filter bags in the air duct system of a Hercules aircraft and recommended that charcoal filters be installed in the bleed airstream.
Michaelis (2007)	Additional sampling data is referenced in this publication's Appendix 10, "Air Monitoring Research Summary." See pp. 741–776.

Note a: For complete bibliographic information on the sources listed here, see Section 9, "References."

Table Abbreviations:
TOCP = tri-orthocresyl phosphate
TPP = tetra-phenyl-porphyrin
CASRN = chemical abstract service reference number
DL = detectable level

TABLE 8.2.5 Thresholds and Limits for Selected Potential Contaminants in Aircraft Cabins (see Note a)

Intention of Value Listed		Protect General Public					Protect Workplace Personnel		Aircraft Crew and Passengers	Odor Threshold
CASRN	Chemical	WHO (values in ppm) (Note b)	EPA IRIS (lifetime values in ppm) (Note c)	EPA NAAQS (values in ppm)	ATSDR(values in ppm for >365 days) (see Note d)	Health Canada (HC) (ppm)	SMAC (values in ppm) (Note e)	ACGIH TLV (Note e)	FAR (values in ppm)	AIHA (values in ppm for lowest accepted detection)
75-07-0	Acetaldehyde (ethanal)	—	0.005		—	5	2	C 25	—	0.0028
67-64-1	Acetone	—	—		13	—	22	500	—	0.4
107-02-8	Acrolein	—	1.1×10^{-5}		0.000009 (I)	0.02 (note j)	0.15	C 0.1	—	0.022
71-43-2	Benzene	0.0003 (lifetime)	0.009 (0.0003) (note f)		0.0004 (I)	—	0.07	0.5	—	0.78
100-41-4	Ethyl benzene	—	0.23		1(I)	—	12	100	—	0.092
64-17-5	Ethyl alcohol (ethanol, ethanole)	—	—		—	—	1000	1000	—	0.34
50-00-0	Formaldehyde	0.08 (30 minute)	—		0.008	0.1 ppm (1 h); 0.04 ppm (8 h) (note j)	0.04	C 0.3	—	0.027
110-54-3	n-Hexane	—	0.06		0.6	—	50 (7 day)	50	—	65
75-09-2	Methylene chloride	0.86 (24 h)	—		0.3	—	3	50	—	1.2
123-38-6	Proprionaldehyde (Valeraldehyde)	—	—		—	—	40 (7 day)	20	—	0.0006
127-18-4	Tetrachloroethene	0.04 (annual)	—		0.04	—	7 (7 day)	25	—	2
6163-58-2	Tri-ortho cresylphosphate (TOCP) (note g)	—	—		—	—	NA	0.1 mg/m^3	—	NA
	Other tricresylphosphate (TCP) isomers	NA	NA	NA	NA	NA	NA	NA	NA	NA
108-88-3	Toluene	0.07 (1 week)	0.11		0.08	—	16	50	—	0.021
1330-20-7	Xylene isomers	—	0.02	—	0.1	—	50	100	—	0.081

TABLE 8.2.5 Thresholds and Limits for Selected Potential Contaminants in Aircraft Cabins (see Note a) *(Continued)*

Intention of Value Listed		Protect General Public					Protect Workplace Personnel		Aircraft Crew and Passengers	Odor Threshold
526-45-53-1	Permethrin	—	—	—	—	—	—	—	—	NA
26002-80-2	Phenothrin	—	—	—	—	—	—	—	—	NA
630-08-0	Carbon monoxide	9 (8 h)	—	9ppm (8 h); 35 ppm (1 h)	—	25 ppm (1 h); 10 ppm (24 h) (note j)	10	25	50 (note h)	NA
10028-15-6	Ozone	0.06 (8 h)	—	<0.075 (8 h) (note k)	—	0.02 (8 h) (note j)	—	0.08 (moderate work)	0.1 (3 h); 0.25 (Note i)	0.0076
124-38-9	Carbon dioxide						3500		5000 (note h)	NA
	PM2.5	25 $\mu g/m^3$	—	35 $\mu g/m^3$ (24 h) (note k)		30 $\mu g/m^3$ (note j)			—	NA
	PM10	—	—	150 $\mu g/m^3$ (24 hour)					—	NA

Table Abbreviations:
AIHA = American Industrial Hygienists Association
ATSDR = Agency for Toxic Substances and Disease
CASRN = Chemical Abstract Service Reference Number
EPA = Environmental Protection Agency
FAA = Federal Aviation Administration
FAR = Federal Aviation Regulations (14 CFR 25)
HC = Health Canada
I = Indicates that value is for intermediate exposure (>14–364 days) and that no chronic exposure value is available
IRIS = Integrated Risk Information System
N/A = Not Applicable
NAAQS = National Ambient Air Quality Standards
SMAC = Spacecraft Maximum Allowable Concentrations (developed by NASA)
TLV = Threshold Limit Value
WHO = World Health Organization

Table Notes:
(a) The use of this table should take into account the purpose for which the regulations/guidelines were adopted and the means by which they were developed.
(b) Values are from WHO (2000), which provides numerical guidance values for all compounds except benzene, upon which the carcinogenic risk estimate was based (unit risk = 6×10^{-6}).
(c) Values reported are Reference Concentrations (RfCs) of compounds with non-carcinogenic harmful effects.
(d) Minimal Risk Levels (MRLs) values reported are for chronic exposure, unless denoted by "I", which indicates intermediate (>14-364 days) exposure and that no chronic exposure value was available.
(e) Occupational exposure limit: values reported are 8-hour time-weighted averages (TWAs) unless otherwise noted (e.g., C = ceiling limit, the concentration that is not to be exceeded during any part of the work day). See also Table 8.2.2. Year 2003 editio of TLVs are reported here.
(f) The IRIS Risk estimate for benzene is 2.2×10^{-6} to 7.8×10^{-6} increase in the risk of cancer based on a lifetime exposure of 0.0003 ppm (1 $\mu g/m^3$).
(g) No exposure limits are available for the tricresylphosphate isomers, only for TOCP.
(h) The FAR for carbon monoxide is an operating standard and a design standard (FAA 1965; FAA 1997). The FAR for carbon monoxide is a design standard (FAA 1997).
(i) The FAR for ozone standard is 0.25 ppm (sea level equivalent) at anytime above sea level and 0.1 ppm (sea level equivalent) as a time-weighted average during any 3-hour period.
(j) Health Canada Standards are for acrolein formaldehyde, CO, ozone, and PM2.5. Allowable limits for aldehydes will drop when more than one aldehyde is present. The dose addition approach outlined in Healthcare Canada (2006; 2008a), para. 4.A.1 Aldehydes; should be utilized to assess the interaction of aldehydes. Health Canada (2010a) limits carbon monoxide exposure. Health Canada (2010b) limits ozone exposure. Health Canada (2008b) limits particulate matter. Health Canada (2011) provides proposed guidance for PM 2.5 in residential indoor air.
(k) EPA (2006) set PM2.5 limit at 35 $\mu g/m^3$ for health protection of the general public. EPA (2008) establishes the limit for ozone. EPA (2011) establishes the limit for carbon monoxide.

TABLE 8.2.6 Odor Characteristics of Selected Bleed Air Containments

CASRN	Chemical	Odor Description (Note b)	Lowest Acceptable Odor Threshold Value, ppm (range of values reported, ppm)			
			Source: AIHA (1989)	Source: EPA (1992)	Source: Devos et al. (1990)	Other Sources
75-07-0	Acetaldehyde (Ethanal)	Pungent/fruity	0.67 (Note c) (0.0028–1000)	0.87 (0.0015–1000)		
123-38-6	Valeraldehyde (Proprionaldehyde)	Sickening/decayed/rancid/acrid/pungent	NR (0.0006–8.2)	0.04 (0.0015–0.72)	0.006	0.28 (ACGIH [2010])
107-02-8	Acrolein	Pungent/choking	NR (0.022–1.8)	1.8 (0.03–1.8)	0.170	0.03 (WHO [1991])
123-72-8	Butyraldehyde	Pungent	—			0.005–9 (AIHA [1989])
100-52-7	Benzaldehyde	Almond	—		0.042	0.042 (NIH 2011)
4170-30-3	Crotonaldehyde	Pungent, suffocating	0.063 (0.063–0.147)			7 (NIH 2011)
50-00-0	Formaldehyde	Pungent/strong	NR (0.027–9770)	NR (0.53–9770)	0.87	0.8–1 (NIH 2011]); 0.02–0.49 (WHO [1991])
66-25-1	Hexaldehyde	Fruity/sharp	—		0.014	
124-19-6	Nonaldehyde	Oily/fatty	—		0.002	
107-92-6	Butanoic Acid	Unpleasant/rancid	—		0.004	
109-52-4	Pentanoic Acid	Unpleasant/rancid	—		0.005	
111-14-8	Heptanoic Acid	Disagreeable/rancid	—	—	0.028	
124-07-2	Octanoic Acid	Unpleasant/irritating	—	—	0.004	0.008 (NIH 2011)
142-62-1	Hexanoic Acid	Sweaty /dirty socks	—	—	0.013	
100-42-5	Styrene	Sharp/sweet	0.17 (0.0047–1.9)	0.017 (0.0047–1.9)	0.14	0.016 (WHO [1991])
108-88-3	Toluene	Sour/burnt (benzene-like)	0.16 (0.021–69)	0.021 (0.021–45)	>1.0	2.4 (NIH 2011); 0.3 (WHO [1991])

Table Abbreviations:
ACGIH = American Conference of Governmental Industrial Hygienists
AIHA = American Industrial Hygienists Association
ATSDR = Agency for Toxic Substances and Disease
CASRN = Chemical Abstract Service Reference Number
EPA = Environmental Protection Agency
HSDB = Hazardous Substances Data Bank (NIH 2011)
NR = Least acceptable odor threshold value NOT REPORTED
WHO = World Health Organization

Table Notes:
(a) See Table 8.2.1 for possible sources of the odors listed in this table.
(b) Sources of odor descriptions: AIHA; EPA; ASDB; Flavornet.
(c) No lowest acceptable value available, geometric mean reported.

Among these three categories, nonepisodic measurements have the most information available because such studies are published in the open literature. The NRC report (2002) and ACARM (Michaelis 2007) provides an excellent summary and critique of such studies. There is no public information available on trend monitoring because little such monitoring has been done to date. Measurements during episodic event investigations are still in a research and development stage, but these events are of most concern to crew members. However, it should be noted that few published reports include measurements of air quality during or after flights involving episodic events, such as the presence of hydraulic fluid or engine oil in the bleed air (Muir et al. 2008; Hanhela et al. 2005; CAA 2004; NRC 2002; Fox and Power 2000) or measurements under simulated oil leak conditions (Bobb and Still 2003; Crane et al. 1983). Very little information is available on standardized procedures for measuring the air quality impact of such events. The following paragraphs discuss approaches for addressing the episodic events. Many of these approaches may also apply to nonepisodic events and trend monitoring.

