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Cabin air quality on civil aircraft - Chemical compounds

Qualité de l'air en cabine d'avions civils - Composés chimiques

Kabinenluftqualität in Verkehrsflugzeugen - Chemische Parameter

This draft European Standard is submitted to CEN members for second enquiry. It has been drawn up by the Technical Committee CEN/TC 436.

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Contents

Page

European foreword

This document (prEN 17436:2021) has been prepared by Technical Committee CEN/TC 436 “Cabin air quality”, the secretariat of which is held by AFNOR.

This document is currently submitted to the second Enquiry.

Introduction

Air quality on civil aircraft requires particular attention, given the characteristics of the cabin environment.

An environmental control system (ECS) is used to regulate the aircraft cabin pressure, temperature and ventilation supply air to provide a safe and comfortable environment for the passengers and air crew. The aircraft cabin by design and operation is enclosed and is a densely occupied environment (with only a small amount of per person dilution volume), creating the potential for elevated levels of bio-effluents in the cabin, such as carbon dioxide (see Annex A). ECS architecture on civil passenger aircraft can be broadly separated in two categories: bleed air ECS systems and bleed free ECS systems (see Annex A). Most aircraft manufactured today, and nearly all aircraft in service, have bleed air ECS.

This document focuses on the chemical compounds potentially present in cabin air. It sets out requirements, recommendations, and supporting annexes to enable airline operators, manufacturers and suppliers to identify - and either prevent or mitigate - exposure to contaminants in the cabin air, with particular emphasis on bleed air contaminants sourced to or generated from engine oil and hydraulic fluid. This includes some limited measures intended to protect workers assigned to troubleshoot and service the aircraft ventilation supply air systems.

NOTE Aircraft accident investigation agencies, aviation regulators from the EU and US, and the International Civil Aviation Organization (ICAO) have recognized that bleed air contamination can compromise flight safety.

The requirements and recommendations in this document take into account that the fluids used in aviation (including jet engine oils) and their pyrolysis products are complex mixtures. Some of these mixtures contain organophosphates, ultra-fine particles, and other chemical compounds.

The requirements set out in the document take into account current and developing legal frameworks in order to enable the industry to meet their legal obligation to provide a safe environment for air crew and passengers. This document also acknowledges, at the European Commission level, the value of using the Precautionary Principle in relation to risk management, and the use of risk assessment in this industry to protect workers and the environment.

Within this document, emphasis is placed upon exposure prevention, sensor technology, worker training, reporting systems, and collation of data and information from air crew and passengers. Safety Management Systems (SMS) can be a useful tool to enable operators to apply these measures to monitor and respond to system degradation.

This document does not define acceptability/suitability for health, comfort, safety, or airworthiness of the cabin air.

Annex I contains a summary of maximum levels of the marker compounds listed in Annex B that have been published.

1 Scope

This document defines requirements and recommendations dealing with the quality of the air on civil aircraft concerning chemical compounds potentially originating from, but not limited, to, the ventilation air supplied to the cabin and flight deck.

A special emphasis is on the engine and APU bleed air contaminants potentially brought into the cabin through the air conditioning, pressurization and ventilation systems.

This document is applicable to civil aircraft in operation from the period that is defined as when the first person enters the aircraft until the last person leaves the aircraft.

This document defines requirements and recommendations in relation to the presence of, and means to prevent exposure to, chemical compounds, including those that could cause adverse effects, taking into account the Precautionary Principle.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 1822-1, *High efficiency air filters (EPA, HEPA and ULPA) - Part 1: Classification, performance testing, marking*

EN ISO 16000-1, *Indoor air - Part 1: General aspects of sampling strategy (ISO 16000-1)*

ISO 29463-1, *High efficiency filters and filter media for removing particles from air — Part 1: Classification, performance, testing and marking*1)

IEST-RP-CC001, *HEPA and ULPA filters*

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1) Published by: ISO International Organization for Standardization http://www.iso.ch/

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at http://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

3.1
adverse effect
change in morphology, physiology, growth, development or lifespan of an organism which results in impairment of its functional capacity or impairment of its capacity to compensate for additional stress or increased susceptibility to the harmful effects of other environmental influences

[SOURCE: ISO 13073-3:2016, 2.1]

3.2
aerosol
system of solid particles and/or liquid droplets suspended in gas

3.3
air crew
people working on an aircraft in the period that is defined as when the first person boards the aircraft until the last person leaves the aircraft, including pilots and cabin crew

3.4
airline operator
entity authorized by an Air carrier Operator Certificate (AOC) from its national Civil Aviation Authority to operate civil transport aircraft flights for commercial carriage of passengers, cargo or mail

Note 1 to entry: The airline operator holds responsibility for compliance with civil aviation authority regulations on its flights, including when the relevant tasks are performed by sub-contractors.

[SOURCE: ISO 16412:2005, 3.3, modified — The terms originally defined were “operator”, “airline” and “carrier”.][2]

3.5
auxiliary power unit
APU
gas turbine-powered unit delivering rotating shaft power, compressor air, or both, which is not intended for direct propulsion of an aircraft

[SOURCE: EASA CS Definitions] [3]

3.6
best available technology
BAT
most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular technologies for providing, in principle, the basis to mitigate, or eliminate exposure to contaminants in cabin air

[SOURCE: Council Directive 2008/1/EC, modified] [4]

3.7
bleed air
air bled off the compressor stages of the aircraft engines or APU, prior to the combustion chamber; source of ventilation air

3.8
cabin air
air within the section of an aircraft in which passengers and/or air crew travel (including the cabin and flight deck)

3.9
cabin material
cabin interior which includes seats, flooring, walls, cabinets and overhead bins

3.10
chemical compound
chemical element or compound on its own or admixed as it occurs in the natural state or as produced, used, or released, including release as waste, by any work activity, whether or not produced intentionally and whether or not placed on the market

[SOURCE: Council Directive 98/24/EC Art. 2(a)][5]

3.11
contaminant
substance emitted into the air adversely affecting air quality

[SOURCE: ISO 4225:2020] [6]

3.12
early warning system
system or a procedure to detect the presence of contaminants that may require intervention

3.13
electrical-environmental control system
E-ECS
bleed-free ECS

3.14
environment control system
ECS
system of an aircraft which provides ventilation supply air, temperature control, and cabin pressurization for the crew and passengers

3.15
fresh air (see also: outside air)
air taken from outside the vehicle

Note 1 to entry: In this document, the vehicle is the aircraft.

3.16
fumes
odorous, gaseous emission of compound(s) and/or aerosols which may be sourced to the cabin/flight deck ventilation supply air vents and is not visible

3.17
hazardous
substance or mixture fulfilling the criteria relating to physical hazards, health hazards, or environmental hazards

[SOURCE: Regulation (EC) No 1272/2008 "CLP", Article 3] [7]

Note 1 to entry: (i) any chemical agent which meets the criteria for classification as hazardous within any physical and/or health hazard classes laid down in Regulation (EC) No 1272/2008 of the European Parliament and of the Council, whether or not that chemical agent is classified under that Regulation; and(ii) any chemical agent which, whilst not meeting the criteria for classification as hazardous in accordance with point (i) may, because of its physico-chemical, chemical or toxicological properties and the way it is used or is present in the workplace, present a risk to the safety and health of workers, including any chemical agent that is assigned an occupational exposure limit value under Article 3.

[SOURCE: Directive (EC) No 98/24, Article 2]

Note 2 to entry This definition of hazardous is different to the definition applied in the airworthiness context.

3.18
marker compound
chemical compound representing/indicating specific/potential sources of airborne contaminants in the cabin air

3.19
outside air (see also: fresh air)
air taken from outside the vehicle

[SOURCE: ISO 19659-1:2017, 3.4.1] [8]

Note 1 to entry: In this document, the vehicle is the aircraft.

3.20
real-time sampling
use of online monitoring using instrumental analysers with sensors; the output describes the change in concentration of the analyte(s) as a function of time during the sampling period

3.21
risk analysis
systematic use of available information to identify hazards and to estimate the risk

[SOURCE: ISO/IEC Guide 51:2014, 3.10] [9]

3.22
safety management system
SMS
administrative framework that is designed to manage safety risks in workplaces and is applied to enable the operator to systematically monitor and respond to fume events

3.23
sensor
electronic device that senses a physical condition or chemical compound and delivers an electronic signal proportional to the observed characteristic

[SOURCE: ISO/IEC TR 29181-9:2017,3.14] [10]

3.24
soot
particulate matter with a particle size of 0 nanometres (nm) to 10 nm produced and deposited during or after combustion

[SOURCE: EN ISO 472:2013, 2.1278 modified] [11]

3.25
steady state
condition during single engine power setting characterized by stable temperature and bleed pressure

[SOURCE: SAE (2018)] [12]

3.26
supply air
air introduced into an enclosure by mechanical means including engines, APU, onboard electric compressors, or ground supply units

3.27
time-integrated sampling
either passive or active sampling methodology, followed by analysis of the collected sample in dedicated equipment or a laboratory; the output describes the average concentration of the analyte(s) during the sampling period

3.28
transient operating condition
condition other than steady state engine power setting characterized by unstable temperature and/or changing pressure; examples include engine start, take-off top-of-descent and changes in engine regime including changing the power setting from idle to take off power and back

3.29
ultra-fine particles
ultra-fine particles (UFP) or ultrafine dust are the most commonly used definitions of airborne particles with a diameter between 1 and 100 nanometres (nm)

[SOURCE: ISO 2007] [13]

4 Cabin air quality — chemical compounds

4.1 Chemical compounds in cabin air

The presence and concentration of many chemical compounds have been measured in the cabin air and are reported in numerous studies, providing a large database of chemical compounds. Most of these data were collected in the cabin or flight deck during normal operating conditions and not during a reported “fume event” (see 4.4). Some of these data were collected directly from a bleed air source.

Monitoring the cabin air for the presence of appropriate chemical marker compounds is a method to indicate the source(s) of contamination, rather than to assess any health effects of exposure.

4.2 Sources of chemical compounds

Chemical compounds can be sourced to the outside environment and can also originate from the aircraft itself. These may include, but are not limited to the following:

- engine oil;
- hydraulic fluid;
- engine exhaust;
- fuel (unburned and vapours);
- de-icing fluid;
- chemical products used to wash engines or turbines;
- occupants;
- cabin materials and cleaning products;
- air conditioning equipment;
- faulty/failed electrical items.

An overview of a subset of the chemical compounds associated with some of these sources that may be introduced to the cabin air is provided in Annex G.

4.3 Sources of engine oil leakage in the bleed air system

The presence of oil fumes in the cabin air can, in some instances, be linked to the oil lubrication system. A description of the oil lubrication system, the seal technology and possible contamination of the cabin air with engine oil are discussed in Annex H.

4.4 Fume event

A fume event is characterized by the presence of fumes in the cabin, emanating from the ventilation supply air vents which can indicate the presence of a specific contamination of the ventilation supply air (e.g. engine oil, hydraulic fluid, de-icing fluid) that has originated from or entered the engine or APU.

Alternatively, the presence of fumes and/or aerosols in cabin may emanate from a source within the cabin (e.g. galley ovens, electrical faults).

4.5 Marker compounds

A subset of marker compounds that can be present in cabin air is listed in Annex B, Table B.1. These marker compounds are associated with major contaminant sources from bleed air and outside air. They are deemed to be useful markers for these specific sources of air contamination in the aircraft environment.

Table B.2 lists “reliability ratings” (A through C) for each marker compound, intended to assist the reader in determining which combination of compounds to monitor for each source of contamination listed in 4.2.

Annex I lists published studies that, together, include measurement data for 14 of the 16 marker compounds in Annex B. The maximum value of each measured compound was commonly reported so is provided in Table I.1 for comparison purposes.

4.6 Environmental control systems (ECS)

The purpose of the ECS is to provide ventilation supply air and regulate the aircraft cabin pressure and temperature in order to provide a safe and comfortable environment for the passengers and crew.

Most commercial passenger aircraft are equipped with an ECS that processes bleed air from engine compressors, whilst some ECS process air from electrical compressors. Airborne chemical compounds can be introduced into the cabin air through the aircraft ventilation supply air system. Further details on these two types of ECSs are provided in Annex A.

5 Precautionary Principle and hierarchy of controls

5.1 General

Airborne chemical agents can be sourced to the ventilation supply air (e.g. engine oil, hydraulic fluid, de-icing fluid, and exhaust fumes) and the aircraft cabin surfaces, equipment, and occupants (see Clause 4). Exposure to these chemical agents can be prevented/minimized through the application of the design and maintenance requirements in this document, all of which shall be planned and implemented according to the Precautionary Principle (see 5.2) and the hierarchy of controls (see 5.3).

The objective of these design and maintenance requirements is to prevent/minimize onboard exposure to airborne contaminants, with a special emphasis on the ventilation supply air. This is accomplished by:

a) implementing an onboard monitoring system that gives, at the earliest possible time, an indication of a system degradation or change in the cabin air quality (see Clause 7). This allows for appropriate operational and/or maintenance actions which will enhance flight safety and protect the health of crew and passengers;

b) using portable monitoring equipment (see 7.3) based on the presence of selected chemical marker compounds (see Annex B) as an additional maintenance monitoring and troubleshooting tool; and

c) adopting other design, operational, and maintenance measures (see Clause 8 and Annex F).

The chemical marker compounds listed in Annex B (see Table B.1) are deemed to be the most reliably associated with the primary contaminant sources (see 4.2) and are, thus, an appropriate basis for onboard and portable monitoring equipment (see Clause 7). However, alternative methods could be also applied to indicate the presence of a specific contaminant source (e.g. by pattern recognition; see 7.1 and Annex D).

In addition to these design and maintenance requirements, requisite administrative measures (i.e. medical monitoring, standardized reporting, airline worker training/education) are described in Clauses 9, 10 and 11.

Also, examples of “best practice” exposure control measures are described in Annex F, and supplemental information on relevant aircraft systems and contaminant sources is provided in the remaining annexes.

5.2 Precautionary Principle

Airline operators, maintenance organisations and manufacturers shall apply the Precautionary Principle while performing a risk assessment to characterize the risks of exposure to the main contamination sources listed in Clause 4.

As a part of this risk assessment for aircraft engines and APUs that supply bleed air, manufacturers shall measure engine and APU-generated contaminants over the full range of engine power settings expected to occur in service, including on-wing testing and transient power settings, and shall assess the potential for fluid loss during normal operation, as well as accidental leaks, spillage, and overfills.

Airline operators shall perform a risk assessment on cabin air contamination, including risks that cannot be avoided. For most carcinogens and mutagens, it is not feasible to identify levels below which exposure cannot lead to adverse effects.

Based on these risk assessments, airline operators, maintenance organisations, and manufacturers shall apply the Precautionary Principle and the hierarchy of controls (see 5.3) to mitigate the risks of onboard exposure to airborne contaminants. This shall include designing systems to minimize fluid emissions during the full range of normal operations.

For additional information on the Precautionary Principle, see Annex C.

5.3 Hierarchy of controls

Airline operators, maintenance organisations and manufacturers shall apply the hierarchy of controls to prevent occupant exposure to airborne chemical agents, as follows:

- avoid risks;
- evaluate risks that cannot be avoided;
- control risks at the source;
- eliminate or reduce hazardous chemical exposures by the design and organization of system;
- adapt to technical progress;
- replace the dangerous by the non-dangerous, less dangerous, or safe;
- develop a coherent overall prevention policy which covers technology, organization of work, working conditions, and the influence of factors related to the working environment;
- give appropriate instructions to the workers; and
- give collective protective measures priority over individual protective measures.

Airline operators, maintenance organisations and manufacturers shall address potential hazards at the source by the application of Best Available Technology (BAT), such as filters, to minimize the presence of outside air and engine/APU-generated contaminants in the ventilation supply air.

