On-board air quality: Literature review and methodological survey

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Short abstract: Future Sky Safety is a Joint Research Programme (JRP) on Safety, initiated by EREA, the association of European Research Establishments in Aeronautics. The Programme contains two streams of activities: 1) coordination of the safety research programmes of the EREA institutes and 2) collaborative research projects on European safety priorities.

This report has been produced as a deliverable for the Project P7 "Mitigating the risk of fire, smoke and fumes". The main objective of this deliverable is to provide an overview of the considerations surrounding on-board air quality, both in terms of how it is currently managed and how it could be further improved by additional methodologies in the future.

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Acronyms

Acronym	Definition	Acronym	Definition
APU	Auxiliary Power Unit	**IMS**	Ion Mobility Spectrometry
CAMS	Central Air Monitoring System	**ISS**	International Space Station
CAQ	Cabin Air Quality	**LBNL**	Lawrence Berkeley National Laboratory
CMOS	Complementary Metal Oxide Sensor	**MEMS**	Microelectromechanical systems
CO	Carbon Monoxide	**MO**	Metal Oxide
CO_2	Carbon Dioxide	**MRO**	Maintenance, Repair, Overhaul
COTS	Commercial off the shelf	**NBS**	National Bureau of Standards
dNPh	Dinitrophenylhydrazine	**NDIR**	Non-Dispersive Infrared
EASA	European Aviation Safety Agency	**NH_3**	Ammonia
EC	Electrochemical	**NIST**	National Institute of Standards and Technology
ECS	Environmental Control System	**NO_2**	Nitrogen Dioxide
EUROCAE	European Organisation for Civil Aviation Equipment	**O_3**	Ozone
FAA	Federal Aviation Administration	**OEM**	Original Equipment Manufacturer
FDM	Field Data Monitoring	**OP**	Organophosphate
FTIR	Fourier Transform Infrared	**PCO**	Photocatalytic Oxidation
GAO	General Accounting Office	**PID**	Photo-ionisation detection
GC/MS	Gas Chromatography/Mass Spectrometry	**PM**	Particulate matter
GC/EI/MS	Gas Chromatography/Electron Impact/ Mass Spectrometry	**RH**	Relative Humidity
GOTS	Government off the shelf	**RTCA**	Radio Technical Commission for Aeronautics
HBr	Hydrogen Bromide	**SO_2**	Sulphur Dioxide
HCl	Hydrogen Chloride	**SVOC**	Semi volatile organic compounds
HCN	Hydrogen Cyanide	**TCP**	Tricresylphosphate
HEPA	High Efficiency Particle Arrestance	**TD**	Thermal desorption
HVAC	Heat, Ventilation and Air	**TGA**	Thermogravimetric Analysis
H_2S	Hydrogen Sulphide	**VIAQ**	Vehicle Indoor Air Quality
IEST	Institute of Environmental Sciences	**VOC**	Volatile Organic Compound

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EXECUTIVE SUMMARY

Problem Area

The overall objective of WP7.3 'On Board Air Quality' is to contribute to, maintain or enhance on-board air quality in aircraft by investigating opportunities offered by technology developments that could offer insight into any effects that introduction of new materials could have. With this objective, sensing technologies and an industrial framework for monitoring of air quality are investigated.

This report aims to gather reference material on the theme of cabin air quality, spanning from outlining its main characteristics to regulation and testing, and also benchmarking with other similar areas (e.g., buildings and vehicles interiors). The document aims to highlight potential methodologies that could be used for understanding air quality and so does not draw conclusions on open issues related to air cabin quality. It is imperative that any regulatory decisions are taken on the basis of up to date, reliable and scientific evidence. For instance, a number of scientific studies – both in flight and in laboratory - have been carried out in the last years to investigate reports of individuals concerned with being exposed to harmful conditions in the cabin. This report will benefit from this latest research, collecting information on methods and approaches used to ascertain cabin air quality.

To achieve Flightpath 2050 it is believed that new aircraft configurations must come to the fore, supported by new systems and enabled by new materials. Even in recent years the development of more lightweight aircraft has seen an increased use of composite materials in primary structures, e.g. fuselage. A particular focus of work package 7.3, for which this report is a deliverable, is to investigate how to account for the possible, if any, impact of new composite materials on on-board air quality. Specifically, we wish to investigate what, if any, gaseous species may be emitted by such materials, whether this can be quantified, and the potential role of detection methodologies and sensor systems in evaluating both materials (for qualification purposes) and cabin air.

The goal of this report is thus to provide greater understanding as to how on-board air quality is regulated and monitored, the challenges and limitations that have been encountered, and recommendations to improve the on-board air quality monitoring, as well as identify potential strategies that could be employed to further improve knowledge of the cabin air environment.

Description of Work

For this report, literature sources were consulted and information was consolidated on the following aspects of on-board air quality:

- the process that is currently employed for regulating and managing air quality, including tackling substances that may contribute to degraded air quality,
- the investigations that have been carried out to address health concerns surrounding on-board air quality, with a particular focus on the methodologies that have been used,

- future technologies/strategies that could be employed to further understand the cabin air environment, including looking to other sectors for ideas.

Results & Conclusions

The regulation of on-board air must ensure that passenger health, comfort and safety are addressed without compromising the structural and operational safety of the aircraft. Operations such as regular air exchanges, particulate filtration and catalytic conversion all serve to ensure adequate ambient conditions while preventing a build-up of substances that could affect passenger's health e.g. exposure to ozone at high altitudes. As cabin air composition is not continuously monitored and logged, the scientific knowledge base concerning air quality under operational conditions is provided by a number of specific in-flight studies.

In general terms, for decades, cabin air is obtained using outside air that is compressed in the engines. The environmental control system (ECS) uses this air to provide air to the cabin and to regulate the pressure and temperature of the cabin air. In the course of time the ECS has evolved, adding, for example, recirculation, filters (e.g., high-efficiency particulate arrestance (HEPA) filters), humidity regulation and ozone regulation. In the recent Boeing 787 the outside air is compressed with electrical compressors. With the ECS both the physical characteristics and the composition of the air are controlled in aircraft.

Before being taken into operation all aircraft undergo rigorous testing to achieve certification of airworthiness. The performance characteristics of the subsystems and their integration are tested for the full operation envelope that the aircraft is expected to encounter, from its normal operating conditions to a safety margin, including abnormal and extreme conditions. Standards and test procedures are used. Two standards commonly referred to are RTCA DO-160G/EUROCAE ED-14G (and the military standard MIL-STD-810), in which both address testing of airborne equipment in view of environmental conditions. Typical tests address flammability, toxicity, pressurisation, and temperature. With the increase of the use of composites the aircraft regulation has been updated. Though currently, dedicated on-board air quality qualification testing for interior materials is not explicitly required by certification authorities as by design, segregation from harm is required and new materials must have safe properties. In general, regulatory authorities are constantly reviewing and updating aircraft standards, addressing aspects such as introduction of new technology or reported air incidents that may be militated against through improved design. Certification institutions and original equipment manufacturers (OEMs) develop the entire product by considering the installed system design, safe operation within the conditions of the aircraft operational window, behaviour during possible fire and other non-standard events (including structural strength and no release of toxic gases) and physical containment of known harmful gases and/or fluids used in the aircraft (e.g. the fuel).

To address concerns on cabin air quality, a number of air quality monitoring strategies have been employed, which also served as feasibility studies into the possibility of continuous air quality monitoring in aircraft. Three approaches are highlighted in this report: (i) monitoring by reporting, i.e. identifying trends from incident reports, (ii) biomonitoring of personnel, i.e. attempting to reconcile symptoms with

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particular events through medical examination, and (iii) monitoring by measurement, i.e. using sensing technology to provide analytical data of air composition. The studies to date have demonstrated the technical feasibility of adopting monitoring procedures based on after-the-fact incident reporting by crew or biomonitoring of crew and / or passengers. Incident reporting can be completed after perceived contamination events; however this approach currently suffers from a lack of standardisation, potential for under-reporting and incomplete reports. Improvements may be possible, however any system based on reporting of infrequent events by individuals is bound to retain an element of subjectivity Biomonitoring studies lacked a standardised procedure across investigations making trends and comparisons hard to identify, and full biomonitoring would be invasive. Studies that employed sensing technologies have encountered challenges such as not capturing the specific intended air incidents e.g. a fume event, or sensors malfunctioning due to their unsuitability for the unconducive cabin environment.

The concern surrounding fume events may be allayed over time by the adoption of new technology in the air supply or filtration systems but do not solve the wider problems inherent in cabin air monitoring for other measurands. Airborne substances may still enter the cabin air from materials used in the aircraft, from the external environment, and from passengers themselves.

To address the need for continuous air quality monitoring in aircraft, some future directions have been suggested. These include miniaturization and ruggedisation of current technologies, which could facilitate a distributed sensor network throughout the cabin. Other strategies include a more heavily computational approach whereby sensor arrays such as the electronic nose (e-nose) are combined with pattern recognition analysis, to provide unique responses to specific environments. Continuous on-board monitoring has to balance the need for small, low cost and rugged sensors against the number of measurands required. A proposal suggested by this work package is to create a model where aircraft conditions could be simulated, e.g. in the event where a new material is introduced into the aircraft, virtual testing could be pursued. In this way potential risks could be identified in advance thus allowing for appropriate mitigation steps to be taken.

Other enclosed spaces such as automobiles, submarines and the international space station were investigated. The knowledge of monitoring methodologies and challenges faced in these specific environments can be of use in order to adapt the best methodology and monitoring equipment to the aircraft cabin environment. Efforts to find common standards for all suppliers and regulators are already evident in the automotive industry, which ultimately could be used as a pathway for the aeronautical industry. Like the aeronautical sector, the submarines sector is also governed by a standard with specifications limits of air contaminants, once again reinforcing the opportunity to use common grounds to try to fine-tune the contaminants of interest to warranty air quality in the aircraft cabin.

Both submarines and the international space station carry a considerable array (rack upon rack) of technology used to continuously monitor air quality and to condition the recirculating air. Technologies successfully deployed in continuous monitoring and in materials qualification include quantitative, dedicated rack-based instruments e.g. spectrometric techniques to detect known contaminants specific to the environment and commercial off-the-shelf (COTS) sensors, which offer complementary benefits.

Cross-checking with different technologies is considered necessary to manage possible malfunction during operations. In the automobile sector, the cost, size and weight requirements of continuous monitoring are stringent, meaning that only very simple, ultra-low cost sensor technology is deployed, if any.

Applicability

To better understand potential effects of composite materials on on-board air quality, laboratory based experimental analysis will be carried out within this work package where a reference composite material will be thermally degraded and volatiles, if any, will be analysed using selected technologies that have been mentioned in this report. This document provides a useful insight into the overall area of on-board air quality, including how it is managed currently and potential avenues that could be explored for air quality monitoring to gain evidence for decision-making regarding concerns about air quality on-board aircraft.

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1 INTRODUCTION

1.1. The Programme

FUTURE SKY SAFETY is an EU-funded transport research programme in the field of European aviation safety, with an estimated initial budget of about € 30 million, bringing together 32 European partners to develop new tools and approaches to aviation safety. The first phase of the Programme research focuses on four main topics:

- Building ultra-resilient vehicles and improving the cabin safety
- Reducing risk of accidents
- Improving processes and technologies to achieve near-total control over the safety risks
- Improving safety performance under unexpected circumstances

The Programme will also help to coordinate the research and innovation agendas of several countries and institutions, as well as create synergies with other EU initiatives in the field (e.g. SESAR,). Future Sky Safety is set up with an expected duration of seven years, divided into two phases of which the first one of 4 years has been formally approved. The Programme started on the 1st of January 2015.

FUTURE SKY SAFETY contributes to the EC Work Programme Topic MG.1.4-2014 Coordinated research and innovation actions targeting the highest levels of safety for European aviation, in Call/Area Mobility for Growth – Aviation of Horizon 2020 Societal Challenge Smart, Green and Integrated Transport. FUTURE SKY SAFETY addresses the Safety challenges of the ACARE Strategic Research and Innovation Agenda (SRIA).

1.2. Project context

Recent studies[1] [2] have shown that, though “fires in flights” as a direct cause represented only 5% of fatalities, “fire/smoke resulting from impact” accounted for 36% of all fatal accidents. Often aircraft occupants have survived the impact only to be incapacitated by toxic fumes and/or heat, e.g. temperatures can rise above 600-700°C after only three minutes[3]. Toxic fumes originate from components such as aviation fuel and combustible materials, producing various gases dependent on the composition of the material.

In recent years the development of more lightweight aircraft has seen an increased use of composite materials in primary structures, e.g. fuselages, as well as secondary and interior structures, such as furnishings. These materials have desirable properties such as corrosion resistance and high strength, however from a safety point of view the use of these materials may require specific controls concerning their behaviour when exposed to fire, or during normal conditions. The project seeks to address this safety aspect within three work packages:

- WP7.1 – The first work package aims to test and thus improve understanding of the effects of fire on these materials

- WP7.2 – The second work package aims to develop and propose improved material solutions to mitigate fire, smoke and fume
- WP7.3 – The third work package, for which this report is a deliverable, aims to investigate the possible effects of such new materials on the on-board air quality, with particular emphasis on both normal operating conditions and deviations from these conditions, e.g. elevated temperatures, where volatiles may be released, though not specifically fire events.