Although air-quality monitoring equipment is typically not carried on board commercial aircraft, when an event is identified, corrective action is normally undertaken by the aircraft operator to identify, isolate, and correct the source(s) of concern. Air quality measurements generally are not made if the source of contamination can be readily identified and if remedial actions can be taken. In instances when the source of concern is not readily apparent, a well-thought-out and written test plan is essential. The phase of flight when an event is noted must be taken into account to assist in determining the cause of the event. In addition, knowledge of the phase of flight can help to determine whether the event can be repeated on the ground or whether a flight test is required to duplicate the event. Phase of flight is the operational phase that the aircraft is in at the time of the event. Examples include taxi, takeoff, climb, cruise, descent, and landing. Other factors, such as deicing, position of other aircraft on the ground, and if the event was reported during ground operations may be noted to provide additional information to help understand the event. Regardless of the phase of flight, the test plan must be developed so that a suitable sample is acquired during such event.

The written plan should be reviewed with individuals experienced in such measurements and in aircraft operations prior to the implementation of the plan. Careful planning for air quality measurements is important. Inadequate measurement techniques may not necessarily identify the source of concern because the conditions that produced the episodic event may not occur during the testing period. Further, the types of contaminants chosen for monitoring may not be the ones that are related to the problem. Also, the measurement method or instrument may not have the needed sensitivity or reliability.

A comprehensive investigation includes all of the following actions. Investigator experience in air quality assessment of episodic events is very important to ensure that a proper monitoring design is developed, appropriate equipment is selected, and a well-documented investigation is implemented. Important factors to be considered in this type of investigation include the following:

- A review is made of aircraft mechanical/maintenance records that could impact air supply systems such as records pertaining to the applicable aircraft maintenance manual chapters 21, 29, 36, 49, 72, and 79.
- A clear hypothesis of the potential cause(s), to guide the investigation, is prepared.
- An accurate history of the events and the aircraft and flight conditions under which the events occur are documented.
- The appropriate type of equipment is selected for sampling and analysis or monitoring. It is critical that the sampling and analysis methods have desirable lower detection limits, range, bias, and precision to properly characterize the presence and magnitude of potential contaminants. ASTM D6399 (1999) provides useful information for selecting methods and instrumentation for characterizing cabin and supply air quality. Table 8.3.1 lists sources of information on methods for sampling and analysis of contaminants.
- Location of sampling equipment is important for optimizing the collection of airborne contaminants. Of critical importance is the need to sample as close to the source as possible.
- The relationship of phase of flight to the episodic event is characterized and documented.

Once the probable source is identified, it is critical to coordinate with maintenance so that the replacement of any component takes into account any potential contamination of secondary sources. Examples of secondary sources would be contaminated pack components (heat exchangers, high-pressure water separators, coalescing socks), ozone converters, ducts, and acoustic mufflers.

Consistent with the above points, investigators of odor events in aircraft cabins can follow the following steps of the experimental approach to assist in determining the sources of odors during episodic events.

1. *Observation and description of a phenomenon or group of phenomena*. Some questions to pose include the following: (a) Was an odor reported by any of the occupants? (b) What are the characteristics of the odor (oil, hydraulic fluid, deicing fluid, grease, electrical, or other)? (c) When does it occur? (d) Where exactly does the odor seem to emanate or is the strongest? (e) What are the aircraft conditions under which the odor is experienced (including phase of flight and nature and duration of the odor)?
2. *Formulation of a hypothesis to explain the phenomena.* In episodic events, some questions might include the following: (a) Were there any mechanical failures? (b) Was there any maintenance carried out prior to the event? (c) Are there any entries in the technical log or maintenance records pertaining to the relevant maintenance manual chapters? (d) Was the aircraft recently treated with pesticides? (e) What are the passenger/crew symptoms?

TABLE 8.3.1 Information Sources on Methods for Sampling and Analysis of Contaminants in Aircraft Cabins

No.	Reference	Comments*
1	ASTM D6399. Standard Guide for Selecting Instruments and Methods for Measuring Air Quality in Aircraft Cabins. *ASTM Annual Book of Standards*, Volume 11.03, ASTM International, West Conshohocken, PA.	Specific to measurements in aircraft cabins. This resource provides guidance in determining data quality objectives and selection of instruments and methods for a variety of chemical contaminants and relevant environmental factors. Both public exposure and workplace exposures are considered. **Note:** ASTM D6399 was originally promulgated in 1999 and is scheduled for updating in 2004.
2	*Air Sampling Instruments*, B.S. Cohen and S.V. Hering, Eds., American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH, 9th Edition, 2001.	Summarizes contemporary air sampling practices and procedures related to both public and workplace monitoring are considered. The book also contains a directory of manufacturers. **Note:** New editions are produced approximately every five years.
3	*NIOSH Manual of Analytical Methods*, M.E. Cassinelli, and P.F. O'Connor, Eds., Department of Health and Human Services, National Institute of Occupational Safety and Health, Washington, D.C., Publication 94-113, 4th Edition, 1994.	Collection of standardized sampling and analytical procedures for determination of contaminants in workplace air, and in the blood and urine of workers who are occupationally exposed; emphasis is on laboratory-based analysis, but the manual does address some portable instrumentation. **Note:** The *NIOSH Manual* was last updated in 1994; updates and corrections are available at http://www.cdc.gov/niosh/nmam.
4	*Compendium of Methods for the Determination of Air Pollutants in Indoor Air*. US Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, EPA/600/4-90/010, 1990.	Collection of standardized sampling and analytical procedures for determination of selected VOCs, SVOCs (PAH and B (a) P), CO, CO_2, and several other contaminants, along with air change. **Note:** This compendium was originally published in 1990; updates and corrections are made available at http://www.epa.gov/ttn/amtic.
5	*Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air*, US Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, EPA 625/R-96-010b, 2nd Edition, January 1999.	Collection of standardized sampling and analytical procedures for the determination of VOCs and SVOCs. **Note:** This compendium was last revised in 1999; updates and corrections are made available at http://www.epa.gov/ttn/amtic.
6	*Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air*, US Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, EPA/625/R-96/01a, July 1999.	Collection of standardized sampling and analytical procedures for the determination of acid-base inorganic aerosols and gases. **Note:** This compendium was last revised in 1999; updates and corrections are made available at http://www.epa.gov/ttn/amtic.
7	Bioaerosols: Assessment and Control, J. Macher, ed. American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 1999.	Comprehensive guide to the assessment and control of bioaerosols in the full range of contemporary workplaces. **Note:** this text is a revision of the previous document: Guidelines for the Assessment of Bioaerosol in the Indoor Environment, ACGIH, 1989.
8	Bioaerosols Handbook, C. S. Cox and C. M. Wathes, eds. Boca Raton, Lewis Publishers, 1995.	Handbook covers the principles and practices of bioaerosol sampling, descriptions and comparisons of bioaerosol samplers, calibration methods, and assay techniques.

* Publications 2–6 discuss equipment and procedures that may be incompatible with limitations of available space and electrical power commonly encountered in aircraft cabins.

3. *Use of the hypothesis to make predictions.* For instance, if it is an electrical odor, check the electric components. If the smell is of dirty socks, check out components that could have oil and air combined and the oil source that could be contributing.
4. *Performance of experimental tests to verify the hypothesis*. Cabin odor events have unique characteristics, including definitions and sampling strategies that do not pertain to normal indoor air quality.
   a. A variety of sampling approaches may be required to fully characterize the cause of an episodic event. The sampling strategy must address identification and detection of contaminants as well as rule out the presence of known potential contaminants. For example, if engine oil is suspected to be the source of an odor, the sampling strategy must address the proper methodology for detecting engine oil and/or breakdown products as well as rule out the presence of lower molecular weight hydrocarbons such as jet fuel and solvents.
   b. When considering appropriate sampling media for investigating episodic events, it is important to utilize a variety of sampling and analysis or monitoring techniques. The use of evacuated canisters, various adsorption tubes, and real-time instrumentation helps detect unknown contaminants and rule out known potential contaminants. It is critical that the person collecting samples be aware of the types

of compounds they are looking for and what techniques must be applied to acquire samples, which can be analyzed at the appropriate detection range for identification.

c. Consideration must be given to the selection of appropriate sampling and analytical methodology, for example per ASTM D6399 (1999). Measurement devices must provide a detection level low enough to address any guidelines that will be referenced. Once potential contaminants have been identified, the laboratory should be contacted to ensure that the methods selected and sample volumes being utilized achieve detection limits that address these guidelines. If this step is not taken, it is possible that the samples collected will not yield meaningful data. Measurement devices must be accurate over the full range of cabin altitudes encountered.

4. Proper sample handling is essential to ensure that samples do not degrade before analysis. Before a test commences, the personnel providing sample acquisition must ensure that they have required capability to keep sample media at correct shipping temperatures and that samples can be transported rapidly enough that hold times are not exceeded.

e. After sample collection, coordination with the laboratory is essential to ensure that analytical methods are used that provide the maximum amount of information. Evacuated canisters are normally analyzed for the presence of volatile organic compounds; however, they could also be used to test for levels of carbon monoxide and carbon dioxide. This requires that the laboratory utilize a different analytical technique. Good coordination with the laboratory ensures that the various samples are properly analyzed for the compound(s) of interest.

The investigator should be familiar with episodic events in order to understand what is necessary to go from episodic event measurement to monitoring nonepisodic levels of compounds. Other issues may still be present in future tests, after repairing episodic problems, that require further evaluation and repair. For example, replacing contaminated parts in an ECS without fixing the original source may allow recontamination of the replacement parts.

Regardless of the category of cabin air investigation, implementing a monitoring design can require a significant amount of time and coordination with airlines and airframe manufacturers. Equipment selected for the investigation must fit into the space available. Multiple units of the same type of equipment may be necessary in order to sample in various locations at the same time. This is a consideration in the final design of the test because it may be impacted by power availability. Electromagnetic interference (EMI) emissions data must be available for all instrumentation to be used on the flight, according to FAA procedures.

VOC collection and analysis with accuracies as high as ppb levels require specialized sampling and analysis equipment and may involve relatively expensive laboratory analyses to complement sophisticated air sampling equipment. Recent advances in air sampling equipment have allowed for detection of some contaminants at the low ppb range by using hand-held instrumentation. An example of this hand-held instrumentation is a photoionization detector. Other considerations that must be evaluated in measurement include the use of experimental versus proven investigation techniques and limited seat availability for equipment and persons on public flights.

