Federal Aviation Administration

DOT/FAA/AM-15/20
Office of Aerospace Medicine
Washington, DC 20591

Aircraft Cabin Bleed Air Contaminants: A Review

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November 2015

Final Report

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM-15/20		

4. Title and Subtitle	5. Report Date
Aircraft Cabin Bleed Air Contaminants: A Review	November 2015
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Day GA	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
FAA Civil Aerospace Medical Institute P.O. Box 25082 Oklahoma City, OK 73125	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Office of Aerospace Medicine Federal Aviation Administration 800 Independence Ave., S.W. Washington, DC 20591	14. Sponsoring Agency Code

15. Supplemental Notes

16. Abstract

The purpose of this paper is to describe potential health-related risks surrounding human exposure to bleed air contaminants generated during "fume events" inside pressurized aircraft. Information was obtained from available literature primarily in regard to carbon monoxide, carbon dioxide, ozone, volatile and semi-volatile organic compounds, and airborne particles.

The quality of air distributed throughout the cockpit and cabin during air transportation in a pressurized aircraft is critically important to human health. Since 1984, public law in the United States has directed research in cabin air quality, including investigation of health risks among individuals exposed to toxic fumes during flight.

Quantification of the potential health risks associated with exposure to bleed-air contaminants in cabin air is not possible without broad identification and measurement of the representative hazardous constituents of bleed air during contaminated air events. Such broad identification and measurement does not exist. Included in Public Law 112-95 is the directive to "assess bleed air quality on the full range of commercial aircraft operating in the United States." Carrying out such a mandate requires adequate funding to support required research.

17. Key Words	18. Distribution Statement
Bleed Air, Bleed Air Contaminants, Cabin Air Quality, Fumes, Toxic Fumes, Toxic Fume Events	Document is available to the public through the Internet: www.faa.gov/go/oamtechreports

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	11	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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PURPOSE AND BACKGROUND

The purpose of this paper is to describe potential health-related risks surrounding human exposure to bleed air contaminants generated during "fume events" inside pressurized aircraft. Information was obtained from available literature primarily in regard to carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3), volatile and semi-volatile organic compounds (VOCs, SVOCs), and airborne particles. Other constituents of contaminated cabin air include those arising from ground support equipment such as auxiliary power units and aircraft emissions. The latter group of constituents has been estimated using the Emissions Dispersion Modeling System (EDMS) (Moss & Sega, 1994) and includes hydrocarbons from incomplete combustion, nitrogen oxides from oxidation of nitrogen in combustion air, and sulfur oxides from jet fuel.

The quality of air distributed throughout the cockpit and cabin during air transportation in a pressurized aircraft is critically important to human health. For more than 30 years, the topic of cabin air quality has been of concern. Congressional hearings in 1983 and 1984 revealed that information describing cabin air quality was contradictory, which prompted the U.S. Congress to mandate a study by the National Academy of Sciences (NAS) (Public Law 98-466, 1984). The subsequent report concluded that there was a lack of data for a scientific evaluation of aircraft cabin air quality and associated health effects. The report also laid the groundwork for necessary research by recommending, in part, the implementation of a program for systematic measurement of the concentrations of several components of cabin air (NRC, 1986). It should be noted that the NAS report contained a recommendation to ban cigarette smoking on all commercial flights; the following year Public Law 100-202 (1987) made it unlawful to smoke in the passenger cabin or lavatory on flights of two hours or less in duration.

In 1989, the Department of Transportation contracted with an independent company to collect measurements aboard 92 randomly selected aircraft that included both smoking (n=69) and nonsmoking (n=23) commercial flights (Nagda et al., 1989). Among the measured components of cabin air were CO and respirable particles, both of which were considered unique components of environmental tobacco smoke. Reported concentrations of these and other measured components were below permissible exposure limits.

