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TRANSPORT AIRCRAFT ENVIRONMENTAL CONTROL SYSTEM AIR QUALITY IMPROVEMENT

Ilan Berlowitz
IBAero Engineering, Israel

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Abstract

Cases of aircraft crew members forced to retire due to chronic health conditions attributed to poor cabin air quality have been highlighted in recent years. The term 'aerotoxic syndrome' first came into use in 2000 after growing numbers of reports of such illnesses. In some cases, these illnesses have been attributed to toxic chemicals fed to the occupied areas of the aircraft, perhaps as a result of leakage of lubricant oils. One ingredient of synthetic oils is a compound called tricresyl phosphate (TCP) which can be toxic to humans in large quantities and much of the researches have focused on this compound.

This paper assesses the existing researches and reports on this subject from scientific, medical and legal sources. The literature review concludes that although there is no evidence to suggest that aerotoxic syndrome exists, it is prudent from a legal perspective for airlines and aircraft manufacturers to investigate the feasibility of detection and/or filtration of TCP and other volatile organic compounds (VOCs) to minimize any risk, to the flight crew and passengers.

The ways in which contaminants could enter the aircraft cabin have been explored, with engine oil, hydraulic fluid and de-icing fluid containing harmful compounds which could theoretically enter the environmental control system (ECS) air supply through faulty seals.

Four main methods of VOC detection have been assessed and reviewed against criteria including accuracy, sensitivity, reliability and ease of operation and installation in an aircraft. A micro-electro-mechanical systems (MEMS) sensor has been selected as most appropriate for use on an aircraft due to its accuracy and ability to distinguish between different types of VOCs. Three contaminant removal methods were reviewed, with an activated carbon filter selected due to its effectiveness in capturing contaminants and the ability to analyze the filter media once the filter reaches its end of life.

A case study has been conducted using an A320 ECS to determine the best place to situate filters, assessed against the effectiveness, air flow pressure drop and ease of maintenance once in that location. The best solution has been shown to be two activated carbon filters situated downstream of the air conditioning packs (ACPs) with an option to fit MEMS sensors either in the aircraft cabin or flight deck, or near the bleed air tapping points of the engines and auxiliary power unit (APU).

Subsequent work would include cost studies to ascertain precise installation and in-service costs of fitting these devices. A cost-benefit analysis could then be undertaken to determine whether installation of detectors and/or filters is a reasonable precaution to take to ensure that aircraft occupants do not suffer ill health as a result of short-term or sustained exposure to potential contaminants.

Background

Engineering, design, regulations, and maintenance practices are combined to minimize occurrences of fire/smoke or fumes (FSF) in pressurized areas of airplanes. When FSF occur, timely and appropriate action by flight and cabin crews is imperative.

FSF cabin penetration is classified as hazardous. The following issues need to be considered:

- Operational consequences and safety risks of FSF events.
- Analysis of past FSF events and review of procedures.
- Recommended procedures.

Modern large airplanes cabin air quality is recognized as excellent. However, quality can be degraded by abnormal and unusual events. Various sources of contamination are possible, either internal, or from outside of the airplane. Under certain fault conditions (engine or APU oil seal or bearing failure, maintenance error/irregularities, or design deficiency), oil, hydraulic fluid, fuel, de-icing fluid may contaminate bleed air, which then enters the cabin.

As a result of the DHC-8-402 (August 4, 2005) cabin smoke incident, recognizing the difficulty to identify the source of FSF, safety recommendation (SR) 2007-002 was issued by the UK Air Accidents Investigation Branch (AAIB), recommending the European Aviation Safety Agency (EASA) and the US Federal Aviation Administration (FAA) to issue a requirement for a flight deck warning of smoke or oil mist in the air delivered by each air conditioning unit.

EASA has published an advanced notice of proposed amendment (A-NPA) 2009-10, on September 28, 2009 with on-line questionnaires and a corresponding comment response document (CRD) was published on May 28, 2011.

After the review of existing and on-going research studies and the analysis of the information collected by the A-NPA, the Agency concluded that this topic will nevertheless be continuously monitored by the Agency, and some recommendations were provided to further improve the knowledge in the fields of toxicity and health impact of oil fumes, and bleed air filter and monitoring technologies.

Introduction

Flights subject the human body to numerous conditions not usually experienced on the ground such as pressurization, vibration and exposure to ozone and cosmic radiation. Each condition is considered carefully by aircraft designers to ensure that the cabin and flight deck are comfortable and safe for all occupants. Figure 1 shows some of the conditions that can have an effect on comfort or safety.

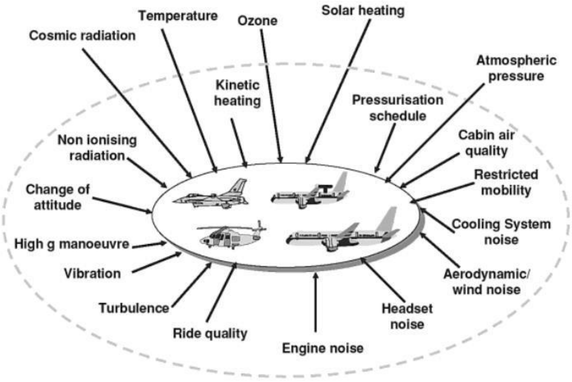


Figure 1: Sources that may affect health of aircraft occupants

Cabin air quality is one of the issues that can be improved by aircraft designers. In the late 1980s, smoking began to be banned from flights, leading to a marked improvement in cabin air quality. Additionally, there were advances in filtration technology, with effective High Efficiency Particulate Air (HEPA) filters fitted routinely on the recirculation portion of the environmental control system to filter out particles, bacteria and viruses.

In recent years, cases of aircrew forced to retire due to chronic health conditions attributed to poor cabin air quality have been highlighted by aircrew support groups, unions and the media. These health conditions include neurological and respiratory issues and were first grouped together under the term ‘aerotoxic syndrome’ in 2000 after growing numbers of reports of such illnesses. In some reports, these illnesses have been attributed to toxic chemicals fed to the occupied areas of the aircraft, with some suggesting this is a result of leakage of lubricant oils found in the engines.

The International Air Transport Association (IATA) states that in 2017, over 4 billion passengers travelled by air (including leisure and business travel), a rise of 8.1% since 2016 (Figure 2).

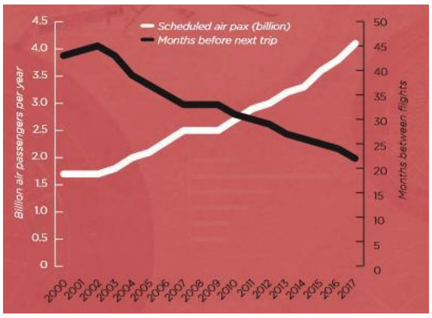


Figure 2: Passenger numbers and months between flights

This paper will consider the effect of cabin air quality on aircraft occupants, investigate methods to detect and filter any contaminants and propose a system architecture to incorporate appropriate technology into existing environmental control systems.

Aircraft Environmental Control System (ECS) & Bleed Air

In order to assess the ways about contamination of cabin air, it is better to understand how an aircraft's environmental control system (ECS) operates. The purpose of an ECS is to provide a safe and comfortable environment for aircraft occupants and equipment. The ECS regulates temperature, pressure, humidity and oxygen levels.

Potential Contamination of Air Supply

Cabin air can contain contaminants originating from within the aircraft cabin itself, such as dust, fibers and chemicals from aircraft furnishings, fixed fittings and cleaning and maintenance products. Aircraft cabin air also contain contaminants from hydraulic fluid, aircraft anti-icing fluids, synthetic jet oils or the compounds which are released when these fluids are pyrolyzed. These could be introduced to the aircraft cabin via bleed air, or from fluid deposits in the ECS ducting. Engine compressor seals in the main engines and the APU should prevent fluid from entering the ECS, but it is possible that these seals could become worn or damaged over their lifetime, allowing contaminants to enter the ECS.

The main emissions due to engine combustion and the corresponding health issues are listed below:

- Volatile organic compounds (VOCs) - nausea and fatigue. Some VOCs are also known carcinogens.
- Semi volatile organic compounds (SVOCs), a sub-group of VOCs with higher boiling point temperatures including tricresyl phosphate isomers and tributyl phosphate isomers.
- Unburned hydrocarbons (UHCs), contributing to smog and ozone formation.
- Sulphur dioxide (SO_2), affecting breathing and possibly aggravating respiratory diseases or conditions such as asthma.
- Carbon mono (CO), limiting the delivery of oxygen to the lungs.
- Particulate matter (PM), contributing to smog and affecting the respiratory system.
- Ozone (O_3), which damages lung tissue not only of people with existing respiratory conditions but also healthy individuals.

The levels of these emissions can vary dependent on the stage of flight. In the cruise stage, passengers will be exposed to higher levels of ozone due to the higher altitude. Particulate matter, SO_2, NO_X, CO_2 and CO are found most commonly in exhaust gases and so levels are higher when the aircraft is on the ground and drawing in this polluted air. In 2010, 19% of all aircraft ground levels emissions at London Heathrow airport were from the APU. The airport's air quality strategy pledges to provide more pre-conditioned air units for aircraft to reduce the requirement for APU use on the ground and so reducing the levels of these contaminants. The contaminants include VOCs and SVOCs, specifically the organophosphates (OPs) of tricresyl phosphate (TCP) and tributyl phosphate (TBP).

VOCs are organic compounds in liquid or solid, having a low boiling point, which indicates a large number of molecules evaporate into the surrounding air at room temperature. SVOCs, organic compounds, have higher boiling points and are either man-made or naturally occurring. A study published in 2014 indicated that 59 VOCs were detected on each flight with a total of over 340 over 107 commercial flights.

