Occupational and Public Health Risks

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Abstract Symptoms reported by passengers and crewmembers on commercial aircraft are described according to individual air quality-related sources, including: (1) elevated levels of bioeffluents; (2) infectious agents; (3) extreme temperatures; (4) exhaust fumes, deicing fluid, fuel fumes, and cleaning products; (5) heated engine oil and hydraulic fluid; (6) reduced oxygen supply; (7) ozone gas; and (8) insecticides. A brief overview of the aircraft regulatory environment and available sources of data on the hazards and associated health effects is also provided.

Keywords Carbon monoxide · Insecticides · Ozone · Tricresylphosphates · Ventilation

Abbreviations

APU	Auxiliary power unit
BLS	US Bureau of Labor Statistics
CAMI	US Civil Aeromedical Institute
CAR	Canadian Aviation Regulation
CFM	Cubic feet of air per minute
CO	Carbon monoxide
CS	European Certification Specification
EASA	European Aviation Safety Agency
ECS	Environmental control systems
ETS	Environmental tobacco smoke
FAA	US Federal Aviation Administration
FAR	US Federal Aviation Regulation
ITF	International Transport Workers' Federation
JAA	Joint Aviation Authorities (Europe)
L/s	Liters per second
NIOSH	US National Institute for Occupational Safety and Health
SARS	Severe Acute Respiratory Syndrome
TB	Tuberculosis
TC	Transport Canada
TCPs	Tricresylphosphates
TWA	Time-weighted average
WHO	World Health Organization

1
Introduction

Passenger and crew reporting of symptoms attributed to substandard aircraft air quality is a controversial subject, and has been a source of debate among regulators, airlines, aircraft/component manufacturers, passengers, and crewmembers. As background, it is helpful to understand: (1) the regulatory environment, (2) the sources of available data on aircraft air quality hazards, and (3) the potential sources of symptoms reported by passengers and crew.

1.1
Regulatory Environment

Air quality standards intended to protect airline worker safety and health are under the jurisdiction of each country's aviation authority. In the US, the Federal Aviation Administration (FAA) asserted its exclusive claim of jurisdiction over airline worker safety and health on registered civil aircraft in operation [1]. Basic protections established and enforced by the US Occupational Safety and Health Administration do not apply to crewmembers, and the FAA has not published occupational safety and health protections for air quality-

related hazards. Aviation authorities in most other countries have the same arrangement. They argue that air quality standards may influence equipment selection and maintenance, which may in turn require modifications to the aircraft structure, which could compromise the safety of flight.

Aviation authorities worldwide issue two basic types of aircraft air quality regulations: design standards that manufacturers must comply with during the aircraft certification process, and operating standards that airlines must comply with when operating an aircraft. There are very few design standards for aircraft environmental control systems (ECS) (Table 1), and even fewer operating standards for such systems (Table 2). There is no requirement to install and operate air quality monitoring equipment on aircraft, so compliance with operating standards that define chemical exposure limits is not ensured.

Aviation authorities occasionally require airlines to implement specific maintenance procedures, sometimes in response to recommendations from aircraft or component manufacturers. For example, British Aerospace issued maintenance recommendations to airlines that operate their BAe146 aircraft in response to incidents that involved impaired performance of flight crew and "circumstantial evidence" that such incidents were caused by oil leaking into the air supply systems [2]. These maintenance procedures have since been incorporated into regulations by several aviation authorities.

Similarly, in response to "reports of smoke and odor in the passenger cabin and cockpit due to hydraulic fluid leaking into the auxiliary power unit inlet, and subsequently, into the air conditioning system," the FAA now requires that airlines implement specific maintenance procedures to increase the robustness of specific hydraulic fluid lines shown to be prone to failure in the auxiliary power unit (APU) of certain aircraft types [3]. This requirement will address one source of contamination on one series of aircraft.

Fleet-wide regulations allow airlines to dispatch aircraft that have an inoperative APU for a limited period of time, typically 10 days. Even if the APU is inoperative due to contamination with oil or hydraulic fluid, the aircraft is still considered airworthy.

No aviation authority requires airlines or aircraft/component manufacturers to provide affected crew or passengers who are exposed to airborne toxins during a flight with either aircraft maintenance or mechanical records (when relevant), or product information. Also, there are no requirements for routine in-flight air quality monitoring. For these reasons, it is often difficult for affected crew and passengers to prove an association between their symptoms and deficiencies in the quality of the air onboard.

1.2
Sources of Publicly Available Data

It is challenging to define the extent of occupational and public health risks attributed to aircraft air quality because there is no large-scale and indepen-

Table 1 Aircraft system design standards published by the US Federal Aviation Administration (FAA), the European Aviation Safety Agency (EASA), and Transport Canada (TC)

	US (FAA)	Europe (EASA)	Canada (TC)
Ventilation	Provide a sufficient amount of uncontaminated air to enable the crewmembers to perform their duties without undue discomfort or fatigue, and to provide reasonable passenger comfort (FAR 25.831(a)). Effective 5 July 1996, systems on new aircraft types must also be designed to provide a minimum 0.55 lb of outside air per min to each **occupant**	Each passenger and crew compartment must be ventilated, and each crew compartment must have enough fresh air (but no less than 10 cubic feet per min per crew member) to enable **crew members** to perform their duties without undue discomfort or fatigue (CS 25.831(a)); see also AMC 25.831(a)	Same as US regulation; see CAR 525.831(a).
Carbon dioxide	Carbon dioxide ≤ 5000 ppm in compartments normally occupied by passengers or crewmembers (FAR 25.831(b)(2)).	Carbon dioxide $< 30\,000$ ppm for crewmembers (CS 25.831(b)(2))	Same as US regulation; see CAR 525.831(b)(2)
Carbon monoxide	Carbon monoxide ≤ 50 ppm (FAR 25.831(b)(1)).	Same as US regulation; see CS 25.831(b)(1).	Same as US regulation; see CAR 525.831(b)(1).
Ozone	Ozone ≤ 0.25 ppm (ceiling) when operating above 32 000 feet, and ≤ 0.1 ppm TWA during any 3-h interval above 27 000 feet (FAR 25.832(a))	None required	Same as US regulation; see CAR 525.832(a)