In 1994, the U.S. Congress mandated that the Federal Aviation Administration (FAA) establish an aircraft cabin air quality research program and to contract with the Centers for Disease Control and Prevention (CDC) to carry out studies specific to cabin air quality (Public Law 103-305, 1994). Thus, the FAA amended an existing interagency agreement with CDC's National Institute for Occupational Safety and Health (NIOSH) to conduct studies of the chemical, physical, and microbiological aspects of cabin air quality. Previous work by NIOSH to study cabin air quality had involved a health hazard evaluation of toxic gases on three Alaska Airlines MD-80 700 series test flights. Among all constituents, NIOSH investigators assessed concentrations of several parameters including CO, CO_2, O_3, VOCs, nitrogen dioxide, and total particulate mass, concluding that the measured concentrations did not reveal evidence of toxic exposures (Sussell et al., 1993). With the amended interagency agreement in place, NIOSH designed and carried out a study to assess exposures to parameters of cabin air quality on 11 of the most common aircraft types during 33 separate flights. Measured parameters of airborne constituents included CO, CO_2, O_3, VOCs, and total particulate mass. Similar to the previous health hazard evaluation, NIOSH investigators concluded that, in general, contaminant levels were low compared to existing standards (Waters et al., 2002).

In 2000, arising from unresolved issues about aircraft cabin air quality and health issues raised by passengers and cabin crew, Congress directed the FAA to arrange an independent study with the NAS (Public Law 106-181, 2000). The study was to include the "collection of new data, in coordination with the FAA, to identify contaminants in the aircraft air and develop recommendations for means of reducing such contaminants." The resulting NAS report (NRC, 2002) included a review of studies performed since the previous NAS report (NRC, 1986). It is important to note that many of the principal components described in the 2002 NAS report were not specific to bleed air or "toxic fume" events (e.g., bacteria and fungi). The authors of the report noted that studies identified had differed considerably not only in the methods used for measuring air contaminants but also in the types of aircraft, numbers of flights, and methods used to select flights for monitoring.

In 2003, in response to the 2002 NAS report (NRC, 2002), Congress mandated the FAA to: "1) conduct surveillance to monitor ozone in the cabin on a representative number of flights and aircraft to determine compliance with existing Federal Aviation Regulations for ozone; 2) collect pesticide exposure data to determine exposures of passengers and crew; 3) analyze samples of residue from aircraft ventilation ducts and filters after air quality incidents to identify the contaminants to which passengers and crew were exposed; 4) analyze and study cabin air pressure and altitude; and 5) establish an air quality incident reporting system" (Public Law 108-196, 2003).

In 2004, the FAA's Office of Regulation and Certification established a National Center of Excellence (COE) for Airliner Cabin Environment Research (ACER, 2004), which in 2007 was broadened and renamed to the National Air Transportation COE for Research in the Intermodal Transport Environment

(ACERite). The ACERite COE brought together airliner cabin environment expertise from academic, industry, and government organizations. Over the next decade, the FAA sponsored numerous cabin air environment research projects. Key research included: 1) health and safety effects of the airline cabin environment on passengers and crewmembers, 2) the efficiency and effectiveness of aircraft environmental control systems, and 3) the study of emerging technologies with the potential to eliminate bleed air contaminants and purify aircraft air supplies. Additionally, the ACERite COE collaborated in a joint study by the U.S. Air Force, the National Aeronautics and Space Administration, and the FAA that was known as Vehicle Integrated Propulsion Research (VIPR) Testing (Hunter et al., 2014). VIPR included the characterization of jet engine emissions during both routine and non-routine operations. At the time of this writing, final reports were not available and, therefore, were not included in this review.