NOTE 1 BAT has been used successfully as a mean to prevent or reduce/minimize exposure to chemical agents.

NOTE 2 Examples of elimination of oil-contaminated bleed air sourced to a mechanical failure, malfunction, or fluctuations in the efficiency of engine seals could be the inclusion of a bleed free architecture, and/or oil free bearing systems.

NOTE 3 See Directive 89/391/EEC [14] (OSH Framework directive) for further information on the hierarchy of controls. Aircraft-specific applications of the hierarchy of controls are listed in the next two sections.

5.4 Elimination measures

Aircraft manufacturers shall take into account the Precautionary Principle and the hierarchy of controls in the design of the ventilation supply air system to eliminate occupant exposure to the airborne chemical agents sourced to the ventilation supply air system listed in 4.2, as follows:

a) ensure breathing air conducive to a safe and comfortable environment for air crew and passengers in all phases of flight, without design features that experience has shown to be hazardous;

b) not cause harm, ill-health, or adverse effects (impairment or incapacitation) to air crew;

c) not cause harm, ill-health or adverse effects (impairment or incapacitation) to passengers;

d) provide monitoring and notification systems (see Clause 7) to provide an alert regarding system degradation or a change in the cabin air quality (per EASA CS 25.1309) [15] which could require maintenance or pilot intervention; and

e) be assessed using a risk analysis which includes normal and accidental leaks, fluid contamination, spillage, overfills, the effects on occupants, and an assessment of the mixture of potential contaminants.

Aircraft manufacturers shall also design the ventilation supply air system to facilitate maintainability of the system by cleaning or replacement of parts.

NOTE Existing airworthiness requirements describe how to analyse the potential for degraded or impaired crew performance or incapacitation due to contamination of the ventilation supply air with engine oil and other aircraft fluids, and to apply an SMS that reflects the full range of operating conditions.

Manufacturers should review service data from airline operators and reporting systems when assessing the frequency of cabin air contamination events.

5.5 Mitigation measures

When elimination by design is not possible, airline operators, aircraft and engine manufacturers, and maintenance organisations, where applicable, shall apply the Precautionary Principle (see 5.2) and hierarchy of controls (see 5.3) to prevent/minimize exposure to chemical compounds, particularly those sourced from the aircraft ventilation supply air system, as follows:

— applying designs with mitigation measures such as filters (see Clause 6) and air monitoring (see Clause 7);

— applying preventive and corrective maintenance measures (see Clause 8); and

— implementing administrative mitigation measures such as medical monitoring (see Clause 9), reporting and analysis (see Clause 10), and airline worker training (see Clause 11).

Airline operators and manufacturers shall give priority to collective protective measures over individual protective measures, as set out in the hierarchy of controls.

Airline operators and manufacturers shall apply the principle of substitution to reduce hazards in relation to products utilized in aviation and engineering solutions. The dangerous shall be substituted by the non-dangerous or the less dangerous, according to manufacturing specifications.

Airline operators and manufacturers shall document procedures to prevent and mitigate cabin air contamination, including in the aircraft maintenance manual (AMM) and troubleshooting manual (TSM) (see Clause 8).

Aircraft and engine manufacturers, maintenance organisations, and airline operators should also apply the “best practice” measures listed in Annex F, as they impact design, maintenance, and operation.

6 Filtration

6.1 General

Aircraft manufacturers and suppliers shall design and install any ventilation supply air filtration systems to remove airborne contaminants (particulate, aerosol, and gaseous) associated with the sources listed in 4.2 in order to prevent/minimize occupant exposure in the occupied zones of the aircraft. Airline operators shall operate maintain and replace the filtrations systems, per aircraft manufacturer requirements. Filtration systems can process contaminants in the outside air stream, the recirculated air stream, or both.

NOTE The terms “filter” and “filtration” are understood to include (a) devices intended to capture particles/gases in the air stream; (b) air cleaning technologies designed to remove impurities from air through chemical reactions; (c) or both.

6.2 Recirculation cabin air filtration

Aircraft manufacturers shall design ventilation supply air systems to ensure that recirculated ventilation supply air is passed through a high-efficiency particulate air (HEPA) filter, or equivalent, before it is supplied to the cabin in order to prevent the recirculation of particles through the ventilation system.

NOTE 1 Particles can contain chemical compounds and pathogens.

NOTE 2 For certain ECS architecture, recirculation filtration may not be an option during certain operations.

Aircraft manufacturers shall design the filters and their mountings to prevent unintentional bypassing of unfiltered air and to prevent filter overloading. The required HEPA filters shall meet one or more of the following standards, or equivalent:

- IEST-RP-CC001; Type A or higher (99,97 % collection efficiency for 0.3-micron particles);
- EN 1822-1; Type H13 (99,95 % overall collection efficiency at the most penetrating particle size MPPS); and
- ISO 29463-1; Type ISO 35 H (99,95 % overall collection efficiency at the most penetrating particle size MPPS).

When recirculation fans are turned on, airline operators shall operate and replace these filters and their mountings, all according to manufacturer recommendations.

Alternative technologies and test methods may be used to meet this requirement if they provide equivalent or better removal efficiency and the test methods are approved by a cognizant authority.

6.3 Catalytic conversion filtration

If an aircraft is equipped with catalytic converters to remove ozone gas from the outside air stream inflight, then the manufacturer and airline operator shall ensure that the devices are designed and maintained according to the relevant regulations.

Devices that utilize catalytic conversion can be used to prevent/reduce exposure to/recirculation of certain gaseous compounds, including but not limited to some of the sources of contaminants in the ventilation supply air and cabin air, as defined in Annex B.

NOTE For more information on the standard to which aircraft ventilation systems have to be designed regarding allowed ozone concentrations as a function of cabin altitude, see EASA CS 25.832 [16].

7 Air monitoring

7.1 General

Airline manufacturers shall install, and airline operators shall operate and maintain, air monitoring equipment intended to identify the presence of at least the following contaminant sources: engine oil, hydraulic fluid, engine exhaust/fuel, and de-icing fluid (see Annex B). When available technology allows, the monitoring data shall also distinguish between these contaminant sources. The monitoring requirements in Clause 7 also apply to maintenance organisations, where applicable.

The primary monitoring objective is to distinguish between normal conditions and system degradation, such as fume events (see 4.4) that may require pilot and/or maintenance intervention. Monitoring the air for those contaminant sources is intended to prevent/reduce onboard exposure.

All air monitoring shall be planned and conducted consistent with defined objectives (see 7.2). Specifically, the location of each sensor shall be defined according to the potential source of contamination (e.g. engine versus APU), the marker compound(s), and the physical constraints related to the sensor itself (e.g. temperature, pressure, and humidity conditions).

All monitoring equipment shall be calibrated and suitable for the intended use (i.e. suitable limit of detection, response time, accuracy, and reliability) and sampling environment to ensure that the data collected is reliable according to the objectives sought (see Annex E).

Where available, sensor technology that can be integrated into the aircraft systems and interpreted in real-time (see 7.3.1) shall be used to meet the requirements of this section. When real-time sensor technology is available but cannot be integrated into aircraft systems, then a portable real-time device should be used. Real-time sensor data could also be analysed post-flight.

Data collected with portable sampling equipment used for time-integrated measurement methods (see 7.3.2) may also be useful, either to supplement real-time data collected onboard or to perform a routine system inspection/maintenance for any of the airborne contaminant sources listed in Annex B.

The following approaches can be applied, either in isolation or in combination, to meet the requirements of contamination source recognition:

a) indicative chemical marker compounds;

b) pattern recognition; and

c) differential measurement.

See Annex D for further information on these approaches.

All sampling data shall be carefully interpreted in the context of the sampling conditions.

Cross-sensitivities should be taken into account.

7.2 Air monitoring planning/development

7.2.1 Overview

In coordination with aircraft manufacturers, airline operators shall establish a monitoring strategy according to EN ISO 16000-1, in order to define the most appropriate methodology to be utilized and to ensure that the integrity of the measurement data are maintained.

Sampling equipment shall be securely located and shall not interfere with aircraft operations, nor alter the air. Monitoring shall be part of a planned approach to prevent or reduce exposure.

Competent persons, with the skill, knowledge, practical experience and training shall plan and oversee monitoring. Trained air crew can manage aircraft-integrated monitoring equipment.

Monitoring objectives shall be defined as part of the air monitoring strategy for both real-time and time-integrated measurements, as applicable.

7.2.2 Overview of sampling environment and objectives

The airline operator shall prepare an overview of the environment that is to be sampled, ongoing operations, materials/products used in that environment, and the pollutants that may be generated from those materials. The airline operator shall incorporate air monitoring methodologies into SMS manuals.

7.2.3 Defining flight phases and whether occupied or unoccupied

Most of the requisite contaminant monitoring will be collected continuously by the airline operator, across all phases of flight (including ground-based operations) when the aircraft is occupied (see 7.1 and 7.3.1).

In addition, to meet the sampling objectives, it may be necessary for the airline operator to collect data for maintenance troubleshooting during specific phases of flight or engine/APU power settings, and only on an unoccupied aircraft.

The airline operator shall use Table 1 below to reference the general flight phases, with or without passengers, during which measurements should be taken.

Tests with the ECS or E-ECS (Electrical Environmental Control System) in full cold or full hot condition may not be possible with passengers on board due to comfort reasons. Among all possible aircraft system configurations, Table 1 summaries the combinations of possible aircraft system settings. For each measurement, these system configuration details shall be recorded.

Table 1 — Possible aircraft system configuration settings by flight phase

Flight phases	Aircraft system configuration and control settings				
	ECS or E-ECS [b]	Humidifier	APU bleed	Engine bleed	Ground air supply unit
Engine start [a]	ON or OFF	OFF	ON or OFF	OFF to ON	ON or OFF
APU start [a]	ON or OFF	OFF	OFF to ON	ON or OFF	
Ramp	FULL HOT FULL COLD 20 °C to 25 °C or actual [c]	ON or OFF [c]	ON or OFF [c]	OFF	ON or OFF [c]
Ramp de-icing [a]	OFF	OFF	OFF	OFF to ON	
Taxi out	20 °C to 25 °C or actual	ON or OFF [c]	ON or OFF [c]	ON or OFF [c]	
Take-off	20 °C to 25 °C or actual	ON or OFF	OFF	ON	
Climb	20 °C to 25 °C or actual	ON or OFF	OFF	ON	
Cruise	20 °C to 25 °C or actual	ON or OFF	OFF	ON	
Descent	20 °C to 25 °C or actual	ON or OFF	OFF	ON	
Taxi in	20 °C to 25 °C or actual	ON or OFF	20 °C to 25 °C or actual	ON	
Engine Shutdown [a]	ON or OFF		ON or OFF	ON to OFF	
APU shutdown [a]	ON or OFF		ON to OFF	ON or OFF	

[a] Airline operators should commence measurements before engine/APU start to ensure bleed air valve opening is recorded. Measurements should continue until after engine/APU shutdown to include situations where the bleed valve does not fully close/slow to close or fails to close.

[b] With ECS or E-ECS in “full hot” or “full cold” setting, measurements should be performed without passenger on board and with all air outlets closed (gaspers) closed.

[c] The selected ECS or E-ECS settings or aircraft system configuration are exclusive and shall be compatible.

7.2.4 Defining sampling locations

Options for sampling locations shall include the ventilation supply air system (upstream or downstream of the mix manifold) and the ambient cabin air.

The most reliable sampling location for ventilation supply air system-sourced contaminants is in the outside air stream, upstream of the mixing manifold. However, it may not be practical to sample there, given the high temperature and pressure. Sampling the mixture of bleed and recirculated air downstream of the mixing manifold will dilute any ventilation supply air system-sourced contaminants and the sampled air is likely to also contain contaminants generated within the cabin environment.

Settled contaminants on cabin and ventilation ducting surfaces are also a source of qualitative data.

7.3 Air monitoring methodology

7.3.1 Real-time monitoring

In addition to the primary monitoring objective defined in 7.1, airline operators shall use real-time monitoring to:

a) guide air crew to isolate a source of abnormal contamination, as early as possible (e.g. on a bleed air architecture, air crew could isolate an engine or APU bleed source);

b) guide maintenance troubleshooting, either in real time or after landing; and

c) provide, on bleed air architecture, data trends over time that could indicate necessary engine/APU maintenance.

NOTE Real-time monitoring assesses changes in contaminant levels as a function of time which can allow an airline operator to identify a range of conditions that require intervention, ranging from the early stages of abnormal leakage through degraded engine/APU seals to component failures.

To accomplish these objectives, sensors shall be designed and operated to measure relevant marker compounds (see Annex B), and the data shall be relayed to a system for interpretation. The system may either identify changes in the levels of marker compounds over time or compare the real-time sensor data to stored data collected under normal/intervention conditions, for example.

Airline operators should also use real-time monitoring to:

d) provide useful information on the efficiency of the filtration system (see Clause 6);

e) indicate that the filtration system is not performing as intended and if servicing/replacement is necessary, in addition to scheduled maintenance; and

f) provide in-service feedback on the performance of other ventilation supply air system components (e.g. pre-coolers, air exchangers, ECS, filtration systems, ozone/VOC converters, ventilation ducting, etc.).

7.3.2 Time-integrated monitoring

Airline operators shall use time-integrated monitoring methods for compounds for which suitable real-time sensors are unavailable.

These methods are recommended to support ground-based troubleshooting in cases where real-time sampling data does not readily identify the contaminant source. Time-integrated methods are suitable for measuring average levels of certain contaminants during routine operations and can supplement qualitative analyses of the chemical contents of an aircraft-installed filter or of wipe samples collected onboard. However, the limitations of time-integrated methods are notable; specifically, the data will not provide early notification of an exposure, which is the primary goal of onboard monitoring. Generally, time-integrated sampling data should be interpreted carefully because the data only defines the average concentration of a contaminant over the sampling period.

When time-integrated methods are selected over real-time methods to measure one or more of the contaminants listed in Table B.1, the rationale for not using real-time methods shall be documented including the relevant limitations, as well as the list of the standards that specify the general requirements for the competence to carry out tests and/or calibrations, and to apply laboratory methods (EN 482 [17], EN ISO 22065 [18], EN 838 [19], EN 13890 [20] and EN ISO/IEC 17025 [21]).

When the sampling strategy is defined and the sampling data are interpreted, the following factors should be considered:

a) flight phase(s);

b) duration of each sampling period;

c) the duration of the flight;

d) potential for variations in concentration within and between flight phases; and

e) challenges of reproducing inflight conditions during ground operations.

The user of the time-integrated monitoring method (or monitoring equipment) shall ensure that it is compatible with the range of and fluctuations in onboard environmental factors (e.g. temperature, humidity, pressure). The user shall also ensure that the analytical method is suitable for the suspected contaminant source, considering potential interferences which may consist of a complex mixture of compounds.

Before and after the sampling period, flows shall be checked by means of a calibrated flow measurement device. Sample duration and sample volume shall be defined by the monitoring objective(s) and will depend on the detection limit of the chosen method. For some time-integrated sampling methods, the limit of detection is low enough that the sampling duration can be short.

NOTE 1 Collection of time-integrated measurement data combines air sampling methods with subsequent laboratory analysis of the sampling media.

NOTE 2 Time-integrated sampling systems typically consist of a pump connected via a tube to the sampling media (collection or adsorption media).

NOTE 3 Time-integrated sampling does not define concentration as a function of time. Variability in concentration as a function of time can provide insight into the contaminant source when interpreted as a function of flight phase and engine power setting, for example.

In-flight sampling is conducted in a reduced and variable pressure environment, both of which will affect the volume of air that the pump actively draws across the sampling media. To address this, sampling shall be performed either with mass-flow controllers correcting for pressure changes, or with pumps that have automatic constant flow, assuring sampling is maintained within ± 5 % of the initial set point and resulting in a constant flow velocity during the whole flight.