* Note: All concentrations provided as sea level equivalent

Table 1 (continued)

	US (FAA)	Europe (EASA)	Canada (TC)
Cabin pressure	Provide an effective altitude (pressure) in the cabin of not more than 8000 feet operating altitude of the airplane under normal operating conditions at the maximum (FAR 25.841(a))	Same as US regulation; see CS 25.841(a)	Same as US regulation; see CAR 525.841(a)
System operation at low temperatures	None required	None required	Must demonstrate satisfactory airplane operation after it has experienced prolonged exposure to ground ambient temperatures equal to or less than − 35 °C (CAR 525.1301-1)
Combustion heating	None required	None required	Combustion heaters must be approved (CAR 525.833)

* Note: All concentrations provided as sea level equivalent

Table 2 Aircraft air quality operating standards published by the European Joint Aviation Authorities (JAA), US Federal Aviation Administration (FAA), and Transport Canada (TC)

	US (FAA)	Europe (JAA)	Canada (TC)
Ozone	≤ 0.25 ppm (ceiling) when operating above 32 000 feet, and ≤ 0.1 ppm TWA during any 4-h interval above 27 000 feet (FAR 121.578(b)); also see AC 120-38.	None apply	Same as US regulation
Ventilation	Each passenger or crew compartment must be suitably ventilated (FAR 121.219)	None apply	Same as US regulation
Carbon monoxide	Carbon monoxide ≤ 50 ppm and fuel fumes may not be present (FAR 121.219)	None apply	Same as US regulation

dent incident reporting system for either crewmembers or passengers. In the US, only incidents that render a pilot unable to perform his or her duties must be reported to the National Transportation Safety Board [4].

Aviation authorities do not collect work-related illness reports from either airlines or crewmembers, although US *airlines* must log crewmember-reported occupational illnesses and "recordable" injuries (i.e., serious enough to require lost work time or medical follow up). Each year, a sample of airlines is enlisted to participate in the US Bureau of Labor Statistics (BLS) annual survey of occupational injuries and illnesses. The BLS has extensive documentation of crewmembers' work-related injuries and illnesses, and its analysts provide extensive information upon request. A major union representing cabin crew collected copies of these injury and illness logs from 13 airlines, and calculated that 10% of the 31 422 employed cabin crew had reported a work-related illness or a recordable injury [5]. The national average across industries for the same year was 3.1% [6]. Although the data that the BLS collects are useful, there is evidence that the lists of air quality-related illnesses currently maintained by the airlines underestimate the true rate, even of *reported* incidents, highlighting the need for independent oversight of any data collection.

Some major government-funded reports have been published on the subject of aircraft air quality [7–12]. The majority of published data is funded by industry sources, which has generated concerns about potential conflicts of interest.

1.3
Health Risks Attributed to Aircraft Air Quality

Symptoms reported by passengers and crew are described in Sects. 2–9, according to the eight potential exposure sources listed in Table 3. Aircraft occupants may be subject to any combination of these, or none at all, during a given flight. Physical hazards such as high noise levels, cosmic/solar radiation, and electromagnetic fields have been documented in the aircraft cabin and cockpit, but are beyond the scope of this chapter.

An historical aircraft air quality hazard, at least in most parts of the world, is environmental tobacco smoke (ETS). Key historical developments in the smoking ban on commercial flights are listed in Table 4 [13–16]. Smoking is prohibited on domestic flights in most countries, and is restricted on most international flights; for example, airlines in the UK, Germany, Italy, and Russia have imposed a voluntary smoking ban on international flights, while airlines in France and the Ukraine allow smoking in sections of the aircraft, depending on the destination [17]. Even in countries that have enacted smoking bans on all commercial flights, the majority of currently employed crewmembers have been exposed to ETS in the aircraft cabin during their careers. ETS exposure for a full-time cabin crewmember on smoking flights has been described as equivalent to living with a one-pack-per-day smoker [18]. Research into tobacco-related diseases among crewmembers is currently being conducted in the US by the Flight Attendant Medical Research Institute, funded by a settlement from a 1991 lawsuit filed against tobacco companies.

Table 3 Potential sources of air quality related symptoms reported by passengers and crewmembers during commercial airline flights

Section	Potential source of air quality related symptom
2	Elevated levels of bioeffluents
3	Infectious agents (bacteria and viruses)
4	Extreme temperatures
5	Exhaust fumes, deicing fluid, fuel fumes, and cleaning products
6	Heated engine oil and hydraulic fluid
7	Reduced oxygen supply
8	Ozone gas
9	Insecticides

Table 4 Key historical developments in the smoking ban on commercial aircraft

Year	Development
1988	The US congress passed legislation that banned smoking on domestic flights lasting 2 h or less [13]
1990	The US smoking ban was expanded to include domestic flights lasting 6 h or less [14]
1992	The International Civil Aviation Organisation issued a non-binding resolution calling for smoke-free flights by 1 July, 1996. Only 13% of the more than 300 member countries had implemented the ban by then [15]
2000	The US congress expanded their smoking ban to include all international flights traveling to and from the US [16].

It has been suggested that some symptoms reported by crew and passengers may be explained, not by problems with aircraft air quality, but with "multiple factors" such as jet lag, dehydration, fatigue, or simply "hysteria." Certainly being on duty for long flights, crossing time zones, and attending to the public are stressors in and of themselves. However, documented symptoms are often correlated with documented air quality problems on aircraft. In some cases, incident type or symptoms are more prevalent on certain aircraft models, aircraft, or flight paths, making air quality related problems easier to define.