Two main organic compounds such as TCP and TBP present in engine & hydraulic oils are harmful to health. TCP, an organophosphate additive found in engine oil, act as a flame-retardant. It is used with plastics, for its flame-retardant properties. Many of the studies which examine ill health in flight crew focus on this compound. The UK's Environment Agency has published a comprehensive document explaining the numerous hazards of TCP to humans, animals and land.

Initial symptoms of TCP exposure to humans include slight or severe nausea and vomiting, diarrhea and abdominal pain. Tri-o-cresyl phosphate (ToCP), an isomer of TCP with a molecular structure as shown in Figure 3, is neurotoxic to humans after repeated oral, dermal, or possibly inhalation exposure.

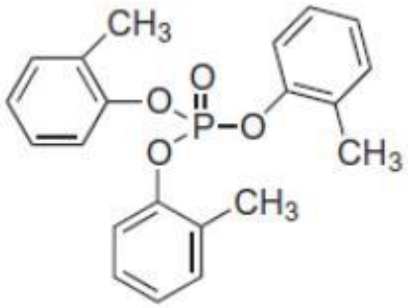


Figure 3: Structure of tri-o-cresyl phosphate (TOCP)

Like TCP, TBP is also an organophosphate. It is used in aviation hydraulic fluids as a flame retardant. When heated, it emits toxic fumes including phosphorus oxides. Inhalation can lead to headaches and irritation to the mucous membranes in the nose and throat.

Entry of Contaminants into the Aircraft Cabin

Small amounts of engine oil, hydraulic fluid and other contaminants like de-icing fluids can enter the cabin air supply via the high-pressure bleed feed if there is leakage past engine seals. Both air and oil seals can be used in turbine engines to control bleed air flow.

In 2004, CAA studied about cabin air quality and examined that the ECS ducting of an aircraft, BAe 146 had numerous fume events. BAe 146 New ECS Ducting and used ducting for almost 25,000 hours are shown in Figure 4. Inside of the old ducting had a thin layer of black particulate and a 'translucent stain' appeared when it was pressed against a white paper, indicative of an oily substance. This duct had been located downstream of the ACP.

Figure 4: BAe 146 new ECS ducting (left) and used ducting (right)

Studies have been conducted which measure levels of contaminants in the aircraft cabin, but these levels are only monitored during research. On occasion, crew and passengers may be able to smell or see mist or smoke, signifying poor air quality. This is known as a 'fume event', 'odor event' or 'smell event'.

Fume and Odor Events

Airbus state in Issue 52 of their Flight Airworthiness Support Technology (FAST) publication that 'a noticeable cabin odor can be generated from ingesting only a very small amount of oil'.

The German Federal Bureau of Aircraft Accident Investigation (BFU) conducted a study into 845 accidents and incidents of German-operated aircraft which were reported to the BFU between 2006 and 2013.

Over 40% of odors were described as 'burning' or 'oil' smells. In 180 reports, health effects were described but could not be firmly attributed to cabin air quality. In most cases, the smells were unpleasant but harmless but in 10 cases, the person reporting the incident was still experiencing long-term health effects up to a year later (Figure 5 & Table 1).

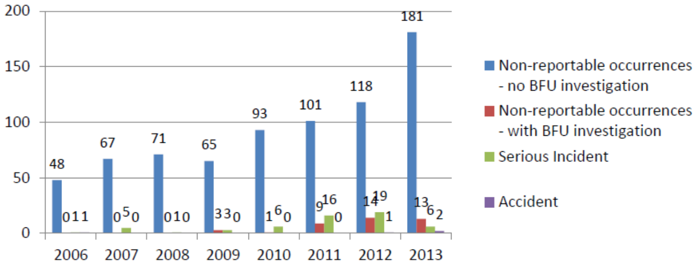


Figure 5: BFU reported incidents (2006-2013)

Table 1: Technical causes of fume events

System	Number	Examples
APU	24	Oil, de-icing fluid
Avionics	13	Fan
Fire	9	
ECS	23	Fan
Electrical systems	33	Fan, other components
Electrical system of the cabin	21	Lights
external contamination	11	Dry ice, cigarettes, luggage
Coffee machine	11	Contamination / defect
ovens	24	Contaminations of foreign objects
System error	9	Leakages of hydraulic and fuel lines
Import of technical compounds	8	Glue, de-icing fluid
Engine	13	
Engine - washing	11	
Engine - oil overfill	3	
Engine - bird strike	10	
Other	5	Cannot be correlated to one of the above-mentioned groups
Not determined	42	
Unknown	386	
None	3	

A report by the United States National Research Council in 2002 offers similar evidence, stating that there were 1.29 ‘air quality events’ - also known as fume events - per 1,000 flights for the Airbus A320, 0.63 per 1,000 for the Boeing 767 and 0.09 per 1,000 for the 737.

Finally, the Australian Transport Safety Bureau (ATSB) and Australian Civil Aviation Safety Authority published a joint report in 2014 which stated that over 1000 fume events were reported in Australia over a 5-year period from 2008 to 2012 (inclusive), most of which were minor in terms of flight safety but which still caused delays.

It is clear from looking at these 3 German, US and Australian sources that there were no definitive statistics or standardized reporting mechanism for fume event frequency, air contaminant levels, cause and associated delay figures (Figure 6).

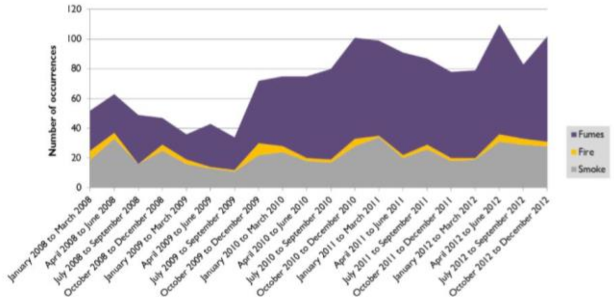


Figure 6: Fumes, smoke and fire reporting to the ATSB

At 2015, ICAO states that operators should ensure that crew can recognize and respond appropriately to any fumes on board and includes a standardized smoke and fume reporting form which operators were encouraged to adopt.

Use of a detection system would ensure that actual air quality values could be added to the ICAO fume event report, making the data set on fume events and typical contaminants larger and more comprehensive, helping manufacturers, operators and regulators to understand air quality better.

A real-time detection system would also be able to identify the presence of air contaminants and show when levels had reduced sufficiently. It could categorize the type of fume event, identifying whether it was due to oil, de-icing fluid or another contaminant which could reduce fault finding time.

In the future, a detection system could even enable predictive maintenance: trends of VOC levels could be monitored to pinpoint potential engine seal failures, for example.

Transmission of Infectious Diseases During Commercial Air Travel

The severe acute respiratory syndrome (SARS) outbreak of 2002 showed how air travel can have an important role in the rapid spread of newly emerging infections and could potentially even start pandemics. In addition to the flight crew, public health officials and health care professionals have an important role in the management of infectious diseases transmitted on airlines and should be familiar with guidelines provided by local and international authorities.

In this study, knowledge about transmission of infectious diseases associated with commercial air travel was reviewed, with particular emphasis on transmission within the aircraft passenger cabin.

The Aircraft Cabin Environment

During flight, the aircraft cabin is a ventilated, enclosed environment that exposes passengers to hypobaric hypoxia, dry humidity, and close proximity to fellow passengers. This space is regulated by an environmental system that controls pressurization, temperature, ventilation, and air filtration on the aircraft. Although this system is wholly automated, the number of air-conditioning packs in operation, zone temperatures, and the mixture of fresh and re-circulated air delivered to the cabin can be manipulated by the flight deck. When parked at the terminal, fresh air is supplied to the aircraft by auxiliary power units. During flight, fresh air is supplied into the cabin from the engines where the air is heated, compressed, cooled, and passed into the cabin to be circulated by the ventilation system. The outside air is assumed to be sterile at typical cruising altitudes. Air circulation patterns aboard standard commercial aircraft are side-to-side (laminar) with air entering the cabin from overhead, circulating across the aircraft, and exiting the cabin near the floor (Figure 7). Little front-to-back (longitudinal) airflow takes place. This air circulation pattern divides the air flow into sections within the cabin, thereby limiting the spread of airborne particles throughout the passenger cabin.

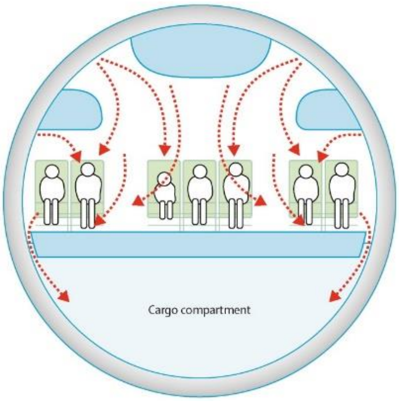


Figure 7: Air circulation pattern in typical airline passenger cabin (arrows show air currents)

Most commercial aircraft in service re-circulate 50% of the air delivered to the passenger cabin for improved control of cabin circulation, humidity, and fuel efficiency. This re-circulated air usually passes through HEPA filters before delivery into the cabin. Normal airline cabin air exchange rates range from 15 to 20 air changes per hour compared with 12 air changes per hour for a typical office building. Ventilation capacity varies substantially, dependent on the aircraft type but typically averages 10 cubic feet per minute (4.7 liter/s). Ventilation rates can also vary within the different cabin sections, such as first and economy class. In general, HEPA filters used on commercial airlines have a particle-removing efficiency of 99.97% at 0.3 microns. These filters remove dust, vapors, bacteria, and fungi. HEPA filters also effectively capture viral particles because viruses usually spread by droplet nuclei. No ventilation operational standards for commercial aircraft are available. Although a survey showed that most air carriers equip their large aircraft with HEPA filters, neither the Civil Aviation Authority nor the Federal Aviation Administration require their use.

