AEROSPACE INFORMATION REPORT	AIR4766™/2	REV. A
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(R) Airborne Chemicals in Aircraft Cabins

RATIONALE

The purpose of this revision is to update the document to reflect some of the changes in the field since its original issue in 2005 and to narrow the scope of the document.

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1. SCOPE

This SAE Aerospace Information Report (AIR) provides information on aircraft cabin air quality, including:

- Origins of chemical airborne contaminants during routine operating and failure conditions.
- Exposure control measures, including design, maintenance, and worker training/education.

This AIR does not deal with airflow requirements.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AIR910	Ozone in High Altitude Aircraft
AIR7521	Measurement Data and Reference Values for Compounds Potentially Found in Aircraft Engine Bleed Air
ARP4418	Procedure for Sampling and Measurement of Aircraft Propulsion Engine and APU Generated Contaminants in Bleed Air

2.1.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR Part 25	Airworthiness Standards: Transport Category Airplanes
14 CFR Part 121	Certification and Operations: Domestic, flag and supplemental air carriers and commercial operators of large aircraft
14 CFR Part 135	Operating requirements: Commuter and on demand operations and rules governing persons on board such aircraft

2.1.3 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany (for visitors and for mail over 1 kg) and Postfach 10 12 53, D-50452 Cologne, Germany (for mail 1 kg or less); Tel: +49 221 8999 000, www.easa.europa.eu.

EASA.2014.C15. “Final report: Preliminary cabin air quality measurement campaign (CAQ)”, S.; Schuchardt, Bitsch, A.; Koch, W.; and Rosenberger, W., 2014.

EASA.2015.HVP.23. “Characterisation of the toxicity of aviation turbine engine oils after pyrolysis (AVOIL),” Report no., Document reference: AVOIL project no. 923642/060.18709. Authored by Houzager, M; Havermans, J; Noort, D; et al. with TNO, RIVM, IVM, and IRAS.

2.1.4 ICAO Publications

Available from International Civil Aviation Organization, 999 University Street, Montreal, Quebec H3C 5H7, Canada, Tel: +1 514-954-8219, http://www.icao.int/.

ICAO Circular 344-AN/202 Guidelines on Education, Training and Reporting of Fume Events

ICAO A38-WP/38 Summary of work undertaken since the 37th assembly in the area of non-chemical disinsection of the aircraft cabin and flight deck for international flights." June 6, 2013.

2.1.5 ASHRAE Publications

Available from ASHRAE Headquarters, 1791 Tullie Circle, NE, Atlanta GA 30329, Tel: 800-527-4723 (U.S. and Canada only) or 404-636-8400, www.ashrae.org.

ASHRAE 957-RP. "Relate Air Quality and Other Factors to Symptoms Reported by Passengers and Crew on Commercial Transport Category Aircraft". Results of Cooperative Research Between the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. and Consolidated Safety Services, Inc. Final Report. [1999].

ASHRAE 959-RP Determine Aircraft Supply Air Contaminants in the Engine Bleed Air Supply System on Commercial [2001]

ASHRAE Guideline 28-2016 Air Quality within Commercial Aircraft

2.1.6 Other Applicable Publications

ATA Specification 100 - Specification for Manufacturers' Technical Data, Revision No. 37. Air Transport Association of America. (1999).

ATA Specification 126. "Recommended Practices for Addressing Cabin Air Quality Events," ATA, Airlines For America, Washington, DC (2020).

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Exxon-Mobil (2017) "Tech topics, Jet engine oil system, part 1," Posted on Exxon-Mobil website on Jan. 2, 2017; accessed Dec. 10, 2020: https://www.exxonmobil.com/en/aviation/knowledge-library/resources/jet-engine-oil-system-1, Exxon-Mobil Corporation.

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Rosenberger, W. et al., [2016]. Airborne Aldehydes in Cabin-air of Commercial Aircraft: Measurement by HPLC with UV Absorbance Detection of 2,4-dinitrophenylhydrazones. J. Chromatogr. 2016. https://doi.org/10.1016/j.jchromb.2015.08.046.

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2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 120-38 Transport Category Airplanes Cabin Ozone Concentrations

2.3 Definitions

AIRBORNE CHEMICALS: Include gases, aerosols, and particulates.

BLEED AIR: As used in this document, air from outdoor origin entering cabin after having been processed through an engine compressor, turbo compressor, or shaft driven compressor.

FUME: Non-visible particles, aerosol, or gaseous emission of a compound, or mixture of compounds, that is typically odorous.

ODOR: A distinctive smell.