If passive sampling methods are considered, the limitations should be recognized.

The airline operator shall send the air or media samples to an analytical laboratory with a demonstrated ability to produce precise and accurate test and calibration data, both for standard methods (as contained in Annex E), and for laboratory-developed methods. If no standardized method exists, adapted or novel methods or devices are allowed, providing they meet the primary monitoring objective (see 7.1).

8 Preventative and corrective actions

8.1 General

Airline operators shall develop and implement the operational and maintenance requirements in 8.2 – 8.5 to both prevent and remedy the presence of airborne chemical compounds (see Annex B), with an emphasis on compounds sourced to the ventilation supply air system. Airline operators shall collaborate with manufacturers, where applicable. Additional recommendations are listed in Annex F.

These requirements shall be incorporated into aircraft maintenance manuals and crew manuals, as appropriate.

8.2 Preventative measures pre-flight

a) To prevent overfilling of the oil reservoirs, airline operators shall install an instructional placard on each oil reservoir that clearly indicates the appropriate filling level and shall develop/implement a task card to train maintenance workers to:

   i) refer to the placard when filling the reservoir;

   ii) service the engine/APU after appropriate shut-down sequence (where relevant) and within specified timeframe; and

   iii) follow procedures intended to ensure an accurate reading and logging of oil level/additions.

   NOTE 1 Further guidance can be found in ASHRAE (2018) Air quality within commercial aircraft, ANSI/ASHRAE Standard 161–2018, ISSN 1041 2336, Section 8.7 – Engine oil.

b) To prevent overfilling of the hydraulic fluid reservoirs, airline operators shall install an instructional placard on hydraulic fluid reservoir that clearly indicates the appropriate filling level and shall develop/implement a task card to train maintenance workers to:

   i) refer to the placard when filling;

   ii) service within specified timeframe (where appropriate); and

   iii) follow procedures intended to ensure an accurate reading and logging of hydraulic fluid level/additions.

   NOTE 2 Further guidance can be found in ASHRAE (2018) Air quality within commercial aircraft, ANSI/ASHRAE Standard 161–2018, ISSN 1041 2336, Section 8.6 – Hydraulic fluid.

8.3 Corrective measures in-flight

Airline operators shall develop approved smoke/fumes checklist procedures for conditions that are not associated with fire when fumes are suspected to be present. The procedures shall include pilots' use of the oxygen mask in the 100 %/EMERGENCY position in order to ensure 100 % oxygen under positive pressure.

These checklist procedures shall include steps to enable pilots to attempt to isolate the source of supply air contamination inflight, when conditions allow.

8.4 Corrective measures post-flight

Airline operators shall use maintenance task cards to enable maintenance workers to reliably identify and remedy contaminant sources post-flight based on the location and nature of sensor data, and data from standardized crew reporting forms. Maintenance task cards shall employ a systematic approach to enable maintenance workers to troubleshoot aircraft systems to locate the presence of airborne contaminants according to each ventilation supply air source (e.g. APU, engine #1, engine #2, electric compressors). Troubleshooting tasks could include, but are not limited to: pack isolation procedures; visual inspection of engines/APU/ECS components and ducting that leads from bleed sources; boroscope inspection; review of oil consumption records; inspection of opened engine cowlings; aircraft walk around that includes check for evidence of fluid streaking around APU inlet; consideration of possible environmental causes; and cabin filter analysis.

Maintenance task cards shall direct workers to review oil/hydraulic servicing records and assess the systems for evidence of overfilling, especially if a mechanical defect/failure is not apparent. These task cards shall explicitly state that APU-sourced fumes can manifest inflight, after the APU has been turned off.

Maintenance task cards shall instruct maintenance staff to systematically inspect and clean systems downstream of an identified source of contamination, which may include ECS components and downstream air distribution/trim air ducting.

Specific to pack burn procedures, task cards for maintenance staff shall be developed and implemented to:

a) isolate the ducting downstream of the packs by routing the pack burn air overboard, where possible;

b) ensure that the aircraft is unoccupied during a pack burn or, if not possible, at least ensure that occupants wear suitably protective equipment; and

c) inspect and either clean or replace soiled downstream components.

NOTE Further guidance can be found in ASHRAE (2018) Air quality within commercial aircraft, ANSI/ASHRAE Standard 161–2018, ISSN 1041 2336, Section 8.2, Remedies (b) and A3.1.

Airline operators shall ensure that reported ventilation supply air contamination events are investigated and analysed according to best practices in order to address root causal factors to prevent repeat events.

8.5 Aircraft Maintenance Manual (AMM)

The maintenance task cards, and the measures described in the aircraft maintenance manual (AMM) should be made available to the pilots to support their decision to accept the aircraft back into service.

9 Monitoring of air crew and passengers

9.1 Monitoring air crew

Operators shall monitor the health of air crew. Monitoring air crew is another source of information about cabin air quality.

Air crew shall be monitored at:

- the commencement of employment (typically pre-engagement medical); and
- after all contaminated air fume events using the current best available technology.

The health monitoring shall utilize the best practice medical protocol specific for aircraft contaminated air exposures [22], [23]. The protocol shall be available for all air crew and their medical doctors.

Following a fume event, urine (time series) and blood samples shall be collected as soon as possible, in accordance with existing medical protocol.

Provision shall be made for the availability of suitable sterile containers as set out in the medical protocol. A chain of custody documentation system shall be in place.

Any medical protocol shall include specified testing and procedures for each member of the air crew:

a) immediately post flight; and

b) periodic follow up, as applicable. Follow up assessments shall refer to the initial test result.

Requirements in a) and b) above shall include a full occupational history including exposure history, incident reports submitted, maintenance undertakings and findings. Information collected shall include, at a minimum; a full list of symptoms categorized as acute, sub-acute, or chronic during periodic follow up; gender; age; past exposure effects; findings and diagnoses; flight hours or years; and whether other air crew or passengers were affected during the flight.

NOTE Other airline workers can also be monitored (e.g. maintenance staff).

9.2 Monitoring passengers

Airline operators are required to take the following actions in relation to passengers in case of a fume event;

a) when air crew report that they have been adversely affected by cabin air quality, enquiries of passengers shall also be made to establish whether they, too, have been affected;

b) when one or more passengers report that they have been adversely affected by cabin air quality, the airline operator shall ensure that their details are recorded, along with any adverse health effects;

c) when one or more passengers have been adversely affected, the airline operator shall as soon as possible provide key information to the passenger(s) as to what they were exposed to on board, which may be useful to their medical advisors, including information on toxicology tests;

   NOTE Product safety data sheet (SDS) is one source of information regarding hazardous substances and potential toxic effects.

d) when air crew report a fume event or exposure to bleed air contaminants, the airline operator shall offer to passengers access to the best practice medical protocol, specific for aircraft contaminated air exposures.

e) when a passenger accesses a medical protocol (as specified in (d)), the airline operator should have access to all relevant passenger data (subject to all data regulation obligations) to enable the airline operator to assess issues of cabin air quality and any adverse effects upon human health.

10 Data compilation, analysis and reporting

10.1 General

Airline operators shall compile the following data:

a) relevant airline operator reports (10.2.1);

b) fume event reports completed by air crew (10.2.2); and

c) required operator sensor data (7.1).

Airline operators shall incorporate these three sources of data into a SMS (or equivalent) framework (see 10.3.1) for analysis and reporting.

NOTE In this context, a SMS is an administrative framework that is applied to enable the operator to systematically monitor and respond to air quality events. The systematic collection, storage, and analysis of relevant data (see Section 6.2 of ICAO Circular 344 [24]) assists the operator in implementing the most appropriate response to a single air quality event and to modify/develop operational procedures based on trend analysis.

10.2 Data compilation

10.2.1 Relevant airline operator reports

The airline operator shall compile records which document the aircraft maintenance history (including relevant servicing records), technical logbook entries, Air Safety Reports (ASR), and Mandatory Occurrence Reports (MOR) for the following types of events:

a) the presence of contaminated air (fumes, smoke, haze) suspected or confirmed by one or more air crew to be associated with one or more of the sources listed in Annex B, Table B.1 (whether transient or sustained) in the ventilation air supplied to the flight deck or cabin;

NOTE 1 Pilots make a technical logbook entry for all known or suspected defects in the aircraft at the termination of a flight. The presence of transient/sustained smoke/fumes/haze indicates a known or suspected defect. This practice of logging defects reflects current regulations; specifically, CAT GEN. MPA.105 of Regulation (EU) 965/2012] "states that the commander shall record at the termination of the flight, all known or suspected defects of the aircraft in the aircraft technical log to ensure continued flight safety" and M.A. 306 of Regulation (EU) 1321/2014 [25] "states that operators shall use a technical log system", which includes all aircraft maintenance details and information necessary to ensure continued flight safety. Annex 1(4)(3) of Regulation (EU) 2015/1018 [26] "states that the presence of contaminated air in the flight deck or passenger compartment, which either has or could compromise flight safety, shall be reported". M.A. 305 of EU Reg. 1321/2014 [25] specifies that the aircraft and engine logbooks and the operator's technical log are both deemed part of the aircraft's continuing airworthiness records.

b) any burning, melting, smoke, fumes, arcing, overheating, fire, or explosion;

c) leakage of any fluid which resulted in a possible hazardous contamination of the aircraft, or which has or could have endangered the aircraft, its occupants or any other person (assessed according to the Precautionary Principle);

d) use of oxygen system by the air crew; and

e) impairment or incapacitation of any member of the air crew in relation to confirmed or suspected cabin air contamination.

NOTE 2 The events described in 10.2.1 (a) through (d) are referenced in Annex 1 (§2.1(4), 4(2), 4(3), 4(9)) of Regulation (EU) 2015/1018 [26]. In addition, incapacitation of any member of the air crew is referenced in Annex 1 (§4(10)) of Regulation (EU) 2015/1018 [26].

ASR and MOR reporting requirements are described in Regulation (EU) 376/2014 [27] and Regulation (EU) 2015/1018 [26]. These reports shall be filed within 72 hours of the termination of the flight.

NOTE 3 Aircraft accident and incident investigations are described in Regulation (EU) 996/2010 [28].

10.2.2 Air crew fume event reports

Airline operators shall create and make available standardized fume event reporting form(s)/system (electronic, hard copy, or both) for air crew. Airline operators shall train air crew in all aspects of using the reporting form(s)/system (see Clause 11).

At a minimum, each form (whether intended for pilots or cabin crew) shall solicit answers to the following questions:

- date of fume event;
- aircraft type;
- tail number;
- flight number and routing;
- apparent source of fumes (i.e. ventilation supply air vents or in-cabin air);
- description and intensity of odour;
- whether or not fumes accompanied by smoke or haze;
- location of fumes (flight deck, forward cabin, mid cabin, aft cabin, entire aircraft);
- phase(s) of flight when fumes were apparent and duration of event;
- whether air crew/passengers have/had symptoms, and which type of symptoms;
- whether onboard oxygen was used;
- whether any air crew sought onboard or on-arrival medical attention;
- maintenance follow-up and information (if known);
- impact on operations (if known); and
- reports of relevant/similar conditions on the same aircraft (if known).

In addition, the following questions shall be included on the pilot reporting form:

a) maintenance history for the aircraft described in the available pages (paper or electronic) of the technical logbook;

b) previous engine oil/hydraulic fluid service of aircraft;

c) de-icing prior to departure;

d) engine wash prior to departure (if known); and

e) other relevant environmental conditions.

NOTE 1 The reporting forms can be modelled on the fume event reporting form in the Appendix to Chapter 4 of ICAO Circular 344 [24]. Examples of "other relevant environmental conditions" are listed in Sections 3 and 4 of the ICAO fume event reporting form.

The reporting system shall be designed to ensure that each reporter/person who submits a form receives a copy of their submitted reporting form for their records.

NOTE 2 Some of the chemical constituents in certain types of fumes are either carcinogenic or mutagenic. Due to the potential latent health effect issues involved, it would be prudent for airline operators to meet the provisions of the EU Chemical Agents and CMD Directives 2004/37/EC [29] which require employers to maintain records of employee exposure to carcinogens/mutagens.

In addition to the air crew training provisions for fume event reporting (see Clause 11), the pilot reporting form shall instruct the pilot, when relevant, to file a report regarding the presence of either transient/sustained fumes with their airline operator in the form of an ASR/MOR or safety investigation report.

NOTE 3 Further information can be found in Article 4 of Regulation (EU) No 376/2014 [27]; Regulation (EU) No. 2015/1018 [26] and Regulation (EU) No 996/2010 [26].

NOTE 4 The reporting instruction for the pilot to report directly to the European Aviation Safety Reporting system, is described in Article 4 of Regulation (EU) No. 376/2014 [27].

NOTE 5 Other persons, including cabin crew, can submit an occurrence report voluntarily, on behalf of themselves or an organization, to the European Aviation Safety Reporting system per Article 5 of Regulation (EU) No. 376/2014 [27].

10.3 Analysis and reporting

10.3.1 Analysis

The airline operator shall create and maintain a SMS (or equivalent) framework to:

a) identify (see Clause 7 and Annex B) and remedy (see 8.3, 8.4 and Annex F) the source of contamination for a specific event;

b) guide preventive policies and procedures for types of events (see 8.2 and Annex F); and

c) develop a database of sensor data, both for events (associated with one or more fume reports from air crew) and for conditions that did not generate any air crew fume reports from air crew (see Clause 7).

The analysis of the sensor data shall be performed by suitably qualified persons with relevant skill, knowledge, and practical experience.

Airline operators shall also document post-incident investigation methods and corresponding countermeasures in relation to bleed air contamination in their SMS. The aircraft manufacturer shall update the corresponding Aircraft Maintenance Manual (AMM) accordingly.

If continuous monitoring of relevant airborne marker compounds was not performed during the reported incident, or if the data were insufficient to identify the root cause, then the post-incident investigation shall include air quality testing which may necessitate aircraft operation over the full range of engine power settings (see also Table 1).

NOTE The requirements for airline operators to report to the competent aviation authority are outlined in Articles 4 and 13 of EU No. 376/2014 [27]. Additionally, requirements for airline operators to report to the competent aviation authority and the aircraft manufacturer are outlined in M.A. 202 of EU 1321/2014 [25] and ORO.GEN.160 Regulation (EU) 965/2012 [30].

11 Airline worker education and training

11.1 General

Airline operators shall develop and implement training/education programmes for pilots, cabin crew, and maintenance workers to enable them to recognize, respond to, and document the suspected/confirmed presence of transient/sustained ventilation supply air system-sourced fumes. This training and education shall be provided at regular intervals, including initial training, and at least annually.

Airline operators shall review and update their training/education programmes and supporting materials on at least an annual basis to ensure that the delivery is effective, and the information is current.

Airline operators shall maintain a record of workers' participation.

11.2 Requirements

11.2.1 Programme provisions applicable to pilots, cabin crew and maintenance workers

Airline operator programmes for pilots, cabin crew, and maintenance workers required in 11.1 shall include material to ensure that workers are educated about the different sources and types of ventilation supply air contaminants and the potential health effects and flight safety concerns associated with exposure to those contaminants.

Airline operators shall ensure that workers are trained to distinguish between a fume event (i.e. fumes sourced to ventilation supply air vents; see 4.4) and the presence of odorous compounds sourced to either an in-cabin item or an external/transient source, and to react, respond and report the fume event to the necessary persons. The collection of standardized reporting data by trained air crew and maintenance workers is intended to supplement online sensor data.

The required programmes shall train workers to follow ground and in-flight protocols, including checklists (see 8.3, 11.2.2), onboard reporting systems (see 10.2.1, 10.2.2), medical monitoring (see Clause 9), procedures to secure medical care (if needed), and instructions to complete post-incident documentation, which may vary by work group.