2
Elevated Levels of Bioeffluents

There is no operating standard for a minimum per person ventilation rate in the passenger cabin. Airlines need only maintain cabin pressure, which requires a per person outside air flow rate of approximately 3 cubic feet per minute (CFM) or 1.4 L/s. Reducing outside air supply conserves fuel. On most commercial jet aircraft, the air supply is approximately 50% outside air and 50% recirculated; this will vary somewhat between aircraft manufacturers [7]. Some regional aircraft operate with 100% outside air.

A discussion of ventilation and bioeffluents (including infectious agents) on aircraft often relies on comparisons to building data. There is a shortage of reliable aircraft data compared to the volumes of documented ground-based investigations into non-specific symptoms that are reported by a proportion of building occupants and typically diminish upon leaving the building. Aside from some obvious differences between aircraft and buildings, there

are five key distinctions that influence exposure to bioeffluents in these environments:

- **Low per person outside airflow:** Published data show that levels of gaseous bioeffluents (such as carbon dioxide) are considerably higher in aircraft than typical building environments, indicative of low per person ventilation rates (Table 5) [19–23]. Although carbon dioxide itself is not considered to be hazardous at the concentrations reported in these surveys, it is an indicator of outside air supply, and elevated levels have been associated with an increased prevalence of non-specific symptoms reported by occupants in ground based environments [24].
- **Low per person recirculated airflow:** The per person *volume* of filtered, recirculated supply air is considerably lower on aircraft (7–10 CFM; 3.3–4.7 L/s) than in buildings (70 CFM; 33 L/s), raising concerns about exposure to increased airborne levels of particulate, including viruses and bacteria. It is possible that the *quality* of recirculated air on aircraft may be higher than in buildings, although the trade off between volume and quality of filtered, recirculated air has not been quantified.
- **Airborne contaminants from off-gassing surfaces:** The per person "building" surface area is considerably smaller on aircraft than in building environments. If surface off-gassing is the primary cause of reported symptoms, then fewer aircraft occupants should report symptoms, all other things being equal. However, it may not be possible to draw a direct comparison because the key sources of off-gassing surfaces are different on aircraft (e.g., lavatory, galley kitchen) than in buildings (e.g., photocopier).
- **Airborne contaminants from aircraft occupants:** The occupant-generated contaminant load per unit volume of space is considerably greater on aircraft than in building environment. If elevated levels of bioeffluents explain reported symptoms then one would expect a higher prevalence of symptoms reported by aircraft occupants, all other things being equal.
- **Small volume of air assigned to each person to dilute contaminants:** The per person volume of air space that is effectively provided to each aircraft occupant for dilution of airborne contaminants is approximately one-tenth that provided to building occupants [25, 26], such that equilibrium concentration of airborne contaminants generated by occupants is reached more quickly. This high occupant density on aircraft compared to buildings also has implications for the overlap of occupants' breathing zones, particularly on full flights between neighboring passengers, and between cabin crew and passengers during beverage and meal services.

Table 5 Results of carbon dioxide monitoring on commercial aircraft

Waters et al., 2002 [19]	Funded by the US National Institute for Occupational Safety & Health to monitor air quality on 36 flights. The average flightlong concentration of carbon dioxide was 1387 ppm
Pierce et al., 1999 [20]	Funded by the American Society of Heating, Refrigerating, and Air Conditioning Engineers to monitor air quality on eight B777 flights. Conditions during ground operations when carbon dioxide levels are expected to peak were not monitored. Average in-flight levels in the cabin were 1509 ppm. Average levels in the aft galley were 2480 ppm, not including a measurement of 4915 ppm that was attributed to a nearby bin of dry ice
Spengler et al., 1997 [21]	Funded by the Boeing Company to collect air quality measurements on aircraft and other modes of transportation. Average CO_2 levels on four B777 flights were reported as 1200–1800 ppm during cruise, and 1000–2300 ppm during boarding
Jurgiel et al., 1994 [22]	Funded by Trans World Airlines to collect air quality monitoring data on two B747-100 non-smoking flights according to the location in the cabin and phase of flight. Carbon dioxide levels during ground operations averaged 2480 ppm. Cabin class also influenced ventilation, with 1047–1510 ppm measured during cruise in the economy section, compared to 884–950 ppm in the first class, and 720 ppm in the upper deck. Cockpit levels averaged 740 ppm
Nagda et al., 1992 [23]	Funded by the US Departement of Transportation to conduct air quality monitoring on 23 domestic, non-smoking flights. The average carbon dioxide concentration was 1756 ppm with 87% of the data exceeded the 1000 ppm upper limit recommended by ASHRAE Standard 62

2.1
Reported Symptoms

In ground-based environments, the following symptoms have been associated with low outside air ventilation rates: digestive problems; dizziness; dry or burning mucous membranes in nose, eyes, or throat; fatigue or lethargy; forgetfulness; headaches; inability to concentrate; irritability; nausea; sneezing; and stuffy or runny nose [24]. Few published studies have investigated either the prevalence of these symptoms reported by crew or passengers on com-

mercial aircraft, or whether there is an association with outside air ventilation rates.

A survey conducted by the US National Institute for Occupational Safety & Health (NIOSH) compared the prevalence of self-reported respiratory symptoms and illnesses between cabin crewmembers, teachers, and an external population of women blue collar workers with no known occupational exposures [27]. Cabin crew were four to six times more likely to report work-related eye, nose, and throat symptoms than the referent working women. Cabin crew were also less likely than teachers or the referent working women to report ever having been diagnosed with asthma (8.2%, 13%, and 12%, respectively).

