On-board air quality – Final report on the effect of new materials

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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 deliverable, produced by the Project P7 "Mitigate risks of fire, smoke and fumes", is the final report on the study of effects of new materials, technology and fuel systems on the on board air quality. It contains conclusions about the literature survey, the listing and classification of possible contaminants, the industrial framework proposal and the possible measurement techniques.

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Acronyms

Acronym	Definition
ACARE	Advisory Council for Aviation Research and Innovation in Europe
AE	Auxiliary/reference Electrode
AMDIS	Automated Mass Spectral Deconvolution and Identification System
APU	Auxiliary Power Unit
ASD-STAN	Aerospace and Defence Industries Association of Europe - Standardization
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning
CAMS	Central Air Monitoring System
CARACAL	Competent Authorities for REACH and CLP
CBM	Condition Based Maintenance
CEN	European Committee for Standardization
CFD	Computational Fluid Dynamics
CH4	Methane
CLP	Classification, Labelling and Packaging
CNT	Carbon Nanotubes
CO	Carbon Monoxide
CO2	Carbon Dioxide
COSHH	Control of Substances Hazardous to Health
COTS	Commercial Off The Shelf
decaBDE	Bis(pentabromophenyl)ether
EASA	European Aviation Safety Agency
EC	European Commission
ECHA	European Chemical Agency
ECS	Environmental Control System
E-ECS	Electrical Environmental Control System
e-nose	Electronic Nose

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EPA	Environmental Protection Agency
EU	European Union
EUON	European Union Observatory for Nanomaterials
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FP7	Framework Programme 7
FTIR	Fourier Transform Infrared
GC	Gas Chromatography
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
H2	Hydrogen
H2020	Horizon 2020
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HEPA	High Efficiency Particulate Air
HVAC	Heat, Ventilation and Air Conditioning
IATA	International Air Transport Association
IFCAS	Industrial cabin air quality Framework based on Continuous Air quality Sensing
ILO	International Labour Organisation
IMA	Integrated Modular Avionics
IMS	Ion Mobility Spectrometry
IR&CSA	Guidance on Information Requirements and Chemical Safety Assessment
ISS	International Space Station
JAR	Joint Aviation Regulations
MEMS	Microelectromechanical systems
MS	Mass Spectrometry
NAAQS	National Ambient Air Quality Standards
NDIR	Non-Dispersive Infrared

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NIST	National Institute of Standards and Technology
NO	Nitric Oxide
NO2	Nitrogen Dioxide
NOx	Nitrogen Oxides
O2	Oxygen
O3	Ozone
OECD	Organisation for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
OSHA	Occupational Safety and Health Administration
PBDE	Polybrominated Diphenyl Ether
PEG	Polyethylene Glycol
PEL	Permissible Exposure Limits
PHM	Prognostics Health Management
PID	Photo-ionisation detection
PM	Particulate matter
PSIG	Pound Square Inch Gauge
REACH	Registration, Evaluation, Authorization, Restriction of Chemical substances
RIPoN	REACH Implementation Project on Nanomaterials
SAE	Society of Automotive Engineers
SESAR	Single European Sky ATM Research
SO2	Sulphur Dioxide
SRIA	Strategic Research and Innovation Agenda (from ACARE)
STEL	Short Term Exposure Limit
SVOC	Semi Volatile Organic Compound
SWaP	Size, Weight and Power
TCP	Tri Cresyl Phosphate
TD	Thermal desorption

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TWA	Trans World Airlines
UN	United Nations
USA	United States of America
VIAQ	Vehicle Indoor Air Quality
VOA	Volatile Organic Analyzer
VOC	Volatile Organic Compound
WAIC	Wireless Avionics Intra-Communication
WCOT	Wall Coated Open Tube
WE	Working Electrode
WP	Work Package
WPMN	Working Party on Manufactured Nanomaterials

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EXECUTIVE SUMMARY

Problem Area

Aircraft architectures, including propulsion concepts, will change disruptively in response to the increased air traffic projections and the global environmental issues. Safety should not be compromised by these changes. These changes allow for a thorough review of the aircraft cabin of the future. This includes the cabin air quality of the future, on which this study is focussing.

Description of Work

This study investigates the state of the art and developments, including related technologies, in cabin air quality, societal trends in air quality, and competitiveness for industry offered by cabin air quality. This study is the final synthesis report of Future Sky Safety Work Package 7.3 "On-board air quality". The WP7.3 team has worked through a number of internal investigations on subjects such as: substances in cabin air and their classification; cabin air sensing; and an industrial framework for cabin air quality.

- The state of the art with respect to air quality definition (e.g. with respect to constituents) and management, air quality monitoring, air quality contributory factors (material, structural) for aircraft cabin interior (and other applications such as submarines, ISS, automotive) has been reviewed. To address concerns on cabin air quality, a number of air quality monitoring strategies have been suggested, which also served as feasibility studies into the possibility of continuous air quality monitoring in aircraft. Three approaches have been studied: (i) by reporting, (ii) by biomonitoring of personnel, and (iii) by monitoring from measurement of selected substances/ contaminants in the air. To address the need for continuous air quality monitoring in aircraft, some future directions/ strategies have been suggested. A large panel of aspects/questions, but also challenges and limitations for future methodologies (in-situ real-time or delayed air analysis, computational approaches) and technologies (bleed air, commercial and research sensors), have been considered: e.g. movement of air in cabin (design of cabin, virtual testing, risks analysis); sensors size (miniaturization), type and locations with respect to multiple objectives (continuous monitoring of the air quality, fire detection, maintenance); regulatory aspects (to enable effective operational use); human perception; added safety costs. Finally, the exercise included: the identification and adaptation of the best methodology and monitoring equipment (quantitative Gas Chromatography/ Mass Spectrometry (GC/MS), rack-based instruments, Commercial Off The Shelf (COTS) sensors, …) from existing standards; the application of other enclosed spaces air quality related specifications to the aircraft cabin environment; the fine-tuning of contaminants of interest to warranty air quality on aircraft cabin (incl. composite materials flammability and toxicity, temperature and humidity, pressure, …). Eventually, general conclusions and recommendations have been proposed.
- A general reflection about the adequate approach (embracing safety, health and comfort) to deal with Cabin Air Quality (CAQ) has been led to configure an industrial framework proposal, framed by

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the need to have cost defensible solutions. Several issues were addressed: concerns on bleed air contamination; introduction of new materials in cabin environment (e.g. based on REACH regulation); increased air traffic projections but also environment changes, increased awareness and active interaction of citizens/ passengers, etc.; data sharing observatory. A scenario of a citizen based approach for cabin air quality was also addressed, namely to understand how incumbent stakeholders – regulators, operators, OEMs – could use them for overall value creation and safety and health enhancement. Recommendations (aligned with the creation of the Cabin Air Quality Measurement Committee by SAE) have been built up for safety perception and possible research directions to improve CAQ with respect to several general axis: synergies between cabin safety and comfort research; full demonstrators/simulators to support academia studies; CAQ big-data observatory; development of a target specification (species, accuracy, size, etc) for gas sensors; low-cost sensors smart (e.g. e-nose) network; CAQ modelling, with multi-fidelity, simulation framework to enable a holistic CAQ approach; certification cost reduction. Finally, a FSS Industrial cabin air quality Framework based on Continuous Air quality Sensing (IFCAS) blackbox concept has been proposed, which gives a generic framework, for instance to place sensors and their processing on-board.

In addition, an experimental set-up along the interest for cabin air quality was investigated, developed and set-up. The first, preliminary experiments with this set-up were carried out.