Airline operators shall provide training in relation to any monitoring (see 7.1, 7.3) that is being carried on the aircraft, where needed, including actions/response required in relation to early warning systems for fume events.

NOTE These requirements support the guidance set out by ICAO Circular 344 [24].

11.2.2 Pilot-specific training and education

In addition to the programme requirements listed in 11.2.1, airline operators shall train pilots to establish communication with the cabin crew during and after a fume event and shall train them to ensure that a completed fume event reporting form (see 10.2.2) is received from the cabin crew. In addition to the required technical logbook entry for all known or suspected defects, including transient/sustained fumes, pilots shall also complete the reporting form (see 10.2.2).

In accordance with existing rules for establishing and modifying pilot checklists, the airline operator shall ensure that pilots are provided with a checklist that outlines procedures explicitly intended to be implemented in the presence of either suspected or confirmed ventilation supply air system-sourced fumes without suspected fire, even when airborne contaminants are not visible. The procedures shall include instructions on pilots use of oxygen mask (see 8.3).

In accordance with existing rules for establishing/modifying pilot manuals, the airline operator shall develop and implement unambiguous and effective pilot manual language intended to support these training and education requirements, in addition to the reporting requirements in Clause 10.

11.2.3 Cabin crew-specific training and education

In addition to the programme requirements in 11.2.1, airline operators shall train cabin crew to establish communication with the pilots during and after a fume event, and to provide the pilots with a completed fume event reporting form (see 10.2.2), including confirmation that an in-cabin source of fumes was ruled out. Cabin crew training shall include training for passenger management during and/or after a fume event.

In accordance with existing rules for establishing/modifying cabin crew manuals, the airline operator shall develop and implement cabin crew manual language intended to support the training, education, and reporting requirements in Clause 8.

11.2.4 Maintenance worker-specific training and education

In addition to the requirements in 11.2.1, operators shall train maintenance staff to:

a) wear appropriate respiratory and personal protective equipment when there is the potential for inhalation/dermal exposure to oil or hydraulic fluid, particularly during engine maintenance, cleaning, and troubleshooting procedures;

b) ensure that cabin crew are not onboard during engine test runs;

c) request and review copies of the cabin and flight deck fume event reporting forms and the maintenance history of the aircraft to assist in maintenance inspection/troubleshooting procedures; and

d) implement relevant maintenance task cards to identify/remedy the primary source of reported fumes and any secondary/downstream contamination.

Annex A
(informative)

Environmental Control Systems (ECS)

A.1 General

The purpose of the ECS is to ensure suitable aircraft cabin pressure, temperature, and ventilation to provide a safe and comfortable environment for the air crew and passengers. The ECS provides sufficient flow of outside air to ensure a partial pressure of oxygen to support the requirements of the air crew and passengers and prevents excessive levels of carbon dioxide building up in the cabin. These requirements are specified by the regulatory authorities. The ECS is also designed to provide homogenous air temperature throughout the cabin.

The principal types of ECS architecture on commercial passenger aircraft are bleed air ECS and bleed-free ECS (also referred to as electrical ECS).

Most commercial passenger aircraft use bleed air ECS (see A.2) which is supplied by outside air from one of several sources. During flight, bleed air is typically supplied to the ECS by the engines (or the APU, in certain circumstances). During ground operations, the air supplied to the ECS is either engine bleed air, APU bleed air, low pressure ground ventilation supply air, or high-pressure ground ventilation supply air. The air conditioning pack is pneumatically driven by the bleed air passing through it.

A bleed-free (or electrical) ECS is supplied with outside air taken from directly from outside of the aircraft via a dedicated inlet and electrical compressor (see A.3).

A.2 Bleed air environmental control systems (ECS)

Figure A.1 shows a typical schematic for a bleed air ECS. ECS architecture will vary depending on aircraft type.

In the case of the bleed air ECS, outside air is taken from a compressor stage of the engine or APU, upstream of the combustion stage, and fed to the air conditioning pack. This air is typically at elevated pressure and temperature. The purpose of the air conditioning pack is to bring the bleed air to a suitable temperature and pressure to maintain desired conditions in the cabin. The conditioned outside air is mixed in the mixing chamber with recirculation air. The purpose of recirculation air is to enable a reduction of outside air flow, for fuel economy, whilst maintaining desired air flows in the cabin to ensure even temperature distribution, suitable mixing of carbon dioxide (CO_2) and increased humidity levels. The mixed air is passed to the cabin. Cabin pressure is primarily controlled by modulation of one or more outflow valves positioned on the aircraft fuselage, often at the rear of the aircraft. There are other sources of air venting including but not limited to avionics, battery, lavatory, and galley ventilation outlets. Typically, 50 % to 60 % of the cabin air is exhausted through the outflow valve and the remaining air is recirculated.

Heating in individual areas of the cabin is achieved by injecting bleed air from upstream of the air conditioning pack directly into the ducting. This is called trim air.

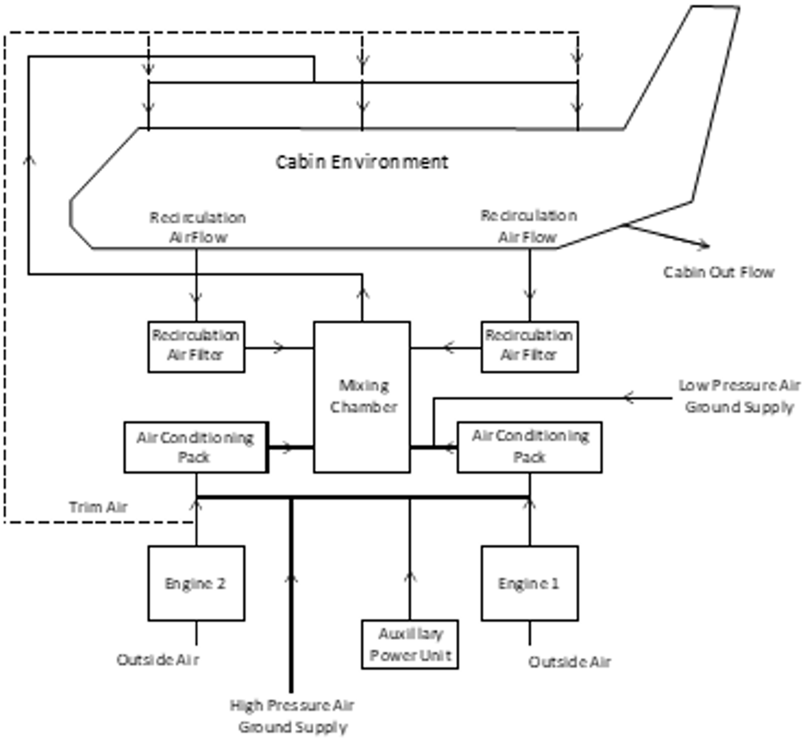

Figure A.1 — Typical schematic for a bleed air ECS

A.3 Bleed-free environmental control system

Figure A.2 shows a typical schematic for a bleed-free ECS.

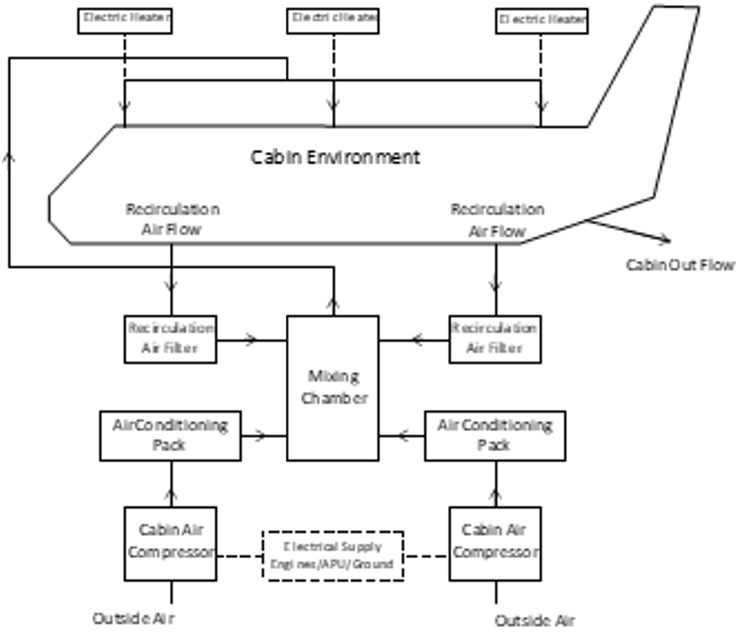

Figure A.2 — Typical bleed-free ECS architecture

The bleed-free ECS system differs from a bleed air ECS in that outside air flow is drawn through cabin air compressors which are powered by electricity generated by the engine or APU. Such a system avoids the possibility of the outside air coming into contact with aircraft fluids contained within the engine. Both bleed air ECS and bleed-free ECS can ingest chemical compounds from the outside environment.

Annex B
(normative)

Chemical marker compounds

Table B.1 lists chemical marker compounds according to relevant sources of airborne contaminants. Table B.2 provides additional information on whether a marker compound will be reliably present for each source.

The intent is to provide a list of chemical marker compounds which may contaminate the outside air drawn into the cabin and flight deck. Additionally, when listed compounds may also be sourced to either occupants or cabin interiors, they are noted.

The following sources have not been included: atmospheric pollution (except ozone), engine wash, tyre degradation, and electrical fumes.

Table B.1 — Sources of airborne contaminants and their associated chemical marker compounds

Chemical compounds	CAS number	Family compound	RELEVANT SOURCE				
			Engine Oil	Hydraulic fluid	Engine exhaust	Fuel (Unburned)	De-icing fluid
Ozone [a,m]	10028–15–6	Inorganic	—	—	x [a]	—	—
Nitrous oxides (NO_x)	—	Inorganic	—	—	x	—	—
CO_2 [b,i,j]	124–38–9	Inorganic	—	—	x [i]	—	—
CO [c]	630–08–0	Inorganic	x [c]	x [c]	x [c]	—	x [c]
Acrolein [d]	107–02–8	Aldehyde	x [d]	x [d]	x [d]	—	—
Formaldehyde [d,k]	50–00–0	Aldehyde	x [k]	x [k]	x [d, k]	—	—
Acetaldehyde [l]	75–07–0	Aldehyde	x [l]	x [l]	x [l]	—	—
Benzene [e]	71–43–2	Aromatic VOC	—	—	x	x [e]	—
Toluene [e]	108–88–3	Aromatic VOC	x	—	x	x [e]	—
Tricresyl phosphate (TCP-mix isomer) [f]	1330–78–5	Aromatic compound/ Organophosphate	x [f]	—	—	—	—
Tributyl phosphate (TBP) [g]	126–73–8	Aromatic compound/ Organophosphate	—	x [g]	—	—	—
C5-C10 Carboxylic acids [n]	—	Organic	x [n]	—	—	—	—
Ethylene glycol [h]	107–21–1	Alcohol	—	—	—	—	x [h]

Chemical compounds	CAS number	Family compound	RELEVANT SOURCE				
			Engine Oil	Hydraulic fluid	Engine exhaust	Fuel (Unburned)	De-icing fluid
Propylene glycol [h]	57–55–6	Alcohol	—	—	—	—	x [h]
Ultra-fine particles (<100 nm) [m]	—	Particulate matter	x	—	x	—	—
TVOC (Total VOC)	—	Volatile Organic Compounds	Marker of organic emission				

[a] The primary ozone source is outside air supplied to the aircraft systems when the aircraft is flying through the stratosphere, especially on high latitude/altitude flights. The aircraft engine and ECS reduce ozone concentration in the outside air supplied to the cabin and flight deck. Ozone converters, when installed, are intended to further reduce the concentration of stratospheric ozone when operated inflight. Engine exhaust is another potential source of ozone in the cabin air. The fumes can be entrained into the aircraft outside air stream, primarily during ground operations.

[b] Occupants are the primary source of CO_2 in the cabin. Dry ice, used for food conservation, is another source.

[c] CO is the product of incomplete combustion of organic material, but only at temperatures above approximately 230 °C. Because the presence of CO in fumes from oil, hydraulic fluid, and de-icing fluid is temperature-dependent, it is not a reliable marker compound for those sources on its own and should, instead be paired with other source-specific markers that are not temperature-dependent. CO is a more reliable marker compound for exhaust fumes, but is not specific to that source.

[d] Acrolein is a combustion marker and is expected to be present in exhaust gas fumes. It is not, however, specific to exhaust gas and may also be present in oil and hydraulic fluid products when decomposed at high temperatures. The temperature at which acrolein is formed will vary by product. Acrolein is not expected to be present when oils and hydraulic fluids are heated to more moderate temperatures and is not expected to be formed in the temperature range of an operating APU. Acrolein is difficult to measure in cabin. Formaldehyde is the dominant marker of engine exhaust, followed by acetaldehyde, acrolein, and then toluene/xylene

[e] Jet fuel contains multiple VOCs including toluene and traces of benzene.

[f] The majority of aviation engine oils contain TCPs (CAS 1330-78-5). At least one aviation engine oil does not contain TCPs; instead, it contains isopropylphenyl phosphate (CAS 68937-41-7). Other organophosphates may also be added to engine oils. All of these organophosphate compounds are semi-volatile, so they can condense in equipment or ducts and may be re-introduced/re-entrained in the ventilation air. The user should refer to the safety data sheet of the engine oil of interest to determine which organophosphate will be a suitable marker compound.

[g] With one known exception, at the time of publication of this document. hydraulic fluids contain TBP. The TBP content ranges from 5 % to 80 %. The user should refer to the safety data sheet of the hydraulic fluid of interest to determine if it will be a useful marker compound.

[h] The majority of de-icing fluids contain a high propylene glycol content and do not contain ethylene glycol. A minority of de-icing and anti-icing products contain ethylene glycol. The user should refer to the safety data sheet of the product of interest to determine which glycol product will be a suitable marker compound.

[i] The concentration of CO_2 in exhaust fumes is higher than in unpolluted outside air, but may not be higher than the concentration of CO_2 in the occupied cabin/flight deck air. As a result, CO_2 can be used as a marker of exhaust fumes, but only if it is measured in the outside air stream or in an unoccupied cabin. Otherwise, any increased CO_2 level from exhaust fumes could be masked by what are likely to be higher concentrations of CO_2 in the cabin air.

[j] The concentration of CO_2 in oil and hydraulic fluid fumes is very low compared to the concentration of CO_2 in either outside air or cabin/flight deck air. Thus, CO_2 is not a relevant marker for either oil or hydraulic fluid fumes because any contribution from the fumes would be masked by the ambient concentration of CO_2.

[k] Formaldehyde is a relevant marker of oil, hydraulic fluid and exhaust fumes if measured in the bleed air. It is not a reliable marker of these fumes if measured in the cabin because of potential in-cabin sources, such as carpet and upholstery.

[l] Acetaldehyde is a relevant marker of oil, hydraulic fluid and exhaust fumes if measured in the bleed air. It is not a reliable marker of oil fumes if measured in the cabin because of potential in-cabin sources, including bio effluents.

[m] Ultra fine particles (UFP) are associated with engine oil and exhaust fumes, and are also usually found when ozone is present.

[n] Carboxylic acids are formed by thermal decomposition of certain engine oil constituents, and are formed at higher concentrations when moisture is present.

Onboard electrical fumes may be sourced to overheated wiring, failed light ballasts, and defective electrical circuity in both the cabin and flight deck. The chemical constituents of the associated fumes will vary according to the plastic coatings, temperature reached, and whether combustion is complete, but potential chemical compounds include CO, CO_2, nitrogen compounds, aldehydes, chlorinated compounds, hydrogen cyanide, hydrogen fluoride, and hydrocarbons. Because there is limited information on the constituents, it can be difficult for an onboard sensor to distinguish between electrical fumes and the sources listed in Table B.1.