SMOKE: Visible particles or aerosol which may be the byproduct of combustion, heat, or friction.

2.4 Acronyms and Abbreviations

AC	FAA or EASA Advisory Circular
ACM	Air Cycle Machine
AD	Airworthiness Directive
APU	Auxiliary Power Unit
ASHRAE	American Society for Heating, Refrigerating and Air Conditioning Engineers
ATA	Air Transport Association
CAS	Chemical Abstracts Service
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COT	Committee on Toxicity
cSt	Centistoke
ECS	Environmental Control System
FR	Federal Register
HEPA	High-Efficiency Particulate Air
LOD	Limit of Detection
MEK	Methyl Ethyl Ketone
MW	Molecular Weight
NASA	National Aeronautics and Space Administration
ppbV	Parts per Billion by Volume
ppmV	Parts per Million by Volume
SVOC	Semivolatile Organic Compounds
TBEP	Tris (Butoxy-Ethyl) Phosphate

TBP	Tributyl Phosphate
TCP	Tricresyl Phosphate Mixed Isomers
TiBP	Triisobutyl Phosphate
ug/m^3	Micrograms per Cubic Meter
VOC	Volatile Organic Compound
WHO	World Health Organization

3. ORIGINS OF CHEMICAL AIRBORNE CONTAMINANTS

Airborne gaseous compounds can be present within the occupied and unoccupied zones of the aircraft, from a myriad of sources both internal and external to the aircraft. There have been several studies within the past 20 years that have reported on aircraft cabin gaseous contaminants (ASHRAE 957-RP; ASHRAE 959-RP; Crump, et al., [2011]; RITE-ACER-CoE-2012-6; EASA.2014.C15.; Guan et al., 2014a; Guan et al., 2014b; UK COT, [2007, 2013]). On an average flight, there may be multiple airborne compounds present; for example, Guan et al., [2014a] identified a total of 346 VOC chemical species during 107 normal flights, with an average of 59 VOC measured per flight. Even a single source of compounds (e.g., oil or hydraulic fluid fumes) can contain a complex mixture [van Netten and Leung, 2000].

VOC compounds concentrations found in aircraft cabin are generally comparable or often even lower than what is typically reported of offices and residences (EASA.2014.C15;RITE-ACER-CoE-2012-6). Nevertheless, the concentration of chlorinated compounds was higher for some aircraft models than found in indoor air. It is unclear whether these compounds are associated with aircraft materials, cleaning practices or personal care products and clothing brought on board by passengers [RITE-ACER-CoE-2012-6]. Design engineers should focus on both compounds generated during normal operation and also failure, maintenance, or operational conditions which can generate fumes or odors in the occupied zones.

One source of information on the origin of airborne chemical agents during conditions that necessitate a maintenance response is the Air Transport Association (ATA) numbering system [ATA Specification, 100] Chapter under which occurrences are documented in the maintenance and aircraft logbooks. Reviewing maintenance data and FAA Service Difficulty Reports, for example, according to ATA Chapter may help a user of this AIR to identify root causes, which may enable more robust engineering designs and maintenance practices in order to minimize occurrences. The ATA Chapters can be consolidated into groups consistent with the potential sources of airborne contaminants in the aircraft cabin that necessitate a maintenance response (Table 1). The ATA chapters listed in Table 1 in bold font are more general and can, thus, reasonably be categorized to represent more than one potential source of airborne contaminants (e.g., ATA Chapter 21: Air conditioning). Note that the ATA chapter that maintenance staff and pilots select for a given condition/event may vary by airline and professional judgment. Also, there may be additional ATA chapters that could be applied to one or more of the contaminant sources listed in Table 1. For these reasons, the ATA chapters assigned to each contaminant source should not be considered fixed or necessarily consistent. Still, ATA chapters are a reasonable starting point for assessing root causes of onboard smoke, fumes, and odor.

Table 1 - Sources of smoke, fumes, and odor and corresponding ATA Specification 100