Results & Conclusions

There is a continuous development of technological innovations in aircraft such as the electrification of propulsive and non-propulsive power and the development of new cabin air filter technology. These innovations can contribute to improvements in cabin air quality. In addition, there is a growing interest to address complex (cabin) air quality issues related to comfort, health, and safety. Some key guidelines for cabin air quality assessment are given. To further address this interest, the "**I**ndustrial cabin air quality **F**ramework based on **C**ontinuous **A**ir quality **S**ensing" (**IFCAS**) is proposed. The core of the IFCAS is a well-placed network of low power, low weight sensors that is distributed across the cabin. Other elements of IFCAS concern the on-board post-processing, storage, and distribution of data during a flight, the storage and sharing of flight data potentially between different stakeholders, and the analysis of the big data that is gathered, potentially combined with modelling and simulations. It is concluded that, depending upon confirmation of stakeholder interest, the development of IFCAS can be started in the near future, while progressively extending it with the latest sensing technologies. Recommendations are given for further research and development of IFCAS to increase its maturity.

Applicability

Applications of IFCAS are foreseen during flight – for example to reduce the number of false fire alarms - and on different time-horizons after flight, including prognostic health management and condition-based health management, evidence-based answers to concerns, and methodical, engineered approaches to improve comfort and to better design the aircraft to control the air inside the cabin.

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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 Programme research focuses on 4 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 [1]).

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], [3] have shown that “fire/smoke resulting from impact” accounted for 36% of all fatal accidents. Only 5% of fatalities are directly caused by “fires in flights”. Often aircraft occupants have survived the impact only to be incapacitated by toxic fumes and/or heat. Temperatures can rise above 600-700°C after only three minutes [4]. Toxic fumes may originate from components such as aviation fuel and combustible materials. Such materials are 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 existing materials,

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- 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 the final deliverable, aims to investigate the possible effects of new materials and technologies on the on-board air quality with the objective to further improve the air quality.

1.3. Research objectives

The overall objective of WP7.3 is to investigate potential opportunities offered by technical developments, including new materials, which 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, and 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, both in flight and during initial materials evaluation.

The objective of this deliverable is to provide a synthesis of the results obtained by WP7.3.

1.4. Approach

The WP7.3 team has worked through a number of internal investigations on subjects related to the WP7.3 objectives such as: substances in cabin air and their classification; cabin air sensing; and an industrial framework for cabin air quality. Results from investigations were shared frequently within the team. Discussions on the results have led to the initiation of further investigations. A part of the results has already been published in the deliverable D7.6 "On-board air quality: literature review and methodological survey" [1]. Part of the investigations in WP7.3 concerned the development of an experimental set-up along the interest for cabin air quality. In addition, first experimental results with this set-up were obtained.

For this final synthesis deliverable of the WP7.3 the results from the prior work were collated and reviewed against the latest developments and insights. Some parts of previous work could be used directly in the synthesis; some other parts from previous work needed further investigations. The latter parts were rewritten from a different perspective, updated, or extended. The synthesis of the experimental investigations in WP7.3 is reported as well in this deliverable.

1.5. Structure of the document

The document consists of six chapters. Chapter 2 contains the overview of the state of the art in on-board air quality, with a focus on cabin air quality, including developments and trends in the whole chain of cabin air quality that have been observed. In Chapter 0 relevant state-of-the-art, developments, and trends in air quality in other environments than the aircraft's cabin environment are highlighted. Chapter 0 focuses on the assessment of the quality of cabin air. The focus is on the use of sensors for such assessment. In addition, general guidelines for the assessment of the quality of cabin air are given. Chapter 5 introduces the industrial framework for continuous air quality sensing that is proposed by WP7.3. The concept for the framework is proposed and analysed against the potential benefits for different stakeholders of cabin air quality. Finally, Chapter 6 presents the conclusions and recommendations.

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2 ON-BOARD AIR QUALITY

2.1. Overview and definition

On-board air is a key element regarding the safety, health, and comfort of passengers and crew in aircraft across their various operational environments, including the hostile environment at cruise flight levels, which may be above 30,000 feet for commercial aircraft. The aircraft's environmental control system (ECS) controls the on-board air for passengers and crew. Its main function is to ventilate, providing fresh air of appropriate pressure and temperature, to the passengers and crew from their entry into the aircraft until their exit. In this study the part of the aircraft in which the air is controlled by the ECS is referred to as the "cabin". The cabin thus includes not only the cabin as the aircraft compartment where the passengers are seated, but also other aircraft compartments such as cockpit, toilets, galleys, cargo compartments, and crew rest compartments. It is this cabin air that is the main focus of the study.

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. For avoidance of doubt, cosmic radiation is not considered as a characteristic of cabin air. In this report noise is excluded.

It should be noted that the aircraft has on-board air that is not in the cabin but still contributes to safety of passengers and crew. Such on-board air concerns for example air in the combustion chamber of engines and air in fuel tanks. Safety of combustion chambers and fuel tanks is addressed in the aircraft regulations. Due to the TWA-800 accident [6] the flammability of fuel tanks received a lot of attention in recent years. Nowadays the flammability of fuel tanks is addressed in regulation and adaptations to past designs are finding their way into the aircraft fleets. Faced with the increasing global interest in air quality

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for humans (see Section 2.4 and Chapter 0), the WP7.3 team focused its work mostly on cabin air quality. The control of cabin air is most challenging for pressurised aircraft. The study will focus on such aircraft.

In this chapter, the following aspects of cabin air quality are addressed:

- How is cabin air quality controlled during aircraft operation and how are these operational aspects addressed during development?
- What are the actual developments regarding cabin air quality and what concerns do they address?

2.2. How the cabin air quality is controlled during aircraft operation

2.2.1. Control of the physical characteristics

In general terms, in most aircraft models, the cabin air is replenished with a mix of 50% of compressed air from the engines and 50% highly efficiently filtered recirculated air. When on the ground, it is usually the auxiliary power unit (APU) that supplies compressed air to the environmental control system [7]. This unit is a small jet engine, which is typically located in the tail cone of the aircraft. The APU also provides electric power when on the ground, as well as pneumatic pressure to start the main jet engines when taking off. The Boeing 787 is the exception, using electrical compressors to provide pressurised cabin air.

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 (following precooling) typically has a temperature of 250 °C and a pressure of 340kPa [8]; this is then conditioned within the ECS to obtain comfortable levels in the cabin (around 23 degrees and up to 8000 ft cabin altitude pressure [24]).

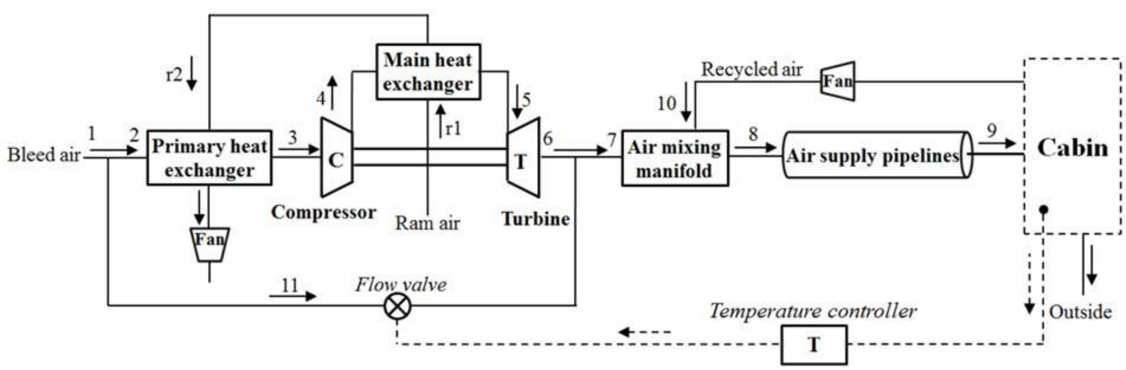

Figure 1 Schematic of typical ECS system in aircraft. (C) corresponds to compressor, turbine (T), r (ram air), taken from [9]

Most of the bleed air is passed through a pneumatically (or sometimes mechanically/electrically) driven air cycle machine, after which the air is introduced in 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 [8]. Pressurisation and ventilation is controlled by varying the opening of cabin outflow valves [10].