Other items to be considered include the following:

- Testing in flight versus ground testing
- Testing as near potential sources as possible
- Testing from various locations within an air-conditioning system
- Testing at various heights within the aircraft cabin
- Number of individuals available to operate the equipment
- Whether the equipment will be used for monitoring over a considerable length of time and, if so, how long it must be able to operate without intervention
- Whether the measurement technique is capable of measuring pollutants created by an episodic event and time duration

Table 8.3.1 provides information of some potential sources of useful information relating cabin air sampling and analysis.

The following steps should be considered before conducting any cabin or supply air quality measurement exercise:

1. *Consider practical constraints.* An investigator may desire to capture an air quality sample in order to identify specific compounds responsible for a specific odor. There are several issues with this approach that must be considered. Odors on board an aircraft consist of a mixture of compounds. Individual levels of compounds may be below odor thresholds, but the mixture may still have a detectable odor. Measurement techniques must provide suitable analytical detection limits to allow use of data when it is below TLV limits. Collection of a sufficient amount of sample requires design of techniques that can do this sampling in short intervals. An important issue that one must face is that downtime on aircraft translates into loss of revenue. Sampling techniques must be capable of acquiring the necessary information without greatly impacting airline operations.
2. *Develop hypothesis.* Developing hypotheses to explain potential causes of complaints needs to be an inherent part of an investigation. Developing a hypothesis means developing a best understanding about the potential causes or, in other words, "a theory" that may explain the problem. Given the complexity of many problems, developing and testing such theories is an iterative process. The investigator should review and analyze information gathered at various points of the investigation and synthesize this information in the form of a hypothesis.
3. *Select or define data quality objectives.* Once the level of concern for pollutants has been identified, one must

define the data quality objectives. These data quality objectives must include the following concepts:

- ***precision:*** a measure of the repeatability of a measured value under a given set of conditions.
- ***accuracy:*** a measure of the correctness of the data, as given by the difference between the measured value and the true or standard value.
- ***method detection limit (MDL):*** the minimum concentration that has a stated probability of being identified and reported to be greater than zero
- ***representativeness:*** the degrees to which measurements are characteristic of the whole medium, exposure, or dose for which the data will be used to make inferences.

The *Indoor Air Quality Handbook* (Spengler et. al., 2000) again covers in some depth determining your data quality objectives. ASTM D6399 (1999) also provides a good discussion on determining data quality objectives.

4. *Evaluate the operational requirements for the testing location.* The *Indoor Air Quality Handbook* (Spengler et al. 2000) provides information useful in evaluating operational requirements. However, when conducting a measurement campaign on board an aircraft, additional issues must be considered before determining which methods or instruments to use for measurements.
   - Availability of power is very limited and may be difficult to obtain without special engineering approval for the airframe in question. Commercial aircraft potentially have several types of power available. Use of aircraft typically requires specialized frequency changers or inverters in order to provide sufficient power for higher energy consumption equipment. Aircraft have 28-volt direct current (DC) power on board, but alternating current (AC) sources are typically 400 Hz and can be either single or three phase. Equipment meant for operation on 50 or 60 Hz will not function properly on a 400 Hz supply.
   - AC power may be available by tapping into galley power and using a static frequency changer or a combination of 28-volt DC inverter and static frequency changer to generate 120 volts AC 60 Hz. Frequency changers are also available that convert power from vacuum cleaner outlets (120 volts AC 400 Hz) to 120 volts AC 60 Hz. Alternatively, a user may be able to obtain three phases of AC power from three separate outlets in order to utilize a static frequency changer. Three-phase static frequency changers may be less costly and provide greater power output than single-phase frequency converters.
   - The airframe manufacturer and airline-engineering department should be consulted to determine the best source of power to meet their requirements. If none of the above options is available, battery-operated equipment may have to be utilized. Consideration should be given to the data objectives to ensure that battery-powered equipment is able to meet these objectives. External portable generators may be used on the ground if one is careful to ensure that ingestion of exhaust by the aircraft system does not adversely affect data quality. EMI emissions testing is required for any electric components brought onto the plane. For ground or in-flight testing, DO-160 in its applicable version (RTCA 2007) applies.
   - In addition to power requirements, consideration must be given to the portability of instruments to be used onboard aircraft. Space on aircraft is very limited. Time schedules require that equipment be easy to set up and have short warm-up times. The equipment must be light enough to easily transport to and from the aircraft, facilitating coordination with the flight crew and security.
5. *Select methods and appropriate instrumentation for measurement.* The user should refer to Table 8.2.3 in order to determine recommended methods for the various pollutants being measured. Equipment manufacturers are continually making improvements to equipment, improving detection limits, reducing size and weight, and reducing power requirements and warm-up times. It is worth the time to perform a study of the variety of equipment available. Users should buy as current a design as their budgets allow. Manufacturers often stop supporting maintenance of equipment after it has been in the field for a number of years because of these improvements. The *Indoor Air Quality Handbook* (Spengler et al. 2000) and ASTM D6399 (ASTM 1999) have gone to great lengths to describe the wide range of measurement equipment available. It should be noted that the ASTM procedure does not cover bioaerosols.
6. *Monitoring designs and sampling issues (including locations, etc).* Airflow, particle, and gaseous contaminant testing should include on-the-ground measurements prior to cabin occupancy, 10 minutes after full occupancy, and just prior to debarking. In-flight testing should be conducted during different phases of flight such as taxi, takeoff, cruise, descent, and upon landing. Designs similar to those created in ASHRAE RP-1262 (BMI 2004) should be considered. Test in occupied locations as agreed upon, such as at tray level, at supply air outlets at the rear of cabin in coach class near the lavatories, at midplane in coach class, and in business or first class near the front of the plane. Note the occupant activity level at each test time: the number sleeping, the number awake, the number eating or drinking, and the number in line to use a lavatory.
7. *Interpret data.* Once testing data results have been obtained, determine the potential origins of any unusual gases and particles and those that exceed indoor air norms or approach standards. Check for cabin sources and sinks using pre- and postcabin occupancy test data. VOC sinks include cabin fleecy materials, ventilation system components, and occupants. Note that sinks can reduce apparent but not actual exposures. Take measures to miti-

gate or eliminate these sources so that norms are not exceeded.

8. *Address quality assurance issues.* Quality assurance issues are discussed in the *Indoor Air Quality Handbook* in some detail. It cannot be stressed enough how important it is to have a suitable quality plan in place for testing. Test results are often revisited and scrutinized in great detail. If attention is not paid to detail at the time of test, it is impossible to go back and recreate test setups. It is important to note that the quality assurance issues must be addressed for both the sampling strategy that was used and the analytical methodology used to evaluate samples.

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(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX A MEASUREMENT METHODS FOR AIRBORNE CONTAMINANTS, CABIN PRESSURE, AIRFLOW, AND AIR VELOCITY

This appendix provides the user with examples of possible methods for conducting measurements of cabin pressure, airflow, and air velocity to determine how an aircraft compares with ASHRAE Standard 161 (ASHRAE 2007) (within estimated margins of error) or simply to assess ventilation airflows and air motion. These methods may be adapted as necessary depending on the aircraft architecture. The methods described are by no means the only acceptable approach.

Some of the recommended methods utilize test instruments that are not permanently mounted within the aircraft, while others require modifications to the aircraft air distribution ducting. Portable instruments may not need to be electromagnetic interference (EMI) certified if these measurements are taken while on ground.

A1. AIRBORNE CONTAMINANTS

A1.1.1 Introduction. Section 7.2 of ASHRAE Standard 161 requires the user to monitor the air supply system for a substance or substances indicative of air supply system contamination by partly or fully pyrolyzed engine oil and hydraulic fluid and to display data at or above a defined "trigger point" in real time in the flight deck. The standard does not require the user to monitor and record exposure to other potential sources of bleed air contaminants, such as deicing fluid or exhaust fumes, although this information may be useful. Ozone monitoring is not required, although ozone monitoring is recommended as a means to comply with the ozone exposure limits in Section 7.1 of Standard 161 that mirror the current federal aviation regulations in the U.S. (FAA 1996).

A1.2 Sensor Location(s). There are several sources of hydraulic fluid and engine oil contamination. Hydraulic fluid from a leaking line or an overserviced reservoir, for example, can be ingested into either the auxiliary power unit (APU) or tail-mounted engines, where it is aerosolized and possibly fully or partly pyrolyzed and, thereby, contaminates the supply air. Engine oil can leak from inside the engine compressors of the APU and wing- or tail-mounted aircraft engines where it is pyrolyzed. The air-cycle machine (ACM) is another source of aerosolized oil on older designs with oil-lubricated bearings, but the temperature is lower than it is in either the APU or engines. The ACM is one component of an air pack that cools and conditions bleed air before it is mixed with recirculated air (typically for the cabin, not the flight deck) and supplied to the occupied zones.

There are multiple air supply source/air pack configurations. For example, either the APU or an engine may supply bleed air to a single pack or multiple packs, although typically at least one pack conditions supply air routed to the cabin, while the flight deck has its own dedicated pack. On some aircraft, supply air from different packs is mixed before it is supplied to either the cabin or flight deck. On other aircraft, there is no crossover supply air between packs under normal conditions.

Section 7.2 requires that the supply air be sampled by at least one sensor before it enters the cabin or flight deck, so the minimum sensor requirements vary depending on the air supply source/air pack configuration. However, a separate sensor is recommended for each air supply source (e.g., APU, each engine). If the packs have oil-lubricated bearings, then a sensor should also be placed downstream of each air pack. The data thus collected would enable both pilots and maintenance staff to identify and isolate a source of contamination more quickly. Prompt identification and isolation limits additional exposure in flight, perhaps preventing a diversion, reducing maintenance time on the ground, and increasing the likelihood that the mechanical fault is identified and rectified prior to further flight.

Secondary considerations for selecting sensor location include space available, temperature and pressure conditions in the air supply system, and ease of access for maintenance. If air-cleaning devices are installed in the bleed airstream downstream of one or more potential sources of contamination, then installing a sensor upstream and downstream of each air-cleaning device provides feedback on air-cleaner life and an extra measure of protection by enabling maintenance to address leaks or spills before the air supply becomes contaminated.

A1.3 Type of Sensor(s). It is difficult to recommend specific technologies for continuously monitoring and recording exposure to pyrolyzed oil and hydraulic fluid in the air supply system because the majority of research and development in the field has focused on means to collect such exposure data either for research purposes or to troubleshoot contaminated air supply systems after an incident has been reported. However, in satisfying the requirements of Section 7.2, it is recommended that the user monitor the air supply system for contaminants that are specific to oils and hydraulic fluids. Doing so should reduce (and in theory eliminate) the rate of false positives likely to occur with more generic air supply contaminants, such as total volatile organic compounds (TVOCs). False positives could be costly for aircraft operators and manufacturers and, worse, eventually even real alarms would be ignored by staff.