1.3. Research objectives

The overall objective of WP7.3 is to investigate potential opportunities offered by technical developments that may contribute to enhanced on-board air quality. Specific avenues that are being investigated include;

- developing an understanding of the whole chain related to on-board air quality as a basis for recommending economically viable and technically feasible methodologies for ensuring continued air quality.
- defining a predictive industrial framework that considers on-board air quality in the context of introduction of new materials, current and future trends in legislation as well as potential technologies that could monitor and/or correct for air quality changes.
- investigating the feasibility of using commercial off the shelf sensors as tools for informing if/when there are any air quality changes as a result of introduction of new composite materials.

The objective of this document is to provide an overview of the area of on-board air quality. This includes how it is currently managed, the substances for which monitoring are recommended, and potential strategies that could be employed to improve knowledge of on-board air quality.

1.4. Approach

The approach taken for compilation of this document comprised entirely literature based research, in preparation for later scientific investigation. Literature sources included

- Reports and communications from national governments and authorities.
- Investigative studies by various experts, often initiated by national governments and/or authorities, as a result of media reported health concerns regarding cabin air quality.
- Peer-reviewed scientific publications.

The intention when preparing this document was to extract information from these sources that highlights the current state of air quality control and monitoring as well as the motivations that prompted further investigations into the quality of on-board air. Additionally, it was intended to outline the methodologies themselves that have been employed thus far to inform on air-quality as well as additional methodologies that could potentially be employed.

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1.5. Structure of the document

The first section introduces the background of the FUTURE SKY SAFETY programme, followed by a summary of the aims and objectives of Project P7, for which this report is a deliverable. Section 2 describes the process of how on-board air quality is controlled and lists some of the methodologies that have been employed thus far to address the question of what needs to be monitored within the aircraft cabin, including the challenges/limitations and recommendations to improve the monitoring . Section 3 describes how the aircraft is tested to ensure that, in the absence of air monitoring, the air quality is maintained. Section 4 expands on the methodologies suggested in section 2, diving deeper into sensor technologies. Section 5 outlines some air quality management strategies for enclosed spaces in other sectors as an insight into the challenges and solutions of managing these spaces. Section 6 concludes the report by summarising the current state of on-board air quality monitoring in order to gain evidence for decision making with respect to, potential air quality concerns.

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2 ON-BOARD AIR QUALITY: AN OVERVIEW

For the purpose of the study the following working definition of cabin air quality has been developed.

Working definition of Cabin air quality
Cabin air quality is the holistic (physical, chemical, biological, radiological) characteristics of cabin air.

The WP7.3 team did not find any formal, accepted, definition of cabin air quality. The working definition has been based on the definitions of, contaminant by the International Labour Organisation (ILO) and Environmental Protection Agency (EPA), hazardous chemical by Occupational Safety and Health Administration (OSHA) and hazardous substances by Control of Substances Hazardous to Health (COSHH).

According to its working definition cabin air quality thus includes, but is not limited, to physical characteristics such as temperature, humidity, pressure of cabin air and the chemical/biological composition of the cabin air. The adjective holistic emphasises that substances in the cabin air are considered together and in the specific physical conditions. In this report noise is excluded.

On-board air quality management systems are designed to provide a well ventilated and comfortable environment for the passengers and crew during all phases of the flight, e.g. from taxiing to cruising. During these phases, the ambient conditions vary considerably, with temperatures from -60 to +50°C; ambient pressure from about 10.1-101 kPa; and water content from virtually dry to greater than saturation i.e. 0-100% relative humidity (RH)[4]. The integrated subsystems must be able to operate in all of these conditions providing adequate pressure and humidity as well as maintaining the temperature at tolerable limits. Typically, ground level human comfort conditions include temperatures of 22±2 ºC, an ambient pressure range of 90-100 kPa, and a relative humidity range of 30-70%. The systems must also be able to operate such that there is no build-up of substances, innocuous or not.

The first section describes the cabin air environment as it is currently. Within this section, the first subsection provides some detail as to how the integrated subsystems operate to control these variables. The second subsection then outlines some potential constituents of cabin air that may be produced as a result of aircraft operations or activities by occupants within the cabin.

The second section presents an overview of how investigations regarding on-board air quality have progressed. Within this section, the first subsection provides a general introduction of typical on-board air conditions to provide context for the reader. The second subsection describes some of the motivations that have prompted on-board air quality investigations to date, including concerns regarding presence of potentially hazardous substances. The third subsection outlines some potential monitoring strategies that have been and could be implemented to inform on on-board air quality, including the challenges and limitations encountered. The final section provides general conclusions and recommendations about on-board air quality.

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2.1. On-board cabin environment

2.1.1. How the cabin environment is controlled

In general terms, with the notable exception of the Boeing 787 that uses electrical compressors to provide cabin air, air is replenished using compressed air from the engines. When on the ground, it is usually the auxiliary power unit (APU) that supplies compressed air to the environmental control system[5]. This unit is a small jet engine, typically located in the tail cone of the aircraft, which also provides electric power when on the ground, as well as pneumatic pressure to start the main jet engines when taking off.

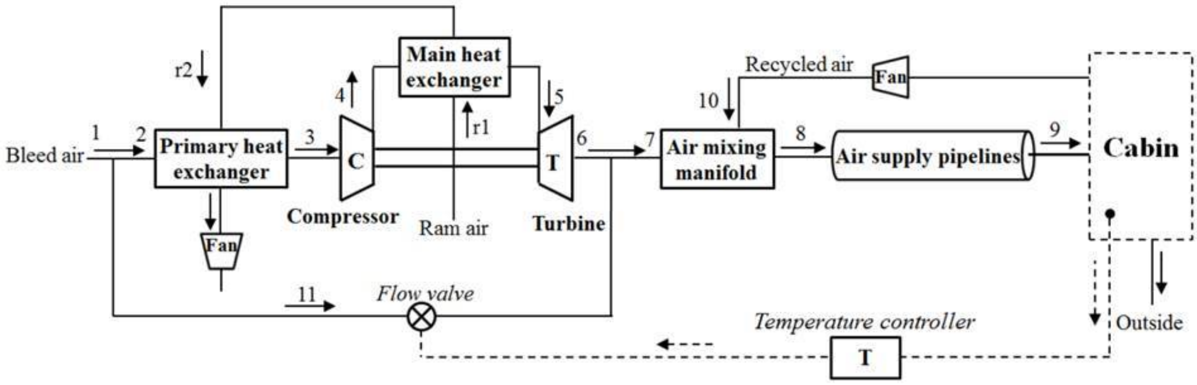

Figure 2.1: Schematic of typical ECS system in aircraft. (C) corresponds to compressor, turbine (T), r (ram air), taken from [6]

The compressed air generated, either from the APU on the ground or main engines when in flight, is ducted through flow valves to the environmental control system. Compressed air, also called bleed air, from the engines typically has a temperature of 250 degrees C and a pressure of 340kPa[4]. Most of the bleed air is passed through a pneumatically (or sometimes mechanically/electrically) driven air cycle machine which contains a primary heat exchanger that cools the air using ram air. The flow rate across the heat exchanger is dictated by temperature control valves and sensors. Pressurisation and ventilation is controlled by varying the opening of outflow valves[7], maintaining a proportional relationship during all operations including cruise, descent and ascent. A compressor further pressurises the air and increases the temperature, before being cooled again in a secondary heat exchanger, using ram air. The air temperature and pressure is further reduced using a turbine, and then mixed with a small amount of bleed air to re-heat before being introduced to the air mixing manifold. A recirculation fan extracts air from the cabin exhaust which, after filtering, is combined with the conditioned bleed air and distributed to the cabin through overhead outlets[4]. In terms of these air circulation activities, the environmental control system operates automatically[8], where temperature and pressure sensors provide feedback that triggers adjustment of flow valves. The components of the environmental control systems are such that each operation can be isolated in the event of a malfunction. For example[9] overheat detectors near the bleed air ducts will issue a warning on the flight deck if a bleed air leak occurs as a result of a ruptured duct. Bleed air shut-off valves, located at various points in the air conditioning system can be used to isolate a component failure. In general, on-board air quality monitoring is limited to sensors forming part of the aircraft's Environmental Control System (ECS). Whilst some air quality parameters are

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independently recorded as part of aircraft flight data monitoring (FDM), i.e. air temperature and barometric pressure, the primary purpose of FDM is the analysis and oversight of the flight trajectory[4]. There is therefore currently only limited collection and analysis of air quality data. An overview of the engineering aspects of air conditioning systems is available in the SAE aerospace information report [10]

2.1.2. Constituents of cabin air

Many of the constituents found in cabin air are common to those of typical indoor environments. Some of the major contributors to degradation of air quality come from the occupants themselves, including general body odours or bioeffluent carbon dioxide from respiration that, in elevated concentrations (e.g. up to 3000ppm[11]), can cause headaches, fatigue, and general feelings of discomfort. Building materials, furnishings, and household products are known to emit many different chemical substances, depending on their make-up[12]. These substances can be directly emitted from the materials or as a secondary emission due to interaction with a reactive species e.g. production of nitrogen dioxide from an ozone reaction with terpenes in wood flooring or furnishings[13]. These two areas, i.e. bioeffluents and chemical substances, along with biological components such as bacteria, viruses and particles such as dust or dirt represent some of the main targets when considering maintenance of indoor air quality, both in terrestrial and aerospace environments.

To prevent build-up of these types of contaminants, ventilation is the key strategy, where, in the case of aircraft environments, outside air is used to dilute contaminants in the air and flush them out of the cabin. Airliner cabins are typically supplied with outside air at rates of about 14-27 m3/h per passenger averaging approximately 15-25 cabin air exchanges per hour [10].

Another consideration is that of airborne bacterial and viral organisms, dust, fungi that can be carried in with passengers with infection or illnesses, or from furnishings. In many airplanes, high-efficiency particulate air (HEPA – High-Efficiency Particulate Arrestance) filters are standard on the recirculation air component, providing up to 99.97% efficient removal of particles with typical diameter greater than 0.3µm e.g. bacteria, fungi and larger viruses) [14]. In 2004, a report by the General Accounting Office (GAO, 2004)[15], surveyed large US airlines whose aircraft used recirculated cabin air. The GAO learned that 85% used HEPA filters. A large percentage (69%) of smaller aircraft operated by regional airlines employed cabin air recirculation as part of the air management strategy, but very few had HEPA filtration. The GAO commented that in order to assess the consequences of presence/absence of air filtration it would be necessary, ideally with Federal Aviation Administration (FAA) funding, to monitor and thus acquire sufficient data on the ventilation systems, as well as the ozone levels.

Commercial aircraft typically cruise at an altitude of 30,000-40,000ft[16] where, though the air is virtually free of most contaminants, ozone levels may be elevated relative to the terrestrial environment, with concentrations ranging from tens to hundreds of ppb[17]. Statistical analysis has suggested that ozone at these levels can be associated with dry eyes, nasal stuffiness and some respiratory symptoms[18] and so it is important to reduce exposure levels. Indeed current specifications require that, at altitudes where ozone concentration may exceed specified limits, the ventilation control system contains ozone control equipment to deplete ozone to within specified limits[19].

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Some considered strategies[20] include using bleed air from the high stage compressor where the higher temperatures cause greater dissociation of ozone or modifying the aircraft design to include technologies that reduce ozone levels. The FAA recommends that either airplanes are operated at altitudes that maintain the ozone concentration below specified limits or to ensure that the ozone concentrations are reduced to below specified limits through the use of ozone converters or a suitable ventilation system[21]. Levels of ozone are also reduced by reaction with materials in the cabin, e.g. seat fabric and plastic. A study by Coleman et. al [16] tested the effect of ozone uptake on by-product formation and found that though surface reactions with materials, in particular clothing and seat fabric, reduced ozone levels the overall concentration of VOCs increased e.g. formaldehyde.

As well as presence of these constituents during normal operations, the possibility of presence of additional constituents as a result of rare abnormal conditions has also been considered in previous work, e.g. introduction of fuel degradation products as a result of leakage from a seal[22].

Substances introduced to the air supply systems as a result of use of outside air cannot be controlled or eliminated through an increased ventilation flow rate. Possible effects and their mitigation strategies depend on the location of the air inlets. If the source of the contaminant exists for only a short time (e.g., de-icing fluid during de-icing procedures), effective control can be achieved by turning off the flow of outside air while the source is present. That control measure is not an option in flight, because of the requirements for pressurization; nor is it an option when the source is present for more than a short time (e.g. 15 min). It has been suggested that some reduction in concentrations of such cabin air contaminants can be achieved by using the minimal practical flow of outside air and increasing the flow of recirculated air if the recirculation filters are effective at removing the contaminants in question[4], However one-off, sporadic events may be too brief for intervention and particulate filters cannot remove VOCs, SVOCs or lighter gases. Mitigation strategies include regular inspection and maintenance such as of oil seals and ducts[21], aided by component failure warning through the use of monitors such as overheat detectors[9]. Additionally, as implemented for example in the Boeing 787 Dreamliner, the use of electrical compressors with dedicated air inlets, rather than the use of bleed air from the engines, removes the possibility of potentially degraded bleed air entering air supply systems.

Table 2.1 provides a summary of the substances that have been discussed, their sources and mitigation strategies that could be considered to prevent their build-up in the aircraft cabin.

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Table 2.1: Potential constituents in on-board air quality, including their sources and mitigation strategies that have been employed to ensure air quality is not degraded.