Most recently, in 2012, Congress directed the FAA to initiate a study of air quality in aircraft cabins to: 1) assess bleed air quality on the full range of commercial aircraft operating in the United States; 2) identify oil-based contaminants, hydraulic fluid toxins, and other air toxins that appear in cabin air and measure the quantity and prevalence, or absence, of those toxins through a comprehensive sampling program; 3) determine the specific amount and duration of toxic fumes present in aircraft cabins that constitutes [sic] a health risk to passengers; 4) develop a systematic reporting standard for smoke and fume events in aircraft cabins; and 5) identify the potential health risks to individuals exposed to toxic fumes during flight." Additionally, to the extent practicable, the FAA was to "implement a research program for the identification or development of appropriate and effective air cleaning technology and sensor technology for the engine and auxiliary power unit bleed air supplied to the passenger cabin and flight deck of a pressurized aircraft" (Public Law 112-95, 2012).

Bleed Air: A Brief Description

Air supplied to a pressurized aircraft cockpit and cabin occurs via an environmental control system (ECS). Fresh air from outside the aircraft, known as replacement or make-up air, enters the ECS in most large transport category commercial airplanes via the aircraft engines. The compressed air is then "bled" through ports and is cooled before being mixed in a manifold with recirculated air, ultimately becoming distributed throughout the cockpit and cabin. Note that the only exception to the bleed air function is the Boeing 787 airplane, which is equipped with a dedicated air inlet. Thus, breathable air inside a pressurized aircraft cabin is a combination of both make-up and recirculated air. Contaminated air events, or "fume events," may occur inside the aircraft as a result of the interaction between incoming make-up air and oils or hydraulic fluids from leaking or failed seals in the engine compartment; contaminated air events may also arise from leaks in or near the auxiliary power unit (APU). Such events arising from the ECS and/or APU are considered non-routine and extremely rare. Factors inside the engine compartment that influence the generation of contaminants include types and amounts of oil and hydraulic fluids, temperature, and humidity. Factors inside the aircraft that influence contaminant concentrations include the size of the occupied space and the number of complete air changes per hour (i.e., the volume of make-up air versus the volume of exhausted cabin air). The 2002 NAS report (NRC, 2002) did not refer to any published studies describing quantitative measurements of air quality under non-routine operating conditions, but it did refer to few studies in which researchers had collected measurements of air contaminants in aircraft cabins under routine conditions. Those studies, however, included only small numbers of flights that varied considerably in the specific contaminants measured, the types of measurement methods used, and the sampling strategies. Consequently, well-characterized cabin air quality under both non-routine and routine operating conditions was considered non-existent.

Fumes and Fume Events

The term "fume" is used commonly to describe any noxious gas, smoke, or vapor in the atmosphere. In the case of contaminated air inside an aircraft cockpit/cabin, the term "fume event" has been used to refer to a potentially toxic environment created by contaminated bleed air. From a scientific perspective, this term does not adequately describe such an event. Indeed, fumes are defined as "solid-particle aerosols produced by the condensation of vapors or gaseous combustion products" (Hinds, 1999). Another term to describe such an event, one that includes fumes and any additional constituents, would be preferred. One possibility is the term "aerosol event," which by definition includes "solid or liquid particles in gas" (Hinds, 1999). However, this term would also be inadequate because it excludes other possible constituents including gases (formless fluids), vapors (liquids converted to gaseous state by heating), smoke (visible aerosol resulting from incomplete combustion), and mist (liquid-particle aerosol formed by condensation). The 2002 NAS report (NRC, 2002) referred to such events as "air quality events" resulting from the "intake of potential contaminants, including engine oils and hydraulic fluids, through the environmental control system into the cabin." Importantly, no matter how such an event is described, contaminated bleed air should be regarded as a heterogeneous mixture of many possible constituents, the exposure to which may result in a spectrum of adverse health effects (Chaturvedi, 2011a, 2011b).

It should be noted that recirculated air in an aircraft cabin likely also contains a number of anthropogenic constituents introduced, in part, by crew and passengers. These contaminants may include dusts and fibers, as well as a variety of bioaerosols such as microorganisms, bacterial cells, fungal spores, pollen grains, skin scales, and viruses. However, because bleed air is not the source from which these contaminates are generated, neither they nor the potential health effects resulting from exposure are within the scope of this review.