Although Section 7.2 defines trigger and exceedance levels for carbon monoxide (CO), CO monitoring alone is not recommended because CO generation is temperature-dependent and the temperature in the operating aircraft engine or APU, under some operating conditions, may not be high enough to generate CO. The air supply bleed source temperature depends largely on the aircraft and engine type, the stage of engine bleed, the air supply source, the phase of flight, and ambient conditions. In-service testing would have to prove the validity of CO as a reliable marker of bleed air contamination over a wide range of engine and operating conditions, which may be unrealistic.

Most commercial aviation engine oils and hydraulic fluids contain tricresylphosphates (TCPs) and tributylphosphates (TBPs), both characterized as semivolatile compounds (SVOCs). Health-based exposure limits suitable for crew-

members and the flying public have not been defined for either TBPs or TCPs. The presence of hundreds of additional compounds in supply air contaminated with pyrolyzed oil or hydraulic fluid further complicates efforts to define acceptable exposure limits, either for individual compounds or families of compounds. A real-time monitoring system that can measure these contaminants reliably at 0.01 $\mu g/m^3$ or lower and differentiate between them is recommended. This level is at the low-end of TCP/TBP airborne concentrations that have been measured in either the cabin or flight deck (Hecker et al. 2009; Muir 2009; Hanhela et al. 2005) and should be used as both a trigger point and an exceedance level. This concentration is not intended to be a health limit; rather, it should be considered an indication of system contamination. The goal should be to prevent any pyrolyzed oil and hydraulic fluid from contaminating the aircraft air supply system. Although there are no off-the-shelf SVOC monitoring systems specifically designed to monitor levels in the aircraft air supply system, there are technologies that may be appropriate. For example, ion mobility spectrometry is particularly sensitive to organophosphate compounds and other SVOCs (e.g., polyalphaolefins). A prototype system capable of simultaneously measuring exposure to SVOCs, VOCs, CO, and particulate in the bleed air system has been developed (Owlstone 2006), combining a field-asymmetric ion mobility spectrometer, an integrated solid state sensor, and a laser scattering detection array.

One option may be to install a contaminant sensor specific to constituents of oil/hydraulic fluid (as described above) downstream of all the contamination sources in combination with a sensor that monitors for more generic contaminants (e.g., particulates) on each air supply source.

Biological monitoring is also of interest, although it would not satisfy the supply air monitoring requirements of Section 7.2. A blood test is under development that will identify two proteins in the blood that are modified in predictable ways upon exposure to a metabolite of TCPs (Kim et al. 2009). The modified proteins have half lives of 11 and 35 days, respectively.

A1.4 Flight Deck Indication. Section 7.2 requires that indication from the sensor(s) be displayed in the flight deck and recorded anytime the concentration is at or above the contaminant's trigger point. It is especially important that flight deck indication be streamlined and unambiguous because a pilot's judgment and reaction time may be impaired upon exposure to fumes in flight (AAIB 2004, 2007, 2009; SAAIB 2006; FAA 2004; SHK 2001; Rayman and McNaughton 1983; Montgomery et al. 1977). It is critical that indicator messages delivered to the pilot be immediate and appropriate. One option for aircraft with an EICAS display is to use text messages with color indicators. Beyond the requisite smoke/fumes checklist, airlines should train both flight deck and cabin crewmembers to recognize and respond to bleed air exposures (CAA 2000, 2001, 2002, 2008).

A1.5 Sampling Data Made Available. Section 7.2 requires that reports of exceedances shall be made available for at least 60 days to airline maintenance staff and occupants with a medical record indicating symptoms that could reasonably be attributed to exposure to one or more relevant contaminants. The sensor data should be sent to a central computer that can easily be accessed by maintenance. In 2008, two FAA-funded research consortia published a healthcare providers' guide intended to educate physicians on the potential health impact of exposure to pyrolyzed engine oil and hydraulic fluid (Harrison et al. 2008). The guide is available online, and the symptom lists in Tables 4 and 5 are recommended as a resource for symptoms that could reasonably be attributed to fume exposure.

A1.6 Response to an Exceedance. The response to an exceedance varies depending on the number, magnitude, and frequency of triggered events. Line maintenance staff generally rely on visual inspection of aircraft systems and on assessing odor in the cabin or flight deck. They have limited ability to troubleshoot internal oil leaks, and sense of smell is an unreliable indicator of exposure because it is easily compromised. In addition to visual inspections, line maintenance staff should receive training on assessing oil use and on analyzing sensor data and maintenance history as they relate to sources of air supply contamination.

A1.7 Portable Monitors for Additional Information. Section 8.2 of ASHRAE Standard 161 notes that sampling and analytical devices that are reliable and easy to operate would be useful in the cabin and flight deck as an additional source of information to validate and/or quantify certain types of contamination events. Three research projects have attempted to either define (Havermans et al. 2007) or field test (Hecker et al. 2009; Muir 2008) sampling equipment intended to capture exposure to oil-contaminated supply air. Each has met with varying degrees of success.

One field survey validated a portable air monitoring device for sampling cabin air for low-level exposures to TCP oil additives, even at contamination levels not associated with visible smoke/fumes or reported symptoms (Hecker et al. 2009). The validated sampler is reliable and easy to operate but does not report data in real time.

Diffusive thermal desorption (TD) tubes were found to have a detectable level that is too high for capturing even a noticeable fume event. While pumped TD tubes may be suitable for troubleshooting cabin or flight deck air during predetermined phases of flight, they may take as long as a minute to deploy and so are not suitable for capturing transient events. A photoionization detector appears to be an ineffective indicator of elevated VOC levels that may indicate air supply contamination (Muir 2008).

A2. CABIN ALTITUDE/PRESSURE MEASUREMENT AND RATE OF CHANGE OF CABIN ALTITUDE/PRESSURE

Cabin altitude is already monitored and controlled on a continuous basis. Those data may be logged on some aircraft. For aircraft without equipment capable of logging cabin altitude/pressure, the following method may be used.

Cabin pressure and cabin pressure rate of change only need to be measured at one location within the aircraft cabin, as the pressure gradients in the cabin are minimal. A single pressure sensor may be used for both cabin pressure and cabin pressure rate of change, or separate sensors may be used for

the two measurements. The measurement systems should provide recording of measurements for the entire flight, from take off to landing, and should retain these values for a minimum of 24 hours. Easy access to measurement system for data download should be provided. Requirements for measuring systems to provide adequate accuracy are as follows:

Cabin Pressure Rate of Change (pressure sensor)
Measurement frequency: at least one pressure measurement every five seconds
Sensor overall accuracy: <0.15 psi (1 kPa) and <0.015 psi (0.1 kPa) pressure change over one minute
Sensor range: 15.8 to 8.3 psia (109 to 57 kPa)

Cabin Pressure
Measurement frequency: at least once every 30 seconds
Sensor overall accuracy: <0.04 psi (0.3 kPa) or <100 ft (30 m) cabin altitude
Sensor range: 15.8 to 8.3 psia (109 to 57 kPa) or –2000 ft to 15,000 ft (4570 m) cabin altitude

A3. AIRCRAFT VENTILATION AIRFLOW MEASUREMENTS

Several measurement methods that have potential application for assessing ventilation airflows in aircraft cabins are described below with strengths and weaknesses. Selection of a particular measurement method may vary depending on particular needs and conditions at a given measurement location. For reliability, it may be advisable to use more than one method. Anyone attempting to collect these measurements must have the necessary expertise with the aircraft systems and measurement methods because the aircraft systems and their operation are complex and require highly specialized knowledge.

Airflow requirements and recommendations in ASHRAE Standard 161 (ASHRAE 2007) are described for occupants (i.e., passenger seats) and for specific areas of the cabin (galleys, jumpseats, crew rest, and lavatories). For the passenger seats, investigators need to ensure that, on average, those in the most densely occupied cabin zones are being provided with the requisite minimum airflow. To do so, investigators must also account for airflow to areas other than the passenger cabin such as cargo, avionics supply duct, flight deck, crew rest, lavatories, and galleys, depending on the aircraft system configuration (e.g., avionics may be a closed system). Investigators should assess compliance with the minimum ventilation requirements and recommendations for the lavatories and the crew work areas (galleys, jumpseats, and crew rest) by measuring flow rates and air velocities at those locations independent of the passenger seating requirements and recommendations. In addition to the basic airflow measurements, it is recommended that investigators identify and address any obvious stagnant or drafty areas of the cabin.

In Section A3.1, three measurement methods are described, including (1) use of airflow hoods placed over air inlets to a zone, (2) use of Pitot static pressure taps (PSPT) permanently installed in aircraft ducting, and (3) use of metered tracer gas. A fourth method is described using concentration differences and mass balances to determine relative flow from multiple sources. In Sections A3.2, A3.3, and A3.4, the application of these methods for determining total airflow to a zone, outside airflow to a zone, and personal airflow outlet (PAO) airflow is described.

This appendix does not reference the use of estimated CO_2 occupant generation rates as a basis for estimating outside air supply flow to a given control zone because of concerns about the accuracy of this measurement method in occupied aircraft. Also, relying on assumptions about occupant CO_2 generation rates, which are influenced by occupant loading, occupant metabolic rates, and cabin pressure, could lead to greater compounding of measurement error.

Cost, ease of implementation, and accuracy of the various methods discussed here vary:

- The airflow hood method is typically inexpensive and simple to implement, but accuracy is likely no better than +0/–25%. This method does not require sample ports but does require custom-made flow hoods. It is typically used for assessing relative balance of airflow in aircraft rather than determining absolute flows.
- PSPTs can provide measurement accuracy of ±10% in ducting with adequate duct lengths upstream and downstream of a probe to ensure uniform flow. Accurate flow measurement is difficult with nonstraight duct configurations, and under such conditions, many more data points are required to determine the velocity profile. In addition, to obtain valid PSPT measurements, probes must be properly positioned and oriented.
- Metered tracer gas methods can provide measurement accuracy of ±10%. Specialized equipment that is more expensive than that of the other two methods is required. Manufacturer test and implementation methods should be strictly observed.
- The mass balance method has been least used of the available methods. This method can only determine ratios of flows and not airflow values. The accuracy of the ratios determined by this method is described in Section A3.1.4.

A3.1 Airflow Measurement Methods. Each of the four measurement methods is described in turn.