2.2.2. 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 personal care products, bio effluents including body odours or exhaled carbon dioxide; if the latter is present in elevated concentrations (e.g. above 3,000ppm [11]) this can cause headaches, fatigue, and general feelings of discomfort. Building materials, furnishings, and cleaning products are known to emit many different chemical substances, depending on their composition [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. bio effluents and chemical substances, along with biological components such as bacteria, viruses, fungi 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 constituents, ventilation is the key strategy, where, in the case of aircraft environments, outside air is used to dilute substances in the air and flush them out of the cabin. Approximately 50% of the air is recirculated and passed through high-efficiency particulate air (HEPA) filters. These filters provide up to 99.97% efficient removal of particles with typical diameter greater than 0.3µm (including bacteria, fungi and larger viruses) [14]. Smaller particles may also be removed as a result of other properties of the filters than the pore size.

Substances introduced in 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 [8]. However one-off, sporadic events may be too brief for intervention and particulate filters cannot remove volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs) or lighter gases. Mitigation strategies include, for instance, regular inspection and maintenance (such as of oil seals and ducts [15]), aided by component failure warning (e.g., through the use of monitors such as overheat detectors [16]).

Typical for aircraft in comparison with terrestrial environments are the potentially elevated ozone levels. Commercial aircraft typically cruise at an altitude of 30,000-40,000ft [17] where, though the air is virtually free of most contaminants, ozone levels may be elevated relative to the terrestrial environment, with

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concentrations ranging from tens to hundreds of ppb [18]. Statistical analysis has suggested that ozone at these levels can be associated with dry eyes, nasal stuffiness and some respiratory symptoms [19] and so exposure levels are reduced Aircraft operating at these altitudes typically also possess equipment for ozone removal (usually catalytic converters).

An overview of potential constituents of cabin air and mitigation strategies is given in Table 1.

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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], [21]
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 [22].
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 suppression 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	

Table 1 Potential constituents of cabin air, including their sources and mitigation strategies that have been employed to ensure air quality is not degraded.

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2.3. How the cabin air quality is controlled during aircraft development

2.3.1. Certification, testing, and standards for cabin air quality

Aircraft development is governed by regulations. Regulations put certification requirements on the ECS in order to ensure aircraft safety, including its own system safety. For example, 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 [21].

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" issues approval of a manufacturing design for specified materials, parts, and appliances. Later stage "airworthiness certification" 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. This includes its normal operating conditions to a safety margin, including abnormal and extreme conditions. Testing is thorough, involving in extreme cases controlled destruction of specimens.

Adjacent to the certification regulation, other bodies than the regulatory authorities develop standards and other regulations. Certification regulation may refer to such standards and other regulations.

Recently (2014 and 2016) ASD-STAN has published the technical reports ASD-STAN-TR4618 and ASD-STAN-TR4666. ASD-STAN –TR4618 [23] covers aircraft internal air quality standards, criteria and determination methods. It includes safety, health, and comfort criteria for selected marker compounds to define the performance of the ECS and environmental criteria. ASD-STAN-TR4666 [24] is focused on aircraft integrated air quality and pressure standards, criteria and determination methods. The standard distinguishes between safety, health and comfort conditions for passengers and crew under a variety of phases of flight, including embarkation and disembarkation.

Both standards list normative references that are indispensable for the application of the documents. Many of these references are related to determination methods, including measuring. In addition, the following references concern standards:

- FAR 25, Airworthiness standards — Transport category airplanes, specifically CFR 14 Part 25.831 (1997), Ventilation and Heating,
- JAR 25, Large aeroplanes (this is now superseded by EASA Certification Standard CS25 [21]),
- ASHRAE Standard 62.2 (2007), Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings,
- ASHRAE Standard 161 (2007), Air Quality within Commercial Aircraft.

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In D7.6 [1] the following standards for air quality in terrestrial environments have been compared on a number of main substances: NAAQS (40 CFR part 50) for ambient air, ASHRAE 62-1999 for indoor air, and OSHA for workplace.

In 2016, IATA requested SAE International to develop standards for portable or fixed installation sensors for CAQ. A new committee, "Cabin Air Quality Measurement Committee" is in the process of creation, with different participants and close collaboration with the already existing AC-9, Aircraft Environmental Systems and E-31, Aircraft Engine Gas & Particulate Emissions Measurement Bleed Air Panel [24]. In Europe the CEN TC 436 was created in 2014 to develop European standards on "Cabin air quality on civil aircraft - Chemical agents" suitable for all stakeholders including passenger organizations, crew associations, aircraft and engine manufacturers, parts and components manufacturers, airlines and OSH (Occupational Safety and Health) representatives [26], [27].

For more information about certification, standards and tests is referred to Section 2.1 and Chapter 3 of [1].

2.3.2. REACH and classification of substances in cabin air

The Registration, Evaluation, Authorization, Restriction of Chemical substances (REACH) regulation is the Regulation (EC) No 1907/2006 of the European Union to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry [28]. REACH regulates what substances are allowed in production and use of products, and standardizes the documentation, signalization and use in their life cycle. REACH is managed inside the European Chemicals Agency (ECHA). It is thus of transversal application, affecting all industries, including aviation.

Inclusion of substances under REACH follows an evaluation process started by a member state request, after an evaluation of possible concern for human health of the environment. This request is made to ECHA that will evaluate the request and decide on follow-on actions. These actions will support an evidence based process that can take several years until a final decision is made. The end result can be a ban on the substance use, restriction or dispel of concern.

A primary chemical safety part of a substance is clear information on the hazardous properties of that substance. The classification of these substances according to their hazard characteristics follows a classification system. In the EU, the classification and labelling of hazard chemicals is governed by Regulation (EC) No 1272/2008 of 16 December, which is also known as the Classification, Labelling and Packaging (CLP) Regulation. The REACH Regulation does not include classification criteria for chemical substances or mixtures; however, REACH refers to the CLP Regulation.

The CLP Regulation intends to ensure a high level of protection of health and the environment as well as the free movement of substances. The CLP regulation integrates the classification criteria of the United Nations Globally Harmonized System of Classification and Labelling of Chemicals (UN GHS) [29] in Community legislation.

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According to CLP regulation, the classification of a substance or mixture reflects the potential risks that it poses to humans and the environment. Hazard identification is the process by which information about the intrinsic properties of a substance or mixture is assessed to determine its potential to cause harm. If the nature and severity of an identified hazard meets the classification criteria in Annex I to the CLP Regulation, a certain hazard class will be assigned to the substance or mixture. There are hazard classes for physical hazards, health hazards, and environmental hazards (annex VI of CLP regulation) and they are divided into hazard categories (the division of criteria within each hazard class, specifying the severity of the hazard). Hazard classes are described below:

Physical hazards: Explosives; flammables gases; flammables aerosols; oxidizing gases; gases under pressure; flammable liquids; flammable solids; self-reactive substances and mixtures; pyrophoric liquids; pyrophoric solids; self-heating substances and mixtures; substances and mixtures which in contact with water emit flammable gases; oxidizing liquids; oxidizing solids; organic peroxides; corrosive to metals.