The Role of Filtration

To reiterate, bleed air is a heterogeneous mixture of constituents that may include gases, vapors, smoke, fumes, and mist, each of which is potentially associated with risk of adverse health effect following exposure. It is important to note that bleed air is cooled but not cleaned (i.e., filtered) before being mixed with recirculated cabin air. Recirculated air, however, is cleaned using high-energy particulate air (HEPA) filtration. HEPA filters, by definition, are designed to capture particles but not gases and vapors, which pass directly through, and collection efficiency is established on the basis of particles that pass through the filter (i.e., penetration efficiency). HEPA filters must be at least 99.97 percent efficient at capturing particles measuring 0.3 micrometers (µm) in diameter (Anna, 2011). Particles with diameters greater than 0.3 µm but less than 10 µm are regarded as respirable (Hinds, 1999), and the goal of HEPA filtration is to collect particles in this size range from recirculated air. Aerosols collected via HEPA filtration include dusts, fibers, bacterial cells, fungal spores, and pollen grains. Viruses are among the smallest of microorganisms, ranging in size from 0.02 to 0.3 µm in diameter (Nevalainen et al., 1993) and are thus too small to be captured by HEPA filters. Likewise, fumes are generally less than 0.05 µm in diameter (Hinds, 1999) which are also too small to be captured via filtration. Also, unless airplanes are equipped with a gaseous filtration system (i.e., activated charcoal imbedded into the weave as on the Airbus A350 and Boeing 787 aircraft), then gases and vapors pass directly through HEPA filters.

Potential Health Outcomes Following Exposure

CO, CO_2, and O_3

Gases contained in contaminated cockpit/cabin air as constituents of bleed air include CO from engine exhaust and CO_2 as a product of incomplete combustion. O_3, originating in the stratosphere (Grewe, 2006), may enter the cockpit/cabin from outside the aircraft via the ECS. The Federal Aviation Regulation (FAR) for ventilation states that the passenger cabin must be free from harmful or hazardous concentrations of gases or vapors; the CO concentration should not exceed one part in 20,000 parts of air, equivalent to 50 parts per million (ppm); the CO_2 concentration during flight must not exceed 0.5 percent by volume (i.e., 5,000 ppm) (CFR, 2015a). NIOSH recommends a 35 ppm upper limit time-weighted average (TWA) concentration for CO for up to 10 hours and a TWA concentration of 5,000 ppm for CO_2 (NIOSH, 2007). Although it has been reported that there is no "safe" level of O_3 exposure (Bell et al., 2006), the FAR states that the TWA O_3 concentration in the cabin should not exceed 0.1 ppm (100 parts per billion [ppb]) for any three-hour period when the aircraft is above 27,000 feet, and that O_3 levels must not exceed 0.25 ppm or 250 ppb when the aircraft is above 32,000 feet (CFR, 2015b). NIOSH (2007) recommended a ceiling exposure concentration of 100 ppb for O_3 that should not be exceeded.

Although exposure to CO can produce anemic hypoxia following exposure to sufficient concentrations (Bloom & Brandt, 2001), CO concentrations inside an aircraft are typically below levels associated with adverse health effects (Nagda et al., 2000). CO concentrations aboard pressurized aircraft have been measured to range between <0.2 and 2.9 ppm (Waters et al., 2002). Spengler et al. (2012) collected measurements from 83 flights and determined that CO concentrations were below 1 ppm.

Exposure to high CO_2 concentrations can lead to symptoms such as headache, dizziness, and restlessness and ultimately lead to asphyxia. Waters et al. (2002) reported CO_2 concentrations aboard pressurized aircraft that ranged between 515 and 4,902 ppm. Spengler et al. (2012) determined the average CO_2 concentration during 83 flights ranged between 863 and 2,056 ppm, with an average concentration of 1,404 ppm. In contrast to the aircraft cabin environment, CO_2 is present in ambient environments such as office buildings at levels averaging about 400 ppm (McDermott, 2001). CO_2 is known to be primarily generated by people on the aircraft (i.e., pilots, aircrew, and passengers) and, therefore, CO_2 concentrations can be used to provide an indication of the amount of make-up air provided per person (Nagda et al., 2000).