In a detailed study into cabin air quality released in 2004, the group concluded that temperature, humidity, air speed, and concentrations of carbon monoxide, carbon dioxide, and microbiological flora aboard 14 commercial flights using British Aerospace 146 and Boeing 300 aircraft were similar to other reported studies. The European Cabin Air study coordinated by the Building Research and Consultancy continues to investigate environmental aspects within the passenger cabin. These efforts will probably lead to improved international regulations for the certification, inspection, and maintenance of aircraft environmental control systems.

Modes of Disease Transmission

Four routes for the spread of microorganisms exist: contact, airborne, common vehicle, and vector-borne. Contact transmission involves direct contact in which body-to-body contact takes place, or indirect in which the susceptible person comes into contact with a contaminated intermediate host (fomite). Table 2 shows the infectious diseases that have been transmitted on commercial airlines.

Table 2: Reported infections transmitted on commercial airlines

	Number of reports	**Comments**
Airborne/fomites		
TB	2	Positive TB skin test only. No active TB.
SARS	4	No cases since WHO guidelines.
Common cold	0	Difficult to investigate.
Influenza	2	None since ventilation regulations.
Meningococcal disease	0	21 reports of ill passengers, no secondary cases
Measles	3	Imported cases and international adoptions
Food-borne		
Salmonellosis	15	No recent outbreaks
Staphylococcus food poisoning	8	No recent outbreaks
Shigellosis	3	No recent outbreaks
Cholera	3	During cholera epidemic
Viral entities	1	Common on other types of transport
Vector-borne		
Malaria	7	Probably underestimated
Dengue	1	Likely to be airport, not aircraft, transmission
Yellow fever	0	No outbreaks since disinfection of aircraft
Bioterrorism agents		
Smallpox	1	Before eradication

Large droplet and airborne mechanisms probably represent the greatest risk for passengers within the aircraft because of the high density and close proximity of passengers. In addition to proximity, successful spread of contagion to other hosts is dependent on many factors, including infectiousness of the source; pathogenicity of the microorganism; duration of exposure; environmental conditions (ventilation, humidity, temperature); and host-specific factors such as general health and immune status. How these factors affect risk of disease transmission within the aircraft cabin is unclear.

Risk of disease transmission within the aircraft cabin also seems to be affected by cabin ventilation. In general, proper ventilation within any confined space reduces the concentration of airborne organisms in a logarithmic fashion, and one air exchange removes 63% of airborne organisms suspended in that particular space. The main laminar flow pattern within the aircraft cabin with the practice of frequent cabin air exchanges and use of HEPA filtration for re-circulated air clearly limits transmission of contagion. Transmission becomes widespread within all sections of the passenger cabin when the ventilation system is nonoperational, as shown by an influenza outbreak when passengers were kept aboard a grounded aircraft with an inoperative ventilation system.

Airborne and Large Droplet-Transmitted Diseases

The significant and high-risk air-borne diseases include tuberculosis and SARS (Figure 8).

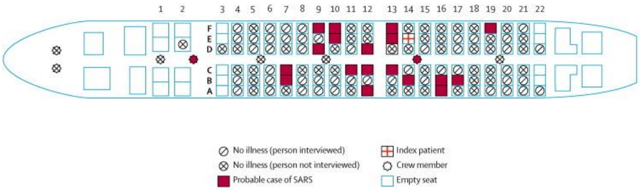


Figure 8: Schematic diagram of SARS outbreak aboard Hong Kong to Beijing flight

The duration of the Hong Kong to Beijing flight was 3 hours and affected passengers were seated seven rows in front and five rows behind the index passenger. Possible explanations for this outbreak distribution include: airborne transmission rather than direct contact spread; a malfunctioning cabin filtration system; and passengers infected before or after the flight. No on-board transmissions have occurred since late March, 2003, when the World Health Organization WHO issued specific guidelines for in-flight containment of SARS.

Existing and Forthcoming Air Quality Systems to Monitor or Improve Air Quality

A system known as AirManager was used by BAe in the ECS of the BAe 146 / Avro RJ aircraft and is shown in Figure 9. It uses close coupled field technology (CCFT) to eliminate smells and break down airborne contaminants and toxins and is fully certified by EASA. The system also holds a supplementary type certificate (STC) for use on B757 aircraft. It works by using non-thermal plasma fields.

Figure 9: AirManager cabin air system installed in BAe 146

There are also two commercial ventures ongoing which are marketing products to address current concerns regarding aircraft cabin air quality.
VN Aerotoxic Detection Solutions (VN-ADS), is used to develop a detection system to allow VOC levels to be routinely monitored in flight. Incorporation of fiber optic measuring technology in handheld devices would monitor VOCs in real time (Figure 10).

Figure 10: VN-ADS image of its VOC detector

The second commercial venture is a cabin air filter which filters all cabin and flight deck air, rather than only the re-circulated air. In 2017, the collaboration of airline EasyJet with Pall Aerospace designed a commercial filter supplier, to retrofit a new cabin air filtration system to EasyJet’s aircraft. These filters use carbon filtration technology to remove odors and VOCs.

Cabin Air Quality Research

The symptoms in exposure to TCP are from eye irritation or respiratory conditions, to neurological. The neurological symptoms relate to both the peripheral nervous system like tingling sensations and the central nervous system like reduced memory function. This diverse range of symptoms has been grouped & named as ‘aerotoxic syndrome’.

The Aerotoxic Association set up in 2007 and its objectives are to provide support for sufferers due to aerotoxic syndrome and work with industry and regulators to implement solutions.

The most abundant VOCs were toluene and limonene. BS EN 4618: 2009 sets a safety limit for toluene of 153 mg/m^3.

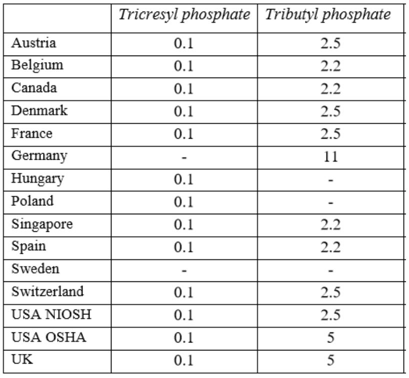
TCP was not detected in over 95% of the cabin air samples and TBP was detected in fewer than 50%. VOCs were detected when the aircraft was on the ground and during take-off and climb. TBP levels specifically were found to be highest during engine start. TCP levels were highest when moving from one flight phase to another, specifically climb, pre-landing and take-off. Target contaminants must be in limits as per standards and guidelines in all studies.

In 2017, EASA commissioned a report on cabin air quality. Researchers from the Fraunhofer Institute for Toxicology and Experimental Medicine took measurements from 69 flights for 8 different types of aircraft (and different operators) and engine configurations. 61 of these were for aircraft where air supply is from bleed air; the remaining 8 flights were carried out on a B787 using its electrically powered ECS that does not use bleed air. This was the first time that there had been a direct comparison between VOC measurements on board aircraft fitted with ECS using bleed-air and those with electrically powered ECS.

Only TCP traces were found, with a mean concentration of 0.009 µg/m^3 in the main study and 0.020 µg/m^3 for the B787. Maximum levels were 1.515 µg/m^3 in the main study and 0.403 µg/m^3 for the B787. The presence of TCP in the B787 cabin air is due to bleed air contamination. Low-level TCP release may be from plastics and other furnishings in all aircraft.

TBP levels had a mean of 0.430 µg/m^3 measured during the main study, and 0.237 µg/m^3 for the B787. The highest levels of both TCP and TBP were, as in the Cranfield University/Department for Transport (DfT) study, experienced during taxi-out and take-off / climb phases of flight. B787 was also fitted with an activated carbon filter in the re-circulated air system, so reduced levels may be due to the lack of bleed air usage, the activated carbon filter, or a combination of both (Table 3).

Table 3: International occupational exposure limits (in mg/m^3)



	Tricresyl phosphate	*Tributyl phosphate*
Austria	0.1	2.5
Belgium	0.1	2.2
Canada	0.1	2.2
Denmark	0.1	2.5
France	0.1	2.5
Germany	-	11
Hungary	0.1	-
Poland	0.1	-
Singapore	0.1	2.2
Spain	0.1	2.2
Sweden	-	-
Switzerland	0.1	2.5
USA NIOSH	0.1	2.5
USA OSHA	0.1	5
UK	0.1	5

A contaminant-free indoor environment will never be possible, contaminant levels in flight deck & cabin air are extremely low, probably assisted by the high air exchange rate, and far below the existing occupational exposure limits.

An article entitled: ‘Aerotoxic Syndrome: A New Occupational Disease?’ concluded that aircraft cabin air contaminated with pyrolyzed engine oil and other fluids, like de-icing fluid, can be linked to acute and chronic health symptoms in aircrew.

Reports from Cranfield and EASA showed that TCP and TBP levels are under ‘acceptable limits’. A clear cause and effect relationship exists between aerotoxic syndrome symptoms and the environment on an aircraft and recommends that a medical investigation protocol is required.

Contaminant Detection Methods

Requirement for a Sensing Method

Installation of filters within the ECS to remove harmful compounds require additional sensors based on filter type, periodic filter analysis to determine the type and concentration of VOCs.

Sensors in the aircraft cabin provide a real-time assessment of the filter's effectiveness, make sure of identifying harmful levels as early before concerning adverse health symptoms by flight crew. Sensor's positioning must be immediately downstream of the bleed air points for each engine and the APU, to analyze elevated VOCs levels during fume event.

Means of Measurement

- **Methos 1:** monitoring the air quality in real-time would allow the presence and level of contaminants to be identified in the flight crew.
- **Method 2:** monitoring the air quality through periodic analysis of samples. An air sampling pump used to take samples from the passenger cabin and flight deck, further require laboratory analysis.
- **Method 3:** monitoring of flight crew health is done by taking hair, urine or blood samples and exposure to VOCs and/or other harmful compounds were assessed.