Health hazards: Acute toxicity; skin corrosion/irritation; serious eye damage/irritation; respiratory or skin sensitization; germ cell mutagenicity; carcinogenicity; reproductive toxicity; specific target organ toxicity – single exposure; specific target organ toxicity – repeated exposure; aspiration hazard.

Environmental hazards: Aquatic toxicity (acute/chronic); hazardous to the ozone layer.

A core principle of the CLP Regulation is the 'self-classification' of a substance or mixture by the manufacturer, importer or downstream user.

2.4. Developments regarding cabin air quality and what concerns are addressed

2.4.1. Comfort

Comfort provides the most visible value differentiator for the aircraft operator. It also contributes to safety enhancement by providing for an improved work environment for the crew through, for instance, leading to greater productivity [30], [31] and less fatigue and better long-term health. In any case, improvement in comfort should not compromise safety and health.

Cabin air quality has a big impact on the aircraft occupants comfort level. Bad smells and odours are at the base of the comfort pyramid, see Figure 2. This leads to an interest in solutions that go beyond eliminating particulates, like the HEPA filters already on-board current models, to those targeting VOCs and odours. In addition, technologies start to appear for tailoring the olfactive space with scent signatures for the cabin, which has long been cultivated by some automotive manufacturers [33].

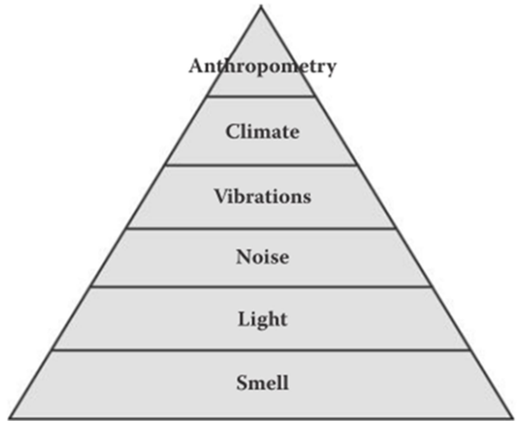

Figure 2 Comfort pyramid from [32]. Smell is the overruling factor. On the other hand, the lower factors - smell, light, noise, vibrations - are of such high standard on current aircraft that main focus has been on anthropometry improvements.

2.4.2. Trends and developments at the aircraft level

Aircraft and cabin developments

Original Equipment Manufacturers (OEMs), suppliers and operators strive for new technologies that bring a market differential to their clients (operators and passengers) and may improve comfort and safety. This plays out in different timescales. Airframes can have a 20 to 30 years plus operational life, meaning their presence in the air transport system for long times. On the other hand, because most are leased or sold during their lifetimes, cabin upgrades, refurbishment and changes also happen during these timespans. Considering this, two main pathways to introduce new technologies into the aircraft cabin can be foreseen: 1) new types arriving in the market; 2) through replacement and refurbishment of old cabins.

Focusing on 1), new aircraft architectures are being introduced into the aviation ecosystem. In addition, new propulsion concepts such as contra-rotating open rotor engines and (hybrid-) electric propulsion lead to significant changes in aircraft architecture. Future cabins will certainly benefit, for instance, from the trends for more electric aircraft, driven by fuel savings and emissions cutting goals. Another factor is the growing introduction of composites into new types. Both these, and others, help to lower altitude pressure and to increase humidity in the cabin. This can already be seen in such types as the Boeing 787 and Airbus A350 or executive types like the Embraer Legacy 500. Additionally, the drive towards more electric aircraft may tend to introduce more electric ECS (E-ECS) like in the Boeing 787. Recently (2016), under the Clean Sky program in Europe, a new E-ECS was flight tested with a 50kW compressor [34].

For 2), refurbishment happens in the aircraft life cycle, when the aircraft goes to a new operator or has a major inspection: The D-check. Generally, D-checks happen every four to six years [35], [36] and are many times also used to refurbish the aircraft interior. One such example was the recent announcement of adoption of new air filters by Easyjet [37].

Recent cabin air quality investigations and publicity

In 2017 EASA published two studies that refer to cabin air quality concerns as background. There are concerns among the international governments, pilots, cabin crew and passengers and other stakeholders of commercial jet aircraft about possible health risks associated with reports of the presence of fumes in the air supplied to aircraft cabins. The EASA study [38] is the final report of a preliminary cabin air quality (CAQ) measurement campaign on board of commercially operated large transport aircraft. This study is perhaps the first study to compare measurements on-board large commercial aircraft with bleed air ECS and measurements on-board large commercial aircraft with non-bleed ECS (Boeing 787). The EASA study [39] addresses the characterisation of the toxicity of aviation turbine engine oil as a mixture of compounds, including potential pyrolysis breakdown products.

EASA, together with the EC, has initiated the FACTS project. The purpose of this project is to find FACTS on the subject of aircraft cabin air quality, and in particular on the potential toxicity of contaminated bleed air [40].

With reference to similar concerns a lot of publicity has been seen in recent years in journals and newspapers, at conferences (e.g., the International Aircraft Cabin Air Conference [41]) and in means addressing the public at large, such as television and internet.

Emerging technologies for enhancing cabin air quality

Technologies for enhancing cabin air quality are emerging from the H2020 research and innovation programme. The BREEZE project [42] "Hybrid photocatalytic air filter for removing pollutants and odours from aircraft cabin zone"- is a Clean Sky project for cleaner air in the plane, with the main objective of developing an alternative recirculation filter to improve cabin air quality with validation for elimination of VOCs, polybrominated diphenyl ethers (PBDEs), ozone and biological contaminants. The ADVENT project [43] – "Advanced ventilation techniques for modern long-range passenger aircraft to promote energy management systems"– addresses alternative or novel ventilation concepts with enhanced heat removal efficiency and local ventilation efficiency.

Such technology developments may be further matured by the industry to finally appear on-board aircraft, see for example [37].

Main substances under investigation in REACH and relevant for cabin air quality

Related with cabin air quality, two main substances can be highlighted within the context of REACH: Bis(pentabromophenyl)ether (decaBDE), used as an additive flame retardant in different industries, and TCP, a possible byproduct of pyrolysed lubricant oils that can penetrate the cabin in bleed air architectures in the case of seal degradation.

decaBDE can be found in the aviation industry used in applications in the plastics/polymers for electrical and electronic equipment. It is also used in the textile sector as interior fabrics in aircraft and in adhesive in the aeronautical sector for civil and defence applications. Because it has been classified as very

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persistent and bio accumulative, several restrictions were imposed on its use. A waiver was obtained for aviation applications, because of flight safety concerns but it is expected this exemption will not hold in the long term. Several OEMs already have cleared this substance from their aircraft (e.g., Embraer) and the issue mainly affects some operating models and not new types.

In 2012, TCP was requested to be placed on the list of substances to be evaluated. A decision made in June 2016 requested information on, amongst others, neurotoxicity, exposure assessment and medical inquiries. The deadline to provide the information is at latest 2nd August 2018. A period of assessment will follow with a further decision expected by August 2019, which can lead to a final deliberation or request for further information [44].

2.4.3. New materials

There is continuous research on new materials and their application in aircraft. In this section, we focus on composite materials, more specifically on the use of nanomaterials, as an example of safety considerations about new materials in general, not only for aircraft applications. The impact of these safety considerations on the application in aircraft is addressed as well.