Exposure to O_3 may be associated with symptoms ranging from irritation to eyes and mucous membranes to chronic respiratory disease (NIOSH, 2007). Bhangar et al. (2008) reported O_3 measurements collected on commercial aircraft were highly variable; from 68 flights, peak hour O_3 measurements ranged from 3 to 275 ppb. Spengler et al. (2012) measured O_3 on eight different airplane models. Among 73 flights, the average O_3 concentration was 15.9 ppb; the highest one-minute measurement was 256 ppb; the highest one-hour measurement was 201 ppb; and no flight exceeded a TWA concentration of 100 ppb over a period of three hours.

It is important to note that O_3 reacts with materials in the cabin, including seat fabric, carpet, plastic, and clothing to emit VOC byproducts (Coleman et al., 2007). In controlled experiments, the most common VOC emissions detected were aldehydes, 6-methyl-5-hepten-2-one, and acetone. Additionally, Weschler et al. (2007) observed O_3 byproducts emitted from surfaces in a simulated aircraft, including emissions from the occupants themselves. These byproducts included acetone, nonanal, decanal, 4-oxopentanal (4-OPA), 6-methyl-5-hepten-2-one (6-MHO), formic acid, and acetic acid. Furthermore, Spengler et al. (2012) reported the formation of carbonyls in O_3 reactions; O_3 was also strongly associated with airborne particles. From these findings, we must recognize that health risks to aircraft occupants may occur from not only exposures to CO, CO_2, and other bleed air contaminants, but also from exposures to O_3 and O_3-reactive byproducts.

Additionally, Overfelt et al. (2012) performed controlled studies to identify gaseous emissions from four different thermally degraded engine oils. The authors reported analytical results indicating that the emissions from oils were complex mixtures of CO, CO_2, methanol, and water.

VOCs

Vapors contained in contaminated cockpit/cabin air may include both volatile and semi-volatile organic compounds (VOCs and SVOCs), both of which are chemical compounds based on carbon chains or rings that also contain hydrogen with or without oxygen, nitrogen, and other elements that represent constituents of jet engine oils, hydraulic fluids, and deicing fluids. Simply stated, VOCs are more volatile than SVOCs. VOCs are characterized by higher vapor pressures than SVOCs that result from lower boiling points. Oils from worn seals and/or hydraulic fluids in the engine compartment may volatilize, producing vapors that are subsequently released into the cockpit/cabin via bleed ports. Volatilization occurs when these compounds are converted from a liquid state to a vapor state by the application of heat, the reduction of pressure, or a combination of the two processes. Deicing fluids and exhaust from jet engines may also enter the bleed air supply during ground operations. Health effects resulting from air contaminated with VOCs and SVOCs may be associated with symptoms including irritation of the eyes and nose, weakness, confusion, euphoria, dizziness, and headache. Exposure to higher concentrations could result in systemic damage (e.g., to liver and kidney).

The first NAS report (NRC, 1986) could identify no study measuring detectable concentrations of these compounds in cabin air. The second NAS report (NRC, 2002) indicated "few data have been collected on contaminants that might be present in engine bleed air under normal operating or upset conditions" and "no available exposure data identify the contaminants present in cabin air during an air-quality incident." Overfelt et al., (2012) reported that "the specific nature and extent of potential decomposition reactions of engine oils and hydraulic fluids are largely unknown" and that "the resulting nature and potential toxicity of any contaminants in the aircraft cabin from such events are highly speculative at the present time."