A survey commissioned by Scandinavian Airlines Systems compared the perceptions of workplace air quality and reported symptoms of crewmembers ($n = 1513$) and office workers ($n = 168$) employed by SAS [28, 29]. At the time, smoking was permitted on intercontinental flights. Crewmembers were less satisfied with their work environment than office workers, and reported more nasal and throat symptoms, as well as dermal symptoms on the hands and face. It would be worth repeating this survey now that smoking is not permitted on aircraft.

A survey commissioned by Cathay Pacific Airways evaluated the health and comfort of cabin crew on 16 international flights over an eight-month period [30]. Most of the surveyed flights were smoke-free except for a few short-haul flights that were divided into smoking and non-smoking sections. On each flight, researchers distributed health surveys to cabin crew ($N = 185$) and collected basic air monitoring data. The average carbon dioxide level was 934 ppm (683–1557 ppm). Half of the respondents classified air quality as "poor" or "adequate", both less than acceptable according to the rating scale.

3
Infectious Agents

Anecdotally, passengers and crew report an association between infectious disease transmission and air travel. These reports are consistent with the close proximity of cabin occupants and the low ventilation rates on aircraft; however, it is difficult to substantiate these claims because of the latency period between infection and symptoms, and the challenge of contacting passengers and crew after any given flight.

Aircraft occupants can be infected by two routes of exposure: (1) airborne, and (2) surface contamination (i.e., touching an infected surface such as a cup or lavatory door handle, and then touching one's mouth or eyes).

Risk factors for airborne exposure include low total ventilation rate per person, inadequately filtered recirculated air, and close proximity of occu-

pants. Seating configuration and activity will also affect the degree of overlap between occupants' breathing zones, and therefore the risk of infection. Risk factors for transmitting an infection via contact with a contaminated surface include inadequate hand washing and touching one's face.

The relative contributions from airborne and surface sources within the aircraft has not yet been defined, although the exposure potential, and therefore, risk of infection, are expected to increase relative to the duration of the flight. Other variables include pathogen type (i.e., clinically relevant dose) and individual susceptibility to infection.

For the airborne route, maximizing the airflow through the cabin will reduce the residency time of airborne infectious agents. Recirculated air that is filtered through properly maintained and installed true high efficiency particulate (HEPA) filters should provide similar protection to outside air, in terms of infectious disease control. Bacteria can easily be trapped by a true HEPA filter and, although viruses are smaller than the pores of a HEPA filter, they should be removed from the air stream if they travel in clusters or on droplets of water or mucous. Even the best HEPA filtered air still contains gaseous contaminants, and therefore does not have the dilution capacity provided by outside air.

The benefit of recirculated air is that it is more humid than the outside air supplied by the engines; one downside is that the source of humidification is aircraft occupants' breath. Presently, although some of the major airlines report that they have done so, there is no minimum requirement to install or properly maintain HEPA filters on aircraft.

3.1
Reported Symptoms

A survey conducted by NIOSH and introduced in the previous section reported that flight attendants were more likely to report five or more episodes of colds or flu in the past year than either teachers or working women in a comparison population (10.2%, 8.2%, and 2.3%, respectively) [27]. Flight attendants were also significantly more likely than teachers and referent working women to report chest illness (33%, 19%, and 7.2%, respectively).

A study of self-reported colds and flu tracked 1100 passengers that traveled on one of 250 2-h flights between the same two US cities, half on aircraft with a 50%–50% mix of recirculated and outside air, and half on similarly configured aircraft with 100% outside air [31]. There was no significant difference in the frequency of self-reported colds and flu between groups, leading the researchers to report "no evidence that aircraft cabin air recirculation increases the risk for (upper respiratory tract) symptoms in passengers traveling aboard commercial jets." A subsequent letter to the editor noted that the rate of upper respiratory infection reported by the cohort of airline passengers was four times the national average, suggesting an increased risk of

disease transmission on commercial flights [32]. This increase may be explained by the overlap of occupants' breathing zones, low per person total ventilation rates compared to other environments, contact with infected surfaces, or some combination thereof.

In its 2003 investigation of Severe Acute Respiratory Syndrome (SARS), the World Health Organization (WHO) defined "contacts" as passengers within two seats rows of an infected person and all on-board cabin crewmembers [33]. Presumably, the WHO recognizes the potential for ambient air to "drift" between seat rows before returning to the air supply system or being dumped overboard. On one flight, passengers sitting seven rows in front and five rows behind a person with symptomatic SARS developed the disease; however, in this case, the route of transmission (i.e., airborne versus contact) was not confirmed. If a cabin crewmember is the suspected or probable SARS case, then all the passengers are considered contacts [33].

The implications of contracting SARS during a flight are especially serious given the overall case fatality rate of 15% [34], and evidence that a surface can stay infected for up to 4 days [35]. To date, there have been 27 reported cases of SARS transmission on aircraft, involving four cabin crewmembers and 23 passengers [36].

There has been considerable interest in the risk of transmitting tuberculosis (TB) on aircraft. One of the more conclusive investigations was conducted by the US Centers for Disease Control and Prevention (CDC) and involved 802 (87%) of passengers and crew who had traveled on one of four flights with a person who had infectious TB [37]. There were two outbound flights and two return flights a month later, by which time the patient's condition was reported to have worsened. On the first three flights, a total of 14 contacts had positive tuberculin skin prick tests, although of these, 13 had other risk factors for TB. However, on the last flight (lasting 8.75 h), 15 contacts had positive tuberculin skin tests and, of these, six had no other risk factors for TB and were seated in the same cabin section as the index case, four within two rows of her. The observed pattern of infection within the cabin suggests the potential for "drift" of infected air between rows. The absence of reported skin-test conversions in other cabin sections implies that bacteria were not transmitted through the aircraft's air recirculation system.