Methods 1 and 2 require a sensor or air sampling device on board in the aircraft. Method 3 would require urine, blood or hair samples from flight crew and then analyzing the exposure.

Hair sampling provides an exposure history lasting about 6 months and analyzed using gas chromatography and mass spectrometry (GC-MS).

Sensor Criteria

Method 1 require sensors on the aircraft to monitor VOCs in real-time. Such a sensor would be required to:

- Measure VOCs levels accurately and consistently
- Measure levels even with varying humidity and temperature ranges.
- Sensitive to detect low VOC levels. The EASA cabin air quality will be used as the reference.
- Need minimal routine maintenance.
- Be simple to install, operate and used for several usages.
- Be economical.

Method 2 require a sampling device to capture a specific air volume. This device is accurate and simple to operate. Four sensor types include

- Gas chromatography and mass spectrometry (GC-MS).
- Photoionization detectors (PIDs).
- Micro-electric mechanical systems (MEMS) sensors.
- Optical fiber sensors (two different types).

GC-MS

The sample is drawn using a pump or injected into the GC inlet before the flow of an inert gas, nitrogen in a GC column. As the sample flows through, the compounds in the sample gets separated by interacting with the inside column walls. The sample travels down the length of the column, eluted from the column at different times. This time taken for a compound to come through the column is known as the retention time. Results are usually presented in the form of a graph, known as a chromatogram, with each separate compound shown by a different peak.

An MS downstream is further able to break each molecule into ionized fragments, usually by electron ionization where the molecules are ionized by a beam of electrons. Separation of these ions based on mass to charge ratio and further be detected, identified and measured. A schematic of GC-MS operation is shown in Figure 11.

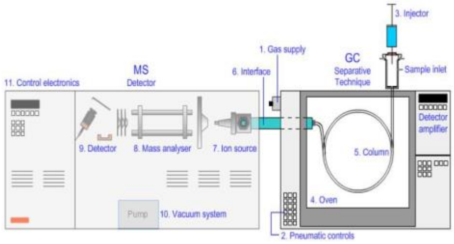


Figure 11: Schematic of GC-MS operation

An example of a chromatogram shows in Figure 12, indicating the presence of compounds in air on the International Space Station, x-axis and y-axis representing the retention time, and intensity or concentration of the compounds. Each peak represents a different compound.

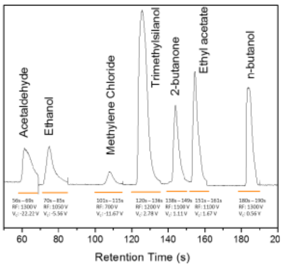


Figure 12: Chromatogram showing concentration of compounds on the International Space Station

Using both GC and MS improve the sensing accuracy. The GC-MS analysis is unable to take place *in situ* on an aircraft. On board portable air sample pump, designed by the Cranfield University/DfT study known as TSI SP730 sampling pump. The sorbent tubes are usually made of passivity stainless steel, with the sorbents themselves selected depending on the analytic of interest.

In recent years, PerkinElmer Torion T9 portable GC-MS weighs just over 14 kg and can operate on battery power for 2.5 hours (Figure 13).

Figure 13: TSI SP730 portable air sampling pump (Left); Torion T9 portable GC-MS (right)

Photo-Ionization Detector (PID)

Cranfield University/DfT used several devices PID to detect VOCs and particles to obtain instant readings on board. Ion Science produce a cheaper, handheld detector which detects VOCs over a range of 0 to 20,000 ppm which also has a minimum sensitivity of 0.1 ppm. Its response time of 2 seconds is short and it can store up to 80,000 data points. It is resistant to 99% relative humidity and can operate continuously for up to 24 hours. It weighs 0.72 kg. The sensitivity for both devices of 0.1 ppm is equivalent to 1.17 mg/m^3 of TBP, which is much more than the mean value of 0.430 µg/m^3 detected during the EASA study (Figure 14).

Figure 14: TVOC fixed PID (left) and handheld PID (right)

A PID works by directing an UV light source at the air sample to break down carbon-containing VOCs into positive and negative ions. The device then detects and measures the charge of the ionized gas. The value of the charge is a function of the concentration of VOCs in the air sample. Once the charge has been measured, the positive and negative ions recombine to reform the original gas, meaning that PIDs do not permanently change the sample air. The operation of a PID is shown in Figure 15.

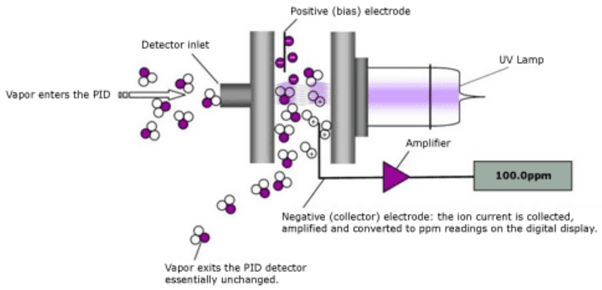


Figure 15: PID operation

Each molecule has an Ionization Potential (IP) value, which is the energy required (using the UV source) to cause the molecule to fragment into positive and negative ions. When molecules are ionized i.e., when the photon energy of the UV light is greater than the IP - the ions are driven in one direction and gathered at another electrode, enabling them to be detected and measured. This value is converted to a digital readout, giving the concentration of the molecule in ppm. The photon energy is measured in electron-volts (eV).

If the IP of a particular compound is less than the eV rating of the PID lamp, then the compound will be detected. If the IP of a compound is greater than the eV lamp rating, the compound will not be detected. IP values for some common chemicals are given in Figure 16.

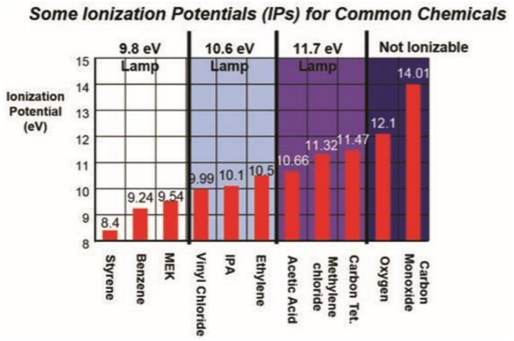


Figure 16: Ionization potentials of common chemicals

Almost all VOCs can be detected by PIDs, depending on the lamp rating, but it is not possible to identify specific VOCs such as TCP (Table 4).

Table 4: Comparison of PID devices

Criterion	Fixed Detector	Handheld Detector
Accuracy	• 0 to 100 ppm: ± 10% or ± 1 ppm (whichever is greater) • 0 to 1000 ppm: ± 10% or ± 1 ppm (whichever is greater)	• 1 ppb, maximum reading 20000 ppm • Accurate to within 5%
Mass/Size	1.6 kg / 188 · 126 · 78 mm	0.72 kg / 340 · 90 · 60 mm
Power	28 V DC	Battery (either Li-ion or Alkaline)
Ease of Installation	Could be attached to an existing bulkhead using a simple bracket	Handheld
Response Time	< 5 seconds	< 2 seconds
Temperature Limit	-20 to 50°C	-20 to 60°C

The advantages of using a PID are as follows:

- The response time is very short, at approximately only 2 seconds, unlike GC-MS.
- The devices offer accuracy of at least +/- 0.1 ppm.
- Both fixed and handheld PIDs are mature technology.
- Handheld PIDs require no modification to the aircraft and are relatively low cost.
- For the fixed PID, no user action is required.

Micro-Electric Mechanical Systems (MEMS)

MEMS technology is the miniaturization of mechanical and electromechanical devices. Physical dimensions of MEMS devices can range from several millimeters on the upper end of the scale, down to below one micron at the lower end. One example of MEMS technology is micro-sensors.

MEMS technology can be applied to resonators to detect chemical and biological substances. Molecular adsorption onto a coated sensing element, usually a cantilever fixed at one end, shifts its resonant frequency and changes its surface stress. This adsorption onto a sensing element composed of two chemically different surfaces produces a differential stress between the two surfaces, causing bending. This process can be either reversible (i.e., the molecules can be released and the bending action ceased before another molecule is detected) or irreversible.

There are two modes of deflection: static and dynamic. The static mode occurs when the adsorbed material causes the cantilever to deflect. This is partly due to the differential surface stress, and partly due to the added mass from the adsorbed molecules. This deflection can be measured, identifying the analytic of interest (shown by the resonator which is deflecting) and the concentration (measured by the magnitude of deflection). The dynamic mode is concerned with the vibration of the cantilever, and the shifts in resonant frequency due to the adsorbed molecules.

To detect a particular VOC, the cantilever is coated with either a metallic or ceramic film with a high affinity to the VOC of interest. If both surfaces of the cantilever are coated with this film, the concentration of VOC in the air will be proportional to the change in frequency. If only one side of the cantilever is coated with the film, then the concentration of the analytic in the air is proportional to the cantilever's deflection.

The operation of a MEMS sensor is shown in Figure 17. The red and grey dots depict different molecules, with the red dots being the molecules of interest. The brown cantilever is coated with a green film which attracts the red molecules, and which causes the cantilever to deflect. This deflection is then measured (sometimes using piezo-resistors or fiber optic displacement sensors) to give the concentration of the analytic.

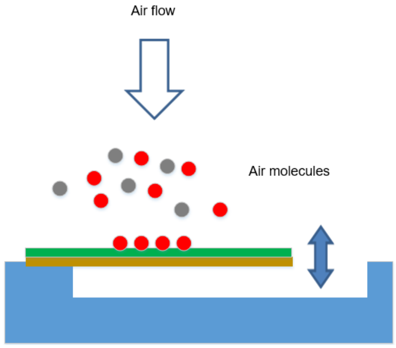


Figure 17: Operation of a MEMS sensor

The optimum operating temperature of these MEMS sensors is usually approximately 300 ºC, and so the sensors are manufactured with in-built micro-heaters. They have a response time of about

35 seconds and a very high degree of sensitivity with a detection limit of low parts per billion (ppb), so are capable of detecting the TBP and TCP levels experienced during the EASA study. However, sensor readings are known to ‘drift’ over time due to charge accumulating on the surface of the cantilever.