Among the many possible VOCs and SVOCs representing constituents of contaminated bleed air, particular concern has been attributed to tricresyl phosphate (TCP; van Netten & Leung, 2000), an organophosphate compound that exists as a mixture of three isomeric forms: tricresylortho phosphate (TOCP), tricresylmeta phosphate (TMCP), and tricresylpara phosphate (TPCP). Among these, TOCP is toxic (DHHS, 1978). Both TMCP and TPCP are relatively nontoxic. TCP is an anti-wear additive that represents approximately 3% by volume of many commercial jet engine oils; TOCP represents only about 0.1% by volume (van Netten & Leung, 2000). The recommended upper limit airborne concentration for TOCP, as a time-weighted average over up to 10 hours, is 0.1 milligrams per cubic meter of air (mg/m^3) (NIOSH, 2007). Inhalation exposure to TOCP exceeding this concentration is associated with a delayed neurotoxic toxic effect (i.e., several days following exposure) manifested by peripheral nervous system abnormalities (Eaton & Klaasen, 2001). Additionally, TOCP can affect the body if it comes in contact with the eyes or skin. Interestingly, reports indicate that TCP and many other volatile derivatives can remain airborne and may be associated with smoke particles (van Netten & Leung, 2000, 2001).

To address Public Law 108-196 (2003), ACERite COE researchers developed methodologies to analyze residue on HEPA filters that were collected from 1) non-incident aircraft, 2) simulated laboratory experiments, and 3) incident or suspected incident aircraft (Chen, et al., 2010). By analyzing oil samples, the researchers were able to identify a fingerprint of oil contamination. Ultimately, they used TCP and its isomers in the correct ratios along with the presence of synthetic hydrocarbons as indicative of oil contamination on the analyzed filters and, thus, in cabin air. They pointed out that such analysis could not be used as single, definitive evidence of oil-contaminated air; however, the methods could be used to identify the source of contamination for aircraft associated with known or suspected contaminated air incidents.

Spengler et al. (2012) measured 64 VOCs in aircraft cabins during 83 flights and 18 SVOCs on 63 flights. As percentages of all VOC samples, 91% contained toluene, 90% contained carbon tetrachloride and tetrachloroethene, 75% contained m- and p-xylene, and 50 to 75% contained benzene, ethylbenzene, o-xylene, methylene chloride, hexane, and styrene. The TCP isomer, TMCP, was detected in only one sample at a concentration of 1 part per trillion. We should emphasize that these samples were collected in one location inside aircraft cabins under routine operating conditions. Therefore, the measured constituents were not directly associated with either bleed air or non-routine operating conditions. The authors reported that the majority of the VOC concentrations measured in aircraft cabins had median values that were similar to or lower than VOC concentrations reported in "non-compliant" office buildings. Concentrations of specific compounds, including carbon tetrachloride, tetrachloroethene, benzene, toluene, ethylbenzene, o-xylene, 1,3-budadiene, and styrene, on some flights were substantially higher than concentrations expected in offices and homes.

Particles

The measurement of airborne particles within an environment can provide information on either mass or number concentration, but without subsequent analyses these measurements cannot distinguish among constituents comprising the particles. Exposure to particles may result in a variety of adverse health effects that range from irritation of eyes, nose, and throat to respiratory and other system disorders. Smoke, a visible aerosol resulting from incomplete combustion, consists of a range of particle sizes. Smoke may include ultrafine particles (UFPs), the diameters of which measure less than 0.1 μm (WHO, 2006), as well as respirable particles with diameters ranging from 0.3 μm to 10 μm (Hinds, 1999). Air sampling research has not been performed aboard aircraft during a smoke event.

Spengler et al. (2012) measured airborne UFPs, which the authors defined as particles measuring in diameter from 6 nanometers to 0.3 μm, aboard 55 flights under routine operating conditions. Concentrations were reported as 15-minute average numbers of particles per cubic centimeter of air (p/cm^3). Maximum concentrations from all flights ranged from 1 to 312,000 p/cm^3. Particle concentrations from 500 to 10,000 p/cm^3 indicated minor events, and concentrations greater than 10,000 p/cm^3 indicated major events. Both types of events were associated with elevated O_3 concentrations, except on flights involving food preparation. Again, it is important to emphasize that these samples were collected inside aircraft cabins under routine operating conditions. As such, the measured constituents were not directly associated with either bleed air or non-routine conditions.