A less conclusive investigation into the risk of TB transmission on aircraft involved 225 (73%) passengers and crew on a 14-h flight with one person who was highly infectious [38]. Of these, 184 had positive tuberculin skin prick tests for TB, although only nine had skin conversions. Of those nine, the possibility of transmission from the index patient could not be ruled out in three cases, although all three were sitting between 15 and 23 rows from the index patient, not a compelling finding. The authors concluded that the risk of TB transmission on aircraft was no greater than that in other confined settings, noting that "TB outbreaks often occur as a result of overcrowded conditions

in poorly-ventilated facilities when there is prolonged close exposure to an infectious person."

An investigation into a pilot with active TB who had flown with 48 other pilots over a 6-month period found no risk of transmission [39]. It is possible that this reduced risk is explained by the approximate 20-fold increase in the supply rate of outside air in the cockpit, compared to the economy section of the cabin.

The potential for transmitting measles and meningococcal disease on aircraft has also been described. From February 1999 through May 2001, the CDC received reports of 21 suspected cases of air-travel associated meningococcal disease from local health departments, an average of one every 6 weeks [40]. In April 2004, the CDC issued a report describing nine young children with serologically confirmed or suspected cases of measles that had traveled by air, three of whom would have been infectious on the aircraft [41]. State and local health departments were concerned enough to attempt to identify and evaluate potential contacts, and provide prophylaxis when indicated.

4
Extreme Temperatures (See also Chap. 3)

Extreme temperatures are primarily a concern during ground operations if there is insufficient capacity for the cooling or heating necessary to effectively manage extreme ambient temperatures. The temperature and humidity of the air supplied to the cabin and cockpit will vary according to destination, season, and air supply equipment. The fuselage while sitting on hot tarmac, especially in the sun, can absorb heat and open doors introduce unconditioned ambient air into sections of the cabin and cockpit. Temperatures as high as 110 °F (43 °C) have been documented in the cabin during ground operations in the northeastern US during the summer [42].

During ground operations, occupants' metabolism is generally elevated as they move through the cabin and stow or retrieve their luggage. The metabolic rate of cabin crew is elevated relative to passengers and cockpit crew throughout much of a given flight. Relative humidity also influences thermal comfort, and will typically change considerably during a flight as a function of flight phase and ambient environmental conditions.

In-flight, cabin crewmembers report: (1) cold drafts at ankle level when working in galleys and sitting in jumpseats adjacent to one or more doors with sweeping door seals; (2) exposure to stagnant, warm air in the upper section of galleys, especially if ovens are operating; and (3) highly variable temperatures between zones on some aircraft types.

4.1
Reported Symptoms

Although there are no published studies dedicated exclusively to temperature on commercial flights, either during ground operations or in-flight, a few surveys have measured temperature and surveyed crewmembers, passengers, or both about perceived comfort. One such study noted that complaints of draftiness, and of temperatures that were too high or too variable, were more common among surveyed crewmembers than office workers, and that female crew were more likely to describe the temperature as too low [29]. Another study found that 23% of surveyed crew rated temperature as "cool" or "too cold", and that too-cool temperature was one of the most common air quality complaints among passengers [30].

Temperature-related incident reports have been submitted to the International Transport Workers' Federation (ITF), an international labor organization that operates a safety and health incident reporting system for crewmember unions [42]. Reported symptoms include heat exhaustion (i.e., clammy skin, dizziness, extreme fatigue, headache, nausea) during excessively hot ground operations, and aching legs and feet from working in cold galleys.

5
Exhaust Fumes, Deicing Fluid, Fuel Fumes, and Cleaning Products

The poor quality and insufficient quantity of air supplied to the cabin while the aircraft is occupied and sitting at or near the gate generate complaints from passengers and crewmembers. The source of the cabin air supply during ground operations will vary according to airport equipment and aircraft type. The most common is a conditioned air intake attached to the base of the passenger boarding bridge. Other options include the auxiliary power unit (APU) located in the aircraft tail, the interior of the airport terminal, the airport terminal supply air ducts, and ground carts. With the possible exception of airport terminal air, these sources supply the cabin with ambient air that can be polluted by the following sources:

- **Exhaust fumes:** Fumes from diesel-powered ground service vehicles and other aircraft can be ingested into the supply air, especially if the air intake is located near to the vehicles. Engine exhaust can contain ozone and nitrous oxides, both respiratory irritants.
- **Deicing fluid:** Deicing fluid that contains propylene glycol, diethylene glycol, or methylene glycol can be ingested into the aircraft engines or auxiliary power unit when the aircraft is being deiced, contaminating the air supply systems [43] and creating a safety hazard on certain aircraft types [44].

- **Fuel vapor:** Fueling operations at the airport, airplane tank venting during filling, and failed engine relights are sources of fuel vapor that may enter the cabin and cockpit air supply systems. Although there have been no formal exposure studies in the aircraft cabin and cockpit, an animal study that reported adverse effects on learning abilities suggests that regular, high-level exposure to jet fuel fumes may carry implications for ground-based fueling workers [45].

In addition, noxious disinfectants and deodorizers can be applied in the cabin, primarily by airline cleaning staff. The labels for these products indicate that they are intended for use in a well-ventilated environment, not the small, enclosed lavatories in the aircraft cabin. The chemical components of cleaning agents are described elsewhere [7].

5.1
Reported Symptoms

Formal investigations into symptoms attributed by crew and passengers to chemical exposures associated with ground operations have not been conducted. Symptoms reported to the ITF include reports of dizziness, eye and throat irritation, headaches, and nausea that crewmembers attribute to exposure to cleaning products, deodorant sprays, lubricants applied to beverage carts when stationed in the galley, and exhaust fumes [42].