Potential contaminant	Source	Mitigation strategy consideration
Carbon dioxide (CO_2)	Respiration from occupants, dry ice from food station, combustion products in smoke/fire events	Regular air exchanges
Volatile organic compounds (VOCs)	Anti-corrosion spray, pesticides, solvents, cleaning fluids, de-icing fluids, bioeffluents, pyrolysis/ combustion of resins, new carpets	
Ozone (O_3)	Atmospheric constituent	Fly at altitudes where ozone concentration is lower, use of high stage bleed air compressor (greater dissociation of ozone), use of ozone converters[20][19]
Airborne bacterial and viral organisms, dust, fungi	Carried in with passengers with infection or illnesses or from furnishings	Use of HEPA filters in recirculation system[15].
Sulphur dioxide (SO_2)	Combination of hydrocarbon fuels and O_2, e.g. ground activities	Ground based air conditioning for ground refuelling activities etc.
Tricresyl phosphate (TCP) & other derivatives	Degradation products of engine lubricating oils and hydraulic fluids (mentioned here as concern regarding these contaminants has been raised)	Regular maintenance of oil seals and ducts, aided by alert systems such as overheat detectors for in-flight bleed air incidents.
Carbon monoxide (CO)	Oil/hydraulic fluid, incomplete combustion products	
Nitrogen oxides (NO_x)	Fuel emissions, High pressure combustion of air	
Hydrogen cyanide (HCN)	Pyrolysis or combustion of nitrogen containing compounds in oxygen deficient conditions	Usually occurs in the event of combustion of products i.e. a fire event therefore fire suppressions or isolation is the main strategy. Evacuation of the plane as soon as possible would be the most desired option for passenger safety
Carbon fibres and nanotubes	Combustion of polymer material in aircraft structure	

A particular consideration for this work package is whether the introduction of new composite materials in aircraft structure could have an effect on the on-board air quality in the cabin. Both normal operating

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conditions where materials function as designed and elevated temperatures where thermal degradation or combustion of the material could occur are considered. It has been reported that during post-crash or in-flight fires, sufficient amounts of hydrogen cyanide and carbon monoxide can be liberated so as to incapacitate passengers[23]. In these cases, evacuation of the cabin as soon as possible is the best strategy for survival.

Regarding these materials, an additional consideration in the event of fire conditions is the liberation of carbon fibres or carbon nanotubes if the conditions allow. There have been many reports about adverse health effects[24], [25] from exposure to carbon nanotubes and results from laboratory animal studies[26] have shown qualitatively consistent adverse lung effects including pulmonary inflammation, granulomas, and fibrosis with inhalation.

The FAA states that from all the materials used inside an aircraft cabin, between 80 and 90% are thermoset composites[27]. These composites are sandwich structures made of fiberglass-reinforced phenolic resin skins on Nomex honeycomb cores which are surfaced with an adhesively bonded poly (vinyl fluoride) decorative film or painted to provide colour and/or texture. These panels are used for example as ceiling panels, partitions, cabinet walls, interior wall panels, galley structures and structural flooring. The remaining 10 to 20 % of the materials found in aircraft cabins include floor coverings, thermo-acoustic insulation, cargo compartment liners, textiles, wall coverings, draperies, upholstery, cushions, blankets, air ducting, trim strips, and moulded and thermoformed plastic parts such as overhead passenger service units and seat components which are often painted.

2.2. On-board air quality: monitoring strategies

Cabin air quality (CAQ) has received much attention over the years. An extensive history of CAQ monitoring in the US has been published[28]. More recently, CAQ has been cast into the public eye through the media, in particular in the US, the UK, Australia, the Netherlands, and Germany, as a result of reported incidents and concerns[29] about the possible health impact of contaminated air. This has prompted many investigations and publications around the topic of CAQ and the health concerns that have been raised.

Monitoring of cabin air quality may help to address these concerns about comfort, safety, and health. In the case of comfort it should be noted that cabin air quality is only one factor; other factors such as noise or passenger space, or indeed a combination of these factors may have a greater impact on overall perceived comfort than the air quality itself. In general terms, monitoring of cabin air quality can indicate cabin air conditions (including their change over time) which could then facilitate assessment as to whether these conditions negatively impact on comfort, safety, or health.

Methods for monitoring CAQ include direct methods, such as measuring chemical composition and physical conditions, as well as indirect methods such as targeted reports and questionnaires for passengers and crew, or biomonitoring such as investigation of blood and urine samples. This section considers direct methods as well as indirect methods and is categorised into the following headings

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- Monitoring based on reporting (e.g. incident reporting, meta-analysis of incident reporting, questionnaires)
- Biomonitoring of aircraft personnel and passengers
- Monitoring by measurement of substances in the air

Literature surveys related to these methods are outlined in the subsequent subsections. Note: the literature for the third bullet point, i.e. relating to measurement of substances in the air, is covered in greater detail in chapter 4 as this aligns more strongly with the approach of this work package group.

2.2.1. Monitoring based on reporting

In the context of this literature study we have focussed on meta-studies of incident reporting rather than on incident reports themselves. The incidence reports generally refer to many other aspects relating to the incident than specifically to cabin air quality. Besides what has been experienced by aircraft personnel, the source of the experience is sometimes described in the incident report as well. Examples of such meta-studies of incident reporting include:

- the analysis of frequency and causes of smell-related incidents, reported over the period 2012-2014 in The Netherlands[30],
- the comparison of incident reporting by crew and incident reporting by maintenance personnel in Australia over the period 2008 - 2012[31],
- the analysis of health incidents reported by air crew as a consequence of exposure to contaminated cabin air (with and without using an oxygen mask)[32].

In Europe, occurrence reporting is governed by the European Regulation 376/2014[33] published in April 2014 and applicable from 15 November 2015. An occurrence is thought of as any safety-related event which endangers or which, if not corrected or addressed, could endanger an aircraft, its occupants or any other person. These reports are usually directed to the appropriate aviation authority in the country. In terms of reporting methodologies, research has ranged from retrospective analysis of incident reports over a time range to questionnaires distributed to occupants during a flight. Some of these methodologies are listed below in Table 2.2, highlighting some of the criteria for reporting and challenges with these methodologies.

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Table 2.2: Examples of some report based methodologies, highlighting challenges and recommendations from the investigations

Methodology	Implementation	Challenge/recommendations of the studies
Motivation: Attempt to reconcile perceived comfort with health [34][18][4]		
Comparison of human perception from questionnaire with in-situ sensing	Questionnaires distributed to passengers and crew during flight, documenting symptoms such as dry skin, nausea, air quality in terms of odour, temperature, air flow, noise, upper respiratory Commercial sensors monitored relevant parameters, e.g. ozone	Low questionnaire return (51%) however was successful as easy to fill out. Reminders to passengers during flight aided completion Simultaneous sensing suggested elevated ozone levels may be of concern
Motivation: To identify specific circumstances of smoke/fume events [31][35][36]		
Identify trends based on retrospective analysis of events	Accessed databases of a number of aviation safety groups where incidents were logged, detailing variables such as aircraft type, location of event, cause, likeliness of reporting	Reporting systems are not standardized so a lot of information missing, potential reluctance of staff to report. Different airlines reported to different authorities. An anonymous centralized system, trend monitoring and data sharing was recommended

A recurring comment amongst these studies was that it was often hard to identify trends due to suspected under-reporting and sparse details about the incidents. For example, causes for smells that appear in incident reports varied from smouldering ovens (mostly food packaging material), short circuiting, bird strikes, air conditioning systems, to APU and engine-related incidents[30]. The methods for identifying the causes were not always explained in the literature. Meta-studies of incidents sometimes included correlation analysis of incident reports and maintenance inspections[31].

It was recommended in a number of studies [10], [31], [37], [38], that it would be worthwhile to implement a common reporting system, where compliance is agreed industry wide so that air quality incidents could be properly characterized. The following specific recommendations/directives have been found:

- The reporting should be internet-based, and through a confidential reporting system[10].
- The reporting and monitoring data should be shared between agencies[31].
- A program should be conducted for the systematic collection, analysis, and reporting of health data with the cabin crew as the primary study group[4].

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- A US public law mandates the FAA to "develop a systematic reporting standard for smoke and fume events in aircraft cabins"[37], [38].
- Smell type events should be addressed in the occurrence records[31].

To successfully implement a central incident reporting system[39], crew members would need to receive sufficient training to be able to identify potential source of a hazard. To further aid this, the reporting system would contain definitions and examples that represent specific events e.g. an odour event might have descriptors such as acrid, burning, oily, pungent, foul, while visible incidents might be categorized with descriptions such as "smoke, haze". The authors suggested that such measures would improve the quality of the recorded data, however any measures based on personal reporting are bound to retain elements of subjectivity. With improved quality data entries and a self-consistent database, regular trend monitoring of this database would be improved.

2.2.2. Biomonitoring of aircraft personnel and passengers.

Aircraft personnel and passengers have been examined. The examinations involved medical tests [35], [40] (e.g. analysis of blood, urine samples) as well as the investigation of personal reports of health issues by air crew [41].

Biomonitoring recommendations from the literature included:

- Linking biomonitoring results with airline records of the aircraft status during that time period, e.g. reports of odours, health symptoms[42]
- To collect and store samples of urine, and possibly blood, from crew members within 48 hours (the earlier the better) after fume events as part of a systematic study with potential analysis for biomarkers of potential toxic pollutants as in papers[43]–[45]
- Applying a continued assessment of health risks to passengers who may be exposed during bleed air events[37].

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Table 2.3: Examples of biomonitoring based methodologies, highlighting challenges and recommendations from the investigations

Methodology	Implementation	Challenges/Recommendations
Motivation: Is there evidence that crew suffer ill effects from exposure to ozone, TCPs? [46][47]		
Comparison of medical results with perception as detailed in questionnaire	Clinical examination (including urine samples, MRI) of crew who complained of dry skin, eye-related and nasal symptoms, and tiredness, dizziness, breathing difficulty, smells	Difficult to assign causal association with particular contaminants as the test sample size was small, the subjects were self-selected, and there was no information about exposures. Suggest periodic medical exams, especially after non routine events. control group also, worker training to recognize symptoms
Motivation: To identify occurrence of events that may have degraded cabin air quality[35]		
Analysis of medical test records where person has been on-board during a fume event	Statistical analysis of medical records that have been received, where burnt gas intoxication or TCP inhalation is cited	Challenge to acquire a large enough dataset (with more reliable statistics) as people do not supply medical records. Recommended standardising of fume event recording and medical examinations if a fume event is reported. Obtain information in a timely fashion from both those on-board and the technician who carries out inspection after the event.

As with the monitoring by reporting, it was found that a lack of standardised procedure when employing biomonitoring of aircraft personnel made it difficult to establish any strong correlations between contaminated air and health impairment. Recommendations included more regular medical examination of aircraft personnel, in particular when a fume event has been reported. Additionally these examinations should be carried out in such a way that they check for possible symptoms of suspected specific exposures e.g. fuel degradation products.

2.2.3. Monitoring by measurement of substances in the air

As mentioned at the start, specific measurement methodologies will be discussed in more detail in chapter 4. This section aims to offer some general conclusions and recommendations that were reached as a result of the investigations carried out. Measurement strategies encompassed both planned experiments such as;

- sensors placed in a certain location in the aircraft (e.g. in the cockpit [48], [49]) during fixed phases of flight operation (e.g. APU operation on-ground), during a certain period of time,
- wipe samples and interior air investigations taken[50], with additional analysis carried out in a laboratory,

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- bioaerosol samples collected in the breathing zone of a seated person, in galleys and lavatories and in supply and exhaust air streams[4],

as well as ad-hoc measurements performed after reported incidents, e.g. measurements with an Aerotracer (by maintenance personnel and by fire brigade) after an event[35]. Specific methodologies are described in more detail in chapter 4. An overview of known air quality studies can be found in[42].

Many literature documents [10], [32], [37], [38], [47], [48], [50], [51], [4] recommend the monitoring of the cabin air quality by measurement (during flight and on ground). Specific recommendations include:

- *Sampling of the measurements*. A representative number of flights to be sampled over a period of 1–2 years is recommended by[4]. A US law [38] mandates “comprehensive sampling program” for measurement of the quantity and prevalence, or absence of identified air toxins that appear in cabin air.
- *Continued monitoring*. It is recommended to continue monitoring flights to ensure accurate characterization of air quality as new aircraft are taken into service and aircraft equipment ages or is upgraded[4].
- *Standardization*. Development of standards for CAQ and involved measurement are considered (e.g. [48]).
- *Trial of equipment.* Special sensor equipment and measurement technologies need to be developed and tested e.g. in aircraft cabins, for use on ground and in flight[10], [37], [38], [48].
- *Distinction between (un)harmful substances*. A sensor system is recommended that distinguishes between harmless smells and harmful events[35]

2.3. Summary

As seen in section 2.1, on-board cabin environment is controlled and managed such that occupants can travel in a habitable environment without compromising the structural integrity of the aircraft. Despite this, a number of concerns have been raised that in the event of a malfunction during operation, the quality of the air may become contaminated with undesirable substances. As continuous monitoring of on-board air quality is not routinely undertaken, it has not been possible to alleviate concerns regarding air quality. A number of investigations have taken place to further understand the composition of on-board air quality, both during routine operations and abnormal events

2.3.1. What challenges or limitations have been encountered

The studies to date have demonstrated the technical feasibility of adopting monitoring procedures based on after-the-fact reporting by crew or biomonitoring of crew and / or passengers. The studies have also highlighted the challenges or limitations that were encountered or are to be expected in the future including:

- *Insufficient data/ unsuitable data.* Meta-analysis of incident reporting is limited by the problem that not all incidents were reported [53] and not all incidents could be matched[31], identifiable contamination events were infrequent and unpredictable [10] and reports were incomplete[30]. Improvements may be possible, however any system based on reporting of infrequent events by individuals is bound to retain an element of subjectivity. Cabin air quality measuring at rare events can be extremely costly, even with state-of-the-art, combined measurement methods. In line with the paper[45]in such a case it is recommended to study the incidence and nature of the rare events and the circumstances in which they occur. Based on the outcome of such a study the measurement strategy may be adopted and less costly. Also it is recommended to investigate if such events can be induced experimentally, which could also be more affordable.