DISCUSSION

The NAS stated in 1986 that "empirical evidence is lacking in quality and quantity for a scientific evaluation of the quality of airliner cabin air or of the probability of health effects of short or long exposure to it" (NRC 1986). Among the recommendations were the need for exposure monitoring, particularly to VOCs, and health monitoring. Although much research relevant to cabin air quality was conducted over the following years, many questions remained unanswered. The NAS stated in 2002 that "no available exposure data identify the contaminants present in cabin air during an air-quality incident" (NRC, 2002). Public Law 108-196 (2003) ensued, prompting formation of the ACER COE (2004), from which much knowledge has been added to what is known about cabin air quality. Finally, Public Law 112-95 (2012) called for a complete assessment of cabin air quality, including the identification and measurement of oil-based contaminants, the assessment of bleed air on aircraft, and the identification of health risks following exposure.

The rare occurrence of air quality events in aircraft cockpits and cabins is a very important factor to consider in designing a sampling strategy for hazardous constituents of bleed air. Rare occurrence is also relevant to understanding the associated health risks following exposure to those hazardous constituents. The proportion of such events has been estimated to range in occurrence from 2.7 to 33 events per million aircraft departures (Mirawski & Supplee, 2008; Overfelt, 2012). The likelihood of randomly selecting a given flight on which to collect air samples during an air quality event is indeed extremely low. A large number of flights would be required to increase the likelihood of collecting samples during such an event. As an example, given the higher of the two previous estimates, we would need to collect samples from approximately 30,000 flights to expect one sample to be collected during a contaminated air event. One of the directives from Public Law 112-95 (2012) was to assess bleed air quality on the full range of commercial aircraft operating in the United States. Therefore, approximately the same number of flights for each aircraft type would need to be applied to meet this requirement.

Another factor to consider is the availability, or lack thereof, of a suite of sampling techniques that allows for the broad characterization and evaluation of contaminants within contaminated bleed air. Public Law 112-95 directed the implementation of a research program for the identification or development of appropriate and effective air cleaning technology and sensor technology for the engine and auxiliary power unit bleed air supplied to the passenger cabin and flight deck of a pressurized aircraft. We are aware that advances have been made in recent years in regard to technology to better and more completely characterize the various constituents of bleed air. VIPR (Hunter et al., 2014), the joint research being performed by the U.S. Air Force, the National Aeronautics and Space Administration, and the Federal Aviation Administration, holds promise in regard to advanced technology for measurement of bleed air constituents in a test system. However, because the final results have not yet been published, further evaluation is not warranted until a written report has been issued.

Research Needs

Much work is needed to carry out the directives of the Public Law 112-95 (2012). This work includes:

- the ongoing study of air quality in aircraft cabins through a comprehensive sampling program for broad characterization and evaluation of the constituents of contaminated bleed air;
- assessment of bleed air quality on the full range of commercial aircraft operating in the U.S.;
- continued assessment of health risks to passengers who may be exposed during bleed air events;
- continued development of instrumentation for sensing bleed air and cleaning contaminated air in pressurized aircraft cockpits and cabins;
- continued development and evaluation of current measurement technologies both on the ground and in flight; and
- development of a systematic reporting standard for contaminated bleed air events.

CONCLUSION

Quantification of the potential health risks associated with exposure to bleed-air contaminants in cabin air is not possible without broad identification and measurement of the representative hazardous constituents of bleed air during contaminated air events. Included in the 2012 mandate (Public Law 112-95) is the directive to the FAA to "assess bleed air quality on the full range of commercial aircraft operating in the United States." Carrying out such a mandate requires adequate funding to support research activities.

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