Table B.2 — Reliability ratings for the presence of chemical marker compounds, according to each source of contamination

Source number in Table B.1	Source [a]	Marker compound [b]	Reliability rating of marker compound [c]	CAS number
1	ENGINE OIL [h]	Tricresyl phosphates [d]	A	1330–78–5
		Acetaldehyde	B	75–07–0
		C_5-C_{10} carboxylic acids [l]	B	n/a
		Formaldehyde [b, h]	B	50–00–0
		Ultrafine particles ($PM_{0,1}$)	B	n/a
		Acrolein (only at high temperatures for selected products) [e]	C	107–02–8
		Carbon monoxide (CO) (formation expected to start at temp. > 230 °C; varies by product)	C	630–08–0
		Toluene	C	108–88–3
		TVOC (only limited data are available, specific to oil)	C	n/a
2	HYDRAULIC FLUID	Tributyl phosphate [j]	A	126–73–8
		Acetaldehyde	B	75–07–0
		Formaldehyde	B	50–00–0
		Acrolein (only at high temperatures for selected products) [e]	C	107–02–8
		Carbon monoxide (CO) (formation expected to start at temp. > 230 °C; varies by product)	C	630–08–0
		TVOC (only limited data are available, specific to hydraulic fluid)	C	n/a
3	ENGINE EXHAUST GAS [h,i]	Nitrous oxides	A	n/a
		Carbon dioxide (CO_2) [h,i]	A	124–38–9
		Formaldehyde [h]	B	50–00–0
		Acetaldehyde	C	75–07–7
		Acrolein [e]	C	107–02–8
		Benzene	C	71–43–2
		Carbon monoxide (CO)	C	630–08–0
		Toluene	C	108–88–3
		TVOC	C	n/a
		Ultrafine particles ($PM_{0.1}$)	C	n/a

Source number in Table B.1	Source [a]	Marker compound [b]	Reliability rating of marker compound [c]	CAS number
4	FUEL (UNBURNED)	TVOC	B	n/a
		Benzene [f]	C	71–43–2
		Toluene [f]	C	108–88–3
5	DE-ICING FLUID	Ethylene glycol (present in selected de-icing and anti-icing fluids; consult product SDS) [g]	A	107–21–1
		Propylene glycol (present in most de-icing fluids; consult product SDS) [g]	A	57–55–6
		Carbon monoxide (CO) (formation expected to start at temp. > 230 °C; varies by product)	C	630–08–0
6	OCCUPANTS	Carbon dioxide (CO_2)	B	124–38–9
		Acetaldehyde	C	75–07–0
		TVOC	C	n/a
7	CABIN MATERIALS	Formaldehyde [b]	B	50–00–0
8	STRATOSPHERIC OZONE	Ozone [k]	A	10028–15–6

[a] The listed sources in this table correspond to the listed sources in Table B.1.

[b] These marker compounds are generally not specific to a single source. To identify the source of contamination, it will usually be necessary to measure more than one marker compound by analytic means or use alternative methods such as pattern recognition. Also, the relevance and interpretation of the presence of marker compounds can vary according to sampling location. For example, formaldehyde in the bleed system could be sourced to oil fumes, although formaldehyde in the cabin air could be sourced to contaminants in the supply air or to in-cabin items such as carpet and upholstery.

[c] Reliability rating definitions (A, B or C)): A: Marker compound is a constituent of the source (e.g. engine oil, hydraulic fluid, exhaust gas etc). B: Marker compound is either a hydrolysis or pyrolysis product or off-gasses from the source. C: Marker compound meets “B” criteria, but with some limitations, such as a pyrolysis product which is generated over a more limited range of temperatures, or is expected to be present at very low levels or for which limited data are available.

[d] The majority of aviation engine oils contain TCPs (CAS 1330-78-5). At least one aviation engine oil does not contain TCPs; instead, it contains phenol, isopropylated phosphate (3:1) (CAS 68937-41-7). Other organophosphates may also be added to engine oils. The user should refer to the safety data sheet for the engine oil of interest to determine which organophosphate will be a suitable marker compound.

[e] Acrolein is a combustion marker and is expected to be present in exhaust gas fumes. It is not, however, specific to exhaust gas and may also be present in oil and hydraulic fluid products when decomposed at high temperatures. The temperature at which acrolein is formed will vary by product. Acrolein is not expected to be present when oils and hydraulic fluids are heated to lower temperatures and is not expected to be formed in the temperature range of an operating APU. Acrolein is difficult to measure in cabin. Formaldehyde is the dominant marker of engine exhaust, followed by acetaldehyde, acrolein, and then toluene/xylene.

[f] Benzene and toluene are ingredients in jet fuel, but only at very low concentrations. As such, they are not likely to be useful markers of fuel fumes. TVOCs may be a candidate for continuous monitoring of fuel fumes, but it may be difficult to determine if the VOCs are sourced to fuel because fuel is not a unique source of VOCs. Alternatively, fuel fumes may be identified by a compilation of known marker compounds added to commercial jet fuel, or by alternative methods such as pattern recognition.

[g] The majority of de-icing fluids contain a high propylene glycol content and do not contain ethylene glycol. A minority of de-icing and anti-icing products contain ethylene glycol. The user should refer to the safety data sheet for the product of interest to determine which glycol product will be a suitable marker compound.

[h] When measurements are performed in the outside air stream, the relative concentrations of CO_2 and formaldehyde may be useful to differentiate exhaust fumes from oil fumes. This is because CO_2 is present in exhaust fumes but is not a decomposition product of engine oil, whereas formaldehyde is present in oil fumes, but only minimally present in exhaust fumes. Note that the formaldehyde content in exhaust fumes may vary depending on the fuel type and the temperatures to which the fuel is heated.

[i] The reliability rating of A for CO_2 for exhaust fumes, refers only to CO_2 measurements collected in the either the outside air stream or an unoccupied cabin (refer to Table B.1, footnotes i and j).

[j] Refer to Table B.1, footnote g.

[k] Refer to Table B.1, footnote a.

[l] Refer to Table B.1, footnote n.

Annex C
(informative)

Precautionary Principle

C.1 Precautionary Principle

This document defines requirements and recommendations in relation to the presence of, and means to prevent exposure to, chemical compounds, including those that could cause adverse effects, taking into account the Precautionary Principle. Taking into account the Precautionary Principle provides a primary goal of removing detriment to such end-users and is in line with the Principles as set out by the EU Commission.

International Treaties and Commentary have created common themes within 'The Precautionary Principle' debate and the creation of Legal Principles:

a) the elimination or mitigation of risk where possible;

b) protection of human health;

c) the application of scientific analysis requiring action or no action;

d) the creation of objective assessments;

e) the adoption of the principle in marine, environment and food scenarios; and

f) the requirement to include a wider cohort of expertise or interested parties.

The themes adopted by the instruments above are reflected within Article 191 of the Lisbon Treaty.

Article 174 of the Maastricht Treaty states: "Community policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Community. It shall be based on the precautionary principle and on the principles that preventive action should be taken."

The Charter of Fundamental Rights of the European Union which accompanies the Lisbon Treaty in Art. 31 and Art. 38 refers to "Every worker has the right to working conditions which respect his or her health, safety and dignity" and "Union policies shall ensure a high level of consumer protection"

Examples of the 'Precautionary Principle' in action within EU Law are referenced within this Annex [31]-[35]. In considering the issue of the 'precautionary principle' and risk analysis, the Commission, commenting on Consumer health and food safety stated within (COM (97) 183 final) [36] that:

> *"The Commission will be guided in its risk analysis by the precautionary principle, in cases where the scientific basis is insufficient, or some uncertainty exists."*

The Precautionary Principle, utilizes the following components of Risk Assessment to be considered and used:

- hazard identification;

- hazard characterization;

- appraisal of exposure; and

- risk characterization.

These four components of risk assessment, as advocated by the EU, is key to developing a methodology and structure in the creation of this document on cabin air quality. The four components are contained within Annex III of the 2000 EU Communication document [37] and for the purposes of this annex, it is re-produced in its entirety with some explanatory notes therein:

> *"An attempt to complete as far as possible these four components should be performed before action is taken.*
>
> *Hazard identification means identifying the biological, chemical or physical agents that may have adverse effects. A new substance or biological agent may reveal itself through its effects on the population (illness or death), or on the environment and it may be possible to describe the actual or potential effects on the population or environment before the cause is identified beyond doubt.*
>
> *Hazard characterization consists of determining, in quantitative (data) and/or qualitative (descriptive content) terms, the nature and severity of the adverse effects associated with the causal agents or activity. It is at this stage that a relationship between the amount of the hazardous substance and the effect has to be established. However, the relationship is sometimes difficult or impossible to prove, for instance because the causal link has not been established beyond doubt.*
>
> *Appraisal of exposure consists of quantitatively or qualitatively evaluating the probability of exposure to the agent under study. Apart from information on the agents themselves (e.g. source, distribution, concentrations, characteristics, etc.), there is a need for data on the probability of contamination or exposure of the population or environment to the hazard.*
>
> *Risk characterization corresponds to the qualitative and/or quantitative estimation, taking account of inherent uncertainties, of the probability, of the frequency and severity of the known or potential adverse environmental or health effects liable to occur. It is established on the basis of the three preceding and closely depends on the uncertainties, variations, working hypotheses and conjectures made at each stage of the process. When the available data are inadequate or non-conclusive, a prudent and cautious approach to environmental protection, health or safety could be to opt for the worst-case hypothesis. When such hypotheses are accumulated, this will lead to an exaggeration of the real risk but gives a certain assurance that it will not be underestimated."*

On the issues of how a risk analysis is to be performed, evidence, and the Precautionary Principle, the Commission has stated the following [36]:

> *"The Treaty requires the Community to contribute to the maintenance of a high level of protection of public health, the environment and consumers. In order to ensure a high level of protection and coherence, protective measures should be based on risk assessment, taking into account all relevant risk factors, including technological aspects, the best available scientific evidence and the availability of inspection sampling and testing methods. Where a full risk assessment is not possible, measures should be based on the precautionary principle."*

C.2 Precautionary Principle considerations: background information

The purpose of this section is to introduce or highlight issues related to the engine and APU bleed air contaminants brought into the aircraft environment that may reveal uncertainty when considering the broader issues of cabin air quality.

There are many aviation and occupational safety and health regulations, directives, standards and accompanying compliance material that are applicable to ensuring the highest standards are maintained for all aviation users.

During normal operations, the design and maintenance of the bleed air system on aircraft can expose aircraft occupants to low levels of engine oil fumes that contain organophosphates (refer to Annexes F, G, H). Occupants can also be exposed to low levels of fumes from other fluids, such as hydraulic and de-icing products. All of these fumes can contain complex mixtures of chemical compounds. In addition, there is the potential for exposure to these low-level fumes during transient short duration exposures (during engine power and ventilation supply air setting changes, for example) and to higher levels during less frequent system degradation conditions (refer to Annex H). The compounds in these fluids and the pyrolysis products include a wide range of hazard classification statements, required by EU law [7]. Applying the precautionary principle has the potential to eliminate or reduce the risk of onboard exposure to ventilation supply air system-sourced fumes.

On aircraft, there is documented evidence of routine, low-level exposure to organophosphate-containing oil and hydraulic fluid fumes. Of concern, *in vitro* testing has found that repeated, low-dose exposure to some organophosphate pesticides increased the vulnerability of neurons to a subsequent higher dose event [38]. Consistent with those observations, a number of cellular mechanisms by which subclinical concentrations of organophosphates could damage neuronal processes have been described [39]. Together, these findings suggest a possible mechanism to explain the observation that air crew are more likely than passengers to report neurological damage after an acute exposure event [40], [41]. Thus, a precautionary approach is further supported.

On aircraft, additionally, engine oil fumes can contain ultrafine particles [43]. Exposure to ultrafine particles can be associated with short-term and long-term health effects [43]-[46] and are also suspected to increase transference of toxicants to the brain [47]. Most chemicals that produce systemic adverse effects do not have a similar degree of toxicity in all organs, but usually produce their major toxicological effects in one or two target organs. These are referred to as target organs of toxicity for that chemical. A major reason why the mammalian brain is a susceptible target organ is that nerve cells last for the lifetime of the organism. Nerve cells are terminally differentiated and cannot, like most other tissues, repair by cell proliferation [48]. When considering irreversible changes (e.g. protein misfolding) to the nervous system caused by toxic substances, the low concentration of toxicants in inhaled air does not preclude harm. Rather, it is the total cumulative dose over time that should be considered. Additionally, in toxicology, it is generally considered that 100 % [49], [50] of the inspired dose of toxicants is retained and can pass directly to the systemic bloodstream without passing through the liver.

In assessing the potential exposure and associated health hazard for air crew, consider that in a 40-year flying career (assuming 500 flight hours per annum), the average person will conservatively, breathe 9 000 000 litres of cabin air (assuming an average inhalation of 8 l of air per minute [51] or 480 l/flight hour). This estimate does not include the time spent inside the aircraft that is not formally counted towards flight time.

When considering irreversible changes:

- Over a 20 000-h career, air crew can breathe at least 9 000 000 litres of cabin air;
- Most toxicology on TOCP/TCP has been performed on oral route exposure studies
- Exposure by inhalation is acknowledged to be more toxic (first pass) than ingestion and all of the dose is assumed to be assimilated; and

Even with a low dose - if it induces irreversible changes (e.g. demyelination, protein misfolding) - then the effect of prolonged exposure will be harmful.

Annex D
(informative)

Approaches for online monitoring

D.1 General

The following approaches can be applied in isolation or in combination to meet the same requirements of contamination source recognition:

D.1.1 Indicative chemical marker compounds

The aim of this approach is to identify individual chemical marker compounds that are reliably associated with the contamination sources listed in Table B.1. When choosing a sampling method, civil aircraft shall be equipped with sensor equipment in the cabin or supply air capable of concurrently monitoring the levels of one or more marker compounds with an assigned “reliability rating” of A (see Annex B, Table B.2.). Alternatively, airline operators can meet this requirement by monitoring for at least two marker compounds with an assigned “reliability rating” of B (see Annex B, Table B.2) for each of the contamination source.

NOTE (delete to address ILNAS 633)

D.1.2 Pattern recognition

Pattern recognition may be more reliable to identify a contaminant source. It uses multiple sensor arrays, each array sensitive to a different range of chemical compounds, capable of generating a unique “fingerprint” response for each chemical source. These devices continuously monitor the cabin air and will respond to the gaseous composition of the air. The chemical sources that they can identify are limited by the library of compounds that it has been trained to recognize.

D.1.3 Differential measurement

This method also identifies contamination sources by individual chemical marker compounds, as in the method described in D.1.1. However, it uses differential measurement of chemical compounds upstream and downstream of the source of contamination. The primary benefit of differential measurements is that they show a change in the system that may be relevant to a specific contaminant source. This method is limited to the marker compounds listed in Annex B, Table B.1.

This method is likely to be complementary to the method described in D.1.1 or D.1.2, given the complexities of sampling upstream and downstream of a contaminant source.