Optical Fiber

Optical fiber sensors are usually composed of an optical fiber, a light source, a sensing element and a detector. The principle of operation is that the sensing element will change some parameter of the light signal, such as wavelength, phase or intensity, which the detector is able to compare against the original light signal.

Two optical fiber sensing methods will be considered:

- Y-type distributor which is being developed by VN Aerotoxic Detection Solutions (VN-ADS) Ltd.
- Long period gratings.

Y-Type Distributor Sensor

VN-ADS have developed a patent for a technology known as mono fiber measuring technology (MOMT). The sensor comprises a Y-type distributor which divides power equally between the input and output channels. The signal is sent from the light source and through the input channel system, which is in contact with the air sample and coated with a thin film. The optical signal is reflected from the interface with the sample and into the output channel, which is connected to a photodiode and amplifier to receive signals which represent the interference patterns created at the interface between the film and the sample. This is shown in the diagram (Figure 18).

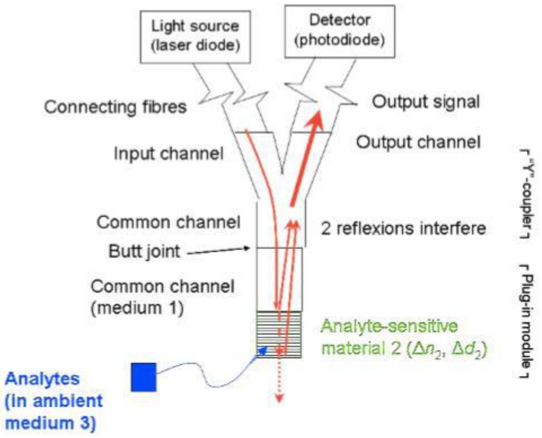


Figure 18: VN-ADS Ltd fiber optic sensor

A small detector receives the signals via an analogue to digital converter to process the signal and provide a measurement. Such a system could be used to detect numerous compounds, provided the waveguide sampling tip is coated with an appropriate material. However, the accuracy and sensitivity of the device is not yet sufficiently proven for this method to be implemented.

Long Period Gratings

One such optical fiber sensor is a long period grating (LPG). In general, fiber gratings work due to a periodic change to the properties of the optical fiber, usually the refractive index of the core. Changes to environmental parameters such as strain, temperature and bend radius will change the LPG period. Figure 19 shows the LPG operation: the input spectrum travels through the optical fiber to a UV-inscribed gratings, continuing through the optical fiber and allowing the transmitted spectrum to be recorded and compared to the input spectrum. Changes to environmental parameters will result in a difference between the input and transmitted spectrums which can be measured using a spectrometer. The change in the spectrum will be proportional to the change in parameter.

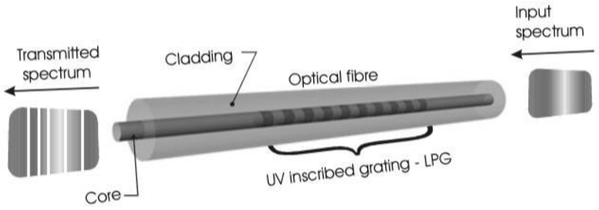


Figure 19: Schematic of an LPG

A sensor has been deemed to be sensitive enough if it is able to sense the lowest concentrations of key VOCs as detected during the EASA study. Although the optical fiber and LPGs are relatively robust, the effectiveness of the coating may be affected by dust or other particles.

Contaminant Removal

A filter is a device which traps unwanted particles or compounds as air passes through it. The main ways in which filter media capture particles are by sieving, diffusion, interception, inertial impaction and electrostatic attraction. These principles rely on particles colliding with one of the media fibers, and then continuing to adhere to it.

Sieving occurs when the particle is too large to fit through the fiber spaces. The other four mechanisms are shown in Figure 20. The red line shows the fluid flow, the yellow dot is the filter fiber and the black dot is a particle. Finally, electrostatic attraction takes place when a filter fiber attracts a particle of opposite charge, which then collides with the filter fiber and adheres to it.

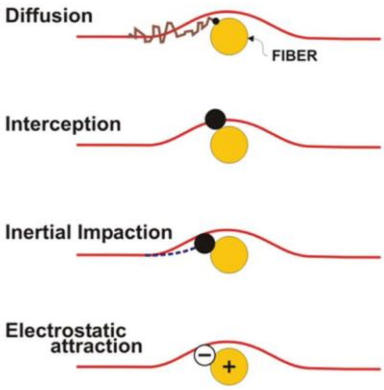


Figure 20: Filtration mechanisms

Existing Filters

As per American Society of Mechanical Engineers (ASME) standard, HEPA filters are fitted to all commercial airliners and must capture a minimum of 99.97% of contaminants of size 0.3 microns. This 0.3-micron size approximates the most difficult particle size for a filter to capture and is therefore used as a benchmark for filter efficiency. A typical HEPA filter on an aircraft ensures that the re-circulated air has a micro-bacterial content as low as fresh air outdoors.

Figure 21 shows a typical HEPA box filter, manufactured by Camfil, with a filter efficiency of 99.995% and with glass fiber filter media. These filters can be manufactured according to the customer’s requirement, and so would be made for a specific duct size.

Figure 21: Camfil Absolute DG HEPA filter

Pall Aerospace manufacture HEPA filters for A320 aircraft. Two filters are installed in an A320, both of which filter the re-circulated air flow and which weigh approximately 3 kg each.

Figure 22 shows the effectiveness of these HEPA+ carbon filters in removing VOCs and odors. With the HEPA+ carbon filter installed, a fume event in the cabin would take over 3 minutes to reduce to acceptable levels as shown by the blue line. Without such a filter, it would take just over 10 minutes for the smell or fumes to dissipate to an acceptable level as shown by the red line. It should be noted that these rates show the effect of dissipation in the whole cabin when only the re-circulated air is filtered using the HEPA+ carbon.

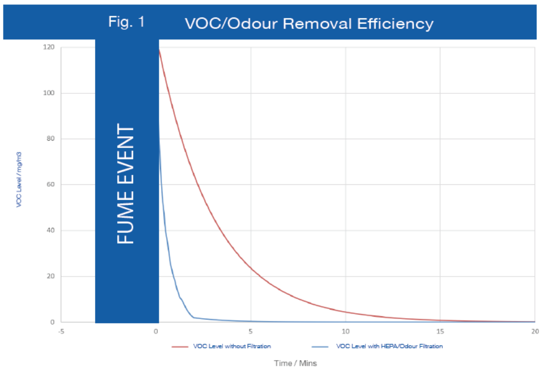


Figure 22: VOC and odor removal efficiency

VOC Filtration Methods

Two main methods of removing VOCs will be considered:

- Filtering using carbon adsorbent material, as used in the HEPA+ carbon filters introduced in the previous section.
- Destruction of VOCs through:
  - Catalytic oxidation.
  - Non-thermal plasma oxidation.

Carbon Adsorbent Material

Adsorption is the accumulation of atoms, ions or molecules from a gas, liquid or solute on to a surface of a solid, as opposed to absorption, where atoms, molecules or ions permeate another substance.

In an activated carbon filter, VOC molecules are attracted to the surface of the carbon adsorbent and are trapped in surface pits, or pores. These pores will be sized depending on the target molecule. Many filters are both microporous, with pore sizes of less than 2 nm, and mesoporous, with pore sizes of between 2 - 50 nm. Molecules with higher molecular weights and higher boiling points such as TCP, with a boiling point of 255 ºC will adsorb more strongly.

Figure 23 shows an activated carbon surface with both mesopores and micropores as seen using a scanning electron microscope. Micropores are the most suitable pore size to adsorb most VOCs.

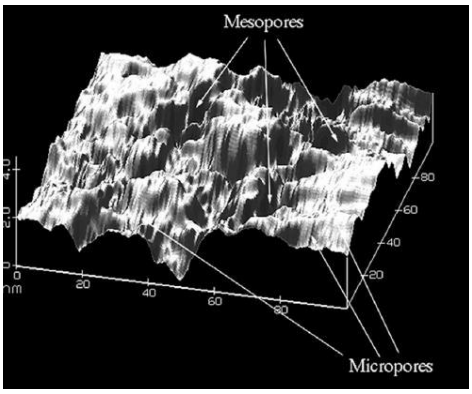


Figure 23: Surface of activated carbon

There are two manufacturing methods. The first is physical activation, where the beads are pyrolyzed at temperatures of between 700 - 1100 ºC in an inert atmosphere, extracting the pure carbon. The material is then activated by coating it with a chemical, usually oxygen. The second production method is chemical activation, where the original material is coated with a chemical selected according to the target molecule to be captured and then heated to temperatures of between 500 - 900 ºC, which carbonizes and activates the material at the same time, resulting in a faster production process. By the end of the process, one gram of activated carbon can have a surface area of up to 3000 m^2 due to the extremely high number of pores created.

Carbon filters can be manufactured to fit existing ducts and can also be fitted into existing HEPA filters, as is the case with Pall Aerospace's Advanced Cabin Air Filter. An example is a HEPA+ carbon filter fitted to an A319 aircraft. The filter is the silver-colored cylindrical component (Figure 24 & Table 5).

Figure 24: Example of a combined HEPA and carbon filter fitted to an A319

Table 5: Filter effectiveness for different VOCs

VOC	**Boiling Point (^{o}C)**	**Percentage of Molecules Captured after Time Period**		
		1,000 hours	3,500 hours	5,000 hours
Toluene	110	50	10	negligible
Limonene	176	80	50	30
Dodecane	216	95	85	80

Oxidation

The catalytic oxidation and non-thermal plasma oxidation processes are methods based on destruction, rather than filtering, where the VOCs are converted into carbon dioxide and water and possibly other compounds, depending on the VOC to be destroyed.