A3.1.1 Airflow Hoods. With this method, the hood must fit tightly to the surfaces surrounding the inlet so there is no leakage and all air from the inlet passes through the metering station. Because of the complex geometry and unique air inlet designs of many aircraft, custom hoods are required. Most aircraft use long, narrow air inlets that may run the entire length of the aircraft cabin. These inlets are generally divided into sections internally, and individual sections may be on the order of 10 ft (3 m) long. It is important that the hood be designed and placed so that the hood boundaries match with the inlet section boundaries (See Figure A-1). The hood must cover an integer number of sections for accurate measurements.

Each inlet or group of inlets are measured in turn until all flows into a zone are measured. Depending on the design of the air supply system and the airflow hoods, the placement of the airflow hood over an air inlet may significantly alter the

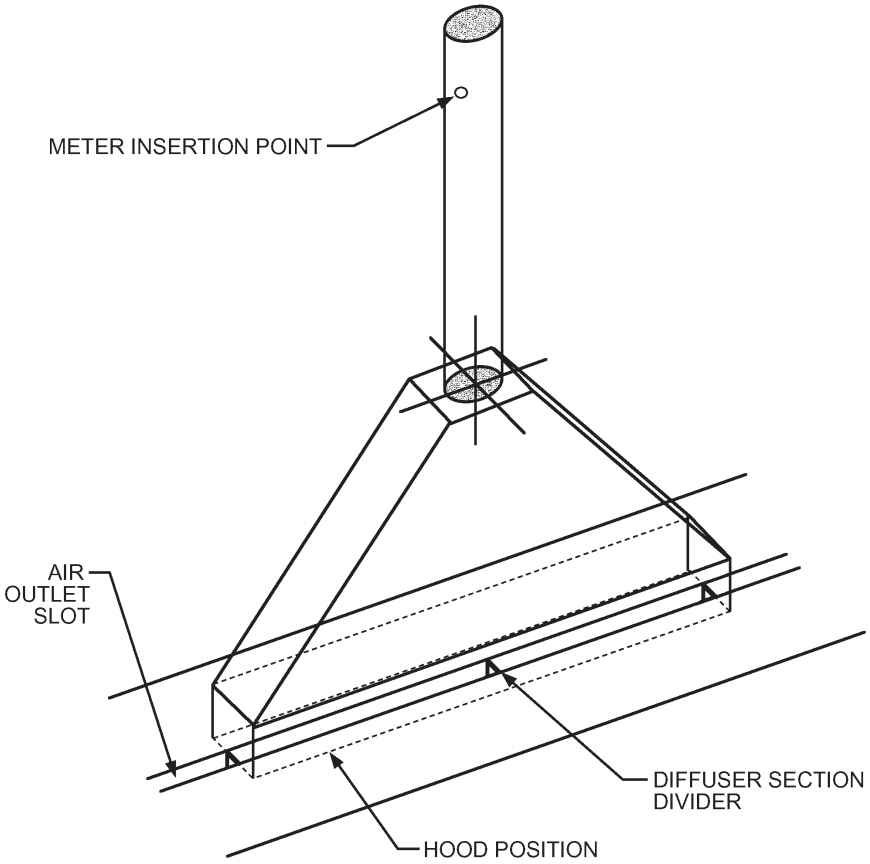

Figure A-1 Position of airflow measuring with respect to diffuser sections.

flow through that inlet. Therefore, the airflow hood measuring system used needs to include back pressure compensation (ASHRAE 2008). The airflow metering device should be verified accurate by calibration to within 5% of the measure flow for the flow range used. Correction factors are applied if needed to obtain this level of accuracy for diffusers of the type utilized in the aircraft (see Figure A-4).

A3.1.2 Pitot Static Pressure Taps. In this measuring technique, Pitot static pressure taps (PSPTs), such as that shown in Figure A-2, are permanently installed at key locations in air ducts in the aircraft. These devices may be installed at the time of manufacture of the aircraft or as a retrofit. Depending on the planned use of the devices, they may be installed in the air supply duct(s) to each cabin zone as shown in Figure A-3. They may also be installed in the recirculated air duct(s) and in pack air supply duct(s). The tubing for connecting to the pressure gauge is capped off during normal operation, but the caps are removed for flow measurement. The caps may be located remotely, with tubing connecting them to a readily accessible location in the cabin.

Since aircraft environmental control system (ECS) air ducts are often of complex geometry with limited straight, uniform lengths of ducts, *in situ* calibration of PSPT is required if the installation does not meet the PSPT manufacturer's requirements for an accuracy at least as good as 5% of reading. Two acceptable methods for calibration follow.

A3.1.2.1 Calibration of PSPT with a Calibrated Air Source. With passenger doors open, a calibrated air source is attached to the supply ducts with all other ducts closed off. The prescribed amount of flow is forced into the system at source and/or branch locations. The caps are removed, and differential pressure transducers are installed at the instrument to measure P_v (velocity pressure) as a function of airflow while the air sources are operating at the prescribed flows (Figure A-4). Airflow should be varied over the full range of flows expected for the duct in operation, and sufficient data points need to be recorded to provide a well-defined calibration curve. The temperature of the air passing through the calibration device and the PSPT should also be measured. The calibration device should be verified accurate to within 2% for the airflows provided. The pressure transducer should be verified accurate to within 2% of the differential pressure reading. The temperature sensor should be verified accurate to within +2°F (1°C) at the temperature of the calibration air. Care must be exercised to verify there are no leaks or other airflow paths between the calibration source and the PSPT. Due to the complexity and inaccessibility of ducting, it may not be possible to isolate all individual zone ducts on some aircraft, which limits the applicability of this method.

A3.1.2.2 Calibration of PSPT with Metered Tracer Gas. For this method, air is supplied from an external source as described in Section A3.1.2.1 or from aircraft systems. Whichever source is used must be able to generate an airflow

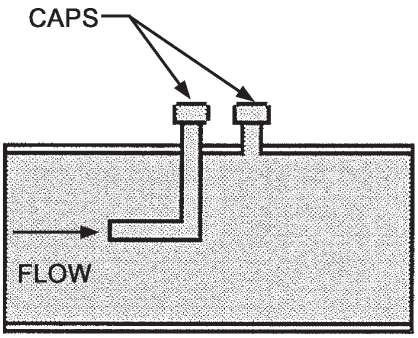

Figure A-2 PSPT installed in duct.

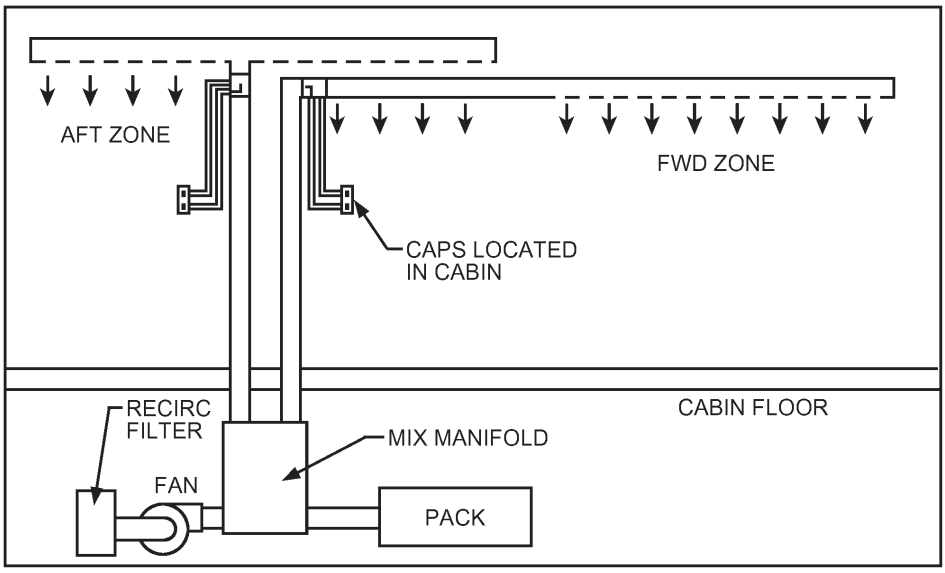

Figure A-3 Pitot static pressure taps located in air ducts with remote caps (similar PSPTs can be located in the pack and recirculated air lines).

through the duct in question at flow rates that include the full range of operation of the ECS. The prescribed amount of flow is forced into the system at source and/or branch locations. The airflow through the duct is measured using the tracer gas method described in Section A3.1.3. The PSPT caps are removed and differential pressure transducers are installed at the instrument to measure P_v (velocity pressure) as a function of airflow while the air sources are operating at the prescribed flows. Airflow should be varied over the full range of flows expected for the duct in operation, and sufficient data points need to be recorded to provide a well-defined calibration curve. The temperature of the air passing through the duct and the PSPT should also be measured. The pressure transducer should be verified accurate to within 2% of the differential pressure reading. The temperature sensor should be verified accurate to within +2°F (1°C) at the temperature of the calibration air.

A3.1.2.3 Special Requirements for Recirculation Air Ducts. Due to the possibility of altered velocity profiles in the duct from uneven recirculation air filter loading over its life, the following additional requirements apply for PSPTs placed in recirculation air ducts if the length of duct upstream of the PSPT is not at least five duct diameters. The PSPT should be of a type that is demonstrated to accurately measure the airflow independent of velocity profile in the duct with no more than 5% variation in reading due to differences in velocity profile over the range of velocity profiles that may be present. Alternatively, the PSPT is acceptable if the airflow indication is in error by no more than 5% with 1/3 of the face area of the recirculation filter blocked. This test is performed at the time of calibration and the test should be conducted with at least two different, nonoverlapping face areas blocked.