6
Heated Engine Oil and Hydraulic Fluid (See also Chap. 10, and 12)

The potential for heated engine oil and hydraulic fluid to contaminate the aircraft air supply due to maintenance, operation, and design failures or deficiencies has been documented in the aviation industry for more than 35 years [46, 47]. Passengers and crew can be exposed to toxic components of these products, such as tricresylphosphates (TCPs), and their heated byproducts, such as carbon monoxide (CO). Despite this history, the frequency and the severity of these contamination incidents are under debate, particularly when not all crew and passengers are affected during a given incident.

Carbon monoxide generation will depend on the temperature at the source of contamination, whether the APU or aircraft engines. Ground-based exposure limits for CO are not applicable in-flight because the reduced oxygen environment will exacerbate the toxic effects. For example, breathing air with 50 ppm CO at a cabin altitude of 6000 feet has been defined as physiologically equivalent to a cabin altitude of 12 000 feet [48]. Similarly, breathing air with 150 ppm CO at a cabin altitude of 8000 feet effectively raises the cabin altitude

to 19 000 feet [49]. Alcohol consumption, elevated physical activity, cardiopulmonary disease, and cigarette smoking will magnify this effect. Smoking 1.5 packs per day can raise a person's carboxyhemoglobin to 10% [50]. This altitude effect has not been tested for other airborne contaminants or for mixtures of contaminants.

Pilot incapacitation is one long-recognized hazard of air supply contamination. In response to a recommendation from the US National Transportation Safety Board, the US Civil Aeromedical Institute (CAMI) exposed rats to heated aircraft engine oils and measured their response time, following "several unexplained crashes of turboprop aircraft that might possibly be due to pilot incapacitation from toxic fumes" [51]. The CAMI rat study claimed to rule out CO as a causative agent, but "did not eliminate the possible presence of an additional (chemical) component with significant animal toxicity." More recently, the UK aviation authority reported incidents of pilot impairment caused by cockpit air supply contamination, emphasizing the need for pilots to be regularly trained in incapacitation procedures [52].

The TCP content of these oils and hydraulic fluids is typically reported as 3% by volume and is likely a complex mixture of up to ten isomers, six of which contain mono- or di-ortho isomers that are five to ten times more toxic than even the tri-ortho isomer of TCP [53], even though the tri-ortho isomer is regularly mistaken as the most toxic isomer [54]. One engine oil manufacturer assessed and ruled out the physical manifestations of organophosphate-induced delayed neuropathy among test animals made to *ingest* these oils [55], but this research does not mimic the exposure pattern of crews and passengers on commercial aircraft, and is therefore of little relevance. Investigations into the causes of Gulf War Syndrome have found evidence of altered brain chemistry and immunosuppression in test animals following the inhalation of sub-clinical concentrations of an organophosphate nerve gas [56, 57]. There is now interest in testing whether these findings apply to other organophosphates, such as TCPs.

6.1
Reported Symptoms

A recent health survey of pilots operating B757, B737, and A320 aircraft at a major airline in the UK identified symptoms associated with 1674 reported incidents of cockpit air supply contamination, all but seven of them on the B757 [58]. Although the response rate was low (106 of 600 pilots), the reported symptoms are cause for concern, given the implications for flight safety. The most commonly reported symptoms were: eye, nose, and throat irritation (63%); headaches, lightheadedness, and dizziness (55%); fatigue, weakness, decreased performance (56%); concentration difficulties, confusion (32%); nausea, vomiting, gastrointestinal problems (22%); skin irritation (21%); short-term memory impairment (19%); numbness (17%); joint pain,

muscle weakness (16%); intolerance to chemicals or odors (16%); and disorientation (12%).

The ITF has been informed of "smoke in the cabin" incidents by flight attendants' safety representatives based in Australia, Canada, Denmark, France, Sweden, the US, and the UK [59]. The reported symptoms are sometimes consistent with exposure to carbon monoxide and neurotoxic agents, and include blurred or tunnel vision, confusion, disorientation, dizziness, giddiness, headache, lack of motor control, loss of cognitive function, nausea, tremors, unusual fatigue, and vomiting.

In 2000, a bipartisan senate committee in Australia released a report summarizing its two-year inquiry into reports of air supply contamination on the BAe146 aircraft [9]. The report concluded that "exposure of air crew and, potentially, passengers to cabin air which may be...even minutely affected, by fumes originating in an aircraft's engines raises the potential of occupational illness and, for certain individuals, an incapacity to continue work". Although the committee had been charged with investigating complaints on the BAe146, their report identified similar problems on other aircraft, including the A320 and MD90, and recommended that the Australian Civil Aviation Safety Administration introduce regulations that dictate specific preventive maintenance procedures, a national standard for checking and monitoring the engine seals and air quality in all passenger commercial jet aircraft, and a national incident reporting system.

In November 1999, on the first two of three flights on a BAe146 aircraft, cabin crew reported symptoms that included fainting, "odd pressure in the head", and the "feeling of moonwalk". On the third flight, both the pilot and copilot were affected and had to don their oxygen masks. Prior to the flights, the airline had found a minor external oil leak in one of the engines. A government investigation found no technical fault that could explain the incident, but attributed it to exposure to "probably polluted air" [60].

In an effort to quantify the extent of air supply contamination at one US airline, the cabin crew union initiated a review of all sources of reported information related to these incidents [61]. The union identified 760 incidents involving 900 crewmembers and passengers over a nine-year period (1989–1998) that involved either a visible aerosol in the cabin and symptoms reported by crew or passengers, or mechanical records that indicated aircraft air supply contamination, or both. This translated into approximately seven incidents per month. In many cases, the documented symptoms reported by crew and passengers were consistent with exposure to TCP additives in the jet engine oils and hydraulic fluids (e.g., abnormal gait, balance problems, chills, delayed peripheral neuropathy, muscle aches, seizures, stomach cramping, and tremors) and/or asphyxiants (e.g., dizziness, metallic taste, severe headaches, and tunnel vision).