- *Detection limitations.* In several cases the oil spilling is found only after several fume events have occurred[32].
- *Limitations on conclusions of studies.* In several cases a remark is made that the studies did not provide enough evidence to reach conclusions on air quality[10], [41].
- *High effort by involved parties.* Air carriers shall allow air quality monitoring on their aircraft in a manner that imposes no significant costs on the air carrier and does not interfere with the normal operation of the aircraft[37], [38]. However, extensive measurement programs may strongly impact operators, including factors that may also impact operational safety in other ways.

2.3.2. What future technologies are addressed

During the literature review the following addressed technologies have been found that may impact CAQ in the future:

- Air filtration systems, e.g. in ECS, air supply lines[10], [28], e.g. using photocatalytic oxidation (PCO) and non-thermal plasma oxidation for VOC/odour removal.
- Use of alternative engine oils[54]–[56].
- Reduction of the bleed air demand[28], e.g. by new technical solutions for bleed air and cabin air recirculation.
- Bleedless ECS (e.g. as used on Boeing B787)[10].

In terms of air quality monitoring strategies for the future it is envisaged that probably only through a combination of low cost sensing, big data capability (data collection, storage and processing), and statistical analysis of association between a reported event and medical record, could a definite assessment of impact on health by these relatively rare (rare when compared to the number of total flights) fume events be achieved.

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3 ON-BOARD AIR QUALITY: AIRCRAFT STANDARDS AND TESTS

All aircraft undergo rigorous testing to achieve certification of airworthiness. Certification is given by an appropriate regulatory body for that region, such as the Federal Aviation Administration (FAA) in the United States or the European Aviation Safety Agency (EASA) in Europe. These regulatory authorities will inspect and certify an aircraft at a number of stages, for example "type certification" which issues approval of a manufacturing design for specified materials, parts, and appliances, or later stage "airworthiness certification" which grants authorization to operate an aircraft in flight. In order to meet the certification requirements, the performance characteristics of the subsystems and their integration are tested for the full operation envelope that the aircraft is expected to encounter, from its normal operating conditions to a safety margin, including abnormal and extreme conditions. Testing is thorough, involving in extreme cases controlled destruction of specimens.

The first section gives a general outline of how certification and standards tests are created and used. The second section introduces typical tests that are carried out on various subcomponents, with a particular focus on those that, if operating incorrectly, could contribute to degraded on-board air quality. The third section introduces the procedure for how tests are updated in the event that new materials are introduced, namely composite materials used in structural components.

3.1. Aircraft standards

In general, standards and test procedures are created by independent bodies from the regulatory authorities, including organisations carrying out research in that area [57], [58], component manufacturers[59] and aircraft operators[60]. The responsibility of ensuring that the equipment performs in the specific conditions of its intended operational environment always rests with the manufacturer and proof of compliance must be accepted by the regulatory authority.

Two standards that are commonly referred to by certification authorities are those of RTCA DO-160G/EUROCAE ED-14G (the two documents are identically worded) and the military standard MIL-STD-810, which relate to safe operation of aircraft embedded equipment. RTCA DO-160/EUROCAE ED-14, titled "Environmental Conditions and Test Procedures for Airborne Equipment", is a joint harmonization effort of the FAA and EASA, and determines the minimum standard environmental test conditions for safe operation of airborne equipment and what laboratories tests should be carried out to verify it.

As stated in [61], "the test categories defined in DO-160 are intended to encompass the full spectrum of environmental conditions that airborne equipment may experience from benign to very hostile". The document does not intend to guarantee service life of equipment or exhaustively cover the full spectrum of environment conditions. In that regard, specific subjects such as hail, acceleration or acoustic vibration are not covered by the current revision. And as mentioned before, the responsibility of ensuring that the equipment performs in the specific conditions of its intended operational environment rests with the manufacturer.

In addition to DO-160, though not specific to airborne equipment, MIL-STD-810,[62] "Environmental engineering considerations and laboratory tests" is also used as a reference for environmental testing for this purpose. This standard has been produced by the US Air Force, US Army and US Navy, for setting and testing of environment conditions for military equipment. The emphases within this document are "to tailor a material item's environmental design and test limits to the conditions that the specific material will experience throughout its service life, and to establish laboratory test methods that replicate the effects of environments on material". In similar fashion to DO-160/EUROCAE ED-14, the document does not set the design or test specifications but, instead, sets the guidelines for managing and engineering of such tests, and what laboratory tests can be used to verify compliance. The final decision on the tests is with the manufacturer and must also take into account limitations of laboratory testing in producing valid results when considering certain operation scenarios. The document itself is divided in three parts, the first for management and engineering guidelines for the design and testing tailoring; the second gives detail on the testing procedures; and the third gives an account of world climatic characteristics (for determining environment operational conditions).

Table 3.1: Some of the typical characteristics that are tested under DO-160 and MIL-STD-810. Note the section numbers have been retained for ease of reference

DO-160		MIL-STD-810	
4.0	Temperature and Altitude	500	Low Pressure (Altitude)
5.0	Temperature Variation	501	High Temperature
6.0	Humidity	502	Low Temperature
7.0	Shock	503	Temperature Shock
8.0	Vibration	504	Contamination by Fluids
9.0	Explosion Proofness	505	Solar Radiation (Sunshine)
10.0	Waterproofness	506	Rain
11.0	Fluids Susceptibility	507	Humidity
12.0	Sand and Dust	508	Fungus
13.0	Fungus Resistance	509	Salt Fog
14.0	Salt Spray	510	Sand and Dust
15.0	Magnetic Effect	511	Explosive Atmosphere
16.0	Power Input	512	Immersion
17.0	Voltage Spike Conducted	513	Acceleration

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DO-160		MIL-STD-810	
18.0	Audio Frequency Conducted Susceptibility	514	Vibration
19.0	Induced Signal Susceptibility	515	Acoustic Noise
20.0	RF Susceptibility	516	Shock
21.0	Emission of RF Energy	517	Pyroshock
22.0	Lightning Induced Transient Susceptibility	518	Acidic Atmosphere
23.0	Lightning Direct Effects	519	Gunfire Vibration
24.0	Icing	520	Temperature, Humidity, Vibration, and Altitude
25.0	Electro-Static Discharge	521	Icing/Freezing Rain
26.0	Fire, Flammability	522	Ballistic Shock
27.0	Smoke Density, Toxicity	523	Vibro-Acoustic/Temperature

It is worth mentioning that a document related to MIL-STD-810 has been produced by the Institute of Environmental Sciences and Technology (IEST) with the title "The History and Rationale of MIL-STD-810". The document exposes the historical rationale of MIL-STD-810 evolution and its tests, due to the increase of knowledge in operation conditions and their spectrum, and the testing sophistication increase due to equipment evolution. This document is mentioned here as a possible aid to the understanding of the requirements and tests on this theme, and as a pointer to possible future changes in light of new understating or supervision requirements.

The FAA also publishes the "Aircraft Materials Fire Test Handbook" that is curated by the International Aircraft Materials Fire Test Working Group (IAMFTWG). The initial version resulted from a contract awarded by FAA to Boeing and McDonald Douglas, detailing the testing already done by these OEMs to comply with FAA regulations. The handbook is also acknowledged and referenced by EASA for certification (Certification Memorandum CM-CS-001, 7.9.2011), forming part of the harmonization efforts of the two agencies with a result of lowering certification costs to OEMs. The tests in the handbook are seen as a possible means of compliance with regulations but they are not necessarily the only way of compliance or; they cannot act as replacement when there are specific tests set in the regulation documents themselves.

3.2. Aircraft sub-components tests

As seen in section 2.1, constituents that may affect cabin air quality can come from activities within the cabin or can be drawn in through the air supply system from external sources. This could include volatiles and odours from[63]:

- off-gassing from interior furnishings

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- food services, cleaning and maintenance activities
- electrical failures
- engine/APU emissions from operation
- ingestion of aircraft fluids including de-icing fluids, hydraulic fluids

With these in mind, some typical tests recommended within the standards are discussed in the context of what characteristics are being tested and the aircraft components that may be subjected to these tests. The characteristics that are discussed are flammability, toxicity, pressurisation, temperature

3.2.1. Flammability and toxicity testing

Because of the hazards that fire can pose on aircraft both in-flight and post-crash, flammability testing is required for most components on an aircraft. The test methods interrogate the components in terms of their performance when in use and also the properties of the materials that they are composed of[21], [64][60]. There are 12 flammability tests[65] that are applicable for testing components within the fuselage e.g. the interior furnishings, electrical wiring, ceiling and wall panels. These test methods include exposing the material to flame such as using a Bunsen burner, where the material is positioned at various angles to assess heat and smoke release, flame spread and resistance to flame. Heat release rate is also tested by exposing the material to a radiant heat source with a constant air flow and measuring the temperature of the exiting air. There are also a number of flammability tests that apply to components outside the fuselage e.g. engine and APU. Flammability tests of these components focus on fire resistance, where components must be able to withstand the effects of fire for between 5 and 15 minutes. As well as demonstrating compliance through the fire tests, within these "designated fire zones" there must be quick acting fire or overheat detectors that can notify the crew quickly if some component has malfunctioned[65].

Another aspect that is considered when exposing components to flame is the smoke toxicity and density that can be produced, especially if the component begins to combust. Typical tests to assess the smoke density include the NBS smoke chamber method[66] where the material is burned in an environmental chamber and the specific optical density is determined using a white light source and photomultiplier detector. This chamber can also be attached to gas detection systems to identify the constituents of the smoke, such as the Airbus Industry Standard AITM 3-0005, where a sample of the smoke is collected in a Draeger tube, which produces a colorimetric response in the presence of the target chemicals. For more quantitative analysis, techniques such as thermogravimetric analysis (TGA) and gas chromatography mass spectrometry (GC-MS) can provide further information about how the material evolves/degrades when subjected to increasing temperature and then the specific volatiles that are emitted during this degradation respectively.

In terms of mitigation, detection, extinction and fire/smoke prevention are the key strategies employed. In the case of engine or APU fires, detection systems e.g. dual heat sensitive loops trigger a fire warning and suppression systems are employed[67]. Suppression techniques include discharging of fire extinguishing agent[68] e.g. if fire warning originates in the cargo compartment or lavatory, or reduction of temperature by exposure to outside air e.g. if landing gear triggers a warning[67]. In terms of

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fire/smoke prevention, the tests carried out exploring flame retardant interior furnishings[69], self-extinguishing electrical wire insulation are chosen with the intention of reducing risk of fire start and propensity for flame spread. One of the challenges that has been noted is that often potential fire hazards e.g. wiring, are located in hidden areas which crew cannot access in the event of a fire[70][71]. Recommendations have included installation of fire access ports in locations where minimal damage could occur or else installation of dedicated fire detection and suppression systems to inaccessible areas[72]. Additionally increased number of sensors and monitoring of components such as fans and air conditioning packs was recommended so that crew could be alerted before a fire has progressed[72]. Regarding bleed air contamination from aircraft fuel or fluids, aircraft are designed such that these fluids are segregated and will not reach the passengers and so are not targeted by requirements for on-board air quality certification. And so, currently, regular inspection and maintenance of components such as oil seals and ducts as well as presence of overheat constitute the main mitigation strategies at the moment.

3.2.2. Temperature, humidity and pressure testing

Components within the aircraft, such as the environmental control system, engine bleed air system and indeed the pressurized cabin itself must be able to operate over large temperature and pressure ranges, ensuring adequate comfort for occupants as well as maintaining structural safety. In terms of passenger comfort, typical pressurization requirements require that the rate of cabin altitude change shall not exceed 1.83kPa/min during ascent and 1.10kPa/min during descent. ASHRAE has recommended that the target temperature range within the cabin should be from 18.3-23.9°C, and should not exceed 26.7°C[73]. In order to ensure that components (and at later stages, the aircraft as a whole unit) demonstrate compliance, static and cyclic fatigue testing is carried out. Static tests include component loading e.g. composite wings are loaded and then checked for deformation or damage when unloaded. Fatigue testing involves placing the component under thermal and /or mechanical loading conditions and cycling these load conditions until the test piece fails, e.g. when the environmental control system no longer controls air flow rate or temperature. When components have been assembled they are usually tested at a facility where extreme temperatures and pressures can be applied to the component. Within this controlled chamber, many parameters are monitored during the test. For example, during jet engines testing, parameters such as fuel consumption, vibration levels, and pressures and temperatures at various locations of the engine will be logged[74]. Once these components are compliant with aircraft regulations they are installed in an aircraft where they will undergo further testing as an aircraft unit. In terms of bleed air contamination, though specific air quality monitoring is not conducted, bleed air intake ducts are subjected to many tests to ensure that they withstand all conditions during flight. These include cyclic fatigue, vibration and shock testing and pressure pulsing to ensure that ducts and seals do not develop a leak.

Regarding potential air quality issues as a result of temperature or pressurization, mitigation strategies are usually considered at the design stage, with many regulated flow valves allowing for isolation of components if a malfunction occurs. For example, in a Bombardier CRJ200[75], if a pressure regulating shut-off valve, which is typically used to lower pressure flowing into the air conditioning pack to prevent

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damage, fails then the valve will close, the air conditioning pack itself will shut down and the pilot will be notified through an alert. The pressure regulating valve that controls flow rate for the second air conditioning pack will then increase the operating pressure so that airflow within the cabin is maintained. During this time, outflow valves will ensure that the cabin remains pressurized by controlling rate of air release from the cabin. Once a warning has been issued by the monitoring system, pilots will often initiate a diversion plan that allows for landing as soon as possible.