A3.1.2.4 Measurements Using PSPTs. Once calibrated, the PSPT may be used to measure the airflow through the duct in which it is installed. To make a measurement, the caps are removed and the pressure lines are connected to a differential pressure transducer. The pressure transducer should meet the same specifications given above for the transducer used for calibration. The pressure measurement and the calibration

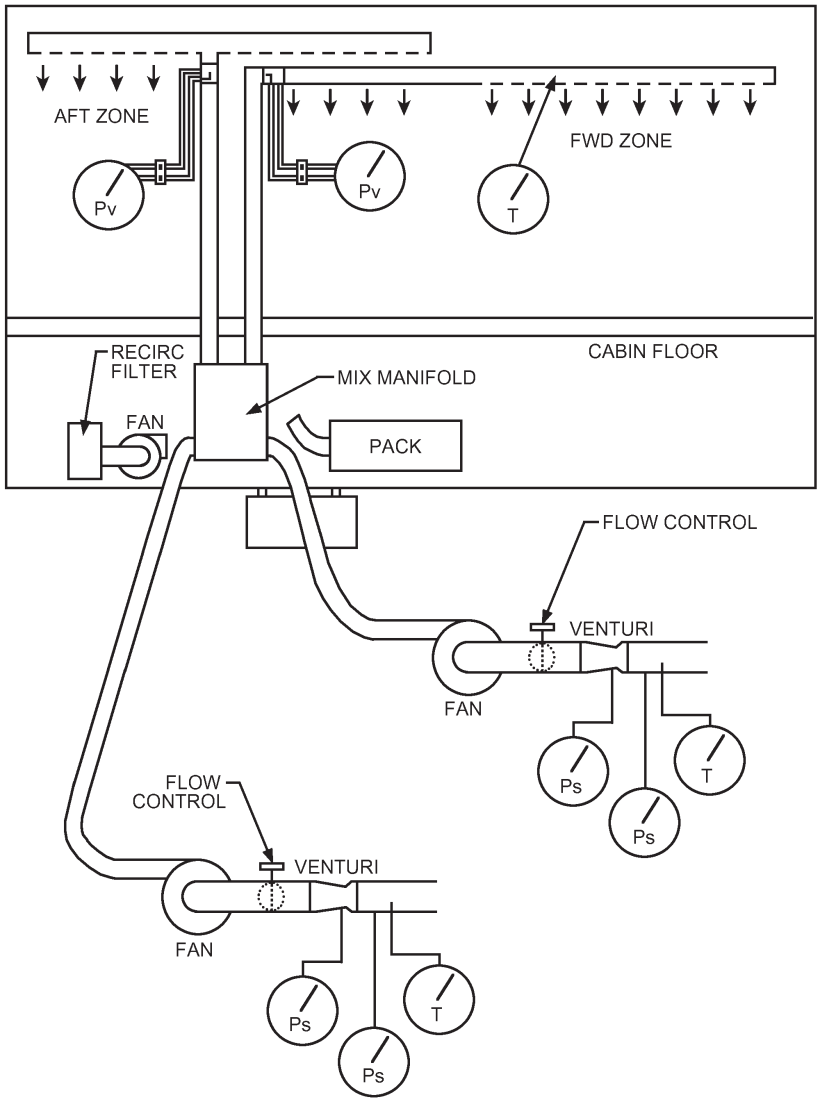

Figure A-4 Flow sources and pressure transducers installed to calibrate a Pitot static pressure tap (flows are measured one zone at a time with ducts to other zones closed).

curve for the device are used to determine the airflow through the duct at the time of measurement.

Since ASHRAE Standard 161 (ASHRAE 2007) specifies airflow requirements in volumetric terms, it is necessary to correct the readings from the PSPTs for cabin altitude and temperature if the purpose of the measurements is for comparison to this standard. The pressure reading is corrected as follows:

$$P_{v,\,\mathrm{cor}} = P_{v,\,m}(T_{\mathrm{cal}} / T_m)(P_{\mathrm{cabin}} / P_{\mathrm{cal}}) \qquad \text{(A-1)}$$

where

$P_{v,\mathrm{cor}}$ = corrected velocity pressure, psi (kPa)

$P_{v,m}$ = measured velocity pressure, psi (kPa)

T_{cal} = absolute temperature of the air provided by the calibration device, R (K)

T_m = absolute temperature of the air at the time of measurement, R (K)

P_{cabin} = barometric pressure of the cabin at the time of calibration, in. Hg (mm Hg)

P_{cal} = barometric pressure of the cabin at the time of the measurement, in. Hg (mm Hg).

The corrected differential pressure is then used with the calibration curve for the PSPT to determine the airflow through the duct.

A3.1.3 Metered Tracer Gas. The basic principle of measuring airflow with a tracer gas is illustrated in Figure A-5. A metered flow of tracer gas is injected into the air duct in question. The amount of tracer gas injected should be no more that 1% of the airflow through the duct by volume or mass so as not to significantly alter the airflow. The airflow through the duct is determined by the rise in concentration of the tracer gas according to

$$V_a = (M_{\mathrm{tg}} / \rho_{\mathrm{tg}}) / (C_d - C_u) \qquad \text{(A-2)}$$

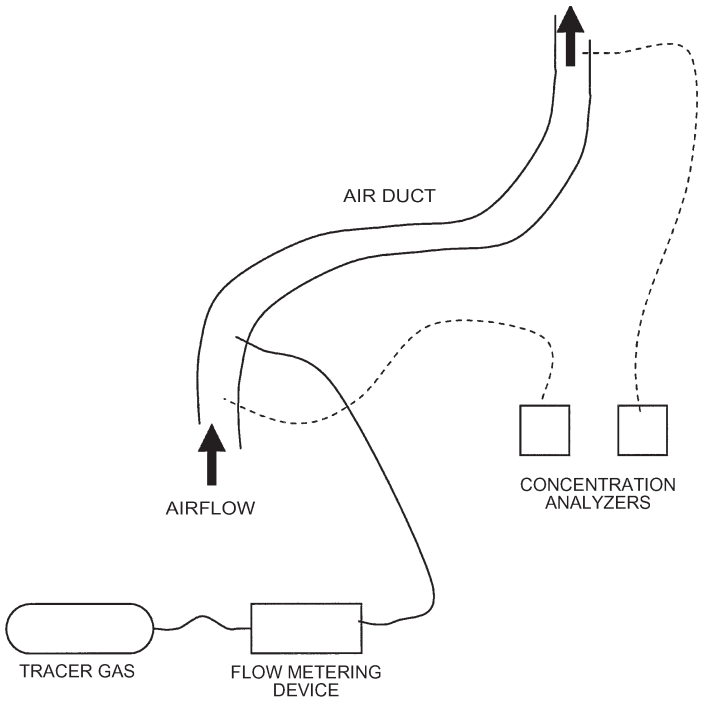

Figure A-5 Airflow measurement using metered tracer gas.

where

V_a = airflow through the duct, cfm (L/s)

M_{tg} = mass flow of the tracer gas, lbm/min (kg/s)

ρ_{tg} = density of the tracer gas at the pressure and temperature in the air duct, lbm/ft^3 (kg/L)

C_u = concentration of the tracer gas up stream of the tracer gas injection, dimensionless

C_d = concentration of the tracer gas downstream of the tracer gas injection, dimensionless

The downstream concentration measurement must be made sufficiently far downstream of the injection location to ensure good mixing of the tracer gas in the airstream. Ten duct diameters of length is sufficient if the flow is fully turbulent (i.e., has a Reynolds number greater than 4000). If the density of the tracer gas is different from the air in the duct due to differences in molecular weight or temperature, care should be exercised to ensure good mixing. The tracer gas metering system should be capable of measuring the tracer gas flow within 3% of reading, and the accuracy of the concentration analyzers should be accurate to with 4% of the difference, $C_d - C_u$.

If this method is to be used in-flight, then special approvals may be required to ensure that the tracer gas does not represent any toxic hazard to the occupants and to assure that the cylinders of compressed tracer gas and other associated equipment are safe to use onboard the aircraft. There is very little experience in using this method on aircraft. Sulfur hexafluoride is one tracer gas that has been demonstrated in aircraft during the EU CabinAir research project (Rydock 2004)

A3.1.4 Mass Balance Methods. If two airflows that contain a trace constituent of different concentrations (e.g., CO_2, water vapor, etc.) mix to form a third flow (e.g., in the mix manifold or a duct Y), as shown in Figure A-6, then it is possible to determine airflows using a mass balance for the mixing flows. Where there is no large pressure difference involved, the general steady state mass balance for the trace constituent in the mixing flows is

$$V_m C_m = V_1 C_1 + V_2 C_2 \quad \text{(A-3)}$$

where

V_m = combined airflow, cfm (L/s)

V_1 and V_2 = mixing airflows, cfm (L/s)

C_m = trace gas concentration in the mixed airstream, dimensionless

C_1 and C_2 = trace gas concentrations in the mixing air streams, dimensionless

Commonly, this method is used to determine what fraction of the combined flow comes from one of the sources, e.g. V_1/V_m:

$$V_1 / V_m = (C_m - C_2)/(C_1 - C_2) \quad \text{(A-4)}$$

In this application, it is not necessary to measure the airflows, but it is necessary to measure the trace constituent concentrations in all three flows.

The source of the difference in concentration of the trace constituent is not important since the concentrations are measured. However, the difference must be sufficiently large to result in an accurate measurement. Normally occurring differences in the trace constituent are sometimes sufficient for application. As a general guideline, the difference, $C_1 - C_2$, must be at least ten times larger than the accuracy of measuring the concentration if the ratio is to be accurate to within 10%. If

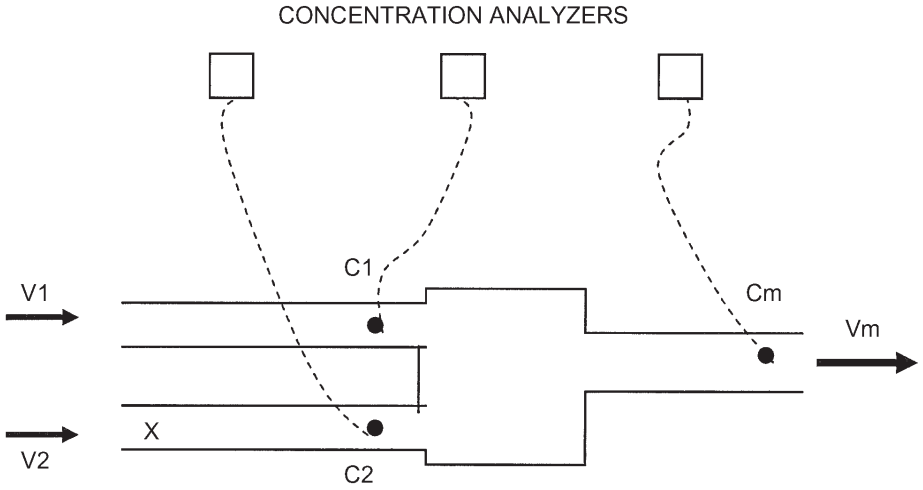

Figure A-6 Measurements for mass balance method.

a normally occurring concentration difference is insufficient, a trace constituent can be injected into one of the supply legs (e.g., location X in Figure A-6) to generate a concentration difference. If a trace constituent is injected, it must be injected sufficiently far upstream to ensure good mixing. Unless special mixing devices are used, the injection should be at least ten diameters upstream of the measurement. Also, the concentration of the trace constituent should be small, generally less than 1% of the air.