The cabin crew union at the same airline also asked NIOSH to investigate the reports of neurological illness associated with "smoke in the cabin"

incidents [62]. Once NIOSH staff had arranged an acceptable sampling schedule with the airline, they monitored CO, carbon dioxide, relative humidity, temperature, and volatile organic compounds on three test flights. The CO data was unusable because the equipment had been improperly calibrated, peak ozone concentrations ranged from 0.058–0.093 ppm, and maximum cabin altitudes were 8064–8218 feet (2459–2505 m), relative to ambient pressure on the ground. Cabin crew reported that their performance was not affected during those three flights, although on one of the flights, three of the four cabin crew reported a headache, and one reported lightheadedness and dizziness. NIOSH measured CO on another 13 flights with direct-reading, continuous electrochemical sensors. Peak CO concentrations were reported as one minute averages that ranged from < 1–25 ppm, but there was no indication as to whether or not cabin crew had reported symptoms during those flights. Also, NIOSH did not identify whether the readings were explained by a CO source or chemical interference. Cabin crewmembers continue to report symptoms that are consistent with exposure to neurotoxic or asphyxiant chemicals on an infrequent but persistent basis.

Similar health complaints from crewmembers, some of which required admission to the emergency department, prompted an investigation into the BAe146 aircraft operated by a Canadian airline [63]. The most common reported symptoms were burning eyes and throat, disorientation, headache, and nausea. Oil contamination was identified in the air supply system on a test aircraft and TCPs were identified in the bulk oil sample. However, due to sampling limitations, TCPs could not be demonstrated in the cabin air.

There is evidence of a possible connection between these exposure incidents and neurological deficits that resemble multiple sclerosis (MS) and Parkinson's Disease, as described by cabin crew in the US, as well as pilots in Australia and the UK. Occupation-specific clusters of symptoms that resemble MS have been documented in another industry, with specific references to exposure to hydraulic and machining fluids that contain TCPs, just like commercially-available aircraft engine oils and many hydraulic fluids [64]. Significant excess in mortality and morbidity from motor neuron disease has been reported among pilots [65, 66], although such associations have never been formally investigated among cabin crew.

Some explanations for differences in individual susceptibilities to the effects of exposure to particular organophosphates include evidence that genetics, levels of particular hormones, health status, and exposures to mixtures of particular chemicals can influence the efficacy of enzymes involved in their metabolism, and could thereby influence the degree of toxic effect [67, 69].

7
Reduced Oxygen Supply (See also Chap. 3, and 4)

The aircraft cabin is pressurized because the oxygen content in unpressurized air during flight is not adequate to sustain life. The introduction of compressed air into the aircraft cabin ensures that the internal cabin pressure (and the corresponding partial pressure of oxygen) is higher than the outside air pressure at the flight altitude. The cabin pressure is usually referred to in terms of its corresponding altitude ("cabin altitude"). Aviation standards require that aircraft systems be designed to maintain a cabin altitude not higher than 8000 feet (2440 m) at the maximum flight altitude during normal conditions (Table 1). This corresponds to a supply of approximately 75% of the oxygen available at sea level.

No regulatory authority has issued an explicit operating standard for cabin altitude, except that when the cabin altitude reaches 10 000 feet (3050 m), essentially an emergency condition, the pilots must don oxygen masks, and at 14 000 feet (4270 m), oxygen masks are automatically provided to the cabin occupants. A recent sampling study reported that the maximum in-flight cabin altitudes on 36 flights ranged from 3000–7500 feet (915–2290 m) [19], although cabin altitudes in the 6000–8000 feet (1830–2440 m) range are probably more typical, and readings as high as 8915 feet (2717 m) have been reported [70].

There is no apparent health-based rationale for the 8000 feet design standard, probably because the FAA was not required to provide substantiating material when it recodified the US Civil Aeronautical board regulations in 1964. Regulators must now thoroughly justify any new standards but the pressurization standard has not been revisited, and an operating standard has never been proposed. Based on the results of pressurization studies conducted in the 1940s, the 8000 feet design standard has been described as "a compromise between the aircraft design and operation requirements and the human performance impairments," and when the standard was first published, 5000–6000 feet (1520–1830 m) was recommended for routine operating conditions [7]. Occupants' oxygen needs vary according to activity level, health status, smoking status, and age.

7.1
Reported Symptoms

Symptoms associated with insufficient blood oxygen saturation include: deficient color discrimination, dizziness, fainting, fatigue, headaches, nausea, slowed reaction time, and weakness for novel tasks. There is little published data on symptoms reported by crew or passenger and blood oxygen saturation. One study on a group of 42 airline pilots on 22 flights measured an average blood oxygen saturation on the ground of 97% (95–99%) compared

to the reduced and more variable saturation of 89% (80–91%) at altitude, although symptoms were not reported [71].

The reduced partial pressure of oxygen and the changes in pressure during a flight have been described as the deciding factors for fitness to travel due to the proportion of in-flight deaths attributable to coronary heart disease [72]. A test on the effects of simulated air travel on 17 patients with chronic obstructive pulmonary disease reported that, for most patients, blood oxygen levels dropped below the recommended levels and their hypoxia was aggravated by mild exercise [73]. A review of medical diversions at one major US airline concluded that neurologic symptoms, including dizziness/vertigo, seizures, headaches, pain, and cerebrovascular complaints, were the largest category of in-flight medical incidents prompting air-to-ground calls [74]. Reports of loss of consciousness/syncope were the most likely to result in an actual diversion of an aircraft. Reduced cabin pressure has been suggested as a risk factor for triggering or exacerbating lymphedema [75], although the question of whether reduced cabin pressure contributes to the risk of deep vein thrombosis appears unresolved [76, 77].

8
Ozone Gas (See also Chap. 3)

At ground level, ozone is unnatural – a component of smog and a public health menace. Exhaust fumes are a source of ozone that can be entrained into the aircraft supply during ground operations, as stated earlier. Generally though, ozone exposure is problematic during flight.