Catalytic Oxidation

A catalytic converter consists of ether a metal or ceramic honeycomb or beaded structure which is coated with a catalyst. The catalyst coating selected will vary according to the target VOC to be destroyed. Catalytic converters are already used on aircraft to treat ozone, and some manufacturers such as BASF Catalysts already supply combined VOC and ozone converters for Airbus and Boeing aircraft (Figure 25).

Figure 25: Side view (left) and top view (right) of BASF Catalysts dual ozone and VOC converter

Tests undertaken in 2002 BASF Catalysts revealed that a dual ozone and VOC converter situated in the bleed air feed reduced the perception of bad odors by 40% and reduced the concentration of VOCs by 20%.

Non-Thermal Plasma Oxidation

Plasma exists when molecules are heated to extremely high temperatures, causing electrons to excite and increase in velocity until they leave their orbits and travel away from the influence of the molecule. This state can also occur at room temperature if molecules are subjected to a strong electrical field: this is known as non-thermal plasma.

Non-thermal plasma occurs using a reactor comprising two electrodes separated by a void space lined with a dielectric material and filled with glass beads, as shown in the Figure 26. As the gas stream flows through the reactor, the voltage passing through the beads exceeds the insulating effect of the beads, resulting in micro-discharges of electricity. This causes extremely reactive free radicals to be created which combine with other atoms or molecules to form new compounds. These free radicals oxidize the VOC compounds, converting them into carbon dioxide (CO_2) and water (H_2O). This method is suitable for removing low concentrations of VOCs.

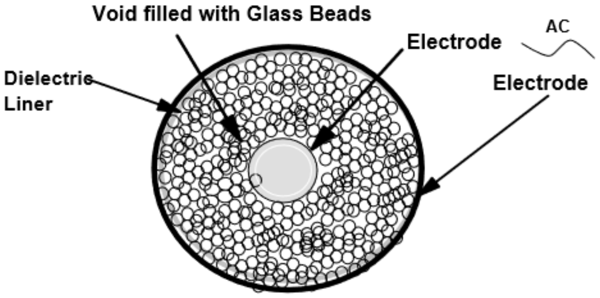


Figure 26: Di-electric barrier discharge type non-thermal plasma reactor

Pressure Drop

Both types of catalytic converters have negligible effect on the pressure of the flow. The air can move through the converters without being impeded by any filter media or other structure. However, filter media as used in the activated carbon filter will decrease the velocity of the air and cause a pressure drop over the filter. HEPA filters typically have a ‘clean’ pressure drop, i.e., before contaminants have accumulated on the filter media, of 0.2 kPa and are changed at 5,000 hours by which time the pressure drop is 2-3 times greater.

The typical pressure of the air flow leaving the ACP when bleed air is supplied by the main engines is between 100 to 120 kPa. To be conservative, even with a filter pressure drop of 0.75 kPa just before the filter is changed, the pressure drop experienced as a proportion is extremely small, and comfortably in excess of the pressure of 75 kPa required to deliver a cabin altitude of 8,000 feet.

The pressure drop of carbon adsorbent filters is slightly higher than that of HEPA filters, with a pressure drop of approximately 1 kPa which could double towards the end of the filter’s life. Even with this pressure drop, there would still be sufficient pressure to meet the cabin altitude requirement set by FAR/CS-25.

An activated carbon filter has the advantage of being proven technology that is already in use on aircraft as part of a HEPA+ carbon filter to remove VOCs from re-circulated air.

A combination of two technologies is by using a carbon filter to adsorb the contaminants, before using photocatalytic oxidation periodically to destroy the contaminants that have accumulated on the filter. This would remove the requirement to change the filter regularly and solve the problem of the flow rate of the air being so great that there is insufficient time to oxidize the compounds. This photocatalytic oxidation uses UV radiation to activate the catalyst, oxidizing the contaminants to carbon dioxide and water. However, some harmful molecules can be produced before being oxidized themselves, mainly formaldehyde and acetaldehyde, and it has not yet been determined whether these by-products could make their way into the aircraft cabin before oxidation. Although prototypes show VOC removal rates of over 90%, this technology is still in early development and has not yet been sufficiently tested to deem it safe for use on aircraft. Hence the most suitable solution is the activated carbon filter. It would need to be situated in an area of the ECS below 70 ºC and in an accessible position to facilitate filter changes, but the technology is effective and reliable.

Case Study: A320 ECS Modifications

A range of filters and sensors have been reviewed to determine their suitability for use in the ECS of a generic aircraft. An activated carbon filter and MEMS sensor have been selected as suitable by meeting the requirements as set out earlier in this paper.

A case study will now be carried out to propose the most suitable locations for these filters and sensors to monitor and filter contaminants from cabin and flight deck air on an A320 aircraft. Two main assumptions have been made:

- A320 aircraft is already in service, so any additional filters and sensors would need to be retro-fitted to the existing ECS.
- A320 aircraft used is already fitted with a HEPA+ carbon filter in the recirculation system to remove VOCs.

The activated carbon filters do not require power to operate, so power supply does not need to be considered. For an A320 aircraft, the filter has an outside diameter of 345 mm and a length of 500 mm.

A320 ECS Schematic

Bleed air from the engines and APU is controlled by two bleed monitoring computers and passed through a pre-cooler. The air is conditioned through two air conditioning packs, including a high-pressure water separator, before being mixed with re-circulated air in the mixer unit. If the air is too cool for a particular ECS zone, is it possible for further bleed air to be added to increase its temperature. This is known as trim bleed air (Figure 27). The conditioned air is then distributed to one of three cabin zones: the flight deck, the forward cabin and the aft cabin.

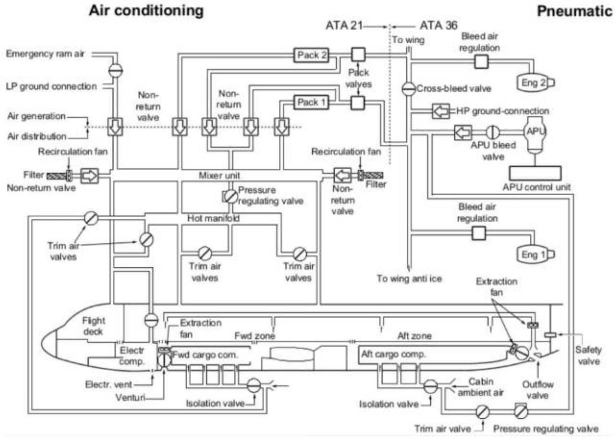


Figure 27: A320 ECS schematic

Figure 28 shows the location of key ECS components in the A320 for reference when assessing the ease of maintenance and installation for each option.

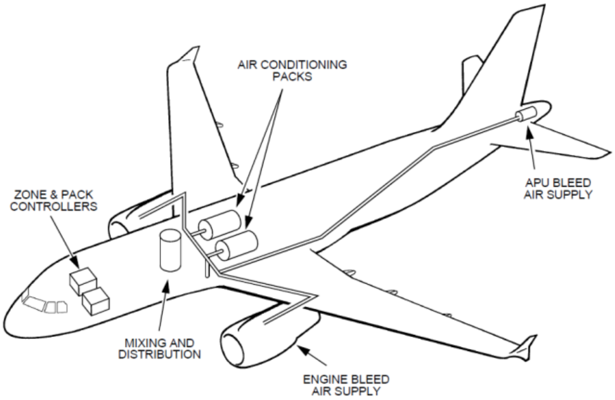


Figure 28: A320 ECS component location

Assessment of Possible Filter Locations

Three different filter positions are assessed (Figure 29):

- **Option 1:** immediately downstream of the main engine and APU bleed regulation.
- **Option 2:** immediately downstream of the ACPs.
- **Option 3:** downstream of the mixing manifold and trim air mixing point.

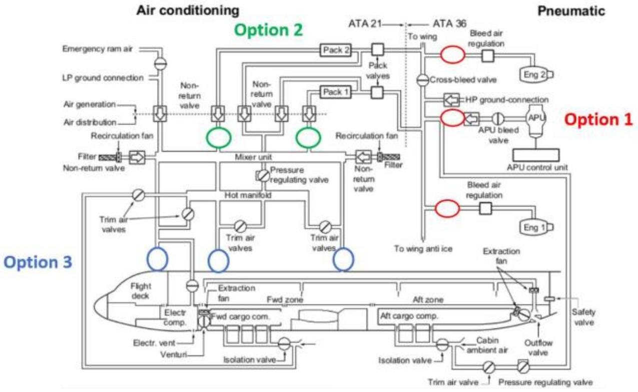


Figure 29: Possible filter locations in A320 ECS

Option #1

Three filters would be positioned immediately after the bleed air regulation and pre-cooler, with one filter for each engine and one for the APU, as shown in the Figure 30.

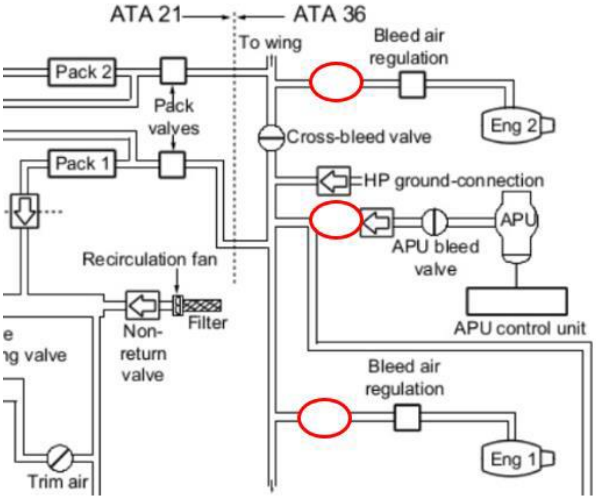


Figure 30: Option #1 filter location

The advantage of this location is that bleed air is filtered at its entry point to the ECS, upstream of the main ECS components. This is beneficial in that all the bleed air supply will be filtered; however, if any contaminants were present further downstream in the ECS, for example such as legacy oil deposits, these would not be filtered out.