Annex E
(informative)

Reference method for real-time and time-integrated measurement of chemical marker compounds and (ultra) fine particles

Table E.1 — Examples of standardized methods for real-time and time-integrated measurements

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
Ozone	10028–15–6	**EN 14625**	EN 14625:2012 Ambient air. Standard method for the measurement of the concentration of ozone by ultraviolet photometry	**X**		For UV photometry detection, the ranges and uncertainty requirements given in this standard may not apply when the standard is used for other purposes than for measurements required by Directive 2008/50/EC (on ambient air quality and cleaner air for Europe). The method covers the determination of ambient air concentrations of ozone in areas classified as rural, urban and urban-background areas.
		EN 45544-4	EN 45544-4:2016 Electrical apparatus used for the direct detection and direct concentration measurement of toxic gases and vapours - Guide for selection, installation, use and maintenance	**X**		The electrochemical detector is a fixed, transportable and portable chemiluminescence apparatus, primarily used for measurement of oxides of nitrogen and ozone. Application range is from a few ppb (v/v) to thousands of ppm (v/v).
CO_2	124–38–9	**EN ISO 16000-26**	EN ISO 16000-26:2012 Indoor air sampling strategy for carbon dioxide	**X**		This standard describes some limitations of using non-dispersive infrared detector (NDIR), including drift and the need for recurrent calibration.
		EN 45544 series	EN 45544-1:2016 Workplace atmospheres -	**X**		This standard states that the lower limit of measurement required for apparatus that measure CO_2 is 500

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
			Electrical apparatus used for the direct detection and direct concentration measurement of toxic gases and vapours			ppm (≈ 900 mg/m^3), although state of the art instruments will measure at lower concentrations (e.g. 100 ppm).
CO	630–08–0	**EN 14626**	EN 14626:2005 Ambient air quality. Standard method for the measurement of the concentration of carbon monoxide by non-dispersive infrared spectroscopy	**X**		Non-dispersive infrared spectrometry (NDIR) can be used to determine the mass concentration of carbon monoxide present in ambient air up to 87 ppm. Note: The ranges and uncertainty requirements given in EN 14626 may not apply when the standard is used for purposes other than the measurements required by Directive 2008/50/EC (on ambient air quality and cleaner air for Europe). The method covers the determination of ambient air concentrations of carbon monoxide in areas classified as rural, urban-background, traffic-orientated, influenced by industrial sources.
		EN 45544 series	EN 45544-4:2016, Workplace atmospheres - Electrical apparatus used for the direct detection and direct concentration measurement of toxic gases and vapours	**X**		The lower limit of measurement required for direct-reading apparatus is 3 ppm, although state of the art instruments will measure at lower concentrations (e.g. 0 – 500 ppm).

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
Acrolein	107–02–8	**ISO 16000-3**	ISO 16000-3:2011, Indoor air — Part 3: Determination of formaldehyde and other carbonyl compounds in indoor air and test chamber air — Active sampling method		**X**	Part 3 of this standard describes how to sample for airborne acrolein using adsorbent cartridges coated with 2,4- DNPH as derivatization reagent, and subsequent HPLC-UV analysis of the hydrazones. One analytical issue with this method is the degradation of acrolein hydrazone which is produced during sampling. The concentration range for acrolein that can be measured with this method is 1 µg/m^3 to 1 mg/m^3.
Formaldehyde	50–00–0	**ISO 16000-3**	ISO 16000-3:2011, Indoor air — Part 3: Determination of formaldehyde and other carbonyl compounds in indoor air and test chamber air — Active sampling method		**X**	Part 3 of this standard describes how to sample for airborne aldehydes using adsorbent cartridges coated with 2,4-DNPH as derivatization reagent, and subsequent HPLC-UV analysis of the hydrazones. The quantification limit for formaldehyde is 1 µg/m^3. The accuracy is to be determined.
Formaldehyde	50–00–0	**ISO 16000-4**	ISO 16000-4:2011 (confirmed in 2017), Indoor air — Part 4: Determination of formaldehyde — Diffusive sampling method		**X**	For sampling periods of 24 h, the applicable concentration range that can be measured with the method described in this standard is 3 µg/m^3 (2.5 ppb) to 1 mg/m^3, but for shorter sampling periods, the concentration range that can be measured will be higher.

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
Acetaldehyde	75–07–0	**ISO 16000-3**	ISO 16000-3:2011, Indoor air — Part 3: Determination of formaldehyde and other carbonyl compounds in indoor air and test chamber air — Active sampling method		X	Part 3 of this standard describes how to sample for airborne aldehydes using adsorbent cartridges coated with 2,4- DNPH as derivatization reagent, and subsequent HPLC-UV analysis of the hydrazones.
Benzene	71–43–2	**ISO 16000-6**	ISO 16000-6:2011, Indoor air – Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA® sorbent, thermal desorption and gas chromatography using MS or MS-FID		X	Part 6 of this standard describes air sampling on Tenax TA® sorbent with subsequent thermal desorption and GC-FID or GC-MS analysis. Concentration range for benzene: ng/m^3 to mg/m^3
		EN 14662	EN 14662, Ambient air quality. Standard method for measurement of benzene concentrations – Parts 1 to 5.		X	**Part 1: pumped sampling** followed by thermal desorption and gas chromatography. Concentration range: approximately 0,5 pg/m^3 to 50 pg/m^3 for 24 h sampling. **Part 2: pumped sampling** followed by solvent desorption and gas chromatography. Concentration range: approximately 0,5 mg/m^3 to 50 mg/m^3 for 24 h sampling. **Part 4: diffusive sampling** followed by thermal desorption and

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
						gas chromatography. Concentration range: approximately 0,5 µg/m³ to 50 µg/m³ for a 14-day sampling. **Part 5: diffusive sampling** followed by solvent desorption and gas chromatography. Concentration range: approximately 0,5 mg/m³ to 50 mg/m³ for a sampling of several days to several weeks.
Benzene	71–43–2	**EN 14662**	EN 14662, Ambient air quality. Standard method for measurement of benzene concentrations – Parts 1 to 5.	**X**		**Part 3: automated pumped sampling with *in situ* gas chromatography.** Semi-continuous measurement method, depending on the duration of each measurement period.
		EN ISO 16017-2	ISO 16017-2:2003, Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography — Part 2: Diffusive sampling		**X**	Part 2 of this standard is applicable to the measurement of airborne vapours of VOCs in a mass concentration range of approximately 2 µg/m³ to 100 mg/m³ for 8 h sampling, or 0,3 µg/m³ to 300 µg/m³ for an exposure time of 4 weeks. The lower range limit depends on the noise level of the detector and on blank levels of analyte and/or interfering artefacts on the sorbent tubes.

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
Toluene	108–88–3	**ISO 16000-6**	ISO 16000-6:2011, Indoor air — Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS or MS-FID		X	Part 6 of this standard describes a method of air sampling for toluene on Tenax TA® sorbent with subsequent thermal desorption and GC-FID or GC-MS analysis. Concentration range: ng/m^3 to mg /m^3
Tricresyl phosphate (TCP-mix isomer)	1330–78–5	**ISO 16000-31**	ISO 16000-31:2014 (confirmed in 2019), Indoor air — Part 31: Measurement of flame retardants and plasticizers based on organophosphorus compounds — Phosphoric acid ester		X	Part 31 of this standard describes a method that detects all organophosphates. Quantification limit and accuracy are to be determined.
Tributyl phosphate (TBP)	126–73–8					

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
C5-C10 Carboxylic acids	-	**ISO 16000-6**	ISO 16000-6:2011, Indoor air — Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS or MS-FID		**X**	The method uses Tenax TA® sorbent with subsequent thermal desorption and gas chromatographic analysis employing a capillary column and a mass spectrometric detector in SIM mode (offline).
Ethylene glycol	107–21–1				**X**	The method uses Tenax TA® sorbent with subsequent thermal desorption and gas chromatographic analysis employing a capillary column and a mass spectrometric detector in SIM mode (offline).
Propylene glycol	57–55–6				**X**	The method uses Tenax TA® sorbent with subsequent thermal desorption and gas chromatographic analysis employing a capillary column and a mass spectrometric detector in SIM mode (offline).
Ultra-Fine Particles (<100 nm)	-	**EN ISO 28439**	ISO 28439:2011, Workplace atmospheres - Characterization of ultrafine aerosols/nanoaerosols - Determination of the size distribution and number concentration using differential electrical mobility analysing systems	**X**		This standard provides guidelines to determine the number concentration and size distribution of ultrafine aerosols and nanoaerosols by use of mobility particle sizers (also called differential mobility analysers DMASs). Limitations, maintenance, measurement, and calibration issues are described. The system is generally not suitable for personal exposure measurements. The differential mobility analysing system (DMAS) available from several vendors is discussed.

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
		EN 16897	EN 16897:2017, Workplace exposure - Characterization of ultrafine aerosols/ nanoaerosols - Determination of number concentration using condensation particle counters	**X**		This standard describes how a condensation particle counter operates and also discusses sampling issues, how to select a suitable instrument, limits of application, use of different working fluids calibration, equipment maintenance, measurement uncertainty, and reporting of measurement results.
		EN 17058	EN 17058:2018, Workplace exposure - Assessment of exposure by inhalation of nano-objects and their aggregates and agglomerates			This standard describes how to assess inhalation exposure of nanoobjects and their aggregates and agglomerates (NOAA).

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
Ultra-Fine Particles (<100 nm)	-	**EN 16966**	EN 16966:2018, Workplace exposure - Measurement of exposure by inhalation of nanoobjects and their aggregates and agglomerates - Metrics to be used include number concentration, surface area concentration, and mass concentration.			This standard specifies the use of different metrics for the measurement of exposure by inhalation of NOAA during a basic assessment and a comprehensive assessment, respectively, as defined in EN 17058.
TVOC (Total VOC)	-	**ISO 16000-29**	ISO 16000-29:2014, Indoor air: Test methods for VOC detectors	X		Part 29 of this standard defines the requirements for measuring VOCs with a photo ionization detector (PID). It addresses response time, stability, and measurement range, to monitor indoor VOC concentrations, as well as to control indoor air quality in portable, mobile, and remote applications.
		ISO 16017-1	ISO 16017-1:2000 (confirmed in 2016), Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography — Part 1: Pumped sampling.		X	Part 1 of this standard describes sampling and analytical methods to measure volatile organic compounds by sorbent tube (pumped sampling) and thermal desorption/capillary gas chromatography. Concentration range: 0,5 mg/m^3 to 100 mg/m^3

Chemical marker compound	CAS No	Standardized method	Title of standard	Real-time	Time-integrated	Comments
		ISO 16017-2	ISO 16017-2:2003 (confirmed in 2019), Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography — Part 2: Diffusive sampling		**X**	Part 2 of this standard describes sampling and analytical methods to measure volatile organic compounds by sorbent tube (diffusive sampling) and thermal desorption/capillary gas chromatography. Range: 0,002 mg/m^3 to 100 mg/m^3
TVOC (Total VOC)	-	**ISO 16000-6**	ISO 16000-6:2011, Indoor air — Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS or MS-FID		**X**	Part 6 of this standard describes sampling and analytical methods to assess TVOC by sampling on Tenax TA® sorbent tubes with subsequent thermal desorption and GC-FID or GC-MS analysis. The method can also be used for individual VOCs. Concentration range is ng/m^3 to mg/m^3.
		EN 16516	EN 16516:2017 +A1:2020 Construction products: Assessment of release of dangerous substances. Determination of emissions into indoor air.		**X**	This standard describes a reference method for the determination of emissions of regulated dangerous substances from construction products into indoor air. The method is based on the use of a test chamber and subsequent analysis of the organic compounds by GC-MS or HPLC. This method is applicable to a variety of compounds, including VOCs.

Table E.2 — Examples of possible methods for real-time measurement of chemical marker compounds and ultrafine particles

Sensor Technology for air quality: At the time of publication of this document this type of measurement system, based on high tech instrumentation, is not achievable without training, experience and proven expertise. This area is still at a pre-normative research level.

This table does not reflect sensor technologies under development. The user of this table may wish to consult literature for real-time sensor technologies that have been developed since this document has been published to ensure latest information.

Chemical marker compound	Sensor type	Technology description
Ozone	**MOX detector**	Due to low selectivity, the MOX sensor needs to be part of a sensor network (with signal and data processing, based on a powerful algorithm, data display, etc.). This technology is still at a pre-normative research level.
	Real-time optical ozone sensor	This type of sensor is made of a mesoporous silica thin film impregnated with methylene blue. It is at the stage of miniaturization and will then proceed to pre-market level.
Acrolein (and other gaseous pollutants)	**Cavity ring down spectroscopy (CRDS)**	Enables the quantification of gaseous pollutants at very low concentrations, but the measurements are not achievable without high tech equipment, training, and expertise.
Formaldehyde	**Photoelectric Photometry**	Combines a reusable sensor cartridge and a photoelectric photometer, which measures a yellowing resulting from the chemical reaction between formaldehyde and ß-diketone. Readings to < 20 ppb.
	Photoacoustic gas analyser	Combines enhanced photoacoustic detection technology with quantum cascade laser source operating at a mid-IR range (fundamental spectral absorption line of formaldehyde). Estimated LOD is approximately 1 ppt. Criteria for re-calibration period to be respected
	Formaldehyde detector, monitor or tester based on electrochemical sensor	Accurate readings are advertised at levels below 20 ppb, without significant cross-sensitivity from typical background levels of other compounds. Limit of detection down to below 5 ppb and up to 1 ppm (to be confirmed for analysers like "*Formaldehydemeter/tester*" (based on sensor).

	Photoacoustic gas analyser	**Photoacoustic gas analyser** (combining enhanced photoacoustic detection technology with quantum cascade laser source operating at a Mid-IR fundamental spectral absorption line of formaldehyde) Estimated LOD is approximately 1 ppt (0,001 ppb). Criteria for re-calibration period to be respected.
Benzene	**Photoacoustic gas analyser**	**Photoacoustic gas analyser** (combining enhanced photoacoustic detection technology with quantum cascade laser source operating at a Mid-IR fundamental spectral absorption line of benzene) Estimated LOD is approximately 1 ppt (0,001 ppb). Criteria for re-calibration period to be respected.

Annex F
(informative)

Examples of best practice intended to prevent or minimize contamination

Table F.1 — Examples of best practice for manufacturers, airline operators, pilots and maintenance operations to prevent or minimize contamination of the aircraft ventilation supply air system

No.	Type [a]	Type of Control Measure	Description of Control Measure
1	D/M	Ensure that oils and engine seals are compatible and upgraded	Engine manufacturers should confirm with the oil and seal manufacturers that each qualified engine oil is compatible with the engine seals, and should confirm that the engine seals are designed, upgraded, and maintained according to manufacturer recommendations, with particular attention to ensuring a proper seal during transient engine power setting conditions.
2	M	Select seal-compatible engine oil(s) that contains lowest levels of reportable toxic substances	For each engine/APU, airline operators should select the qualified oil that contains the lowest levels of reportable toxic substances (e.g. TCPs, TXP, and PAN), per the product safety data sheets.
3	M	Inspect and maintain oil supply system	Airline operators should inspect and maintain the oil supply system according to a regular schedule to prevent degradation that can cause bleed air contamination. [Reference ANSI/ASHRAE Standard 161–2018, Sec. 8.7, Maintenance (b).] [52]
4	D	Protect APU inlet from fluid ingestion	Aircraft manufacturers should ensure that the location and mechanics of the APU inlet are designed to prevent ingestion of hydraulic fluid (e.g. locate the inlet above the “six-o-clock” position, install a diverter assembly to protect inlet, etc.).
5	D	Implement additional design measures to minimize the potential for hydraulic fluid ingestion	Where applicable, aircraft manufacturers should evaluate and implement additional design features to prevent/minimize hydraulic fluid ingestion into the Environmental Control System, focusing on ingestion through the APU inlet.