3.3. Composite materials testing

Composite materials are being used more widely in the construction of aircraft, where traditionally metallic structural sections are being replaced with lighter, corrosion resistant polymers. Two such examples are those of the Airbus A350 and the Boeing 787 Dreamliner, where 50% of the plane is made up of composite material, including the wings and fuselage. This has brought with it the need to update aircraft regulations to accommodate this new reality of more extensive use of aircraft materials. For example, regulatory sections governing potential flammability and toxicity risks from components do not incorporate the consideration that the aircraft structure itself may further compound these factors if exposed to elevated temperatures or other components going on fire. This was not necessary before as structural components were traditionally metallic. To account for this, in the case of the Boeing 787, a type certificate with special conditions was applied for[76]. As current standards were still evolving to account for the use of composite based structures, the Federal Aviation Administration stated that the 787 must "provide the same level of inflight survivability as a conventional aluminium fuselage airplane". This required factors such as thermal/acoustic insulation, resistance to flame propagation and combustion product toxicity to be evaluated and found acceptable. To address these requirements, the composite materials used in the fuselage were subjected to the same types of tests as those of the interior composite furnishings, such as burn through, flame propagation and the use of a cone calorimeter to assess smoke toxicity. This is particularly pertinent when considering on-board air quality as not only could the material sustain a fire if it has originated from a nearby component, but combustion of these materials can themselves contribute toxic products that may reduce chances of survival.

According to the Government Accountability Office (GAO)[77], a big consideration regarding the use of composite materials in this way is the maintenance, repair and overhaul (MRO), The four key safety-related concerns that they identified were-(1) limited information on the behaviour of airplane composite structures, (2) technical issues related to the unique properties of composite materials, (3) standardization of repair materials and techniques, and (4) training and awareness. The FAA continues to address these concerns with circulation of documents like the advisory circular 20-107B as well as working closely with composites manufacturers, standards providers to amend test procedures as and when more knowledge is gained.

Currently certification of composite aircraft structures is captured in by the document EASA AMC 20-29, which is harmonised with FAA AC20-107B. Within this document i.e. EASA AMC 20-29, item "d. Environmental Considerations" states that:

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"Environmental design criteria should be developed that identify the critical environmental exposures, including humidity and temperature, to which the material in the application under evaluation may be exposed. Service data (e.g., moisture content as a function of time in service) can be used to ensure such criteria are realistic. In addition, the peak temperatures for composite structure installed in close proximity to aircraft systems that generate thermal energy need to be identified for worst-case normal operation and system failure cases. Environmental design criteria are not required where existing data demonstrate that no significant environmental effects, including the effects of temperature and moisture, exist for the material system and construction details, within the bounds of environmental exposure being considered."

From the above it is recognized that the material is chosen in such a way that there is no structural performance degradation across its designed operational envelope. Provision shall be made also, for instance, to insure safe egress in case of emergency.

- For interior parts, the threat of toxic elements inhalation as a result of heat or ultraviolet radiation parts degradation is implicit in the design guidelines; the material selection is carefully made during design phase, and all Material Safety Datasheet shall guarantee that its behaviour will be innocuous to the passenger.

- For structural composite parts, certification institutions are focused on structural endurance in case of fire as it is fundamental for aircraft safe landing; it is suggested that OEM´s must also analyse materials toxicity of structural composite parts under fire, to ensure safety, because there is no Material Safety Datasheet for this kind of materials.

3.4. Summary

Dedicated on-board air quality qualification testing for interior materials is not explicitly required by certification authorities as by design, segregation from harm is required and new materials must have safe properties. Certification institutions and OEMs develop the entire product using the following premises:

- Airborne installed systems are designed, developed and tested taking into account the environment operational conditions within the aircraft operational window, and therefore are developed with the consideration that they will not be a toxic threat to passengers;
- Structural parts offer mechanical strength within a period of time in fire threatening conditions, for safely landing. Materials are selected so not to release toxic gases that would prevent the safe escape of passengers;
- Interior part´s materials are carefully selected taking into accounts their surrounding environment, and therefore are selected so as to not be a toxic threat to passengers in any situation or operational window;
- Secondary toxic gases and/or fluids used in the aircraft are enclosed within aircraft operational window and therefore, considering "zero leakages situation", the gases and/or fluids will be entrapped and will not be a toxic threat to passengers.

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4 METHODOLOGIES FOR ASSESSING ON-BOARD AIR QUALITY

As mentioned in chapter 2, a particular focus of this work package is to investigate whether the increased use of composite materials in aircraft could contribute to adverse air quality in the cabin. A review of investigative studies that have been carried out to assess on-board air quality was conducted to gain a better understanding of the potential technologies that could be employed for our specific interest.

A number of different strategies have been employed during these studies where, for example, portable sensors have been used within a subset of commercial passenger flights, to measure specific target compounds both during flight and on the ground. Additionally, where specific aircraft components are thought to have contributed to adverse on-board air quality, laboratories studies interrogating these components have been carried out. The focus of this study is on the methodology itself rather than the specific measurands as some methodologies are common to a number of studies. The methodologies are categorised as follows:

- In-flight real time analysis using commercial sensors with sampling tubes for delayed analysis (divided into general contaminant monitoring and bleed air contaminants specifically)
- Laboratory testing of commercial sensors for suitability
- Laboratory test relating to bleed air contamination specifically (both simulated and retrospective analysis)

4.1. In –situ measurements (real time and delayed analysis)

4.1.1. General substance monitoring

As seen in chapter 2, currently there is no dedicated air monitoring equipment as standard in commercial aircraft. Despite this, current aircraft standards and regulations apply exposure limits to carbon dioxide (CO_2), carbon monoxide (CO) and ozone (O_3)[73]. These three gases and their effects are well understood, with quantified permissible exposure limits in line with typical indoor air quality recommendations. Indoor air quality in terrestrial applications is heavily regulated and as a result, numerous commercial off-the-shelf sensor (COTS) configurations have been developed to cater for the various requirements of the market. In terms of gas sensing, electrochemical and semiconductor based technologies are the most popular due to their high efficiency (accurate, large measurement range) and low cost (≈$40 per unit for electrochemical and ≈$2-5 per unit for semiconductors)[78]. The sensor chosen by the end user will be motivated by factors such as size, cost, accuracy, and suitability for the application. A number of studies are summarized in Table 4.1, listing the general methodologies and how they were implemented, including some of the challenges that were faced.

Table 4.1: Examples of in-situ analysis carried out for cabin air quality applications

Methodology	Implementation	Challenge/recommendations
Motivation: Evaluate relationship between flight factors e.g. size, occupation, and environmental parameters[34], [79]–[82]		
Real time analysis using commercial sensors with sampling tubes for delayed analysis. Typical targets included CO, NO, O_3, VOC's	Sensors placed in cabin seating area, Sampling probes were clipped on the aisle seat backs above the breathing zone (36 flights)[79]	Pressure correction factors applied Maintaining calibration in the field could be a challenge, need more sensitive VOC method
	For cabin air - in suitcases under passenger seat[34] For bleed air – sample from the gasper with recirculation off (4 flights)[34].	Ethanol attributed to alcohol intake. Acetone originated from passengers as a human bioeffluent. Substantial operator attention was required for passive samplers
	User operated sampling tube with GC/MS analysis (107 flights)[81]	Presence of substances varied with activities e.g. CO_2 elevated when on the ground before air conditioning systems was switched on
	Mobile pump used to extract samples into sorbent tubes (VOC), PU foam (SVOC), (DNPH cartridge (carbonyl), at different flight phases[80]	Had some ketones e.g. sulcatone, that may derive from ozone reactions

As the cabin environment is somewhat similar to terrestrial conditions, the commercial off the shelf sensors for the most part were able to make quantitative measurements. It was noted that over time, some sensors could be subject to drift and that maintaining calibration could be a challenge e.g. pressure changes could affect the reading. In terms of the constituents themselves, the majority of volatiles detected were those that would be expected as a result of human activities e.g. alcohol consumption, cleaning, respiration. As a methodology, a manifold of COTS could conceivably be an option for cabin air monitoring however they would need further adaptation to the aircraft environment, in terms of size, cost and resilience to ambient changes during the flight phases.

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4.1.2. Bleed air monitoring

In an effort to address concerns raised about bleed air contamination from engine fuel leakages, a number of investigations were carried out focusing specifically on identifying by-products from fuel combustion e.g. organophosphate derivatives. The methodologies and their implementations are summarized in Table 4.2.

Table 4.2: Examples of in-situ analysis carried out with a specific focus on bleed air contamination

Methodology	Implementation	Challenge/recommendations
Motivation: See if engine malfunction contributes to bleed air contamination[83]–[87]		
In flight test to see if exposure to OP's occurs	Personal air monitor during flight, sampling tube analysed using GC/MS[86]	Elevated levels of TCP's when APU was in use, corresponded to discovered oil duct leak. Sampling tube remained intact even with 6 week time period between sampling and analysis[86]
	Sorbent tubes and filters for sampling in cockpit with GC analysis[85][84]	TCP's were below the level of detection in all samples with higher concentrations only at higher engine power[84] or when a leak was detected[87]
	Wipe sampling with GC/MS analysis[87]	Concentrations of bleed air contaminants were very low and unlikely to produce adverse health effects. Recommended washing the ECS heat exchangers with acetone when maintenance permits, to further reduce levels[85]
Motivation: Develop a procedure for air monitoring of TCP in aircraft cockpit/cabin air, also identify if TCP exposure is a risk for ground crew[87]		
In flight test to see if exposure to OP's occurs	Analysis of fume event on grounded aircraft. TD tubes with GC-EI-MS analysis	Recommend development of short and long term sampling instruments so as to account for changeable aircraft schedules

As no suitable portable technologies exist to detect these types of compounds, the methodologies carried out employed delayed analysis techniques where air samples were collected and brought to a lab for further analysis using spectrometry techniques. Results from these studies found that organophosphate (OP) derivatives such as TCPs were in general found to be present in concentrations below the level of detection with elevated concentrations detected if an oil leak occurred. Recommendations suggested that these techniques, i.e. sampling tube with delayed analysis, could be useful for detecting oil leaks earlier than maintenance checks.

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4.2. Laboratory testing

Carrying out investigations during in-flight operations is difficult, with substantial operator input required and a lot of additional safety requirements for sensor operation within that environment. It is important to have a good knowledge of how the sensing technology will perform in the environment so that the most suitable technology can be chosen e.g. appropriate detection limit, resilience to low humidity etc. This section again is categorized into general laboratory testing and with a specific focus on bleed air contamination from engine fuel.

4.2.1. Testing of commercial sensors for suitability

Table 4.3 summarizes studies to identify sensors suited for continuous use on board aircraft.

Table 4.3: Examples of laboratory based analysis carried out investigating sensor suitability for implementation in aircraft air monitoring applications

Methodology	Implementation	Challenge/recommendations
Motivation: To identify suitable sensors for implementation on-board air craft [22], [39][15][88][87]		
Commercial sensors tested, where environmental conditions were controlled in a lab. Typical targets included pressure and O_3 as a priority, followed by CO, CO_2, RH	Wireless sensor network field test on mock up cabin within environmental simulation[22]	Wireless network showed variable environment conditions. sensor packaging and maintenance/calibration methods must be adapted
	Commercial sensors placed in environmental chamber[15], e.g. NDIR, EC,	Variation in humidity, pressure and temperature caused unpredictable and variable measurements in EC and MO sensors.
		IR sensors need miniaturisation Recommend testing of research phase and COTS sensors for aircraft purposes, collaborate with aircraft engineers on best sensor technologies[15]
	Hydrolysed oil to cresol so could be detected using a glassy carbon EC[88]	Some fouling on electrode from cresol, which reduced response. Work on optimising for automatic sensing

Results of these investigations showed that, as for the in-flight measurements, the commercial sensors were subject to drift in calibration due to the changing ambient conditions. It was recommended that collaboration with the aircraft engineers would be worthwhile to select the most useful sensing technologies for aircraft air monitoring.

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4.2.2. Bleed air contaminant investigation

Table 4.4 presents a laboratory test (experimental simulation) relating to bleed air contamination.

Table 4.4: Experimental simulation of potential bleed air contamination.