ATA Chapter Numbers	ATA Chapter Titles	Potential Source of Airborne Chemical Agents Identified During Maintenance
21, 72	AIR CONDITIONING, ENGINE	Bird strike
21, 30, 36, 49, 72	AIR CONDITIONING, ICE AND RAIN PROTECTION, PNEUMATIC, AIRBORNE AUXILIARY POWER, ENGINE	Deicing/anti-icing fluid
21, 36	AIR CONDITIONING, PNEUMATIC	Ducting (blow out, debris)
21, 22, 23, 24, **25**, **26**, 27, **29**, **30**, 31, **32**, 33, 34, **36**, **38**, 39, 44, **49**, 51, 52, 53, 56, 77	AIR CONDITIONING, AUTO FLIGHT, COMMUNICATION, ELECTRICAL POWER, EQUIPMENT/FURNISHINGS, FIRE PROTECTION, ICE AND RAIN PROTECTION, FLIGHT CONTROLS, HYDRAULIC POWER, ICE AND RAIN PROTECTION, INDICATING/RECORDING SYSTEM, LANDING GEAR, LIGHTS, NAVIGATION, PNEUMATIC, WATER/WASTE, ELECTRICAL – ELECTRONIC PANELS AND MULTIPURPOSE COMPONENTS, CABIN SYSTEMS, AIRBORNE AUXILIARY POWER, STANDARD PRACTICES AND STRUCTURES, DOORS, FUSELAGE, WINDOWS, ENGINE INDICATING	Electrical (incl. galley equipment such as oven, coffee pot, hot plate, flashlight, etc.)
21, 36, 49, 72, 75, 79	AIR CONDITIONING, PNEUMATIC, AIRBORNE AUXILIARY POWER, ENGINE, BLEED AIR, ENGINE OIL	Engine oil
21, 72	AIR CONDITIONING, ENGINE	Engine wash
21, 25	AIR CONDITIONING, EQUIPMENT/FURNISHINGS	Fans
26	FIRE PROTECTION	**Chemicals:** Fire extinguisher
21, 28, 48, **49**, 73, **78**	AIR CONDITIONING, FUEL, INFLIGHT FUEL DISPENSING, AIRBORNE AUXILIARY POWER, ENGINE – FUEL AND CONTROL, EXHAUST	Fuel/exhaust
21, 29, 32, 49, 72, 75, 78	AIR CONDITIONING, HYDRAULIC POWER, LANDING GEAR, AIRBORNE AUXILIARY POWER, ENGINE, BLEED AIR, EXHAUST	Hydraulic fluid
38	WATER/WASTE	Lavatory

3.1 Sources of Contaminants Encountered During Normal Operation and Maintenance

3.1.1 Aircraft Materials

Gaseous compounds from the aircraft surfaces are generally low in concentration due to high air exchange rates. Sources may include ducts, carpets, seats, and other interior components, in addition to cleaning/disinfection products and pesticides. New aircraft materials are more likely to off-gas into the aircraft cabin environment, in particular from high temperature operation of metallic ducts. The envelope space between the cabin panels and the outer skin is a potential source of VOC or SVOC. These VOC and SVOC are shown to be very low from in-flight measurements (ASHRAE 957RP; EASA.2014.C15; RITE-ACER-CoE-2012-6; Wolkoff et al., 2016) since the aircraft cabin is pressurized during flight. Sources within the envelope include sound dampening materials, anti-corrosion (cure hard or non-cure hard) and fire protection treatments and insulation materials that have previously absorbed contaminants from the cabin or ventilation system. Sorption/desorption or absorption/extraction of compounds in the envelope is enhanced by frequent thermal and altitude cycling and by stack effect-induced cabin/envelope air circulation created by differences in temperature and pressure on either side of the cabin wall panels.

3.1.2 Passengers and Crew

Numerous gaseous compounds found within an aircraft cabin originate from passengers and crew or their activities (EASA.2014.C15; NASA, 1995; Wolkoff et al., 2016). Human bioeffluents are a substantial source. Additionally, carry-on contents, and food/beverage service may contribute. Historically, environmental tobacco smoke has been a source of airborne contaminants on aircraft, but smoking has largely been banned onboard commercial flights since the mid-1990s.

3.1.3 Ground Operations in the Airport Environment

Airborne contaminants inside the cabin which are sourced to the external environment include exhaust smoke, fumes, or odors from other aircraft and ground service vehicles, de-icing fluids, engine cleaning fluids, jet fuel, airport-related construction (e.g., fresh asphalt), ambient pollution, and residual engine oil and hydraulic fluid smoke, fumes, or odor vented into the ambient aircraft environment.

Ground power carts and airplane service equipment can represent a significant contamination source when the cart is operated close to engine or APU air inlets. Depending on the aircraft APU/engine inlet and exhaust design, and wind condition, exhaust gases can be re-ingested during push-back, lining up for departure, and during landing when deploying thrust reversers. A growing number of qualitative and quantitative environmental studies are being conducted in airport areas and surroundings, especially by the U.S. EPA (www.epa.gov/otaq) in connection with the FAA's Office of Environment and Energy (www.aee.faa.gov).