No.	Type [a]	Type of Control Measure	Description of Control Measure
6	O	Prevent exhaust fume contamination of outside air supplied to the cabin	Responsible parties, including airport authorities, ground service providers, and airline operators, should review the use of ground service vehicles and equipment, and develop procedures intended to prevent ingestion of unfiltered engine exhaust into the APU/engine bleed air stream. Recommended procedures include, but not limited to, training equipment operators to maintain an appropriately protective distance between exhaust sources and APU/engine intakes, minimizing idling of ground service vehicles, scheduling routine vehicle maintenance, and transitioning to either electrical or non-diesel ground service equipment.
7	P	To prevent contamination of the cabin air after starting the APU	In order to prevent contamination of the cabin air after starting the APU, the pilots should delay turning the APU bleed ON (three minutes is a reasonable time; also refer to applicable manufacturer recommendations). If there is residual oil in the ventilation ducts, the fumes will be evacuated before entering the air conditioning circuit.

[a] Type of exposure control measure: D (design), O (operation), P (pilot) or M (maintenance).

NOTE These recommendations are supported by the measures to address contamination of the cabin and flight deck air listed in Sections 8.2 (General), 8.4 (Exhaust fumes during ground operations), 8.6 (Hydraulic fluid), 8.7 (Engine oil) and Sec. A3 (ECS cleaning procedure) of ASHRAE “Air quality within commercial aircraft,” ANSI/ASHRAE Standards 161–2018 [53], American National Standards Institute, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, USA.

Annex G
(informative)

Chemical marker compounds introduced into the cabin

Table G.1 — Chemical marker compounds introduced into the cabin via the outside air to the ventilation system

Source/type of compound	Examples of means by which source/type of compound can contaminate cabin air	Examples of associated chemical compounds
Engine oil	may contaminate the supply air through leaking oil seals or degraded/failed bearings in the engine/APU, and also as a result of maintenance practices (e.g. oil reservoir overfill); secondary sources of oil fumes include soiled ducting and ECS components	tricresyl phosphates or alternative phosphate (refer to the oil Safety Data Sheet), formaldehyde, toluene, ultrafine particles, phenyl naphthylamine, etc
Hydraulic fluid	may contaminate the supply air through ruptured hydraulic fluid supply lines; also, maintenance practices can lead to overfilling of the hydraulic reservoir	tributyl phosphate, triisobutyl phosphate, triphenyl phosphate, epoxy resins, etc.
De-icing fluid	may contaminate the supply air if the engines/APU inlet are sprayed during a de-icing application	propylene glycol, ethylene glycol, patented additives
Engine exhaust	may contaminate the supply air if exhaust gas from operating aircraft or ground service vehicles/equipment is drawn into the supply air associated with ground operations and increased likelihood of exposure at busy airports, especially while waiting in line to take off NOTE: Ozone may be generated when NOx and hydrocarbons from exhaust react with each other in the presence of UV light.	nitrous oxides, ozone, particulate matter, aldehydes, toluene, xylenes
Fuel (unburned) and vapours	Fuel spills and vapours may be drawn into the APU inlet.	petroleum distillate, xylene
Ozone (stratosphere, inflight)	may contaminate the supply air when flying through elevated concentrations of ozone in the stratosphere; particularly at high latitudes/altitudes in early spring	ozone gas can also react with other compounds in the cabin air, producing secondary reactive compounds
Industrial/airport related pollution, volcanic eruption clouds	may contaminate the supply air when flying into or out of polluted urban areas and any airport environment and/or flying through volcanic eruption clouds	nitrous oxides, ozone, particulate matter, sulfur-containing compounds

Birds	may be ingested into the aircraft engines	organic material, carbon, particulate matter
Particles from brakes and tyres	may contaminate the supply air with particles from touch down zone	aromatic hydrocarbons, ultrafine particles
Fans	are widely used onboard, including in the ventilation supply air system, galley, and flight deck; some fan failures generate electrical fumes (e.g. overheated or burning wire insulation); other fan failures generate fumes from failed/defective bearings and maintenance grease products	nitrous oxides, ozone, particulate matter (including metals), VOCs from wire insulation, molybdenum disulfide-based grease

Table G.2 — Chemical marker compounds generated within the aircraft cabin environment

Source/type of compound	Means by which compounds can contaminate cabin air	Examples of chemical constituents
Occupants	high density of occupants exhaling in the cabin space characterized by small per-person dilution volume	carbon dioxide (CO_2), ethanol, acetaldehyde,
Pesticides	products are applied either in response to insect sightings or to comply with international quarantine regulations	typically, either 2 % permethrin or 2 % phenothrin, solvents, propellants
Electrical fumes	may be sourced to failed or defective in-cabin items such as inflight entertainment systems, galley equipment, flight deck electronics	nitrous oxides, ozone, particulate matter, VOCs from wire insulation
Flame retardants	sources include upholstery, carpeting, seat cushion foam, and other cabin interior items; compounds can migrate into airborne dust	polybrominated diphenyl ethers and chlorinated compounds; seat cushion foam may also be treated with organophosphates such as tris(chloro-ethyl) phosphate
Cleaning products	cleaning products and deodorants used in the lavatories, galleys, and on other cabin surfaces	limonene, solvents
Lavatory fluids/odours	blue fluids in the lavatory, human waste products	non-glycol freeze point depressant, deodorants, etc.
Carry-on bags	migration of liquid or gaseous contaminants from carry-on bags stored in overhead bins or under the seats	food, personal care items, animals, solvents, etc.
Catering/dry ice	dry ice is used to preserve perishables at low temperature. It sublimes into large quantities of carbon dioxide gas	CO_2

NOTE Occupants are also sources of infectious material (virus, bacteria) but such materials are beyond the scope of this document.

Annex H
(informative)

Sources of engine oil leakage into the bleed air system and ventilation supply air

H.1 Description of oil lubrication system

The oil used in the aircraft engines and APU performs a number of functions. These include to lubricate and cool the bearings in the bearing compartment and to wash away particles that can be released from the bearings and gears during normal engine/APU operation and to support mechanical face seals. Engine/APU manufacturers will utilize varying designs to retain the oil in the lubricated areas such as bearing chambers, however a general design principle is described here. A controlled flow or leakage of pressurized air from the engine/APU compressor is passed into the bearing chamber to act as a seal, by creating an inward flow to prevent the oil from passing out. This is accomplished by maintaining the air flow at a higher pressure outside the bearing chamber than inside. The engine oil is sent back to the oil tank via a scavenge pump. The pressure air from the oil-lubricated bearing chamber is vented outboard the engine. However, a very small fraction of the oil from the bearing chamber passes through the de-oiler system and is vented outside the engine, which is considered part of the permissible oil consumption during normal operations. The object of the drainage system design is to capture oil that may have leaked past the engine/APU seals. In some conditions, a lesser amount of oil can migrate back over seals into the engine/APU airflow, including the compressor, or can be lost via oil leaks (see Figure H.1).

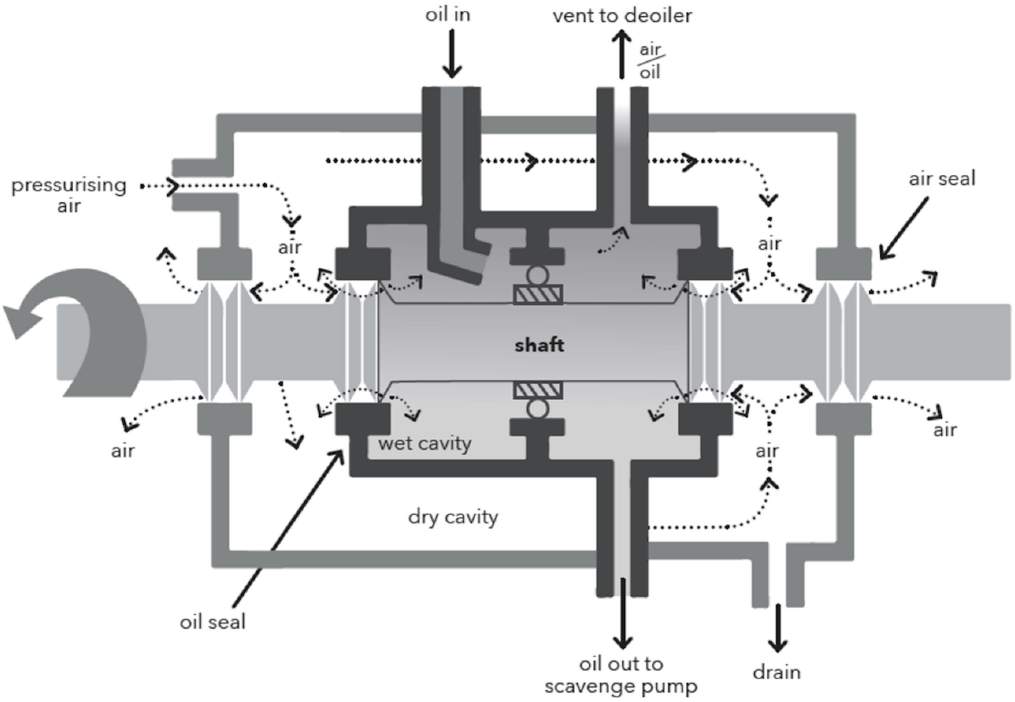

Figure H.1 — Typical oil-bearing pump

H.2 Description of seal technology

Pressurized compressor air is used to seal the engine bearing chambers and is responsive to variations in engine/APU operating conditions. Dynamic seals can leak, with a leak rate depending on many factors including seal design, balance, lubricating regime, operating conditions, compartment condition, seal wear and distortion. Labyrinth seals operate with a clearance, while mechanical face seals operate with a lubricated face, with both types of seals designed to limit sealed product migration and therefore limiting emissions. The ultimate objective for manufacturers is to prevent oil migration. Some advancements in seal and lubricant system designs in recent years strive to improve sealing and thus, minimize leakage, in certain operating conditions.

H.3 Oil path into bleed air system and ventilation supply air

As described, oil may leak out of the engine or APU bearing chamber and migrate back into the compressor air under both normal operating and system degradation conditions. If the leakage or emissions occur prior to the compressor bleed air off-take ports, then the oil can enter the bleed air system and the ventilation supply air

Oil that leaks into the external environment can also be re-ingested into the APU or engine air inlets and enter the bleed air off-takes ports. An ECS using electric compressors can also ingest oil via its compressor inlet and enter into the ventilation supply air. Oil entering the bleed air offtake ports can also be sourced to other areas including propeller pitch systems and anti-ice systems used in some engine spinners and nacelles.

The ultimate objective for manufacturers is to prevent oil migration past the engine and APU seals. However, during steady-state engine conditions, very low-level oil leakage past these seals can occur. During transient engine conditions, seal effectiveness is reduced as a function of momentary engine/APU performance changes (e.g. temperature, speed, power, phase of flight, application, and ambient conditions) because the seals are reliant on the correct air/oil pressure differentials over the seals and bearing chambers. This reduction in seal effectiveness can occur during start up, acceleration, and deceleration, and when there are low differential pressures across the seals, such as during descent, taxiing and shut down. A reduction in seal effectiveness can also occur when switching ventilation supply air configuration (i.e. bleed air port) or source (e.g. engine, APU), and when changing engine/APU speeds (where relevant). Various design factors are utilized in the lubrication system in order to limit oil leakage from the lubricated areas.

Because oil circulates throughout the engine/APU, it can contain microscopic particles of metallic and other elements (together known as wear materials) which are released from the bearings, seals, and gears during normal engine/APU operation. While the design will ensure that the majority of the wear materials are captured by the lubrication filter system and chip detectors, some wear materials may be carried by the low levels of oil from either the engine or the APU into the compressor and ventilation supply air. Therefore, additional actions should be undertaken to prevent wear materials from entering the ventilation supply air. Also, abradable engine materials from engine fan and compressor sections areas can pass through the seals, momentarily distorting the seals, and cause a brief increase of oil leakage and a potential fume event.

When system performance starts to degrade, more oil can cross the seals due to wearing seals and increasing seal clearances. Also, oil can enter the compressor due to oil spillage/overfill during oil servicing, and other maintenance factors. Less frequently, greater amounts of oil can cross the seals during failure conditions, such as worn or failed seals and bearings, or other parts.

H.4 Maintenance response to oil fumes sourced to bleed air system (renumber H.4)

The majority of reported oil fume events (whether incidents or accidents) with operational and health impacts are odorous, but do not include visible smoke/haze. At present, there is some recognition that maintenance identification practices are more suited to higher levels of oil leakage associated with smoke or high oil consumption, rather than the more frequent lower level (non-visible) events that have been reported during engine/APU operation. Enhanced oil leakage identification procedures for non-visible fume events may be beneficial.

Annex I
(informative)

Overview of aircraft cabin air and bleed air monitoring studies

I.1 Introduction

Table I.1 lists studies in the public domain of measurements of 14 of the 16 marker compounds (Annex B; no data for ethylene glycol or nitrous oxides), collected either in the cabin air or the engine/APU bleed air. While most of the studies relate to normal engine/APU operation, some studies refer to system degradation. The maximum level of each compound recorded in each study is presented because this metric was commonly reported, so provides some means of comparison. If a study described a maximum value associated with a specific sampling condition, then more than one maximum value may be reported for that study/marker compound. The user should refer to the original studies to review the measurement methodology and the complete data set, where available. In particular, the user should note whether the sampling was conducted during a fume event or not. Also, it is important to note whether the reported maximum concentration of each marker compound listed in Table I.1 represents an instantaneous measurement or a time-integrated measurement, and if the latter, over it is important to define the period of time during which the measurement was collected/averaged. A comprehensive list of chemical compounds measured either in the cabin air or the engine/APU bleed air is published elsewhere (citation to be determined). Table I.1 — Overview of aircraft cabin air and bleed air monitoring studies

NOTE 1 LOD - Limit of detection

NOTE 2 The presentation of the concentration values in Table I.1 follow CEN internal regulations Part 3, section 9. numbers, quantities, units and values (https://boss.cen.eu/ref/IR3_E.pdf). A comma is used as a decimal sign; for example, 70,2 represents a value between 70 and 71. Also, a space is added after every set of three digits; for example, 0,002 287 and 12 092.