Methodology	Implementation	Challenge/recommendations
Motivation: To ascertain whether bleed air was becoming appreciably contaminated with volatilised fuel derivatives[22], [89]–[91]		
Laboratory test where bleed contamination is simulated and resultant oil products are analysed. Also analysed used filters from aircraft. Typical targets include Engine oil, hydraulic fluid. Organophosphate derivatives	CO was detected when mass change occurred for engine oil – potential oil contaminant indicator? Good response, COTS trend with FTIR, Calibration considerations due to pressure response	Suggestion that tri-butyl phosphates may not be detected as they remain within aerosols also suggest swab analysis of ventilation ducts for possible condensate Wireless network showed variable environment conditions. sensor packaging and maintenance /calibration methods must be adapted Variation in humidity, pressure and temperature caused unpredictable and variable measurements in EC and MO sensors. IR sensors need miniaturisation. Recommend testing of research phase and COTS sensors for aircraft purposes, collaborate with aircraft engineers on best sensor technologies[15] Some fouling on electrode from cresol, which reduced response. Work on optimising for automatic sensing Smoke coating the NDIR sensor packaging and maintenance/calibration methods must be adapted Challenges – collections of residue from many hours of service. Some of the target compounds may have vaporized from the filter Success is highly dependent on identifying unique signatures for an air-quality incident Potential for higher concentrations of TCPs during fume events

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In terms of air quality monitoring a numbers of locations could be considered in addition to cabin and cockpit:

- Environmental Control System (ECS). Commercially available air quality sensors are addressed that may detect various types of ECS contaminations [28],
- Bleed supply lines. Real-time monitoring in the bleed supply lines is recommended[48]. Wireless sensor networks for monitoring bleed air quality supplies (and CAQ) are described in [92].
- Engine. Examples have been found in literature of monitoring the physical conditions that may be related to the CAQ, e.g. engine health monitoring, gas path monitoring and lubrication monitoring [93]–[96]

4.3. Research phase sensors

As was noted, some of the technologies in the previous sections have been tested in-situ with varying success. As detailed in a report by the Lawrence Berkeley National Laboratory (LBNL) [15], ideally sensors should be simple to use, rugged and give a satisfactory performance with limited attention required by the crew and maintenance staff. In terms of quantifying this:

- Performance requirements suggest accuracy (±15%), sensitivity (low ambient levels), and sampling interval (≤60 s).
- Physical attributes suggest limitations on the size of sensor elements (≤ 3/8" in diameter), weight of sensor systems (≤1 kg), supply voltage (28 V)
- Cost motivated suggestions include frequency of maintenance (coincident with service schedules), required operator skill (minimal) and target cost for replaceable sensor elements (≤ $100).

Limiting factors of current sensor technologies include an inability to tolerate ambient conditions, size of sensors, and a prohibitive cost. The sensitivity to ambient conditions is more pertinent in chemical based sensors where active surfaces are concerned e.g. electrochemical sensors with aqueous solutions or metal oxide sensors with chemical reactions at the surfaces.

A number of portable handheld sensors have been tested in-situ however the size of these sensors means that it would not be realistic to introduce them into more suitable, enclosed locations on the aircraft, such as in the air plenum. These point source detectors can potentially measure a wide range of gases, e.g. VOC detection using PID's, meaning that they are possibly over specified for the task, and as a result come with a prohibitively high cost for mass implementation. To overcome these limitations, some research strategies have focused on miniaturization of whole sensing technologies that are currently too large to be portable e.g. creation of handheld IMS, or manufacturing tailored sub-components to remove the limiting operational factors in current COTS sensors, e.g. aqueous conducting solutions in EC sensors or high temperature requirements in MOS sensors. A final approach envisages that, once the composition of the cabin air is understood and specific target components are identified, a sensor array could be specifically tailored to provide identification of these components.

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4.3.1. Miniaturization of analytical sensor systems

Increased detection sensitivity is often achieved by introducing increased complexity into the detection system. For example benchtop analytical instruments such as GC-MS, FTIR and IMS are still the preferred methods where high quality identification of complex mixtures of a sample is required. These instruments tend to be large, expensive and fragile with dedicated gas lines and powerful vacuums. Metal oxide sensors on the other hand, are small devices offering increased sensitivity but with poor selectivity, often cross-reacting with other species. As a result, a large driving force for research in this area was to provide miniaturized low power consumption analytical devices offering adequate sensitivity and selectivity, with intended implementation into handheld devices or in distributed sensor networks, often via the use of MEMS.

Micro-Electro-Mechanical Systems, or MEMS can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that have been made using microfabrication techniques. They vary in size from microns to a few millimetres, and have the ability to control, sense, and actuate on the microscale, producing effects at the macroscale. For example, researchers have been able to steer an aircraft using microminiature devices by placing small microactuators on the leading edge of aerofoils of the aircraft [19]. Specific functionality on-a-chip is achieved by combination of the micro-devices, e.g. sensors, electronics and actuators onto a common substrate with integrated circuits. The microsensors detect whatever parameter in the environment they have been designed for through measuring mechanical, thermal, biological, chemical, optical, or magnetic phenomena. The microelectronics then process the information obtained from the sensors and direct the actuators to respond by moving, positioning, pumping, and filtering, thus regulating the environment as desired.

Regarding the high quality analytical devices, fabrication of miniature pumps, electronics, modifying geometries of internal components e.g. the ion trapping region in an mass spectrometer, has resulted in instruments that, though not as sensitive as their benchtop counterparts provide adequate resolution and range for the end user to rely on[97]. Typical size, weight and power (SWaP) specifications that have been achieved with commercial products as listed by market leaders in this field are size 10.6x18.0x4.65cm, weight 0.58kg, and power 9Vdc. Another, more consumer focused strategy has exploited the high resolution and processing power of smart phone technology to create a miniature FTIR[98].

FTIRs typically gain their high resolution by use of an optical interferometer. In the new sensor, a novel crystal technology is used to create a low cost 2D array of optically interfering paths in a configuration where the user can map the array onto a camera sensor. This kind of approach, once the correct wavelength regions are achieved, could provide a low cost, easily accessible sensor allowing human reaction to events to be backed up by analytical data.

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Figure 4-1: Miniature handheld FTIR vs. typical benchtop FTIR, taken from [144] **and** [145]

Regarding aircraft cabin air monitoring, a miniature IMS within a manifold of other sensors has been patented by Airsense Analytics GmbH[99], suggesting that this technology may become a commercial entity. In this particular application steps taken to safeguard performance of the IMS technology within the variable cabin air environment has included the introduction of a membrane to reduce the effects of interfering quantities, such as humidity, pressure and temperature, on the measurement signal, though this has slowed the response of the sensor.

4.3.2. Overcoming COTS limiting factors

Building on from the previous section where whole sensor technologies were miniaturised using the MEMS approach, another focus for research was to overcome the issues encountered in current COTS sensors. Two examples include the potential for drying out of the aqueous conducting solution in EC sensors or the high temperature requirement for increased reactivity and thus sensitivity in metal oxide sensors. One important development, especially for applications in batteries was the replacement of the conducting liquid electrolyte with a solid polymer[100], called a solid polymer electrolyte . A polymer electrolyte is an ion conducting membrane with moderate to high ionic conductivity ($10{-}4 Scm^{-1}$) at room temperature[101]. For gas sensing most commonly used polymer is Nafion, a combination of Teflon with a sulfonic acid which provides high proton conductivity, high H_2O diffusivity, high gas permeability, chemical and electrochemical inertness, and compatibility with processes used for electrode preparation[102].

In general the advantages of using a solid electrolyte include no drying out or leakage of conducting electrolyte, no additional diffusion barrier is required to control concentration of species exposed to the measuring electrode, stable electrode to electrolyte interface as they are bonded directly to the solid polymer. Some hydrated versions of electrochemical sensors have also been created[103], [104] where one side of the electrolyte membrane is flooded with distilled water and so the sensor cell is self-humidifying and independent of external humidity. These sensors can exhibit slower reaction times, as well as resulting in increased cost as compared with their liquid based counterparts. In terms of the gas relating to cabin air quality, one emerging technology of note is the nanostructured electrochemical sensor for monitoring ozone as being developed by Synkara technology[105]. These sensors incorporate a solid polymer electrolyte to increase stability and remove leakage issues and ultra-small electrodes

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featuring nanometer length scales for increased sensitivity, as well as using fabrication techniques that facilitate mass production or low power devices at low cost.

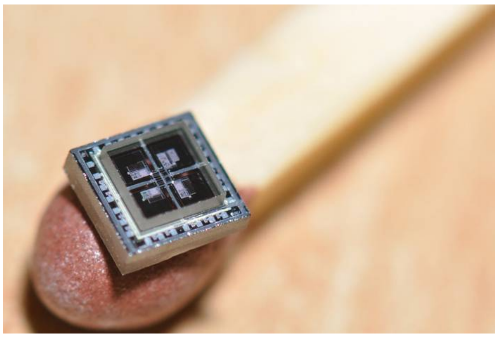

Figure 4-2: MEMS can vary in size from 1 to 100 microns, taken from[146]

Metal oxide sensors have likewise seen considerable attention in an effort to improve selectivity as well as reducing operational demands such as elevated temperatures. One motivation for pursuing micro and nano-scaled technologies is to exploit the properties of materials as they are miniaturized[106], for example nanoparticles have lower melting point than bulk metals and thus are compatible with low temperature microsystem manufacturing. Additionally nanoparticles tend to be more stable and resilient to surface oxidation compared to corresponding bulk materials. Nanostructures, such as nanoparticles, nanowires and nano-crystals offer enhanced sensing performances due to their high sensitivity and fast response as a result of increased surface-to-volume ratio and more targeted chemical reactivity[107]. For example a team in South Korea created a sensing device array intended for gas sensing application, containing multiple types of heterogeneous nanomaterials i.e. CuO nanospikes, ZnO nanowires, and TiO_2 nanotubes, which offered high accuracy and low power consumption[108]. These nanomaterials however still require high temperatures (>200°C) for operation and so another focus of research has been to create materials that are suitable reactive at room temperature.

One such body of work has demonstrated the potential for room temperature gas sensing using specific nanowire materials where the active surfaces reacted in the presence of NO_2, NH_3, and H_2S[109]. Humbert et. al [110] have demonstrated a complementary metal oxide sensor (CMOS) where multiple polymer based structures have been integrated to remove cross-sensitivity issues e.g. CO_2 and relative humidity. The sensor was manufactured using conventional CMOS fabrication techniques and operated at room temperature, all serving to drive down the cost. In terms of air quality monitoring, though not aimed specifically for cabin air, there have been a number of emerging developments, both in research[111] and commercial phase[112] using MEMS based structures to facilitate detection of a range of VOCs. In these two cases, air quality in automotive vehicles has been targeted, using MEMS and metal oxide sensing technology to produce low power, fast small sensors.

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4.3.3. Multi-gas sensor arrays

However, such developments do not improve the biggest potential drawback of MOS sensors, namely their lack of chemical specificity. Attempts to improve this have included temperature profiling and use of different materials and / or materials of different thicknesses in arrays known as electronic noses.

Electronic noses aim to mimic olfactory function where identification of compounds originates from pattern recognition of the responses of several hundreds of highly cross-reactive olfactory receptors, rather than just reacting to a single species as is done for typical COTS sensors. The nose can distinguish many types of volatile analytes, though it is not equally sensitive to all analytes. An electronic nose configuration typically includes a multisensor array, some information-processing system that can handle multiple inputs simultaneously, software with digital pattern-recognition algorithms based on previous calibration, and reference-library databases. The sensor array consists of different sensors chosen to respond to a range of chemical groups whilst being able to discriminate diverse mixtures of possible components. The collective responses from the sensors are then integrated to produce a distinct digital response pattern. Using pattern recognition algorithms, this unique pattern can be compared with the reference database to identify and classify the component mixture.

Two e-nose strategies are described here, an optical based system and an electronic based system. Askim *et al.*[113] took an optical approach using colorimetry (i.e., quantitative measurement of absorbance or reflectance spectra) where a diverse array of chemo-responsive dyes was created. These dyes can be classed according to the intermolecular interactions that cause an optical change. For example Lewis acid-base dyes i.e. metal ion containing dyes, have a preference for strongly odorous VOCs such as amines, or sulphur containing compounds. These dyes thus respond to an odorant or mixture of odorants generating a pattern. Though the colorants of the array may react to multiple odorants, the pattern of the array will be unique. The resultant pattern can be converted into an optical output, thus acting as an optoelectronic nose. For gas sensing applications, the array was digitally imaged before and after exposure, and the colour changes were determined by digital subtraction.

One challenge for these types of arrays is that they do not have very high sensitivity to the less reactive VOC's, which include common indoor air pollutants such as aromatic hydrocarbons or some organic solvents. One strategy to increase the sensitivity towards these less reactive VOCs is pre-oxidation which produces more reactive species such as carboxylic acids, phenols, and aldehydes that produces up to 300 times greater sensitivity. An approach taken by Oord *et al.* [114] has been to use electronics and dedicated software presentations to measure *deviations* from required air quality. To achieve this, a metal oxide based sensor was thermally cycled, thus producing unique graphs corresponding to the chemical reactions taking place. This approach, it was said can provide the reproducibility that optical array sensors cannot, as long as the temperature is well regulated.

By pre-loading algorithms related to these unique graphs for each contaminant of interest, abnormalities from "normal air" can be detected as well as the probable situation it corresponds to e.g. compressed oil-like air. In general both approaches still suffer from ambient conditions if not controlled, e.g. humidity can cause interference with the optical technique while temperature variation can affect the accuracy of the

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metal oxide sensor approach. In terms of application, the hardware and software is available for implementation and so once the potential deleterious constituents are identified, prototype e-noses could be created and tested in the cabin air environment. The technology is low power, low cost and low weight and though not as sensitive as benchtop analytical instruments could provide an early warning system to crew. A major issue, hampering large scale introduction of electronic noses in various application areas, is the reproducibility of the arrays. Manufacturing limitations means that each array will have small dimensional differences from one to the next. This necessitates individual calibration of every electronic nose unit[114]. A further issue affecting many such e-nose or o-nose systems is that if the device is presented with an unknown background matrix, its response may not be predictable. The pattern recognition algorithms are only valid within the boundaries of the original test database; without full chemical specificity, or a reliable mechanism providing chemical classification, the device may not fail safe when faced with an unknown situation.

4.4. Methodologies for continuous cabin air quality monitoring

It is clear from the previous studies that to ensure that cabin air environment is being accurately monitored with the complete picture a multi-sensor approach is needed. Of course this raises a number of questions such as what sensors should be incorporated into this detection system, where should the sensors be located and how many, do these sensors assume a passive role merely alerting staff to potential incidents or will they trigger some safety reactions such as combination of fire detection with water mist suppressions and on-board fuel inerting systems in the event of smoke and fire incidents[115], [116]. A more pre-emptive conceptual approach is suggested in the second section where a computational framework could be created, simulating expected physico-chemical behaviour of materials in aircraft during typical operating conditions so that potential hazards as a result of these scenarios could be understood in advance and any resultant hazards mitigated. The final section considers a more human focussed approach, attempting to reconcile the actual scenario with human perceptions.