The main issue with this option however is the operating environment. Activated carbon filters can only operate effectively at temperatures of up to approximately 70 ºC. However, the temperature of pre-cooled bleed air, prior to entry to the ACP, can be up to 200 ºC. This location is difficult to access, has very little space available to fit additional filters, may be too far upstream to filter out all contaminants and is in too hot area for the activated carbon filter to work effectively. It is therefore not suitable for further consideration.

Option #2

Two filters would be fitted in the ducting immediately downstream of the ACPs, prior to the conditioned air entering the mixer unit (Figure 31).

There is sufficient space between the ACPs and the mixer unit to allow installation of a cylindrical carbon filter. The ACPs are accessible through existing maintenance access under the cabin floor, ensuring that the filters could be accessed with relative ease if required. According to Airbus, it takes approximately one hour to remove and replace a HEPA+ carbon filter on an A320 and conduct a leak test. The activated carbon filters are likely to take a similar length of time to remove and replace.

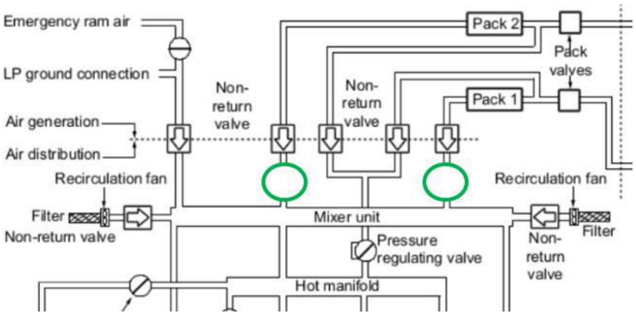


Figure 31: Option #2 filter location

As shown in the figure, once conditioned air has been filtered, it would enter the mixer unit and subsequently the hot manifold. At this stage, just prior to distribution to one of the three aircraft zones, further pre-cooled bleed air from the engines, as trim air, can be mixed with the conditioned air. This trim air bleed feed bypasses the ACP to the hot manifold, and so it would not pass through the filter, making it possible for engine contaminants to be introduced into the ECS air.

Airliners in cruise would usually require air to be supplied which is cooler than the cabin's ambient air, to offset the heat produced by passengers, equipment and solar heating. The A320 aircraft has three cabin zones, and the packs will produce conditioned air to meet the coldest temperature demanded from any of the zones. If one of these zones requires a lower temperature than the other two, for example if there is higher passenger loading in that particular zone, the other two zones may require trim air, controlled by trim air valves, to avoid them being uncomfortably cool.

Some sources describe the amount of trim air as 'small' but do not quantify the proportion that might be expected during a routine commercial flight. However, Airbus state that for an A320, only 5% of the total air flow (over a complete flight) is from the trim air. This seems a reasonable figure for an A320 where no large heat loads are likely to be exclusively in one zone, and so where any difference in temperature demand between zones is likely to be small. For larger aircraft with 3 or 4 cabin classes, the trim air usage in a particular zone may be greater to account for the large differences in passenger densities in different zones (for example, occupants of a first-class cabin will generate less sensible heat per unit area than economy class occupants as there are fewer of them).

More trim air may be used on the ground if the aircraft has been stationary for some time where the outside temperature is very cold, for example before the first flight of the day. SAE ARP 85F regulations state that in this situation, the APU must be capable of heating the cabin to a temperature of 23 °C within 30 mins. A similar cabin cooling regulation exists for hot climates, but this does not need to be considered as trim air will not be used. This cabin cooling case, known as ‘pull down’, is known to use a trim air proportion of up to 20%, leading to a much higher proportion of air not being filtered. However, the risk of passengers or crew being exposed to high contaminant levels is low, as the passengers and crew will not yet be on board.

Locating the filters downstream of the ACPs allows good access once installed with sufficient space to fit the filters in the existing ducting (with a small modification). Another benefit is that only two filters are required, reducing the initial purchasing expense and modifications required, however this does mean that the filters will saturate slightly faster than if three were fitted (as in Options #1 and #3). Locating the filters downstream of the ACPs is not a perfect technical solution, as a very small proportion of bleed air will not be filtered, though at least 95% of the air is likely to be filtered overall, therefore, this option is feasible.

Option #3

In this option, 3 filters are fitted near the three main distribution ducts for the 3 different ECS zones. Once the air has been conditioned by the ACPs, it passes through the mixer unit, on to the hot manifold where trim air is added as required. The final conditioned air is then distributed through the three main ducts to grilles and directional outlets in the cabin ceiling (Figure 32).

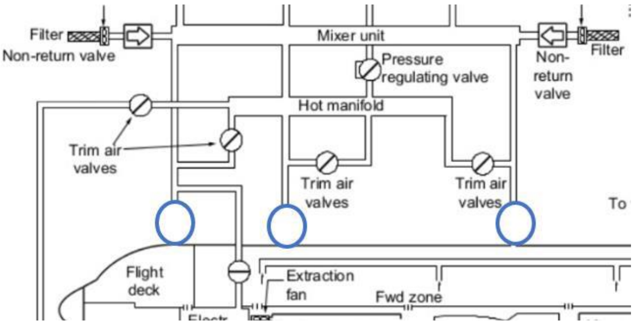


Figure 32: Option #3 filter location

Locating the three filters immediately prior to cabin distribution at the closest possible point to passengers and flight crew ensures that 100% of the bleed air passes through the filters, maximizing the filters’ effectiveness. However, there is less space available in this area and accessibility for maintenance and initial installation would be more time consuming, meaning that the location is not as advantageous as option #2.

This option would also mean that three filters are fitted. Although this would mean a greater initial cost outlay, with the total cabin air being distributed via three filters rather than two, the filters would take more time to become saturated, particularly for the flight deck zone which is the smallest in size.

Option #3 location is not as convenient as option #2, however, this is technically the best solution as all the bleed air entering the cabin would be filtered.

Assessment of Possible Sensor Locations

Activated carbon filters are designed to be replaced approximately every 5,000 hours, assuming that the levels of VOCs recorded during both the Cranfield University/DfT and EASA studies continue to be typical.

There are three main possible sensor positions:

- **Option A:** immediately after the bleed air feed from both engines and the APU.
- **Option B:** within the distribution duct just prior to the point of entry to the cabin.
- **Option C:** in each of the 3 cabin zones.

These sensor positions will now be assessed against the effectiveness of the sensor in each position, available power and space, and ease of installation and maintenance.

Option A

Locating sensors immediately after the bleed air feed from both engines and the APU, as shown in Figure 33, offers several benefits.

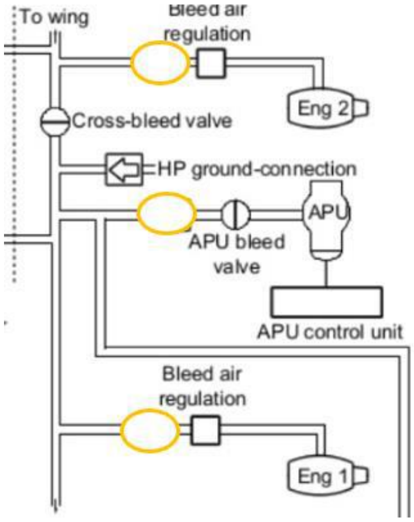


Figure 33: Option A sensor position

First, this location could assist in diagnostic checks following a fume event. With each sensor measuring the contaminant levels from a particular engine (or the APU), it could be possible to pinpoint the bleed air feed causing the problem.

Also, if contaminant levels, particularly of TCP and TBP, were monitored over a period of time, it may be possible with numerous data to identify any trends that could predict seal deterioration or other faults that may lead to leaks.

However, positioning the sensors here only gives a measurement of the air quality of the bleed air itself, rather than the air actually inhaled by passengers and crew in the cabin and flight deck zones. It is possible that older ECS harboring oil deposits or other sources of contamination may have elevated levels of some contaminants at final distribution, but normal levels as measured by the sensor at the bleed air tapping point.

MEMS sensors are small enough to be situated in these bleed air lines, and their optimum operating temperature is 300 ºC. Situating the sensor alongside the bleed air regulation valves means that existing power and cabling already existing for bleed air regulation could be used for the sensors.

Option B

Three sensors could also be positioned near the final distribution point to the cabin zones, as shown in the Figure 34 and similar to option #3 for the filter location.

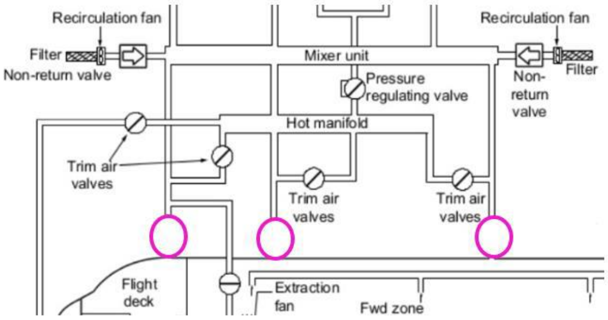


Figure 34: Option B sensor position

The sensors are small enough to fit inside the existing ducting and there are already temperature sensors in this area with cabling and power. Situating the sensor here gives an accurate assessment of the air the aircraft occupants are breathing, as it is as far downstream as possible within the ECS and close to the point of distribution. It specifically measures the quality of the filtered air supplied by the ECS.