A3.2 Total Supply Airflow to a Zone. Sections A3.2.1, A3.2.2, and A3.2.3 describe three potential methods for measuring the total airflow to a zone. The measurement methods described in these sections do not include any flow to the zone through PAOs as part of the total supply airflow that is determined. Depending on the environmental control system design, the airflow through the PAOs may or may not impact the airflow through the main air supply diffusers. For the aircraft as a whole, opening PAOs will, if anything, increase the total airflow to the cabin when the PAO airflow is added to the total, even if they reduce the airflow through the main supply ducts. In general, ignoring the PAO flow in the measurements will, if anything, result in conservative values of total airflow. However, it is conceivable that opening PAOs in one zone will decrease the flow to another zone, again depending on the design of the air supply system. The following requirements are intended to ensure that the impact of the PAOs, if anything, results in conservative values of total airflow to the zone.

If the aircraft is equipped with personal air outlets (PAOs), all PAOs in the zone for which measurements are being collected should be turned off during the measurement of total airflow, if feasible. When it is not feasible to turn off all of the PAOs, such as when measurements are conducted on a revenue flight, the minimum feasible flow through the PAOs should be used. For all other zones, a minimum of 50% of the PAOs should be turned fully on if feasible. When it is not feasible to turn on a large portion of the PAOs in other zones, such as on a revenue flight, the maximum feasible flows for the maximum number of PAOs in other zones should be used.

The methods described in Sections A3.2.1 through A3.2.3 should be conducted in the same mode of operation for which they are intended to apply. If the purpose is to determine compliance during flight, then the measurements need to be taken during flight. If the purpose is to determine compliance during ground operations, the measurements need to be taken on the ground with the same mode of operation (e.g., taxi, at gate connected to an external air supply, etc.).

A3.2.1 Airflow Hood Measurement. Because of their intrusiveness, it is generally not feasible to measure total airflow to most zones using airflow hoods during revenue operations. Airflow hoods are most commonly used by manufacturers during flight test of an initial model or of a new configuration of an existing model.

The aircraft environmental control systems should be brought to steady state operation. Each air inlet to the zone should be identified, PAOs excluded. The flow through each air inlet or section of air inlet to the zone should be measured as prescribed in Section A3.1.1. The airflow at each measurement location must be measured for a period of time sufficient to obtain an accurate average. If an inlet serves more than one zone, the flow from the inlet is apportioned to each zone in proportion to the area of the inlet in each zone. If the airflow hood does not give results in actual volumetric flow at cabin pressure, then the measured values are corrected to actual volumetric airflow according to the methods specified by the hood manufacturer.

The total airflow to the zone is the sum of the time-averaged flows for all of the inlets within the zone. The sum underestimates total airflow due to leakage and backpressure effects of the flow hood.

A3.2.2 PSPT Measurements. The PSPT method may only be used to measure the total airflow to a zone if there are PSPTs, as described in Section A3.1.2, in all air supply ducts leading to the zone in question and these ducts must supply only the zone in question. Typically, a single duct exclusively supplies a single zone and only one PSPT is involved in determining the total airflow to the zone.

The aircraft environmental control systems should be brought to steady state operation. The airflow through each PSPT must be time averaged for a minimum of five minutes with readings collected at least once every 30 seconds as specified in Section A3.1.2 in order to ensure accurate results. Since the PSPT devices are inherently nonlinear, the time averaged value may not be determined by averaging velocity pressure readings unless maximum velocity pressure variations do not exceed +10% during the averaging period. If the variations exceed this value, then the average flow rate is determined by finding the flow rate for each pressure reading and then averaging the flows calculated from each pressure reading.

The total airflow to the zone is the sum of the airflows measured through all of the PSPTs for the zone.

A3.2.3 Tracer Gas Measurements. The tracer gas method requires that the airflow through each duct supplying a zone be measured using the method described in Section A3.1.3. Each such duct must supply only the zone in question. Typically, a single duct exclusively supplies a single zone.

The aircraft environmental control systems should be brought to steady state operation. The airflow through each duct must be time averaged for a minimum of five minutes with readings collected at least once every 30 seconds as specified in Section A3.1.3 to ensure accurate results. The airflow for each reading is calculated using Equation A-2, and the averaged flow is determined by averaging all of the airflows thus calculated for the duct.

The total airflow to the zone is the sum of the airflows measured through all ducts for the zone.

A3.3 Outside Airflow. The primary approach to determining the outside airflow to a zone is to first determine the fraction of the supply air that is outside air and then multiplying the total airflow to the zone by this fraction.

A3.3.1 Fraction of Outside Air. The fraction of outside air, FOA, can be determined by direct measurements of airflows coming into the mix manifold using the methods described in Sections A3.1.2 and A3.1.3 or a combination thereof or through the mass balance method described in Section A3.1.4

The method described in Sections A3.3.1.1 and A3.3.1.2 should be conducted in the same mode of operation for which they are intended to apply. If the purpose is to determine compliance during flight, then the measurements should be taken during flight. If the purpose is to determine compliance during ground operations, the measurements should be taken on the ground with the same mode of operation (e.g., taxi, at gate connected to an external air supply, etc.).

The methods described in Sections A3.3.1.1 and A3.3.1.2 require there be a singly mix manifold, such as that shown in Figure A-3, which supplies a mixture of outside and recirculated air to the zone.

A3.3.1.1 Direct Measurement. In this method, the individual flows coming into the mix manifold are measured using methods described in Sections A3.1.2 or A3.1.3 or a combination of the two. The fraction of outside air is determined by

$$\text{FOA} = V_o/(V_o + V_r) \qquad \text{(A-5)}$$

where

V_o = measured flow of outside air from air-conditioning packs to the mix manifold, cfm (L/s)

V_r = measured flow of recirculated air to the mix manifold, cfm (L/s)

The values of V_o and V_r are measured using the procedure described in Sections A3.1.2 or A3.1.3. The aircraft environmental control systems should be operating under steady state conditions during measurements. The airflows need to be time averaged for a minimum of five minutes with measurement taken no less frequently than every 30 seconds during the averaging period to ensure accurate results. If there is more than one outside air duct or more than one recirculated air duct connected to the mix manifold, then the values of V_o and V_r in Equation A-5 are the sums of the respective airflows.

A3.3.1.2 Mass Balance Method. For an aircraft loaded with people, there is normally a large difference in the CO_2 concentration in the recirculation air and the CO_2 concentration in the outside air. Using these two flows, the fraction of outside air can be determined with Equation A-4 and measurements of CO_2 concentrations in the recirculation and supply air as described in Section A3.1.4:

$$\text{FOA} = V_o/V_r = (C_s - C_r)/(C_o - C_r) \qquad \text{(A-6)}$$

where

V_s = supply airflow, cfm (L/s)

V_o = outside airflow, cfm (L/s)

V_r = recirculation airflow, cfm (L/s)

C_s = CO_2 concentration in the supply airstream, dimensionless

C_o = CO_2 concentration in the outside airstream, dimensionless

C_r = CO_2 concentration in the recirculated airstream

The method described in this section does not depend on determining the CO_2 generation rate of occupants and, thus, is not limited by the accuracy of such estimates. However, it does require adequate CO_2 generation in the aircraft to provide sufficient elevation of CO_2 concentration in the aircraft. This method should not be used unless the difference, $C_r - C_o$, is at least 500 ppm and the CO_2 concentration measurement accuracy is +50 ppm or better.

The air supply concentration is measured in an air inlet supplied by the mix manifold prior to the air entering the cabin (e.g., a sample tube inserted into the air inlet). The recirculated air CO_2 concentration is measured in the recirculated air duct supplying the mix manifold or at the face of the recirculation air filter. If recirculated air enters the mix manifold from more than one duct, then the concentration for each duct is measured, and the values are averaged in proportion to the respective flows.

Prior to recording any measurements used, the aircraft environmental control systems should be operated under steady state conditions for a minimum of 30 minutes to allow

CO_2 concentrations to come to equilibrium, and the steady state conditions need to be maintained throughout the measurement period, which must also must be at least 30 minutes. Concentration measurements need to be taken at least once every minute and be time-averaged over the measurement period to ensure accurate results. All measurement requirements of Section A3.1.4 apply.

If the measurements are conducted on the ground, then C_o must be measured. If the measurements are conducted in flight, then a value of 375 ppm is an acceptable estimate of C_o if the concentration in the outside air cannot be measured and if the aircraft is at least 10,000 ft (3000 m) above ground level. This method should not be applied in flight between ground level and 10,000 ft (3000 m) above ground level unless the value of C_o is measured.

A3.3.2 Outside Airflow Determination. The outside airflow to a zone is determined by multiplying the value of total airflow, V_t, determined by the methods of Sections A3.2.1, A3.2.2, A3.2.3 by the fraction of outside air determined by the methods of Sections A3.3.1.1 or A3.3.1.2, as follows.

$$V_o = \mathrm{FOA}(V_t) \quad \text{(A-7)}$$

where

V_o = outside airflow to the zone, cfm (L/s)

V_t = total airflow to the zone, cfm (L/s)

A3.4 PAO Total Supply Flow. The primary purpose of personal air outlets is to provide occupant adjustable, local airflow. Personal air outlets may also be used to meet part of the total or outside airflow requirements of a zone. The procedure described in Section A3.4 is intended to address the airflow requirements related to local airflow and is not intended for addressing the contribution of PAO flows in meeting total or outside airflow requirements for a zone.

Personal air outlets (PAOs) can provide all outside air, all recirculated air, or a mix of outside and recirculated air, and can come off the main air distribution system or be supplied by an independent system. Depending on the design of the PAO air system, the amount of airflow through a given PAO may depend upon the operation of other PAOs. That is, opening other PAOs may decrease the flow through a given PAO. ASHRAE Standard 161 (ASHRAE 2007) does not specifically address the state of the other PAOs in the system when meeting the required flow rates. The procedure that follows is intended to represent realistic PAO usage with respect to the operation of other PAOs. For all measurements in Section A3.4, a minimum of 50% of all PAOs in the aircraft should be fully open. Additionally, a minimum of 50% of the PAOs of each type should be fully open (e.g., coach passenger, business passenger, crew work station, etc.). To the extent possible, the open PAOs should be uniformly spaced throughout the aircraft.

The airflow through each PAO at a crew work station, crew rest area, or jump seat is measured individually. Generally, it is not practical to individually measure the flow through every single passenger PAO in an aircraft and a sampling procedure is required. The airflow for a minimum of three PAOs for each seat location (i.e., each seat letter, A, B, C, etc.) in each seating class or type (coach, economy plus, business, etc.) should be measured to obtain a representative sample. The PAOs evaluated should be spaced uniformly throughout the respective seating class or type. Generally, if the airflow through all of the PAOs evaluated meets the specified requirements, then the aircraft as a whole is considered to meet the PAO flow requirements.