4.4.1. A computational approach; pattern recognition & conceptual framework

In the context of smoke and fumes in aircraft, it is worth mentioning a methodology[117] that has been developed for predicting smoke toxicity, based on the toxicological interactions of the complex gas mixtures produced in fire situations. The method works by burning materials using a bench-scale method that simulates the realistic fire situation, and then measuring the concentrations of the primary gases, namely CO, CO_2, O_2, HCN, HCl, HBr, and NO_2. The toxicity of the smoke is predicted using an empirical mathematical model called the N-Gas Model. The model predicts the overall smoke toxicity using a linear combination of the individual concentrations of the substituent gases. Determining an appropriate (linear or otherwise) model is potentially difficult, since toxicological studies tend to consider species in isolation, however the use of a simple linear model may be a suitable starting point. This philosophy offers the potential of working backwards from a measured concentration of a single species or limited number of species, via a model of the likely mix of species, to give the predicted hazard for the overall mixture.

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This type of approach may be advantageous for potential future development of standards where it may not be feasible to have all of the appropriate commercial sensors in-situ. Furthermore it may be a useful predictive tool in the event of more unusual volatiles being detected using the laboratory instrumentation, for which there are no commercially available sensors or where the cost of in-situ detection would be prohibitive. For example it was suggested[79] that the concentrations of bioeffluent VOCs, such as acetone are likely to correlate with those of carbon dioxide as both are related to the metabolic rate, and so CO_2 sensors could be used to provide estimates of bioeffluent concentration if needed. Clearly, the model required could be sensitive to the situation, mix of materials used or type of aircraft.

In terms of sensor selection, studies to date demonstrated that COTS sensors that have been applied in aircraft monitoring applications each have their own strengths and limitations, e.g. electrochemical sensors provide high sensitivity but have a short lifetime (2 years is typical), shortened further when placed in in a low relative humidity atmosphere. Once target species are identified, designing the appropriate monitoring system for the aircraft could apply a chemometric approach. Statistical analysis of COTS sensors based on factors such as their selectivity, sensitivity and robustness etc. could aid design of a sensor manifold that produces the optimum combination of sensors that best addresses end user specifications, e.g. a specific cost or detection limit.

Where compact COTS sensors are not available to monitor certain substances (e.g. TCP), one suggested solution[39] was to incorporate an electronic sensor system that detected a high probability of a certain event based on an anomaly being detected by one or more sensors e.g. a CO sensor registering a high concentration may suggest bleed air contamination. When this occurs, the system would trigger collection of an air sample for delayed analysis. This could provide a cost-effective means of regular air quality monitoring but still allow for fume events to be captured analytically. The system would be used to understand the nature of any perceived air quality issues and widen the dataset used by the industry as an input to the design of real-time measurement systems. Statistical analysis can also be employed for single sensor arrays, where, as described in section 4.3.3, an array of sensors deliberately cross-respond with a substance to produce a pattern that is unique to that substance. The powerful sensing potential for these technologies lies in the application of intelligence via computational analysis which, once optimised for the cabin environment could provide a low-cost low-power sensor solution. In general, a more intelligent approach to this type of monitoring would allow for greater integration with the aircraft operational systems, allowing for more selective sensing options and faster notification in cases of a fume event. It has been found for example in outdoor air quality monitoring that arrays of low cost sensors can be operated in such a way as to make the outputs greater than the sum of their parts, via use of algorithms that take sensor data as their inputs and create meaningful information for their outputs, sometimes negating the need to calibrate the sensors and extending the boundaries of their performance[118].

A pre-emptive proposal is that a conceptual computational framework could be developed to account for the introduction of new materials into aircraft structures. This is similar in some ways to the "materials genome initiative" being undertaken by National Institute of Standards and Technology (NIST)[119], where materials discovery and optimization are beginning to be achieved using computational approaches based on material models, leading to reduced development times and higher performance materials. This framework would include tools capable of simulating the physico-chemical behaviour of the aircraft materials and possible interactions with their surroundings in whatever prescribed conditions are submitted and for relevant lengths of time. This would work in an analogous way to flight profiles in use today where a convergence and hybrid approach of computational and experimental methods is used to ascertain structural fatigue. Being able to predict how materials will behave in aircraft conditions would also help to alleviate concerns amongst the public regarding perceived risk when odours are detected e.g. if during taxiing an odour enters from ground vehicles and is perceived as some malfunction/leak within the aircraft itself.

4.4.2. Human perception approach

Along with the challenge of identifying the presence of potentially hazardous substances, linking health concerns and cited symptoms to particular substances or events has proved to be just as inconclusive. Regardless of whether a fume event has actually occurred or not, the variability amongst passengers in terms of age, health level of distraction and just general mood at the time e.g. being tired, will have a huge bearing on their perceived on-board experience. On-board air conditions such as low relative humidity and pressure can produce adverse effects such as nausea, dizziness or throat irritation, all of which contribute to the occupant's perception of the cabin environment. Some studies have postulated that[18], [46], as well as low relative humidity ozone-initiated chemistry e.g. reaction of ozone (which in itself can cause dry eyes and lips) with cabin materials could be producing additional exacerbating factors e.g. reaction products such as formaldehyde. Indeed it was suggested that the detected odours and resultant health complaints from occupants often do not correspond with expected effects from what is actually measured. It has been suggested[120] thus that making ambient conditions more comfortable, e.g. higher humidity, installation of ozone converters could be a worthwhile strategy. Addressing the occupants' comfort perception, the design of the recent Boeing 787 Dreamliner has included additional features such as a reduction in noise from for example air conditioning systems, increased humidity to 10-15% and additional gas filters designed to remove odours such as dining related smells, more efficiently.

The perception of odour has been studied extensively under standard ground conditions, since this affects human experiences as well as safety measures such as the odorisation of natural gas. Trained (calibrated) odour panels assess odour in controlled conditions, and it is known that chemical analysis of constituent gases can be of limited value in assessing odour levels. Relatively little research has been conducted on the human physiological response to conditions of low pressure and humidity, and its link to human perception of smell. It has been shown that human perception of the taste of food is affected in flight[121], and it is known that this comprises both taste sensors on the tongue and nasal receptors of smell. There may be the potential to investigate these effects further using odour panels in conditions representative of flight.

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5 CABIN AIR QUALITY IN OTHER ENCLOSED SPACES

The subject of air quality is a source of concern across a number of industries, and so it is useful when considering potential methodologies for monitoring cabin air quality to look to other enclosed spaces to see how adequate air quality is maintained. Some of these are discussed in the following sections, namely automobile, submarine and spacecraft environments.

Many standards and regulations that were developed for these industries surrounding air quality strived to achieve the permissible air quality limits given for terrestrial open conditions. These are summarised in Table 5.1; this list is not exhaustive and focuses on "criteria" pollutants.

Typical terrestrial ambient conditions consist of atmospheric pressure ≈ 101kPa, temperature ≈ 20°C, and comfort humidity of ≈ 50-60% R.H.

Table 5.1: Comparable Air quality standards in terrestrial environments e.g. ambient air, workplaces.

Pollutant	Ambient air NAAQS (40CFR part 50)	Indoor air ASHRAE 62-1999	Workplace standard OSHA PEL 8hr TWA
Carbon dioxide (CO_2)		<700ppm (AOAC[a])	5000ppmv
Carbon monoxide (CO)	9ppm (8 hrs) 35ppm (1 hr)	9 ppmv 8-hr***	50ppmv
Nitrogen dioxide (NO_2)	100ppb (1 hr) 53ppb (1 yr)	0.055 ppm [annual]	5 ppm
Ozone (O_3)	0.07ppm (8 hrs)	0.05ppm	0.1ppmv
Particle matter (PM)	$PM_{2.5}$ 12µg/m^3 (1yr) 35µg/m^3(24hrs) PM_{10} 150µg/m^3(24hrs)	$PM_{2.5}$ n/a PM_{10} 150 µg/m3 24-hr	total particulates: TWA 15 mg/m^3
Sulfur dioxide (SO_2)	75ppb (1hr)		TWA 5 ppm (13 mg/m3)

* sea level equivalent (i.e. corrected for altitude), time weighted average during any 3-hr interval
** sea level equivalent (i.e. corrected for altitude), at any time above 32,000 ft
*** based on NAAQS outdoor air standard rather than being specific for indoor air standard

a above outdoor air concentration which are typically 300-500ppm
b Particulate matter 10 µm or less and 2.5µm or less in diameter respectively

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These substances constitute some of the main pollutants of concern. Enclosed spaces, such as in aircraft or submarines ordinarily are hostile to human life and so there are additional challenges to create a habitable environment, without introducing additional pollutants through for example, air generation methods or human activities.

The following sections describe some of the challenges for these environments, outlining potential pollutants, and how as a result the air quality is regulated.

5.1. Automobiles

The cabin environment of an automobile differs from an aircraft in that the ambient conditions correspond to terrestrial conditions e.g. atmospheric pressure, as well as it is possible to self-ventilate with atmospheric air i.e. through opening the windows, or operating the heating, ventilation and air-conditioning (HVAC) system. Despite this, various studies into vehicle interior air quality (VIAQ) have raised concerns that occupants are potentially being exposed to unhealthy concentrations of airborne chemicals, in some cases as much as three times greater than in other indoor environment[122], [123]. The principal contributors to VIAQ, both in new and used vehicles, are thought to be volatile organic compounds (VOCs), which originate from the materials and components used in vehicle interiors, but can also be found in material adhesives as well as in cleaning materials and compounds used in preparing and maintaining vehicle interior surfaces. These include carcinogenic agents such as benzene formaldehyde and styrene. Contaminants may also be drawn in through ventilation systems[124], [125] e.g. exhaust fumes from own and other vehicles, containing carbon monoxide, ozone, NOx gases as well as some of the carcinogenic VOC's already. Poor ventilation, i.e. having the heating on and no windows open could result in a low O_2 atmosphere and a build-up of CO_2. In terms of regulation, standards have been implemented in a handful of countries providing component suppliers and original equipment manufacturers (OEMs) with an independent method of testing chemical emissions profiles of their products. However these standards differ from each other in terms of permissible limits of certain VOCs e.g. some of which are listed in Table 5.2, preparation of whole vehicle samples for testing, the duration of testing phases, and the analytical methods used to assess air samples.

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Table 5.2: Some typical limits VOC limits as recommended by specific standards

Pollutant	Korea Control standard for in-car air quality for new motor vehicles (MOLIT No. 2013-546 (µg/m^3)	China Voluntary standard GB/T 27630-2011 - Guidelines for air quality assessment of passenger vehicles (µg/m^3)	Japan Japanese Automobile manufacturers association Voluntary standard - Guidelines for Reducing Vehicle Cabin VOC Concentration Levels (µg/m^3)
Formaldehyde	210	100	100
Benzene	30	110	-
Toluene	1000	1100	260
Ethyl benzene	1600	1500	3800
Acrolein	50	50	-

The fragmented nature of how vehicles are regulated can become an issue when selling to international markets. In an effort to harmonize requirements for whole vehicle assessments of VOC concentrations in new automobiles, the standard ISO 12219 ("Interior air of road vehicles – Part 1: Whole vehicle test chamber - Specification and method for the determination of volatile organic compounds in cabin interiors") has been created, with a number of different test methodologies available as a 5 part standard (and continues to be updated and expanded)[126]. The typical testing procedures range from testing individual components in a small chamber to a whole cabin test in a large chamber. Here, it is possible to condition the environment, e.g. exposing the cabin to elevated temperatures to simulate prolonged exposure to sunlight.

According to ISO 12219-1:2012, measurements of VOCs are carried out according to standard ISO 16000-6, by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS or MS-FID. On the other hand, sampling and analysis procedure for formaldehyde and other carbonyl compounds is carried out according to ISO 16000-3, by collecting air on to cartridges coated with 2,4-dinitrophenylhydrazine (DNPH) and subsequent analysis by high performance liquid chromatography (HPLC) with detection by ultraviolet absorption. Formaldehyde and other carbonyl compounds can be determined in the approximate concentration range 1 µg/m3 to 1 mg/m3. The VDA 278 standard is a reference method for the determination of VOCs and SVOC using a thermal desorption gas chromatography-mass spectrometry method (ATD-GC/MS). For whole cabin tests, sampling is carried out at the breathing zone of the driver. Temperature measurements are often made at the front dashboard and the parcel shelf at the back.

At this stage, OEM uses material and component test data from, VOC emissions and testing requirements addressed in a variety of ways, depending on the manufacturer, which may combine various elements of existing standards or develop entirely new requirements. In this way and as already mentioned before, various available material and test methods are being harmonized under the ISO 12219 set of standards. Current tests for VIAQ employ sample grabbing, using appropriate grab-bags, sorbent tubes, or appropriate cartridges, which are then analysed using chromatographic techniques to qualitatively and quantitatively analyse the compositions[122], [126], [127].