Another potential source of external airborne contaminants at the gate is the ground pre-conditioned air unit which is connected to the aircraft ECS as an alternative air supply. The ground pre-conditioned air unit may introduce fungal and bacterial contaminants, particulate, and other debris. Flexible ducting may deteriorate, such that insulation and lining material can be transferred to the recirculation system and can result in a reduction in or loss of air flow at locations where material blocks flow restrictors.

3.1.4 Ozone

On the ground, ozone is a constituent of exhaust fumes. Inflight, ozone may be naturally present in the troposphere and the stratosphere, especially at higher latitudes and altitudes, and varying by season. At all latitudes, increases in altitude generally correspond to increases in ozone concentration. Ozone is regulated to less than 0.25 ppmv at any time and less than 0.1 ppmv on a three-hour time weighted average basis by 14 CFR 25.832 and a four-hour basis by 14 CFR 121.578. The FAA provides guidance on ozone in Advisory Circular 120-38, and additional information can be found in AIR910. Most widebody aircraft have ozone converters installed, *including dual function ozone/VOC converters,* while some narrow-body aircraft do not carry ozone converters and rely on flight planning to demonstrate ozone compliance.

3.1.5 Engines and APU

During normal operations, engines have a defined, permissible low-level oil consumption, some of which is consumed through the deoiler, oil seals, and oil leaks (Exxon-Mobil, 2017). This can occur when the pressures change over the seals during transient power changes or low power settings (Chupp et al., 2006; Michaelis, 2018). In a recent publication, EASA assumed that, during normal operations, low level oil contamination of the compressor may be present, although an observable low leak rate has not been confirmed by measurement data (EASA.2014.C15). However, most sampling studies have not used continuous methods to characterize low-level, transient changes in oil-based compounds.

3.1.6 Pesticides

Pesticides/rodenticides are sprayed in cabins, either to comply with foreign quarantine rules or to treat rodent/insect infestation. Pesticides may be applied on the ground prior to boarding or inflight. Pesticides applied on the ground may produce residue on treated surfaces that are intended to be active during passenger boarding. Regarding pesticides, the residue may be present in cabin air due to migration of sprays from cargo compartments or from direct spray into the cabin. The World Health Organization has recommended the use of some specific chemical pesticides (WHO; [2018]), although the feasibility and efficacy of non-chemical alternatives for onboard insect control are being reviewed [ICAO A38-WP/38].

3.2 Sources of Contaminants During Failure Conditions

See Table 2 and Figure 2 below for detailed sources and frequency of events.

3.2.1 Electrical

Sources of electrical fumes include wiring, lights, transformers, power ports, and batteries. The inflight entertainment system can be a source of chemicals that result in an electrical smell. Lightning strikes can also result in electrical odors/smells.

3.2.2 Engines and APU

In addition to the conditions described in 3.1.5, engine oil smoke, or fumes can be generated in the engine/APU compressor and contaminate the bleed air supplied to the cabin and flight deck for ventilation, whether during ground operations or during flight. Oil contamination of the compressor may be caused by engine oil reservoir over-servicing, failed seals, bearings, and other components in the compressor, as well as improper drainage/reingestion of oil into the compressor. Hydraulic fluid leaks or spills (e.g., over-serviced reservoir, ruptured line) may be ingested into the APU or (less commonly) the engine compressor and, thus, contaminate the bleed air fraction of the ventilation air.

3.2.3 Mechanical

Sources of chemicals from mechanical equipment include bearing failures and worn windings from recirculation, avionics, equipment cooling, cargo, and gasper fans. Other sources of mechanical failures may include air cycle machines, or valve failures. Advancements in designs of aviation fans include technologies to reduce the impact of failures, such as alternative bearing designs. The air cycle machine (ACM) is a component of the ECS. Since the mid-1990s the majority of ACM installed on new aircraft use oil-free air bearings. No commercial airplanes currently in production have ball-bearing ACM. While they are being phased out, some old aircraft types may still utilize ACM with oil-lubricated ball bearings which in unusual failure conditions may be a source of oil introduced to the cabin and flight deck. Oil, deicing fluid, hydraulic fluid, and environmentally sourced compounds may contaminate equipment and ducting which become a secondary source of smoke, fumes, or odor.

3.2.4 Lavatories

Lavatories can provide odorous chemicals when seals fail.

3.2.5 Galleys

Sources of airborne chemicals in the galley include ovens, coffee makers, chillers, and other equipment. This can result from either failure of the component or malfunction of galley equipment and burnt or spoiled food.