Option C

The final option is to have the sensor situated in the cabin itself, with an option to have a real-time readout accessible to cabin crew. This is the most accurate measurement of air quality inside the cabin, as it will measure VOCs produced from within the cabin before they have been filtered, either through the HEPA+ carbon filter, or by the additional, newly-fitted filters. These levels will be partly dependent on the behavior of the aircraft occupants, and on the VOCs emitted by the aircraft itself, such as furnishings. However, as the MEMS sensor can differentiate between types of VOC, it would still be possible to identify compounds which may exist mainly due to bleed air or ECS component contamination, such as TBP and TCP, and those which are elevated due to passenger activity. For example, a passenger liberally applying hairspray in the vicinity of the sensor.

The sensor itself could be mounted on the cabin bulkhead next to the ECS control panel using existing power supply, provided this was in an area that was typical of the general atmosphere inside the aircraft, rather than near the toilets or the galley for example.

Discussion

Filter Options

It has been shown that option #1, where filters are located immediately downstream of the bleed air feeds is not possible as the temperature is too high for the filters to be effective in this position. Options #2 and #3, with filters located downstream of the ACP or immediately prior to cabin distribution respectively, both have sufficient space for a filter to be installed.

In the A320, the ECS air is de-humidified in a high-pressure water separator before being expanded in the turbine. It is therefore possible that with low cabin air inlet temperatures, ice particles may accumulate on the filter media if positioned downstream of the ACP. It is therefore important to ensure that air can bypass the filter so that even if ice does accumulate, the FAR/CS-25 minimum cabin air flow rates will continue to be met. Also, if air is supplied by an APU in flight (due to an emergency where bleed air from the main engines is not available) which provides lower bleed air pressure than the main engines, the pressure drop through the filter may mean that the minimum FAR/CS-25 flow rates are not met unless a bypass is fitted. The requirement for this filter bypass requires additional space for bypass ducting.

Two filters would be required for option #2 - one for each ACP, and three filters for option #3 - one for each ECS zone. For normal filtering operations for option #2, where both engines are in good condition with no damaged seals, it is likely that both filters would capture a similar amount of contaminants and so would reach end of life at similar times, streamlining maintenance requirements and ensuring that the filters are changed at the optimum time, and not too early, wasting money on new filter media that is not yet required.

The addition of a third filter, as in option #3, could reduce the maintenance burden of changing the filters. If the air was distributed equally between three filters rather than two, it could mean that fewer contaminants are captured per filter, increasing the life. Filters fitted in option #2 would filter approximately 95% of the air in the cabin, with approximately 5% provided by the trim air bleed air feed, remaining unfiltered. However, this unfiltered air would be filtered during recirculation. Option #3 would filter all cabin air.

It is proposed that option #2 is the best option. Technically, option #3 is a better solution, with 100% of all cabin air being filtered. However, with trim air only routinely making up 5% of the fresh air volume and only used in two out of the three cabin zones at any time, this is only a small disadvantage, particularly when it will be eventually filtered during subsequent recirculation. However, the access to the filters for option #2 is significantly better than for option #3, with the existing access to the ACP able to be used. There is also more space available in this area of the aircraft for modifications to be made and for a filter bypass to be fitted.

Sensor Options

It has been stated previously that activated carbon filters can be analyzed on removal to show the type and level of contamination captured. It would be possible for filter manufacturers, airline operators and any other interested parties to gain more data on typical cabin air quality by conducting periodic analysis of filter media.

However, if airline operators wanted to determine cabin air quality on particular flights or flight phases, sensors gathering real-time information on air quality could be fitted.

Option C, with the sensor fitted in the cabin, gives the most accurate representation of what the aircraft occupants are breathing. This could provide reassurance to passenger and crew that levels are safe, even if unusual smells are present. The sensors could be straightforward to install using existing power supplies in the vicinity of the existing ECS control panels. It is recommended that one sensor would be fitted to each of the three cabin zones.

Option B, where sensors are mounted in the ducts just prior to distribution, would be less susceptible to damage as they are fitted away from occupants, but this is a small advantage when compared to the more complex installation in this area.

Option C offers the benefit of being able to pinpoint elevated levels of contaminants to a particular engine (or the APU), and over a period of time being able to monitor contaminant levels which could anticipate developing faults. Both Options A and C therefore offer useful information to airline operators which may help to avoid delays, either by reassuring occupants that air quality is adequate (option A) or by helping to save time during diagnostics and maintenance (option C).

For either of these options to be useful, it is important that the MEMS sensors are reliable and consistent. Although MEMS sensors are used successfully for healthcare and military applications, they are untested on aircraft in this role. Although it has not been possible to find precise reliability data, MEMS equipment can be subject to failure modes including particle contamination, which may affect the mechanical operation, and stiction, one of the most common failure modes in MEMS devices. Stiction occurs when surface forces cause the microscopic structures to stick together when they come into contact with each other. Any erroneous readings showing elevated contaminant levels would result in unrequited fault finding and possible aircraft delays.

The benefits of these sensors are not sufficient to outweigh the installation cost, complexity and untested reliability of these sensors. Operators and manufacturers can show that they are taking reasonable steps to monitor cabin air quality by periodically analyzing used filter media. The final system architecture can therefore be found in the Figure 35, including the two activated carbon filters downstream of the ACPs.

Finally, it is important to note that this solution is for the A320 ECS architecture only and may not be suitable for other aircraft. Access to the ACPs on other aircraft may be more difficult, there may be less space available to install the filters or, in the case of aircraft with multiple cabin zones, the use of trim air may be much greater than 5%. Separate studies would need to be conducted to find the best solution.

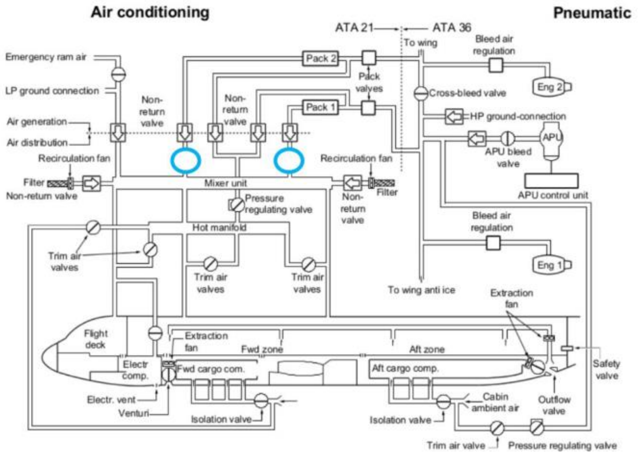


Figure 35: Final filter positions

Summary & Conclusions

A range of sources were examined to review the current evidence available on cabin air quality and aerotoxic syndrome and to understand the legal risk to airlines. It was determined that during the two major cabin air quality studies: the EASA report of 2017 and Cranfield University/DfT study in 2011, all compounds measured in the aircraft cabins were below published safe limits, comparable to other indoor environments, and should pose no hazard to aircraft occupants. However, the legal advice is that airlines should investigate methods to detect and/or filter contaminants to minimize any potential risk that may exist. This ensures that a full analysis of the costs of modification versus the severity of the risk can be conducted.

Four types of sensors with the ability to measure VOCs on an aircraft, either in the cabin or within the ECS itself, were researched or compared. The main requirements were to be able to identify specific VOC levels, be sufficiently sensitive to measure typical levels as found during the EASA study and be simple to install and operate, without requiring considerable input from the crew to obtain readings. A MEMS sensor was selected due to its accuracy, sensitivity and mature technology. Optical sensors such as LPGs look promising for this application in the future, but the technology is not yet mature enough and the sensor coatings are not widely available commercially. A portable GC-MS detector may also be possible in the future if the sensitivity of this technology will be improved.

Two main methods of contamination removal were considered: an activated carbon filter and oxidation methods (catalytic and non-thermal plasma), they installation, maintainability, and maturity of technology. An activated carbon filter was selected due to its lack of harmful by-products during operation, its proven technology and good efficiency, with up to 80% of high boiling point VOCs still being captured after 5,000 hours of use. The main advantage of the oxidation methods is that, unlike the filter, the reactors would not need to be changed frequently However, the risk of creating by-products potentially more harmful than the original contaminants makes them unsuitable for use.

The ECS system architecture of an A320 aircraft was used as a case study to examine the most suitable positions for detectors and filters on this aircraft. Detectors could be placed either in the cabin, to measure the air quality of the actual air inhaled by the occupants, or immediately downstream of the bleed air tapping points, to measure the quality of the bleed air from the engines or APU. The proposed position for the filters is just downstream of the ACPs, where access is good for installation and maintenance, minimizing the time and cost for the modification itself and the maintenance penalty when in service. There is also sufficient space in this area for filter bypass ducting. Although some unfiltered trim air will still enter the cabin or flight deck, this is a very small proportion (approximately 5% during cruise). The filters would have a life of 5,000 hours, or earlier if a fume event is known to have occurred, in which case the filter should be removed and analyzed.

The next step would be for airlines to carry out cost studies to ascertain precise installation and in-service costs. With this knowledge, a cost-benefit analysis could be undertaken to determine whether installation of detectors and/or filters is a reasonable precaution to take to ensure that aircraft occupants do not suffer ill health due to short-term or sustained exposure to low levels of contaminants. However, as a sample of activated carbon filters could be analyzed once they reach their end of life, the additional data from MEMS sensors is unlikely to justify the financial cost of fitting them, and the risk of erroneous readings due to unproven reliability.

It is feasible for detectors and filters to be fitted to an A320 aircraft which would allow continuous real-time data to be gathered on cabin air quality and filter out harmful compounds such as TBP and TCP, although the benefits of installing detectors are unlikely to outweigh the likely cost, time and technical difficulties.

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Contact Author Email Address

The corresponding author, Ilan Berlowitz can be contacted at the email address below: iberlowitz24@gmail.com

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