In recent years, a number of technologies have been used for continuous monitoring in-situ, often being connected to the HVAC system where the ventilation flaps will react to stop air intake when high levels of certain pollutants are detected. From a cost, power demand and compactness point of view, it is thought that Semiconducting Metal Oxide (SMO), Electrochemical (EC) and Infra-Red Optical sensors present as the best choices for installation into vehicles[124], [128]. According to [129] a study where CO and O_2 gas sensor were designed, developed and on-road tested concluded that sensors should not be located in front of passengers where exhaled CO_2, which can displace O_2, and humidity may not reflect the average air quality of the cabin. Additionally sensors must be able to withstand vibrations, electrostatic discharge, electromagnetic interference and other toxic substance that may poison the sensor

5.2. Submarines

Submarines, like aircraft, operate in environments that are hostile to humans, where outside pressures of up to 580psig and temperatures close to 0°C is reached. The (typically battery operated) air circulation systems are designed to condition the air to approximately 26°C and 50% relative humidity, while pressure is kept at atmospheric pressure due to the hull strength preventing compression. The evolution of nuclear powered, and the more recent air independent propulsion (AIP) submarines (a diesel engine that runs on liquid oxygen when diving) facilitated longer periods of full submersion, thus requiring development of new regenerative air purification systems [130]. A number of methods are used to ensure adequate air quality in these environments. When these vessels are diving, “snorting” masts cannot be used; instead oxygen is commonly generated using a self-contained oxygen generator, such as by electrolysis of seawater[131] or chemical reaction e.g. heating sodium chlorate[132]. In terms of air purification, a strong base such as mono-ethanol amine can be used to scrub CO_2 from the atmosphere while CO-H_2 burners, used controlled heating to remove hydrogen and carbon monoxide. Older non-regenerative technologies such as oxygen candles (for oxygen production) and soda lime/lithium hydroxide canisters (for CO_2 purification) are still kept on-board as a quick response in emergency situations[133]. Air purification strategies for targeting other contaminants include a multiple filtration system, such as the Koala Sub installed in Italian submarines, which removes dusts, aerosols and bacteriological pollutants using a number of technologies i.e. mechanical filtration, special activated carbon filtration and ionic filtration and germicide lamp[130]

In terms of air quality, some typical limits on air contaminants for submarines are given below in Table 5.3[134], as well as typical sources[15]

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Table 5.3: Some typical limits on air contaminants and common sources in submarines

Compound	Limit	Typical source	Compound	Limit	Typical source
NO_2	5 ppm	Catalytic burners	NH_3	25 ppm	CO_2 scrubbers
CO_2	5000 ppm	Respiration, refrigeration leak	O_3	0.1 ppm	Electrostatic precipitators
CO	35 ppm	Cooking, smoking, combustion engine exhaust	H_2	2 %	Batteries, biologic sources
SO_2	2 ppm	Fire	Cl_2	1 ppm	Batteries (electrolysis of seawater)
Formaldehyde	2 ppm	Paints, diesel generator	Acrolein	0.1ppm	Lubrication oil, edible fats

Two air monitoring trials on submarines, i.e. the Victoria class HMCS Windsor[135] and the Oberon class HMAS OVENS[136] found that during normal operating conditions air contaminants remained within maximum permissible limits (according to the Royal Navy air specification BR1326).

The trial on the Oberon HMAS OVENS [136] using commercially available gas sensors, showed the main contaminants to be hydrocarbon vapours e.g. from diesel fuels and aerosols e.g. engine exhaust fumes. The concentrations became higher after certain events, such as poor ventilation at engine shut-down. The work demonstrated the potential for use of commercially available sensors, though it was cautioned that cross-checking of data is required to ensure that sensors are not malfunctioning. Additionally the photo-ionisation detection (PID) system is non-specific when it comes to hydrocarbons and so when interpreting concentrations of specific VOC's it must be considered that the PID is reacting to a mixture of hydrocarbons, including some that may be innocuous[137]

In terms of monitoring it is recommended that continuous monitoring of environmental condition such as pressure, temperature, humidity, O2 partial pressure and CO2 partial pressure is carried out [138]. The US Navy use a Central Atmosphere Monitor System (CAMS) MK1 [139], a combination mass spectrometer-infrared analyser which continuously monitors oxygen, nitrogen, carbon monoxide (CO), carbon dioxide (CO2), hydrogen, water vapour, and three refrigerants (R-11, R-12, R-114). The network of gas tubing allows for various locations throughout the submarine to be sampled and monitored. The disadvantages of this system are the initial cost, the reliance on only one gas analyser and the need for networks of tubing, whose length could result in loss of reactive gases[133]. Another, more cost effective approach is the distribution of specific sensors throughout the submarine. This would include a combination of technologies, such as electrochemical and infrared sensors. These represent a cheaper option however have a shorter life and require regular calibration. Portable sensors are often used to perform routine checks or when a specific activity is taking place e.g. monitoring hydrogen during battery changing operations, using a photo-ionisation detector if torpedo-fuel leaks are suspected. Delayed analysis is also performed to monitor any exposure to VOC's such as ozone, amines or acrolein, where sorbent tubes are used and analysed by chromatographic techniques as soon as the crew are ashore again. It has been

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suggested that the air quality systems used in the international space station, such as monitoring using FTIR sensors could be explored for submarine applications.

5.3. International Space Station

The atmospheric conditions around the International Space Station (ISS) consist of a high vacuum where a pressurised environment is almost non-existent at 10^{-27} torr, and temperature extremes of -100 to +100°C are experienced [140]. On the ISS, the atmosphere is maintained at typical atmospheric conditions (14.7psig, 18-26degC and 60% RH) by the environmental control and life support system (ECLSS)[141]. Additional functions that are performed include providing oxygen, potable water, removing carbon dioxide as well as filtering particulates, trace gases and microorganisms from the air. Like the submarine environment, focus has been on regenerative methods for these functions i.e. electrolysis of water to produce oxygen or recovering potable water from wastewater using a distillation process.

In terms of air monitoring, the major constituents that are continuously monitored are oxygen, nitrogen, methane, hydrogen, water vapour, and carbon dioxide. Several of the instruments used to monitor the ISS cabin atmosphere in real-time are listed below [142].

Table 5.4: Air monitoring instruments on ISS US orbit segment, taken from [142]

Analyzer	Technique	Analytes
Major Constituents Analyser	Mass spectrometry	O_2, N_2, CO_2, H_2, H_2O, and CH_4
Compound Specific Analyser – Combustion products	Electro-chemical	O_2, CO, HCl, and HCN
Compound Specific Analyser – Oxygen	Electrochemical	O_2
Carbon Dioxide Monitoring Kit	Infrared spectroscopy	CO_2
Volatile Organic Analyzer (VOA)	Gas chromatography/ ion mobility spectrometry siloxanes	methanol; ethanol; 2-propanol; 2-methyl-2-propanol; 1-butanol; ethanal (acetaldehyde); benzene; xylenes (m-, p-, o-); methyl benzene (toluene); dichloromethane; chlorodifluoromethane (Freon22); 1,1,1-trichloroethane; 1,1,2-trichloro-1,2,2-trifluoroethane (Freon 113); hexane; 2-propanone (acetone); 2-butanone; trifluorobromomethane (Halon 1301); ethyl acetate; isoprene,

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Many of the technologies used on the International Space Station are similar to those that have been mentioned in the previous chapter.

5.4. Summary

The aircraft cabin is not the only environment where concerns have been expressed over air quality. Submarines and the international space station also share the issue of an environment in which crew cannot leave or simply open the windows if there is an incident or funny smell. Exposure times in these environments are longer than in aircraft cabins; a continuous 6 month exposure would not be unusual in both cases. Consequently both types of craft carry a considerable array (rack upon rack) of technology used to continuously monitor air quality and to condition the recirculating air. The methodologies developed for managing the introduction of new materials for example to such environments can offer this project a great deal. Technologies successfully deployed in both continuous monitoring and materials qualification include quantitative GC/MS and COTS sensors, which offer complementary benefits.

The automobile is a further environment in which concerns have been raised concerning cabin air quality. Here, there are numerous polymer based materials used in the cabin, and as with aircraft, the ability to pick up exhaust fumes, VOCs from fuel and particulate from the outside air, as well as the physical proximity of passengers. The cost, size and weight requirements of continuous monitoring are stringent, meaning that only very simple, ultra-low cost sensor technology is deployed, if any.

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6 CONCLUSIONS AND RECOMMENDATIONS

To gain evidence for decision-making with respect to on-board air quality concerns, this study has investigated the state of the art with respect to air quality management and air quality monitoring for aircraft. Its specific focus is air quality contributory factors such as materials used in the cabin interior and in structural parts of the aircraft. It collates learning from this and other applications concerning methodologies used to investigate this area.

The regulation of on-board air must ensure that passenger health, comfort and safety are addressed without compromising the structural and operational safety of the aircraft. Operations such as regular air exchanges, particulate filtration and catalytic conversion all serve to ensure adequate ambient conditions while preventing a build-up of substances that could affect passenger's health e.g. exposure to ozone at high altitudes. As cabin air composition is not continuously monitored and logged, the scientific knowledge base concerning air quality under operational conditions is provided by a number of specific in-flight studies.

Within Europe, EASA is the body that sets standards for any change to current requirements for cabin air quality. The role of aircraft designers and operators is to meet minimum standards as well as have regard for the need to maintain the safety of passengers and crew more generally, and to balance this against other operational requirements (which might also have other safety implications). Thus, decision makers in different parts of the industry require a sound evidence base for those decisions. At the time of writing there is an on-going prenormative research study supported by EASA to collect data on air quality issues, which may lead to a more comprehensive study. Supported by National Aviation Regulators, cabin air quality remains a priority area of investigatory concern, with difficult challenges to fully understand the potential problems and any effective regulatory solutions. Regulatory authorities are constantly reviewing and updating aircraft standards, addressing aspects such as introduction of new technology or reported air incidents that may be militated against through improved design.

To address concerns on cabin air quality, a number of air quality monitoring strategies have been employed, which also served as feasibility studies into the possibility of continuous air quality monitoring in aircraft. Three approaches are highlighted in this report: (i) monitoring by reporting i.e. identifying trends from incident reports, (ii) biomonitoring of personnel i.e. attempting to reconcile symptoms with particular events through medical examination, and (iii) monitoring by measurement i.e. using sensing technology to provide analytical data of air composition. The studies to date have demonstrated the technical feasibility of adopting monitoring procedures based on after-the-fact incident reporting by crew or biomonitoring of crew and / or passengers. Incident reporting can be completed after perceived contamination events, however currently suffers from a lack of standardisation, potential for under-reporting and incomplete reports. Improvements may be possible, however any system based on reporting of infrequent events by individuals is bound to retain an element of subjectivity Biomonitoring studies lacked a standardised procedure across investigations making trends and comparisons hard to identify, and full biomonitoring would be invasive. Studies that employed sensing technologies have

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encountered challenges such as not capturing the specific intended air incidents e.g. a fume event, or sensors malfunctioning due to their unsuitability for the unconducive cabin environment.

To address the need for continuous air quality monitoring in aircraft, some future directions are suggested. These include miniaturization and ruggedisation of current technologies, which could facilitate a distributed sensor network throughout the cabin. Other strategies include a more heavily computational approach whereby sensor arrays such as the electronic nose e-nose or are combined with pattern recognition analysis, to provide unique responses to specific environments. Continuous on-board monitoring has to balance the need for small, low cost and rugged sensors against the number of measurands required. A proposal suggested by this work package is to create a model where aircraft conditions could be simulated e.g. in the event where a new material is introduced into the aircraft, virtual testing could be pursued. In this way potential risks could be identified in advance thus allowing for appropriate mitigation steps to be taken.

In terms of implementation, any consideration of the use of sensors for routine air quality monitoring would need to apply a detailed understanding of the movement of air within the cabin. This is part of cabin design but also more detailed studies for particular reasons are sometimes required. Considerations for sensor location include the desire to monitor close to the location of passengers and crew, ease of maintenance and possible additional roles in fire detection

The application of air quality sensors, whether providing a real-time output or output recorded for later analysis, would require regulatory consideration to enable effective operational use. Would there, for example, be a follow-on need to monitor crew for long-term exposure? If, for example, some pre-determined limit was exceeded during a flight what would be the operational consequences? The regulatory concerns are holistic in that taking some action for health considerations might have negative safety considerations. For example it may sound like a good idea in principle to have more fire detectors on aircraft. However given that most fire warnings are false[143] and that pilots will initiate a diversion, which in itself introduces risks, there may actually be a net safety cost.

Other enclosed spaces such as automobiles, submarines and the International Space Station were looked at. The knowledge of monitoring methodologies and challenges faced in these specific environments can be of use in order to adapt the best methodology and monitoring equipment to the aircraft cabin environment. For example, the automotive industry has taken great effort to try to find common standards for all suppliers and regulators, presenting as a strategy that ultimately could be used as a pathway for the aeronautical industry. Like the aeronautical sector, the submarines sector is also governed by a standard with specifications limits of air contaminants, once again reinforcing the opportunity to use common grounds to try to fine-tune the contaminants of interest to warranty air quality on aircraft cabin.

Both submarines and the international space station carry a considerable array (rack upon rack) of technology used to continuously monitor air quality and to condition the recirculating air. Technologies successfully deployed in continuous monitoring and in materials qualification include quantitative GC/MS, dedicated rack-based instruments to detect known contaminants specific to the environment and

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commercial off-the-shelf (COTS) sensors, which offer complementary benefits. Cross-checking with different technologies is considered necessary to manage possible malfunction during operations. In the automobile sector, the cost, size and weight requirements of continuous monitoring are stringent, meaning that only very simple, ultra-low cost sensor technology is deployed, if any.

To conclude, the report has provided insight into the overall area of on-board air quality including how it is managed. Cabin air quality is an ever evolving subject, and safety and comfort regulations will evolve likewise as we gain further understanding and new technologies are adopted.

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