Composite materials can provide a much better strength-to-weight ratio than metals: sometimes by as much as 20% better [45]. Composites are versatile, used for both structural applications and other components, in all aircraft and spacecraft, from hot air gondolas and gliders, to passenger airliners or fighter planes. Several types of composites, as the ones reinforced with fiberglass, carbon fibre and aramid fibre are commonly used in the aerospace industry. Nevertheless, composite technology continues to advance. The advent of new types such as nanotubes may accelerate and extend composite usage.

One of the main expected applications of nanomaterials in aircraft is in the airframe structure as they promise to be lighter and stronger than other kinds of widely used composites. In this way, an indirect contribution is given to cabin air quality, as the airplane will be capable of sustaining a higher cabin pressure and humidity levels, which may allow a more comfortable journey for airline passengers. The other major promise of these materials is enabling multi-functionality, for instance enabling electrical conductivity in composites, self-sensing structures or heating capability, among others.

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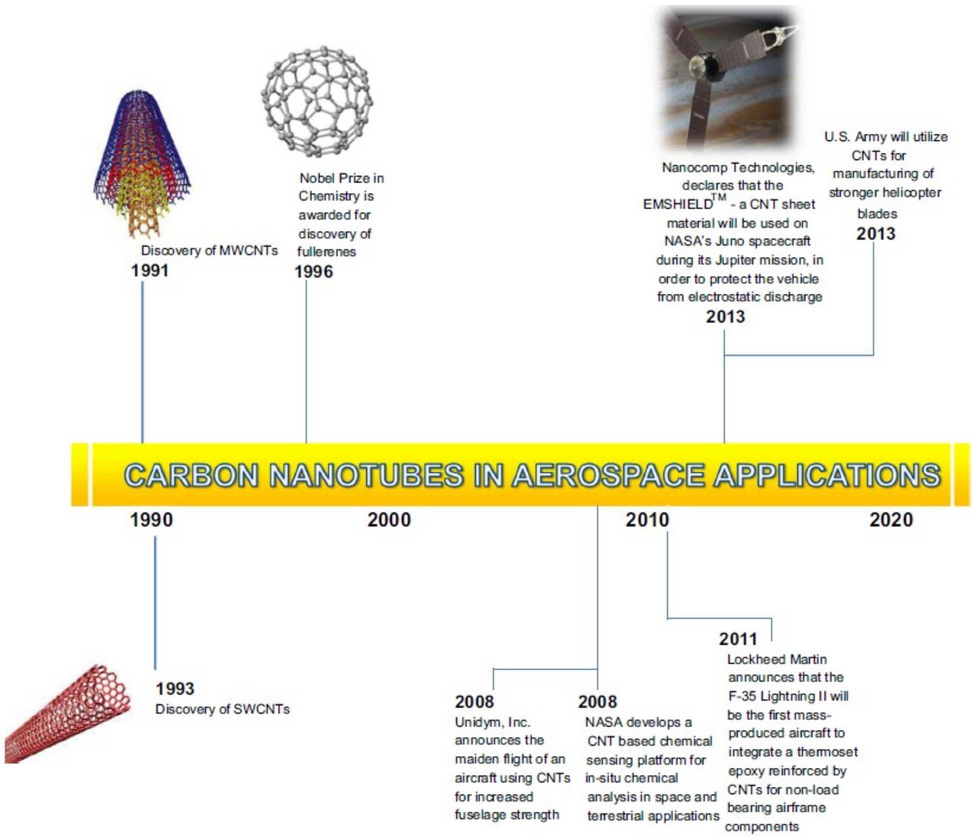

Figure 3 Milestones of carbon nanotubes (CNTs) and their application in aerospace sciences **[46]**

Nanotechnology has been identified as one of the key enabling technologies for the EU competitiveness. Several initiatives within the EU address safety issues related to nanomaterials. The NanoSafety Cluster [47], for instance, provides a one-point-entry to different projects regarding nanomaterials safety issues and is also active in the front of international cooperation. The European Commission has setup the European Union Observatory for Nanomaterials (EUON) [48], to give information for the public, industry, policy makers, etc., on nanomaterials safety, market and technology. The EUON is maintained by ECHA, which is also leading the directives on the use of nanomaterials through REACH, see Section 2.3.2.

Outside the EU, the Organisation for Economic Cooperation and Development (OECD) established the Working Party on Manufactured Nanomaterials (WPMN) and has recently released test guidelines that target specifically nanomaterials [49].

The Commission launched a comprehensive REACH Implementation Project on Nanomaterials (RIPoN) in 2009 to provide advice on key aspects of the implementation of REACH with regard to nanomaterials concerning Substance Identification (RIP-oN1), Information Requirements (RIP-oN2) and Chemical Safety Assessment (RIP-oN3).

Based on the scientific and technical state of the art recommendations in these reports ECHA published three new appendices on 30 April 2012, updating Chapters R.7a, R.7b and R.7c of the Guidance on Information Requirements and Chemical Safety Assessment (IR & CSA). These three new appendices were recommendations for registering nanomaterials. The final report was available but it was not possible to reach consensus on the recommendations amongst the experts. Further work of the Commission, in collaboration with the Competent Authorities for REACH and CLP (CARACAL), were required before recommendations could be forwarded to ECHA. In May 2017, consensus was reached and ECHA published the updates of the Appendices to Chapters R.7a [49], R.7b [50], and R.7c [51] of the Guidance on IR&CSA (Endpoint specific guidance) on "recommendations for nanomaterials" regarding human health endpoints. The three draft appendices provide a number of updates on e.g. testing and sample preparation, advice on non-testing methods, considerations regarding lung-overload, repeated dose testing and update on mutagenicity.

It is noteworthy that future implementation of CNTs in particular for manned air and space vehicles should be considered solely on the basis that full health impact assessment and studies are conducted on the possible implications that such implementation might have on the health of the passengers and crew. Such implementation will most likely solely take place, following a rigorous certification process, in which the aforementioned factors have been accounted for. This specific certification process is further one of the reasons due to which a rapid implementation of CNTs in aeronautics and in particular commercial aircraft has not yet been actualized.

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3 AIR QUALITY IN OTHER ENVIRONMENTS

3.1. Outdoor air quality

Whereas outdoor air quality monitoring has been carried out already for many years in western industrialised environments, in recent years major developments have occurred:

- Air quality concerns and their public awareness have significantly increased in the fast-growing industrial regions in Asia, where the outside air pollution has worsened, and in many western main capitals,
- Low cost sensor devices have become available as a product, either stand-alone or able to be coupled to portable multipurpose devices like smartphones. Many of these products are already designed to send data to online databases, for sharing with other users or the general public. The convenience of these sensor devices is increasing,
- The number of crowdsourcing initiatives has increased fostered under "active citizenship" banners.

In Europe, the development of citizen observatories was already funded in the Framework Programme FP7 in projects such as Citisense [53] and "Odour Monitoring and Information System based on Citizen and Technology Innovative Sensors" (OMNISCIENTIS) [54]. In the H2020 programme, the project hackAIR [55] has the objective to develop and pilot test an open platform that will enable communities of citizens to easily set up air quality monitoring networks and engage their members in measuring and publishing outdoor air pollution levels, leveraging the power of online social networks, mobile and open hardware technologies, and engagement strategies. The H2020 project ClairCity [56] aims at citizen-led air pollution reduction in cities.

USA initiatives include the EPA initiatives Air Sensor Toolbox [57] to educate the citizen how to measure and share air quality data and Community Multiscale Air Quality Modelling System [58] to provide an open-source modelling suite for air quality simulations.