At altitude, ozone occurs naturally and is generally classified as protective of public health because it filters some of the ultraviolet light that can otherwise burn skin and initiate cancer. Commercial aircraft prove the exception to this rule because they operate within the ozone layer, such that the naturally occurring ozone gas not intended for human consumption can be captured and concentrated in the air supply systems. Ozone levels start to increase in the troposphere (approximately 26 000 feet altitude at the poles and 50 000 feet at the equator) and generally continue to increase with altitude up to 90 000 feet. The troposphere drops to lower altitudes in the late winter and early spring, such that ozone concentrations increase at flight altitudes, accordingly.

Some ozone will be removed from the air supply when it reacts with the inside surface of the air supply ducts; some ozone will be converted into oxygen if a catalytic converter is installed and operating; some ozone is delivered to the cabin and cockpit.

Ozone exposure limits are many and varied. The average 8-h workplace limits include an enforceable limit of 0.1 ppm [78] and a recommended limit of 0.05–0.1 ppm, depending on the level of exertion [79]. For the

public, a maximum 8-h average of 0.056 ppm has been recommended to protect public health, and a maximum 1-h average of 0.092 ppm recommended for "population information" [80]. Ambient ozone levels deemed acceptable on aircraft are considerably higher (Table 1, Table 2), and vary with operating altitude, suggesting that they are not health-based. Airlines need not monitor the air to demonstrate compliance with ozone limits; they need only show by analysis that ambient ozone levels are unlikely to exceed the said limits. The accompanying degree of statistical uncertainty that must be demonstrated for these analyses is substantially higher ($p < 0.16$) than what is generally considered sound scientific practice ($p < 0.05$) [81].

Recent sampling conducted on 36 flights, half of them polar (i.e., some portion of the flight operating above 50° latitude), and all on aircraft equipped with catalytic converters, reported gate-to-gate average levels of ozone ranging from < 0.05 to 0.24 ppm on flights with maximum cabin altitudes on the low end of operation (3000–7500 feet or 915–2290 m) [19].

Documented ozone concentrations during flight are variable, largely due to flight path, altitude, and season, but the location of monitoring equipment can also influence results because ozone gas is so reactive. One survey found that 40% of the ozone present at ceiling height in the economy class section had "disappeared" when measured at a height of 4 feet above the floor [82], presumably because it had already contacted and reacted with surfaces in the cabin, including the occupants.

8.1
Reported Symptoms

The adverse effects of ozone on the respiratory system – even at very low concentrations – are well documented. One comprehensive literature review [83] reported that "a single ozone exposure to healthy, non-smoking young adults in the range of 0.08–0.12 ppm produces a complex array of pulmonary responses." The observed association between long-term ozone exposure at 0.25 ppm and progressive and persistent lung function and structural abnormalities in test animals raises serious concerns about the effects of chronic exposure on people. Cited animal studies also support the hypothesis that chronic ozone exposure accelerates the aging of the human lung.

Respiratory symptoms associated with exposure include: aggravated asthma; chest tightness; cough; inflammation of the lung tissue; painful, labored, or rapid and shallow breathing; pulmonary edema; and temporary decrease in lung capacity. There is also evidence that ozone gas can induce immune system changes [84] and increase susceptibility to infection. Children, asthmatics, and people with existing respiratory disease are most at risk. Both physical exertion and heat stress have been shown to exacerbate the effects of exposure to ozone. The reduced supply of oxygen at altitude

may magnify the effects of exertion because of the attendant increase in the breathing rate.

A series of articles on ozone-related symptoms reported by crewmembers was published in the early 1980s in response to hundreds of complaints received by commercial airlines after the B-747-SP high altitude aircraft was introduced into passenger service in 1976 [81]. Sampling data collected by the US National Aerospace Administration in 1977 indicated significantly elevated ozone levels on the B-747-SP aircraft compared to the standard B-747, and the cabin ozone levels increased as the flights progressed. In one survey, self-reported symptoms consistent with ozone exposure were reported three to four times more often by cabin crew employed by airlines operating high altitude, long-distance flights, than by those employed by airlines operating low altitude, short duration flights [85]. Symptoms included burning sensations in the throat and eyes, chest pain, coughing, shortness of breath, and wheezing. The study was limited by a relatively low response rate (61% of active crewmembers) and the airlines' refusal to allow in-cabin monitoring. Another survey reported a significant association with self-reported ozone-related symptoms and 747-SP flights, although the survey response rate was again low [86].

9
Insecticides (See also Chap. 9)

Insecticides are applied on aircraft for three key reasons: routine control of domestic insects, particularly in the aircraft galleys; response to on-board insect sightings; and compliance with foreign quarantine regulations. Sixty countries publish and enforce foreign quarantine regulations that require insecticide spraying on incoming aircraft to kill any insects that may be on board and may carry disease or damage the environment [87]. Insecticides (typically pyrethroids) are applied in occupied or soon-to-be-occupied aircraft cabin, and neither passengers nor crew are warned in advance. Historically, DDT and Sevin have been applied in the aircraft cabin [88]. Current efforts focus on a possible mechanical means of disinsection as an alternative to the current chemical spraying [89].

9.1
Reported Symptoms

There are few epidemiological studies into either the acute or chronic effects of exposure to insecticides applied on aircraft specifically. The most common symptoms recently reported by crewmembers exposed to pyrethroids were cardiovascular, dermatological, gastrointestinal, neurological, ocular, and respiratory [90]. In addition to the potential for acute illness, the po-

tential for cumulative or chronic health problems associated with pyrethroid exposure has been acknowledged both on [90] and off [91] aircraft. A moderate association between self-reported application of DDT on aircraft and elevated risk of breast cancer among female flight attendants has also been reported [92]. See also Sect. 4.

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