3.2.6 Unusual or Failure Conditions in the Airport Environment

Bird ingestion by engines can result in temporary odors, as can ingestions of various fluids (such as de-icing fluid, more detail below) or foreign object debris. Designers should attempt to reduce this through FOD doors on inlets for RAM and cabin air compressors where possible.

3.2.7 De-Icing

Chemicals introduced from de-icing fluid occur from ingestion of fluids used to de-ice the wings and engines of airplanes in the airport environment. Procedures have been developed to stop air conditioning function during ground de-icing to prevent deicing fluids from being ingested into the aircraft supply air. These procedures typically involve turning off the air supply system to prevent ingestion of deicing fluid while it is being sprayed on the aircraft and also avoiding the application of spray products in and around the engines.

3.2.8 Ozone

Ozone converters are life-limited components because during operation the internal catalyst surfaces are subject to contamination via bleed air. The contamination mostly stems from atmospheric particulates at low altitudes, but abnormally operating engines or APU can also contaminate the ozone converter. As the converter becomes gradually more contaminated the conversion efficiency decreases. On airplanes using ozone converters for compliance with regulations pertaining to cabin ozone concentration limits, periodic servicing of the ozone converter is required. If the ozone converter becomes more contaminated than the airplane maintenance schedule allows for, and the airplane is flying through conditions of high atmospheric ozone concentration, cabin concentration limits may be exceeded.

3.3 Data Summaries of Reported Smoke, Fumes, or Odors Onboard, by Source

Airline reports to the FAA per the Service Difficulty Reporting (SDR) regulations is one source of information on onboard airborne contaminants associated with a maintenance response. Specifically, per 14CFR121.703, U.S. airlines are required to report confirmed mechanical failures or defects if they generated inflight smoke or fumes. SDR are also required by 14CFR §135.415.

A summary of the sources of fumes cited in SDR reports on U.S. registered aircraft from 2002 to 2011 that included one or more of the words fume, odor, smell, smoke, and bleed air are summarized in Table 2 (Anderson, 2019)[1]. Airlines had classified these SDRs into 21 “nature/condition” categories defined by the FAA, including “smoke/fume/odors/sparks” (84%), “fluid loss” (5.4%), “warning indication” (2.9%), and “other” (2.6%). Electrical was the most prevalent category of fumes in airline reports (36%). Combining the categories “bleed source,” “oil,” and “hydraulic fluid” created the second most prevalent source (26%), not including the “air conditioning packs” category, some of which would have involved oil or hydraulic fumes, although the detail in the SDR was limited. The next most prevalent category of onboard, inflight fumes with a confirmed mechanical failure or defect was fans (8.3%). Also, for 9.3% of the reports, the source of fumes was either unknown or undefined in the report.

Aircraft manufacturers also collect data from airline operators on the type of reports of onboard airborne contaminants and they may also review the reports that airlines submit to the regulatory body. SDR reports specific to one major aircraft manufacturer from 2012 to 2017 which airlines classified as “smoke/fume/odors/sparks” are presented in Figure 1 [Sigler et al., 2020]. Note that the FAA’s SDR reporting rule 14CFR121.703 only requires airlines to report fume events for which the “failure, malfunction, or defect” that caused the smoke or fumes was identified. Also, airlines must only report events that occurred in-flight (defined as wheels-up) unless the airline deemed that flight safety could have been compromised, had operations continued. As such, the datasets summarized in Table 2 [Anderson, 2019] and Figure 1 [Sigler et al., 2020] will undercount smoke/fume events for which maintenance staff were either unable to confirm the mechanical source/defect or that occurred during ground operations. Airline underreporting of fume events to the FAA has also been noted.

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[1] NOTE: The dataset includes 12437 fume event reports. A total of 53 were classified in two categories (sources) based on maintenance summary, so percentages add to slightly more than 100.

Table 2 - Sources/frequency of smoke, fumes, and odor reported by U.S. airlines to FAA (2002 to 2011)

Category	Total	% Reports
Electrical	4532	36%
Bleed source (but specifics not defined)	1797	14%
Oil	1339	11%
Fan	1028	8.3%
Fuel	635	5.1%
Oven	387	3.1%
Hydraulic fluid	167	1.3%
Deicing fluid	137	1.1%
Duct (blown, disconnected, clogged)	134	1.1%
Battery	73	0.6%
Bird strike	42	0.3%
Engine wash	40	0.3%
Other, defined but not otherwise categorized (primarily air conditioning packs)	1020	8.2%
Source unknown or too vague to classify	1159	9.3%