3.2. Indoor air quality

Some of these initiatives for outdoor public observatories also cover indoor air quality (e.g. Citisense [53]). For indoor air quality, there have been many initiatives on sensors and sensor networks, which will be discussed in Chapter 0.

This section focuses on indoor air quality in specific environments that show similarity with aircraft cabins: automobiles, submarines, and the International Space Station (ISS).

Despite the possibility to self-ventilate the car with atmospheric air, 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 VOCs. Contaminants may also be drawn in through ventilation systems[124], [125] e.g. exhaust fumes from own and other vehicles.

This awareness of air quality is already leading to innovation. In recent years, a number of technologies have been used for continuous monitoring in-situ, often being connected to the Heat, Ventilation and Air Conditioning (HVAC) system where the ventilation flaps will react to stop air intake when high levels of certain pollutants are detected. Innovations come on the market as can be seen from the Tesla bio defence mode [59] or Volvo Interior Air Quality System [60].

Submarines, like aircraft, operate in environments that are hostile to humans, where outside pressures of up to 580psig and temperatures close to 0°C are reached. The evolution of submarines facilitated longer periods of full submersion, thus requiring development of new regenerative air purification systems [61]. 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 [61]. The US Navy use a Central Atmosphere Monitor System (CAMS) MK1[62], 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). 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 certain 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.

The atmospheric conditions around the ISS consist of a high vacuum where a pressurised environment is almost non-existent and temperature extremes of -100 to +100°C are experienced [63]. Like the submarine environment, focus has been on regenerative methods, e.g., electrolysis of water to produce oxygen.

Major air 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 [64].

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Analyser	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	Electrochemical	O_2, CO, HCl, and HCN
Compound Specific Analyser – Oxygen	Electrochemical	O_2
Carbon Dioxide Monitoring Kit	Infrared spectroscopy	CO_2
Volatile Organic Analyser (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,

Table 2 Air monitoring instruments on ISS US orbit segment, taken from [64].

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4 ASSESSMENT OF THE QUALITY OF CABIN AIR

4.1. Overview

This chapter describes methods and guidelines for the assessment of the quality of the cabin air. First the focus is on the assessment of the cabin air quality by sensing. Next, other assessment methods are described, including also the use of human-based information. Furthermore, specific work is highlighted that was carried out on experimental characterisation of air quality with COTS sensors. Finally, the WP7.3 team highlights some guidelines for the assessment.

4.2. State of the art cabin air quality sensors

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)[65]. The sensor chosen by the end user will be motivated by factors such as size, cost, accuracy, and suitability for the application. For example, for automobiles it is thought that Semiconducting Metal Oxide (SMO), Electrochemical (EC) and Infra-Red Optical sensors present as the best choices for installation into vehicles from a cost, power demand and compactness point of view [66], [67].

For cabin air quality there are many examples of real time analysis using commercial sensors with sampling tubes for delayed analysis (e.g., GC-MS) ([68], [69],[70] ,[71] , [72]). Typical targets included CO, NO, O_3 and VOC's. 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. As a methodology, a manifold of COTS sensors 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 cabin air changes during the flight phases.

A number of studies [73], [74], [75], [76], [77] have focussed specifically on measuring engine oil constituents and by-products (due to the heating of the oil) in cabin air. 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. Measurement methods included a personal air sampler with sampling tubes analysed using GC/MS [76], sorbent tubes and filters for sampling in cockpit with GC analysis [74], [75] wipe sampling with GC/MS analysis [77], and TD tubes with GC-EI-MS analysis (sampling on-ground).

Experiments in laboratories were conducted to investigate the suitability of commercial sensors for measurement of cabin air quality (e.g., [78], [79], [80], [81], [77]). Typical targets included pressure and O_3

as a priority, followed by CO, CO_2, and relative humidity. 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.

Various small, integrated, low cost devices to monitor indoor and/or outdoor air quality are currently on the market, many being part of distributed reporting networks of citizen (see Chapter 0), such as:

- uHoo [82]. Temperature/Humidity/CO2/VOC/PM2.5/Air Pressure/CO/O3. Target indoor monitoring. Cloud based,
- Awair [83]. Measures temperature, humidity, CO2, chemicals and particles. Links to other appliances or systems to provide for a smart environment (home or office),
- Airbeam and Aircasting [84]. Measures temperature, humidity, carbon monoxide (CO) and nitrogen dioxide (NO2) gas concentrations but also links to other equipment (e.g., mobile phone for noise). It connects to the aircasting network,
- Egg [85]. Measures CO, VOC, CO2, SO2, particulates and NO2. Connects to a crowdsourced air quality network,
- uRADMonitor, developed by Radu Motisan, is a global network of interconnected hardware devices that work as detector for various chemical and physical pollutants. The current detectors can measure air temperature, barometric pressure, humidity, dust concentration, VOC but also Alpha, Beta and Gamma radiation. The latest uRADMonitor model D [86] uses the BME680 sensor from Bosch (uRADMonitor featured by Bosch) to assess air quality. Checking the price list of the authorized distributors (2017), it is possible to conclude that the average price of the BME680 sensor is around €5.45 and €8.33, depending on the quantity ordered.

Consistent with the findings in this section, the suitability of these sensors for measurement of cabin air quality during flight would need to be investigated before any conclusions can be drawn from their measurements.

4.3. Research phase cabin air quality sensors

As detailed in [87], 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).

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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. Metal oxide sensors are small devices offering increased sensitivity but with poor selectivity, often cross-reacting with other species.

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 Ion Mobility Spectrometry (IMS), or manufacturing tailored sub-components to remove the limiting operational factors in current COTS sensors. A large driving force for research 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 Micro-Electro-Mechanical Systems (MEMS). 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 Fourier Transform Infrared (FTIR) sensor[88].

Figure 4 Miniature handheld FTIR vs. typical benchtop FTIR, taken from [89] and [90]

A miniature IMS within a manifold of other sensors has been patented by Airsense Analytics GmbH [91], suggesting that this technology may become a commercial product. Additional research developments to overcome COTS sensor limitations are described in [1].

The current H2020 Clean Sky 2 MACAO project [92] - Development of VOCs and ozone Micro-analysers based on microfluidic devices for Aircraft Cabin Air mOnitoring – targets development of two analytical instruments to measure VOCs and ozone concentrations based on microfluidic devices. These devices will address the constraints of compactness, security, automatic pressure correction, autonomy and real-time monitoring.

4.4. Other assessment methods

Besides single sensor developments there are two other directions for assessment of cabin air quality:

- Multi-sensor networks that combine measurements from multiple sensors,
- Human-based assessment of cabin air quality.

Multi-sensor networks or arrays can support cross-checking. Cross-checking with different technologies is considered necessary to manage possible malfunction during operations. Electronic noses are another example of multi-sensor arrays. Additional research developments in e-noses are described in [1]. E-nose technology is already in use for maintenance. Aerotracer [93], for instance, allows the detection and identification of common VOCs and is sensitive enough to classify odour concentrations on a sensing scale. 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.

Sensor networks have been investigated in many projects, such as the USA Community Air Sensor Network (CAIRSENSE) [94] and the FP7 projects on indoor air quality SENSIndoor [95], MSP [96], OFFICAIR [97], and Airlog [98].