Table I.1 — Overview of aircraft cabin air and bleed air monitoring studies

Study	**Maximum concentration**	**Notes**
ACETALDEHYDE (CAS 75-7-0)		
ASHRAE, 2001	70,2 µg/m^3	
BRE, 2003	31 µg/m^3	
Brunsell, 2003	15 µg/m^3	
Fox, 2012	51 ppb	
Fox, 2000	26 µg/m^3	
Fox, 1998	0,03 mg/m^3	
Rosenberger et al., 2018	234 µg/m^3	De-icing but no reported fume event

Study	Maximum concentration	Notes
ACETALDEHYDE (CAS 75-7-0)		
Rosenberger et al., 2016	90 µg/m^3	
Rosenberger, 2014	52 µg/m^3	
Space et al., 2017	225 ppb	
Spengler et al., 2012	75,79 µg/m^3	
Weisel et al., 2017	20 ppb	
Honeywell, 2000a	91 µg/m^3	
EASA, 2017	42 µg/m^3	
ACROLEIN (CAS 107-02-8)		
ASHRAE, 1998	< 1,5 ppb	
BRE, 2003	4 µg/m^3	
Brunsell, 2003	< 1 µg/m^3	
EASA, 2017	1 µg/m^3	
Fox, 2012	1,7 ppb	
Honeywell, 2000b	61,5 µg/m^3	differential measurement collected in the bleed air stream [bleed outlet] – [bleed inlet]
Fox, 1998	0,02 mg/m3	
Rosenberger et al., 2016	6,1 µg/m^3	
Rosenberger, 2014	0,4 µg/m^3	
Space et al., 2017	18 ppb	
Spengler et al., 2012	0,528 µg/m^3	
Weisel et al., 2017	9 ppb	
BENZENE (CAS no. 71–43–2)		
ASHRAE, 2004	0,6 ppb	
ASHRAE, 2001	7,3 µg/m^3	
BRE, 2003	4,5 µg/m^3	
Brunsell, 2003	< 0,5 µg/m^3	
Dumyahn et al., 1997	6 µg/m^3	
EASA, 2017	53,4 µg/m^3	
Honeywell, 2000b	4,9 µg/m^3	differential measurement collected in the bleed air stream [bleed outlet] – [bleed inlet]

Study	Maximum concentration	Notes
BENZENE (CAS no. 71–43–2)		
Guan et al., 2014	77,9 µg/m^3	
Honeywell, 2000a	0,000 61 ppm	
NIOSH, 1993	“trace”	
Spengler et al., 2012	62 341 ng/m^3	
Wang et al. 2014	145,46 µg/m^3	
CARBON DIOXIDE (CAS no. 124–38–9)		
ASHRAE, 2001	2 093 µg/m^3	
ASHRAE, 1998	1 758 ppm	
Battelle, 2004	1 344 ppm	
Brunsell, 2003	> 2 000 ppm	
EASA, 2017	> 5 000 ppm	> 5000 ppm – measured in the galley, possibly associated with dry ice
EASA, 2017	2 771 ppm	maximum in-cabin measurement
Fox, 2000	3 800 ppm	
Honeywell, 2000b	5 ppm	differential measurement collected in the bleed air stream [bleed outlet] – [bleed inlet]
Honeywell, 2000a	1 400 ppm	
NIOSH, 1993	4 882 ppm	
Rosenberger et al., 2018	5 177 ppm	
Spengler et al., 2012	2 056 ppm	
van Netten, 1998	900 ppm	
CARBON MONOXIDE (CAS no. 630–08–0)		
ASHRAE, 2004	< 2 ppm (LOD)	
ASHRAE, 2001	0,7 ppm	
ASHRAE, 1998	7 ppm	
Brunsell, 2003	< 10 ppm	
Crump et al., 2011	7 ppm	
EASA, 2017	4,8 ppm	
Fox, 2012	6,8 ppb	This equates to 102 µg/m^3
Fox, 2000	4,5 ppm	

Study	Maximum concentration	Notes
CARBON MONOXIDE (CAS no. 630–08–0)		
Honeywell, 2000b	1 374,7 µg/m^3	Differential measurement collected in the bleed air stream [bleed outlet] – [bleed inlet]
Honeywell, 2000a	3,1 ppm	
NIOSH, 2006	13 ppm	
NIOSH, 1993	25 ppm	
Rosenberger et al., 2018	2,2 ppm	
Spengler et al., 2012	< 1ppm	
van Netten, 1998	3 ppm	
CARBOXYLIC ACIDS		
CAA, 2004	*	pentanoic acid (CAS 109-52-4); qualitatively identified in duct swabs, but no quantitative data provided
CAA, 2004	*	hexanoic acid (CAS 142-62-1); qualitatively identified in duct swabs, but no quantitative data provided
CAA, 2004	*	heptanoic acid (CAS 111-14-8); qualitatively identified in duct swabs, but no quantitative data provided
CAA, 2004	*	octanoic acid (CAS 124-07-2); qualitatively identified in duct swabs, but no quantitative data provided
CAA, 2004	*	nonanoic acid (CAS 112-05-0); qualitatively identified in duct swabs, but no quantitative data provided
CAA, 2004	*	decanoic acid (CAS 334-48-5); qualitatively identified in duct swabs, but no quantitative data provided
EASA, 2017	16,6 µg/m^3	hexanoic acid (CAS 142-62-1)
EASA, 2017	8,1 µg/m^3	octanoic (caprylic) acid (CAS 124-07-2)
EASA, 2017	6,1 µg/m^3	nonanoic acid (CAS 112-05-0)
Honeywell, 2000b	*	pentanoic (valeric) acid (CAS 109-52-4); qualitatively identified but no quantitative data provided
Weisel et al., 2017	*	pentanoic (valeric) acid (CAS 109-52-4); qualitatively identified in cabin air but no quantitative data provided
Weisel et al., 2017	*	octanoic (caprylic) acid (CAS 124-07-2); qualitatively identified in cabin air, but no quantitative data provided

Study	Maximum concentration	Notes
FORMALDEHYDE (CAS no. 50–00–0)		
ASHRAE, 2001	13 µg/m3	
ASHRAE, 1998	4,9 ppb	
BRE, 2003	15 µg/m^3	
Brunsell, 2003	< 5 µg/m^3	
Dechow, 1997	26 ppb	
EASA, 2017	48 µg/m^3	
Fox, 2012	47 ppb	
Fox, 2000	5,7µg/m^3	
Honeywell, 2000b	40,9 µg/m^3	differential measurement collected in the bleed air stream [bleed outlet] – [bleed inlet]
Fox, 1998	0,01 mg/m^3	
Honeywell, 2000a	58 µg/m^3	
NIOSH, 1993	< 0,07 ppm	
Rosenberger et al., 2018	7,5µg/m^3	
Rosenberger et al., 2018	134 µg/m^3	de-icing, but no fume event
Rosenberger et al., 2016	44 µg/m^3	
Rosenberger, 2014	24 µg/m^3	
Space et al., 2017	325 ppb	simulated bleed air leak
Spengler et al., 2012	11,72 µg/m^3	
Weisel et al., 2017	26 ppb	
OZONE (CAS no. 10028–15–6)		
ASHRAE, 2004	194 ppb	
EASA, 2017	62 ppb	
PROPYLENE GLYCOL (CAS no. 57–55–6)		
Breuer et al., 2012	360 µg/m^3	
Honeywell, 2000a	80 µg/m^3	
NIOSH, 2006	≤ 2 µg/m^3	
Rosenberger et al., 2014	2,47 mg/m^3	measurement after de-icing with running APU

Study	Maximum concentration	Notes
TOLUENE (CAS no. 108–88–3)		
ASHRAE, 2004	27,3 ppb	
ASHRAE. 2001	45 µg/m³	
BRE, 2003	64 µg/m³	
Crump et al., 2011	170,2 µg/m³	
Dechow,1997	135 ppb	
Dumyahn et al., 1997	29 µg/m³	
EASA, 2017	62 µg/m³	
Fox, 2012	56 ppb	
Fox, 2000	22,5 µg/m³	
Honeywell, 2000b	18 µg/m³	differential measurement collected in the bleed air stream [bleed outlet] – [bleed inlet]
Fox, 1998	0,04 mg/m³	
Guan et al., 2014	209,3 µg/m³	
Honeywell, 2000a	0,00220 ppm	
NIOSH, 2006	≤ 2 µg/m³	
NIOSH, 1993	< 8 ppm	
Rosenberger et al. 2018,	3,4 µg/m³	
Rosenberger et al., 2014	0,056 mg/m³	measurement after de-icing with running APU
Spengler et al., 2012	132 926 ng/m³	
Wang et al., 2014	237,32 µg/m³	
TRIBUTYL PHOSPHATE (CAS no. 126–73–8)		
BRE, 2003	< 20 µg/m³	
Breuer et al., 2012	35 µg/m³	
Crump et al., 2011	21,8 µg/m³	
EASA, 2017	6,4 µg/m³	
Fox, 2000	< LOD	
Muir et al., 2008	42 µg/m³	
Rosenberger et al., 2018	1,99 µg/m³	
Rosenberger, 2014	3,5 µg/m³	

Study	Maximum concentration	Notes
TRIBUTYL PHOSPHATE (CAS no. 126–73–8)		
Rosenberger et al., 2014	3,15 µg/m^3	In-cabin on a flight prior to de-icing experiment
Solbu et al., 2011	4,1 µg/m^3	routine cabin air sampling
Solbu et al., 2011	12 µg/m^3	value associated with oil leakage
Solbu et al., 2010	9 400 µg/m^3	technicians were performing wheel well maintenance
Solbu et al., 2010	5,6 µg/m^3	ground personnel performing loading tasks
Solbu et al., 2010	27 µg/m^3	measurement collected during simulated oil leakage
TRICRESYL PHOSPHATES, mixed isomers (CAS no. 1330–78–5) **(may include combination of ortho, meta, and para isomers of TCP)**		
Battelle, 2004	< LOD	
BRE, 2003	< 130 µg/m^3	sampling during descent
Crump et al., 2011	37,7 µg/m^3	TCP detectable in the flight deck in one or more 5-minute sample collected on 25 of 100 flights;
Denola et al., 2011	51,3 µg / m^3	TCPs; Military - visual smoke
de Ree et al., 2017	155 ng/m^3	Sampling in flight deck from engine start to top-of-climb
de Ree et al., 2017	17 ng/m^3	Sampling in flight deck during cruise
de Ree et al., 2017	66 ng/m^3	Sampling in flight deck from top-of-descent to engine shutdown
de Ree et al., 2017	32 ng/m^3	Sampling in flight deck – averaged over the duration of the flight
de Ree et al., 2017	7,1 ng/m^3	Stationary sampling on ramp
TRICRESYL PHOSPHATES, mixed isomers (CAS no. 1330–78–5) **(may include combination of ortho, meta, and para isomers of TCP)**		
de Ree et al., 2017	1 660 ng/m^3	Sampling during tire change/refuelling
de Ree et al., 2017	11 410 ng/m^3	Sampling during post-flight inspection
de Ree et al., 2017	62 230 ng/m^3	Sampling during oil check
EASA, 2017	1,515 µg/m^3	
Fox, 2012	100 µg/m^3	TCPs, excl. ToCP
Honeywell, 2000b	20,3 µg/m^3	Differential measurement collected in the bleed air stream [bleed outlet] – [bleed inlet]

Study	**Maximum concentration**	**Notes**
TRICRESYL PHOSPHATES, mixed isomers (CAS no. 1330–78–5) **(may include combination of ortho, meta, and para isomers of TCP)**		
Honeywell, 2000a	4,9 µg/m^3	
Hanhela et al., 2005	49 µg/m^3	Sample collected in flight deck of military aircraft in the presence of oil spill near APU inlet; canopy was open and smoke was present
Hanhela et al., 2005	21,7 µg/m^3	Sampling in flight deck of military aircraft during ground operations
Hanhela et al., 2005	< 4 µg/m^3	Sampling in flight deck of military aircraft, not including two notably elevated measurements
Hecker et al., 2014	0,0896 µg/m^3	
Muir et al., 2008	1,3 µg/m^3	
Rosenberger et al., 2018	0,981 µg/m^3	TCP, excl. ortho isomers (not de-icing or diversion flight)
Rosenberger et al., 2013	0,246 µg/m^3	
Rosenberger et al., 2014	0,17 µg/m^3	In cabin during flight prior to de-icing experiment
Solbu et al., 2011	0,51 µg/m^3	sampling in the cabin after engine change post oil leak event
Solbu et al., 2011	5,9 µg/m^3	sampling in cabin after confirmed oil leak
Solbu et al., 2010	31 mg/m^3	sampling during simulated oil leak exhaust
Solbu et al., 2010	280 µg/m^3	sampling during general maintenance tasks
Solbu et al., 2010	52 µg/m^3	sampling during loading tasks
Space et al., 2017	0,8 ppb	“TCP meta”
Space et al., 2017	0,2 ppb	“TCP para”
TNO, 2013	155 ng/m^3	
van Netten, 2008	0,108 µg/m^3	
TRICRESYL PHOSPHATES, ortho isomers **(CAS no. for ToCP is 78–30–8; CAS nos. for MoCP and DoCP are undefined)**		
Breuer et al., 2012	< 2 µg/m^3	ToCP
CAA, 2004	1 µg/g	“ortho isomers” of TCP measured in sample of ducting material
EASA, 2017	< LOD	ToCP

Study	Maximum concentration	Notes
TRICRESYL PHOSPHATES, ortho isomers **(CAS no. for ToCP is 78–30–8; CAS nos. for MoCP and DoCP are undefined)**		
EASA, 2017	< LOD	mono-ortho cresyl phosphate isomers
EASA, 2017	< LOD	di-ortho cresyl phosphate isomers
Fox, 2012	0,000996 ppb	ToCP
Honeywell, 2000b	< LOD	ToCP; differential measurement collected in the bleed air stream [bleed outlet] – [bleed inlet]
Hanhela et al., 2005	1 μg/m^3	mono-ortho and di-ortho isomers; estimated based on Hanhela 49μg/m3 total TCPs (smoke/oil spill/canopy open)
Hanhela et al., 2005	0,05 μg/m^3	mono-ortho and di-ortho isomers; estimated based on Hanhela 3.5μg/m3 total TCPs
Crump et al., 2011	22,8 μg/m^3	ToCP detectable in the flight deck in one or more 5-min sample collected on 13 of 100 flights;
Hanhela et al., 2005	7 μg/m^3	ToCP; assumed based on Hanhela 49 μg/m3 TCP sample (smoke/oil spill/canopy open)
Hanhela et al., 2005	0,5 μg/m^3	ToCP; assumed based on Hanhela 3.5 μg/m3 TCP sample
Honeywell, 2000a	< LOD	ToCP
Rosenberger, 2014	< LOD	ToCP
Rosenberger et al., 2014	< LOD	ToCP
Rosenberger et al., 2013	0,067 μg/m^3	ToCP
Space et al., 2017	< 0,1 ppb	ToCP during simulated bleed air leak
TRICRESYL PHOSPHATES, tri-meta, tri-para, and mixed meta/para isomers **(CAS no. 78–32–0; includes meta isomers formerly classified under CAS no. 563–04–2)**		
Breuer et al., 2012	4,8 μg/m^3	TCP, meta
Breuer et al., 2012	< 2 μg/m^3	TCP, para
CAA, 2004	8,1 μg/g	TCP, para; swabs of ducting
CAA, 2004	68, 1 μg/g	TCP, meta; swabs of ducting
EASA, 2017	0,057 μg/m^3	TCP, ppp
EASA, 2017	0,428 μg/m^3	TCP, mmm

Study	**Maximum concentration**	**Notes**
TRICRESYL PHOSPHATES, tri-meta, tri-para, and mixed meta/para isomers (CAS no. 78–32–0; includes meta isomers formerly classified under CAS no. 563–04–2)		
EASA, 2017	0,691 µg/m^3	TCP, mmp
EASA, 2017	1,515 µg/m^3	TCP, meta and para
EASA, 2017	0,339 µg/m^3	TCP, mpp
Rosenberger, 2014	0,014 µg/m^3	TCP, para
Rosenberger et al., 2014	0,012 µg/m^3	TCP, para
Rosenberger, 2014	0,128 µg/m^3	TCP, meta
Rosenberger et al., 2014	0,050 µg/m^3	TCP, meta
Rosenberger, 2014	0,107 µg/m^3	TCP, mpp
Rosenberger et al., 2014	0,049 µg/m^3	TCP, mpp
Rosenberger, 2014	0,176 µg/m^3	TCP, mmp
Rosenberger et al., 2014	0,058 µg/m^3	TCP, mmp
Spengler et al., 2012	1,51 µg/m^3	TCP, mmm
TOTAL VOLATILE ORGANIC COMPOUNDS (TVOC)		
ASHRAE, 1998	1,5 mg/m^3	
Breuer et al., 2012	760 µg/m^3	
Crump et al., 2011	> 10 ppm	
Rosenberger et al., 2018	1,180 mg/m^3	
Rosenberger, 2014	2,14 mg/m^3	
Rosenberger et al., 2014	> 4 mg/m^3	after de-icing with APU in operation
Solbu et al., 2011	1,3 mg/m^3	
Solbu et al., 2010	34 mg/m^3	
ULTRAFINE PARTICLES (UFP)		
BRE, 2003	256 183 p/cm^3	
Crump et al., 2011	> 500 000 p/cm^3	
Space et al., 2017	1 000 – 10 000 000 p/cm^3	injected oil into bleed air stream to simulate fume event; particle count increased with injection rate and was highest in 10 – 30 nm range (overall range 1 - 100 nm)
Spengler et al., 2012	312 000 p/cm^3	

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