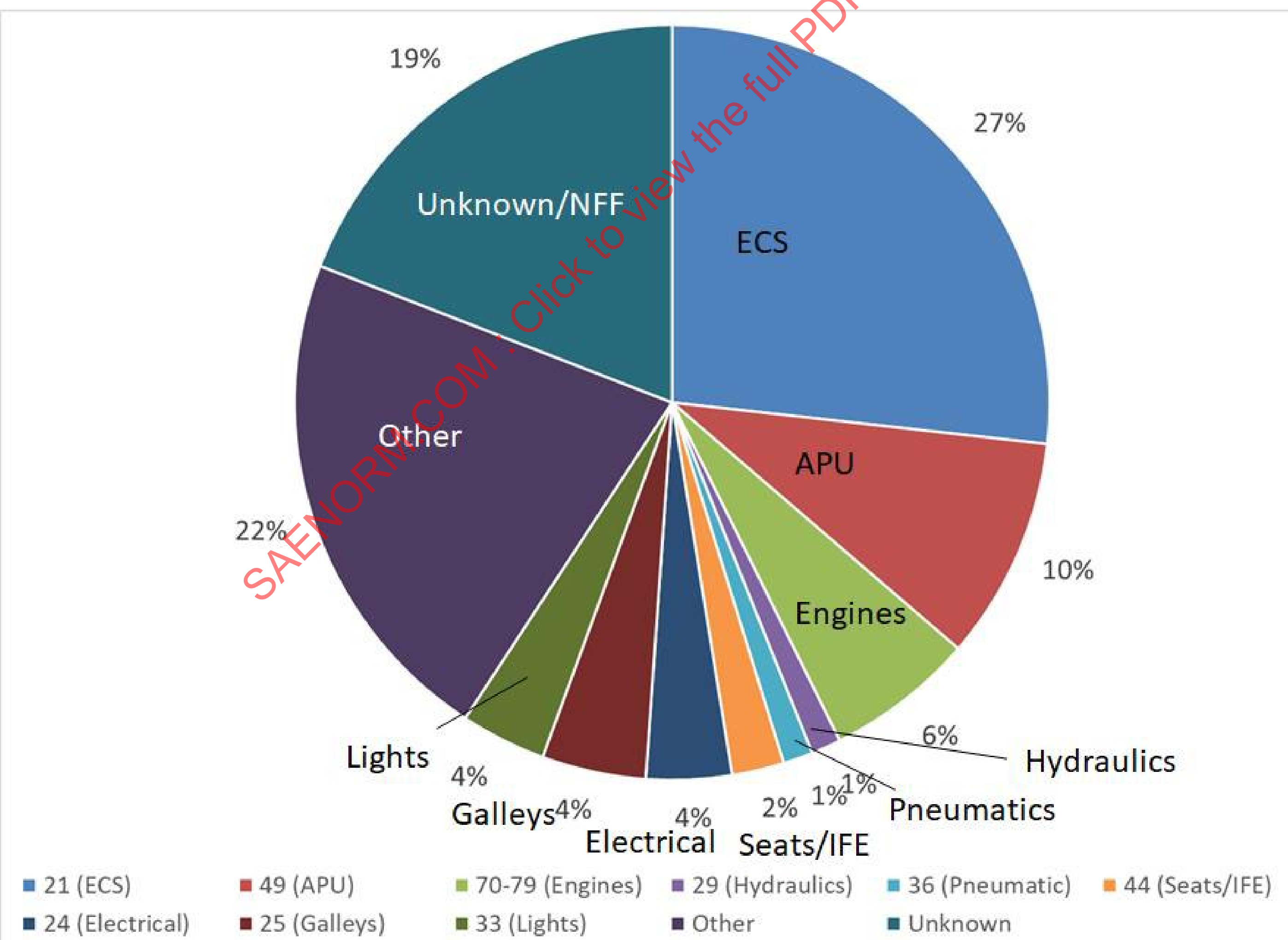

Figure 1 - Sources and frequency of smoke/ fume/ odor reports reviewed by one aircraft manufacturer, 2012-2017
Reprinted with permission from [Sigler et al., 2020] © 2020 The Boeing Company

4. SELECTED MARKER COMPOUNDS

Table 3 provides summary data for a subset of selected marker compounds identified by the AC-9M and E31B Committees as being a relevant subset of markers for bleed air contaminants sourced to engine oil, hydraulic fluid, ozone, deicing fluid, and exhaust fumes. The intent of the E31B committee was to select markers suitable to detect engine exhaust and oil fumes with a minimal number of tests, all during steady-state engine conditions on an engine test stand [ARP4418]. AIR7521 includes summary data from some published cabin air studies without documented fume events for five marker compounds. Table 3 contains a data point from a flight that was diverted for a reported oil odor [Rosenberger, 2018] but without accompanying information on mechanical cause or symptom reports. The 100th percentile (Maximum Value) may include samples with special cause conditions. Crump [2011] reports some data points for ToCP that are above prior published levels. Cranfield Study authors in later work stated "the reported ToCP concentration could have been overestimated due to chromatographic overlap with other ortho isomers" [Wolkoff, 2016].