Human-based assessment of cabin air quality has been investigated with two approaches: (i) monitoring by reporting i.e. identifying trends from incident reports and (ii) biomonitoring of personnel i.e. attempting to reconcile symptoms with particular events through medical examination (e.g., [99], [100], [101], [102], and [103]) . 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 currently suffers from a lack of standardisation, potential for under-reporting and incomplete reports. Improvements may be possible, but any system based on reporting of infrequent events by individuals is bound to retain an element of subjectivity. Recently, guidelines for reporting on fume events were issued by ICAO [99]. It provides guidance to States to support the development of relevant advisory material for operators to provide suitable awareness and/or training to flight crew, cabin crew and aircraft maintenance technicians to enable them to prevent, recognize and respond to the presence of fumes, particularly aircraft air supply system-sourced fumes.

Biomonitoring studies lacked a standardised procedure across investigations making trends and comparisons hard to identify, and full biomonitoring would be invasive.

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4.5. Experimental investigation of COTS sensors

4.5.1. Methodology for the characterisation of gas emissions from composite materials at elevated temperatures

The work investigated here serves as a feasibility test of the applicability of commercial off-the-shelf (COTS) gas sensors employed in safety monitoring or in early fire detection. It also serves to investigate a methodology that may be applied to make quantitative measurements of volatile and gaseous emissions from different materials at operational and elevated temperatures using a combination of these sensors plus laboratory analytical techniques.

The described methodology allows the characterisation of gas emissions from composite materials inside an air-tight tube furnace (E-1 in Figure 5) that can be operated up to 1200 °C. Instrumentation details are given in Table 3. Cleaning procedures and possible condensation issues have been evaluated.

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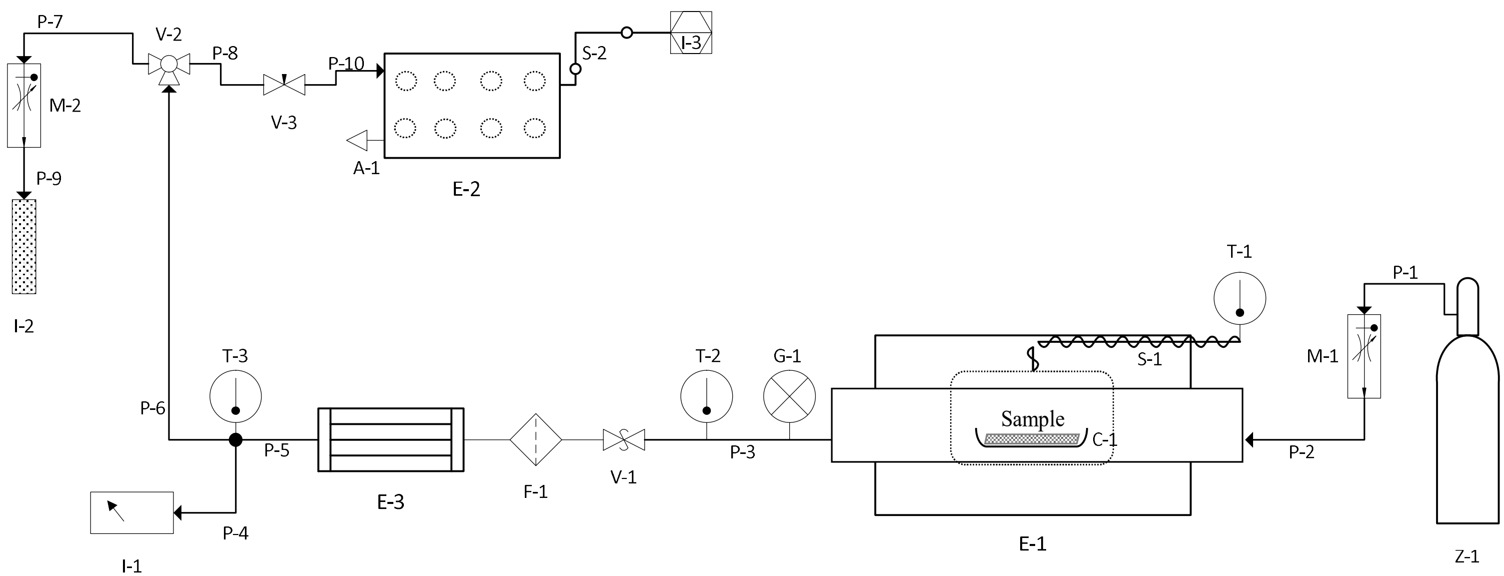

Figure 5 A schematic diagram of the methodology for characterisation of gas emissions at elevated temperatures in real-time using commercial gas sensors and thermal desorption tubes.

Item	Description	Item	Description	Item	Description
A-1	Exhaust port	G-1	Pressure measurement	S-1	Heat trace
C-1	Combustion boat	I-1	Humidity and temperature sensor	S-2	Output signals/ data
E-1:	Air-tight single zone tube furnace	I-2	Stainless-steel thermal desorption tube	T-1	Temperature measurement and control inside the furnace
E-2	Manifold of commercial gas sensors	I-3	Data acquisition	T-2 & T-3	Temperature measurement
E-3	Cooling apparatus	M-1, M-2	Mass flow controllers	V-1, V-2, V-3	Stainless-steel valves
F-1	Particulate filter	P1-10	Electro polished stainless-steel tubing	Z-1	Hydrocarbon free air

Table 3 Instrumentation List

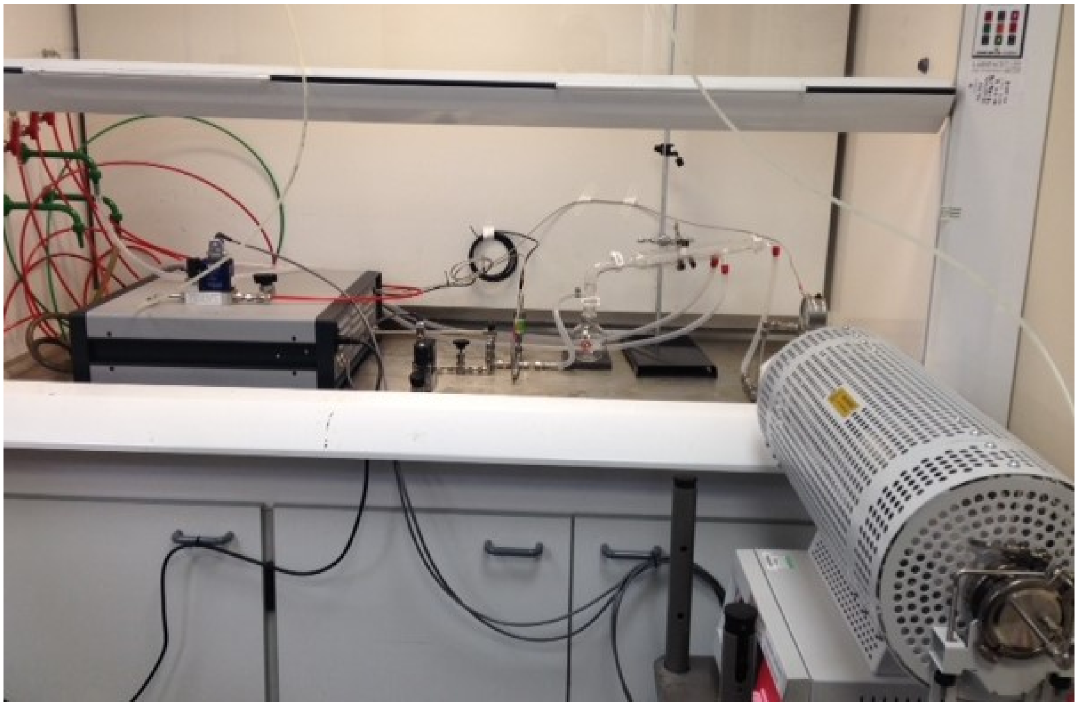

Figure 6 Experimental apparatus for characterisation of gas emissions at elevated temperatures in real-time using commercial gas sensors and thermal desorption tubes.