The sampling plan should be defined prior to the airflow measurements and PAOs that do not meet the required flow should not be removed from the sampling plan. In addition to the requirements above, the sampling plan should attempt to include areas of the aircraft that are potentially stagnant or drafty.

If there is a question about the airflow in specific PAOs, then the measurements may be limited only to those PAOs. However, the conclusions from those measurements may not be extended to the aircraft as a whole.

The measurements should be conducted with the aircraft in the same mode of operation for which they are intended to apply. If the purpose is to determine compliance during flight, then the measurements should be taken during flight. If the purpose is to determine compliance during ground operations, then the measurements should be taken on the ground with the same mode of operation (e.g., taxi, at gate connected to an external air supply, etc.).

The aircraft environmental control systems should be brought to steady state operating conditions prior to taking measurements. The PAO should be in the fully open setting. The airflow through a given PAO should be measured using an airflow hood specifically designed for PAO measurements. All of the requirements of Section A3.1.1 apply. The airflow needs to be measured at least once every 30 seconds for a period of time sufficient to obtain an accurate average through the PAO. If the airflow hood does not provide results in actual volumetric flow at cabin pressure, then the measurements are corrected to actual volumetric flow as specified by the manufacturer of the airflow hood.

A4. AIR SPEED IN UPPER BODY AREA

Measurement Principle: Measurement of local air velocity should be calculated as a maximum value averaged over a two-minute sampling period. A two-minute sampling period is suggested to provide time and spatial averaging of velocity measurements due to the rapid response characteristic of most aircraft cabin ventilation systems. Refer to Section 6.2 of this guideline and to ASHRAE Standard 55 (ASHRAE 2004) for thermal comfort criteria. Refer to Table 5.2-1 of ASHRAE Standard 161 (ASHRAE 2007) for local air velocity parameters.

Measurement Method: Local air velocity in the upper-body region should be measured at head-level with the PAO turned on and with the PAO turned off. Three-dimensional hot-wire anemometers are not recommended for use due to their fragile nature and susceptibility to damage.

Aircraft System Setup: A three-dimensional sonic anemometer is recommended for areas that will accept its

physical size (typically 43 × 48 cm, with a pair of 14 cm diameter measuring heads) and weight (as much as 11 lbs [5.5 kg]). Sonic anemometers typically lose reporting accuracy at flow velocities of 10 ft/min (0.05 m/s) or lower.

For areas with limited space, an omnidirectional thermal anemometer is recommended. This type of anemometer should be rigidly mounted, as inadvertent hand-held movement can introduce errors of up to 10 ft/min (0.05 m/s). Omnidirectional probes should typically be evaluated for accuracy at low flow velocities (below 25 ft/min [0.125 m/s]), due to thermal plume effects. An omnidirectional probe does not provide flow direction information. If directional information is useful, smoke puffers can be used in conjunction with omnidirectional anemometers.

Both the sonic anemometer and the omnidirectional thermal anemometer are best suited for average velocity measurements and are not recommended for measuring small-scale/short duration turbulence in airflows.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

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(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX C
ADDENDA DESCRIPTION INFORMATION

ASHRAE Guideline 28-2016 incorporates ASHRAE Guideline 28-2012 and Addendum *a* to ASHRAE Guideline 28-2012. Table C-1 lists the addendum and describes the way in which the standard is affected by the change. It also lists the ASHRAE approval dates for the addendum.

TABLE C-1 Addenda to ASHRAE Guideline 28-2012

Addendum	Section(s) Affected	Description of Changes*	Approval Dates: • Standards Committee • ASHRAE BOD
a	8.1.2.14 Flame Retardants 9 References	This addendum adds a new Section 8.1.2.14 on flame retardants. It provides a brief description of the use of flame retardants in the passenger cabin, as well as a short summary of some flame retardant exposure data collected on aircraft and a list of references for the user to review some of the related health hazard literature.	January 18, 2014 January 22, 2014

* These descriptions may not be complete and are provided for information only.

NOTICE

INSTRUCTIONS FOR SUBMITTING A PROPOSED CHANGE TO THIS GUIDELINE UNDER CONTINUOUS MAINTENANCE

This guideline is maintained under continuous maintenance procedures by a Standing Guideline Project Committee (SGPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the guideline. SGPC consideration will be given to proposed changes within 13 months of receipt by the Senior Manager of Standards (SMOS).

Proposed changes must be submitted to the SMOS in the latest published format available from the SMOS. However, the SMOS may accept proposed changes in an earlier published format if the SMOS concludes that the differences are immaterial to the proposed change submittal. If the SMOS concludes that a current form must be utilized, the proposer may be given up to 20 additional days to resubmit the proposed changes in the current format.

ELECTRONIC PREPARATION/SUBMISSION OF FORM FOR PROPOSING CHANGES

An electronic version of each change, which must comply with the instructions in the Notice and the Form, is the preferred form of submittal to ASHRAE Headquarters at the address shown below. The electronic format facilitates both paper-based and computer-based processing. Submittal in paper form is acceptable. The following instructions apply to change proposals submitted in electronic form.

Use the appropriate file format for your word processor and save the file in either a recent version of Microsoft Word (preferred) or another commonly used word-processing program. Please save each change proposal file with a different name (for example, "prop01.doc," "prop02.doc," etc.). If supplemental background documents to support changes submitted are included, it is preferred that they also be in electronic form as word-processed or scanned documents.

For files submitted attached to an e-mail, ASHRAE will accept an electronic signature (as a picture; *.tif, or *.wpg) on the change submittal form as equivalent to the signature required on the change submittal form to convey non-exclusive copyright.

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Attn: Senior Manager of Standards
404-321-5478

The form and instructions for electronic submittal may be obtained from the Standards section of ASHRAE's Home Page, www.ashrae.org, or by contacting a Standards Secretary via phone (404-636-8400), fax (404-321-5478), e-mail (standards.section@ashrae.org), or mail (1791 Tullie Circle, NE, Atlanta, GA 30329-2305).

FORM FOR SUBMITTAL OF PROPOSED CHANGE TO AN ASHRAE GUIDELINE UNDER CONTINUOUS MAINTENANCE

NOTE: Use a separate form for each comment. Submittals (Microsoft Word preferred) may be attached to e-mail (preferred) or submitted in paper by mail or fax to ASHRAE, Senior Manager of Standards, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: change.proposal@ashrae.org. Fax: +1-404-321-5478.

1. Submitter:

Affiliation:

Address: City: State: Zip: Country:

Telephone: Fax: E-Mail:

I hereby grant ASHRAE the non-exclusive royalty rights, including non-exclusive rights in copyright, in my proposals. I understand that I acquire no rights in publication of the guideline in which my proposals in this or other analogous form is used. I hereby attest that I have the authority and am empowered to grant this copyright release.

Submitter's signature: _____ Date: _____

All electronic submittals must have the following statement completed:

I *(insert name)*_____, through this electronic signature, hereby grant ASHRAE the non-exclusive royalty rights, including non-exclusive rights in copyright, in my proposals. I understand that I acquire no rights in publication of the guideline in which my proposals in this or other analogous form is used. I hereby attest that I have the authority and am empowered to grant this copyright release.

2. Number and year of guideline:

3. Page number and clause (section), subclause, or paragraph number:

4. I propose to: [ ] Change to read as follows [ ] Delete and substitute as follows
(check one) [ ] Add new text as follows [ ] Delete without substitution

Use underscores to show material to be added (<u>added</u>) and strike through material to be deleted (~~deleted~~). Use additional pages if needed.

5. Proposed change:

6. Reason and substantiation:

7. Will the proposed change increase the cost of engineering or construction? If yes, provide a brief explanation as to why the increase is justified.

[ ] Check if additional pages are attached. Number of additional pages: _____

[ ] Check if attachments or referenced materials cited in this proposal accompany this proposed change. Please verify that all attachments and references are relevant, current, and clearly labeled to avoid processing and review delays. *Please list your attachments here:*

POLICY STATEMENT DEFINING ASHRAE'S CONCERN FOR THE ENVIRONMENTAL IMPACT OF ITS ACTIVITIES

ASHRAE is concerned with the impact of its members' activities on both the indoor and outdoor environment. ASHRAE's members will strive to minimize any possible deleterious effect on the indoor and outdoor environment of the systems and components in their responsibility while maximizing the beneficial effects these systems provide, consistent with accepted Standards and the practical state of the art.

ASHRAE's short-range goal is to ensure that the systems and components within its scope do not impact the indoor and outdoor environment to a greater extent than specified by the Standards and Guidelines as established by itself and other responsible bodies.

As an ongoing goal, ASHRAE will, through its Standards Committee and extensive Technical Committee structure, continue to generate up-to-date Standards and Guidelines where appropriate and adopt, recommend, and promote those new and revised Standards developed by other responsible organizations.

Through its *Handbook*, appropriate chapters will contain up-to-date Standards and design considerations as the material is systematically revised.

ASHRAE will take the lead with respect to dissemination of environmental information of its primary interest and will seek out and disseminate information from other responsible organizations that is pertinent, as guides to updating Standards and Guidelines.

The effects of the design and selection of equipment and systems will be considered within the scope of the system's intended use and expected misuse. The disposal of hazardous materials, if any, will also be considered.

ASHRAE's primary concern for environmental impact will be at the site where equipment within ASHRAE's scope operates. However, energy source selection and the possible environmental impact due to the energy source and energy transportation will be considered where possible. Recommendations concerning energy source selection should be made by its members.

ASHRAE · 1791 Tullie Circle NE · Atlanta, GA 30329 · www.ashrae.org

About ASHRAE

ASHRAE, founded in 1894, is a global society advancing human well-being through sustainable technology for the built environment. The Society and its members focus on building systems, energy efficiency, indoor air quality, refrigeration, and sustainability. Through research, Standards writing, publishing, certification and continuing education, ASHRAE shapes tomorrow's built environment today.

For more information or to become a member of ASHRAE, visit www.ashrae.org.

To stay current with this and other ASHRAE Standards and Guidelines, visit www.ashrae.org/standards.

Visit the ASHRAE Bookstore

ASHRAE offers its Standards and Guidelines in print, as immediately downloadable PDFs, on CD-ROM, and via ASHRAE Digital Collections, which provides online access with automatic updates as well as historical versions of publications. Selected Standards and Guidelines are also offered in redline versions that indicate the changes made between the active Standard or Guideline and its previous edition. For more information, visit the Standards and Guidelines section of the ASHRAE Bookstore at www.ashrae.org/bookstore.

IMPORTANT NOTICES ABOUT THIS GUIDELINE

To ensure that you have all of the approved addenda, errata, and interpretations for this Guideline, visit www.ashrae.org/standards to download them free of charge.

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