Table 3 reports total TCP rather than a breakdown of the various isomers of TCP. Denola [2008] provides an analysis of the distribution of TCP isomers in a sample of aviation engine oils (CAS 1330-78-5). The EASA study by Schuchardt [EASA.2014.C15] measured compounds in cabin air on bleed air aircraft and on B787 aircraft which use carbon loaded HEPA recirculation filters to reduce contaminants present within the aircraft. It is not known if the bleed air aircraft in that study were outfitted with carbon-loaded HEPA recirculation filters because they are optional equipment.

Table 3 - Marker compounds and measured contaminant ranges

Substance	Minimum	Mean	Median	95th Percentile	Maximum
Carbon Dioxide CAS 124-38-9 1.8 µg/m^3 = 1 ppbV	Cabin 969 ppmV Cockpit 611 ppmV [Rosenberger, 2018] *Main Study*: *Short haul*: Cockpit 629 ppmV Cabin 1050 ppmV *Long haul*: Cockpit 594 ppmV Cabin 955 ppmV *B787 Study*: Cockpit 473 ppmV Cabin 968 ppmV [EASA.2014.C15]	Cabin 1883 ppmV Cockpit 1026 ppmV [Rosenberger, 2018] *Main Study*: *Short haul*: Cockpit 835 ppmV Cabin 1417 ppmV *Long haul*: Cockpit 753 ppmV Cabin 1282 ppmV *B787 Study*: Cockpit 603 ppmV Cabin 1242 ppmV [EASA.2014.C15]	*Main Study*: *Short haul*: Cockpit 740 ppmV Cabin 1298 ppmV *Long haul*: Cockpit 708 ppmV Cabin 1230 ppmV *B787 Study*: Cockpit 561 ppmV Cabin 1213 ppmV [EASA.2014.C15]	Cabin 2604 ppmV Cockpit 1669 ppmV [Rosenberger, 2018] *Main Study*: *Short haul*: Cockpit 1408 ppmV Cabin 2202 ppmV *Long haul*: Cockpit 1029 ppmV Cabin 1712 ppmV *B787 Study*: Cockpit 828 ppmV Cabin 1608 ppmV [EASA.2014.C15]	Cabin 5177 ppmV Cockpit 4040 ppmV [Rosenberger, 2018] *Main Study:* *Short haul*: Cockpit 1918 ppmV Cabin 2771 ppmV *Long haul*: Cockpit 1976 ppmV Cabin 2674 ppmV *B787 Study*: Cockpit 1229 ppmV Cabin 2019 ppmV [EASA.2014.C15]
Carbon Monoxide CAS 630-08-0 1.15µg/m^3=1 ppbV	Cabin <LOD Cockpit <LOD LOD 0.5 ppmV [Rosenberger, 2018] *Main Study*: Cockpit <LOD Cabin <LOD *B787 Study*: Cockpit <LOD Cabin <LOD LOD =0.5 ppmV [EASA.2014.C15] <LOD LOD=1 ppmV [Crump, 2011]	Cabin 1.0 ppmV Cockpit <LOD LOD 0.5 ppmV [Rosenberger, 2018] *Main Study*: Cockpit <LOD Cabin <LOD *B787 Study*: Cockpit <LOD Cabin <LOD LOD =0.5 ppmV [EASA.2014.C15] 1 ppmV [Crump, 2011]	*Main Study*: Cockpit <LOD Cabin <LOD *B787 Study*: Cockpit <LOD Cabin <LOD LOD =0.5 ppmV [EASA.2014.C15] 2 ppmV [Crump, 2011]	Cabin 1.6 ppmV Cockpit 0.5 ppmV [Rosenberger, 2018] *Main Study*: Cockpit <LOD Cabin 0.6 ppmV *B787 Study*: Cockpit <LOD Cabin 1.06 ppmV LOD =0.5 ppmV [EASA.2014.C15] >5 ppmV [Crump, 2011]	Cabin 2.2ppmV Cockpit 1.7ppmV [Rosenberger, 2018] *Main Study*: Cockpit 4.8 ppmV Cabin 3.0 ppmV *B787 Study*: Cockpit 0.6 ppmV Cabin 1.6 ppmV [EASA.2014.C15] >5 ppmV [Crump, 2011]
Acetaldehyde CAS 75-07-0 1.8 µg/m^3 = 1 ppbV	A380 0.3ug/m^3 A321 0.5ug/m^3 [Rosenberger, 2016]	A380 7.7ug/m^3 A321 5.3ug/m^3 [Rosenberger, 2016] *Main Study:* *Taxi-out:* 9.1 ug/m^3 *Take Off-Climb:* 4.9 ug/m^3 *Descent-land*: 3.4 ug/m^3 *Entire flight:* 2.8 ug/m^3 *B787 Study:* 5.2 ug/m^3 [EASA.2014.C15]	A380 5.1ug/m^3 A321 4.1ug/m^3 [Rosenberger, 2016] 6.3 ug/m3 [Rosenberger, 2018]	A380 24ug/m^3 A321 8ug/m^3 [Rosenberger, 2016]	A380 52 ug/m^3 A321 90 ug/m^3 [Rosenberger, 2016] 234 ug/m3 [Rosenberger, 2018] *Main Study*: 42 ug/m^3 *B787 Study:* 15 ug/m^3 [EASA.2014.C15]

Substance	Minimum	Mean	Median	95th Percentile	Maximum
Acrolein CAS 107-02-8 2.29 μg/m^3 = 1 ppbV Note: RITE-ACER-CoE-2012-6, Airline C data are inconsistently higher for acrolein than the other datasets. The researchers could not provide a reason for their acrolein data being an order of magnitude higher than other published data. This emphasizes that careful consideration should be utilized when assessing acrolein since potential detectable levels are near the analytical limit of detection, and well below the reported range of Laboratory LOQ. [AIR7521]	A380 0.1ug/m^3 A321 0.1ug/m^3 [Rosenberger, 2016]	A380 0.2ug/m^3 A321 0.7ug/m^3 [Rosenberger, 2016] *Main Study*: *Taxi-out:* 1.0 ug/m^3 *Take Off-Climb:* 0.8 ug/m^3 *Descent-Land:* 0.4 ug/m^3 *Entire flight:* 0.1 ug/m^3 *B787 Study*: <LOD [EASA.2014.C15]	A380 0.2ug/m^3 A321 0.6ug/m^3 [Rosenberger, 2016]	A380 0.3 ug/m^3 A321 1.3 ug/m^3 [Rosenberger, 2016]	A380 0.4ug/m3 A321 6.1ug/m3 [Rosenberger, 2016]
Formaldehyde CAS 50-00-0 1.23 μg/m^3=1 ppbV	A380 0.4ug/m^3 A321 1.2ug/m^3 [Rosenberger, 2016]	A380 5.1 ug/m^3 A321 6.3 ug/m^3 [Rosenberger, 2016] *Main Study*: *Taxi-out:* 13.9 ug/m^3 *Take Off-Climb:* 7.0 ug/m^3 *Descent-Land:* 4.8 ug/m^3 *Entire flight:* 2.7 ug/m^3 *B787 Study*: 5.9 ug/m^3 [EASA.2014.C15]	A380 4.5ug/m^3 A321 5.3ug/m^3 [Rosenberger, 2016] 5.7 ug/m3 [Rosenberger, 2018]	A380 10ug/m^3 A321 13ug/m^3 [Rosenberger, 2016]	A380 24ug/m^3 A321 44ug/m^3 [Rosenberger, 2016] 134 ug/m3 [Rosenberger, 2018] *Main Study*: Study: 48 ug/m^3 *B787 Study*: 17 ug/m3 [EASA.2014.C15]
Toluene CAS 108-88-3 3.77 ug/m3=1 ppbV	*Main Study:* <0.005 ug/m^3 *B787 Study:* 0.1ug/m^3 [EASA.2014.C15] <LOD [Crump, 2011]	*Main Study:* 11.5 ug/m^3 *B787 Study:* 3.5 ug/m^3 [EASA.2014.C15] 6.3 ug/m^3 [Crump, 2011]	*Main Study:* 8.3 ug/m^3 *B787 Study:* 2.2 ug/m^3 [EASA.2014.C15] 170.2 ug/m^3 [Crump, 2011]	*Main Study:* 32.4 ug/m^3 *B787 Study*: 8.5 ug/m^3 [EASA.2014.C15] 50.1 ug/m^3 [Crump, 2011]	*Main Study:* 62.0 ug/m^3 *B787 Study:* 17.0 ug/m^3 [EASA.2014.C15] 170.2 ug/m^3 [Crump, 2011]