The apparatus (Figure 6) was initially used to test a standard high strength carbon fibre reinforced composite material supplied by CEIIA. The test system was designed to provide a controlled flow of clean hydrocarbon-free air through the furnace, which was controlled via a thermocouple inside the heating zone. After the air passed over the sample it was able to carry any emitted volatiles and gases, first to a set of cooling apparatus (used to protect sensors and analytical equipment) and then to an array of COTS sensors and / or an analytical sampling point. Temperature sensors were used at different downstream locations to (a) ensure that the samples gases were not at a temperature that would cause any damage to the apparatus, and (b) to provide temperature correction for the sensor outputs. COTS sensors implemented included a photo-ionisation detection (PID) for volatiles, Non-dispersive infrared sensor (NDIR) for CO_2, and electrochemical sensors for NO, NO_2, SO_2, CO and O_2. Finally, the exhaust fumes were safely vented into the fume cupboard that housed the apparatus.

The data acquisition (output voltage, gas concentration, gas temperature, gas humidity) was automatically acquired using LabVIEW 2014 software and National Instruments devices, and one sample per second was recorded and averaged every minute.

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4.5.2. Manifold of commercial gas sensors

Commercial off-the-shelf (COTS) gas sensors acquired from Alphasense were mounted inside the sensors box, allowing the detection of gas emissions in real-time. All the sensors were pre-calibrated at Alphasense, where commercially available calibration gases were used for each sensor.

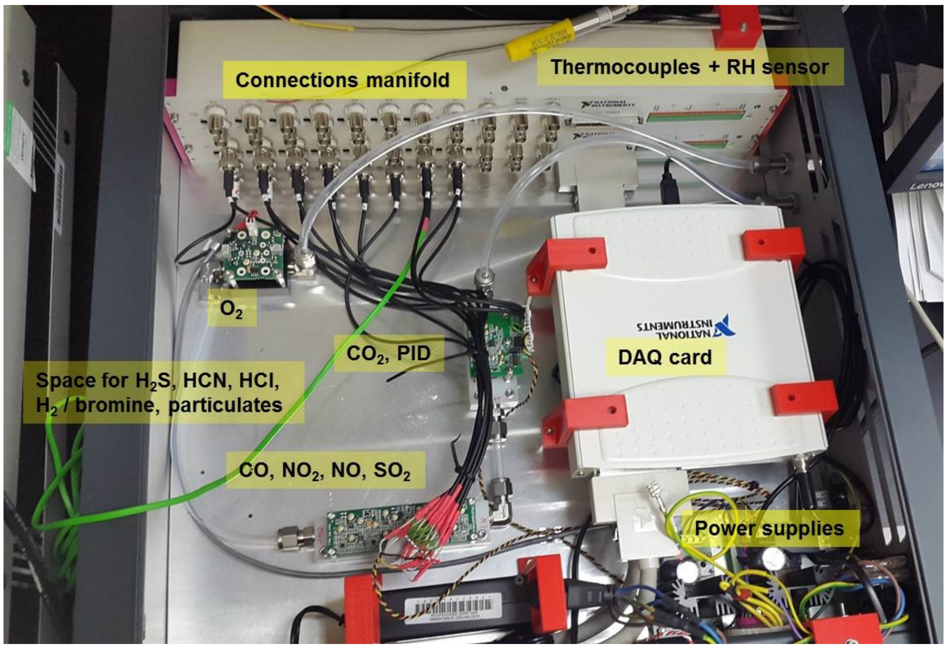

Figure 7 Sensors box equipped with COTS gas sensors. Labels are highlighted in yellow.

The photoionisation detection (PID) gas sensor (photoionises trace organic compounds (volatiles) to produce an ionisation current which is then amplified. The resulting voltage is proportional to the gas concentration (ppb-ppm). As is standard practice, the PID sensor was calibrated with isobutylene and therefore its output is referenced to this gas; it has known cross-response to a wide range of other volatiles [105].

The principle of operation of NDIR relies on the Beer-Lambert law that gives the level of light transmitted through an absorbing medium such as a gas. Certain gases absorb infrared radiation at specific wavelengths; the sensor used here is specific for CO_2. Each sensor consists of an infrared source, optical cavity, dual channel detector and internal thermistor. The sensor comprises an active channel where the gas absorption occurs and a reference channel used to compensate for changes in the emission of the source.

Four electrochemical gas sensors (NO, NO_2, SO_2, CO) were mounted inside the sensors box. These sensors enclose a reference electrode and a working electrode where the electrochemical oxidation or reduction occurs. The charged species generated yield an electrical signal proportional to the gas concentration (ppb).

An oxygen sensor (O_2) was fitted inside the box in order to control and monitor the oxygen levels (%) inside the tube furnace.

4.5.3. Thermal desorption – gas chromatography – mass spectroscopy

The technique of thermal desorption – gas chromatography – mass spectroscopy (TD-GC-MS) is capable of providing analysis across a broad range of volatile compounds. If care is taken to control gas flows and appropriate calibration standards are used, it can also be quantitative. It has the advantage of not requiring prior knowledge of the contents of a volatile mixture before analysis. A disadvantage is that samples must be taken at set times only, and online information is not available. Samples are extracted onto TD tubes from the volatile gas stream emitted from the material under test, the TD tubes trapping the compounds and additionally providing a concentration step before analysis. At a later date, volatiles are desorbed at high temperature before being passed into a gas chromatograph (which provides separation of different molecules as a function of time) and finally mass spectrometry (which provides additional information that aid identification of compounds).

Chromatography is a physical separation process, where volatiles undergo separation along the GC column according to their relative affinity for the stationary phase of the column. Chromatographic analysis with GC-MS generally uses fused silica capillary columns, liquid phase coated with the stationary phase, called wall coated open tube (WCOT) column. The stationary phase of these columns is generally constituted of siloxane based polymers or polyethylene glycol (PEG) [106]. The column selectivity, thermal stability, and inertness are critical to resolving volatiles. Rxi®-624Sil MS columns offer reliable resolution of volatiles and also provide lower bleed and greater inertness than other columns.

The separation of volatiles of different volatilities requires the use of temperature ramps, allowing the separation of compounds at different retention times. The volatiles are then detected in the mass spectrometer (MS). GC-MS data analysis is performed through the aid of AMDIS (Automated Mass Spectral Deconvolution and Identification System) software, and followed by reliable identification using the NIST (National Institute of Standards and Technology) mass spectral library.

4.5.4. Preliminary results

All the sensors were pre-calibrated with commercially available calibration gases. Table 4 indicates the baseline levels for each sensor.

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Gas sensor	Baseline Voltage (V)
PID	0.109
NDIR Act	1.037
NDIR Ref	0.746
NO_2 WE	0.280
NO_2 AE	0.311
SO_2 WE	0.250
SO_2 AE	0.261
NO WE	0.278
NO AE	0.291
CO WE	0.263
CO AE	0.254
O_2	4.000

Table 4 Response of the sensors under hydrocarbon free air and the respective baseline voltages (WE – working electrode, AE – auxiliary/reference electrode, Act – active, Ref – reference).

The response and performance of CO_2 sensor against a standard concentration of 20% CO_2 was evaluated here, see Figure 8 in order to characterise the gas flow response time.

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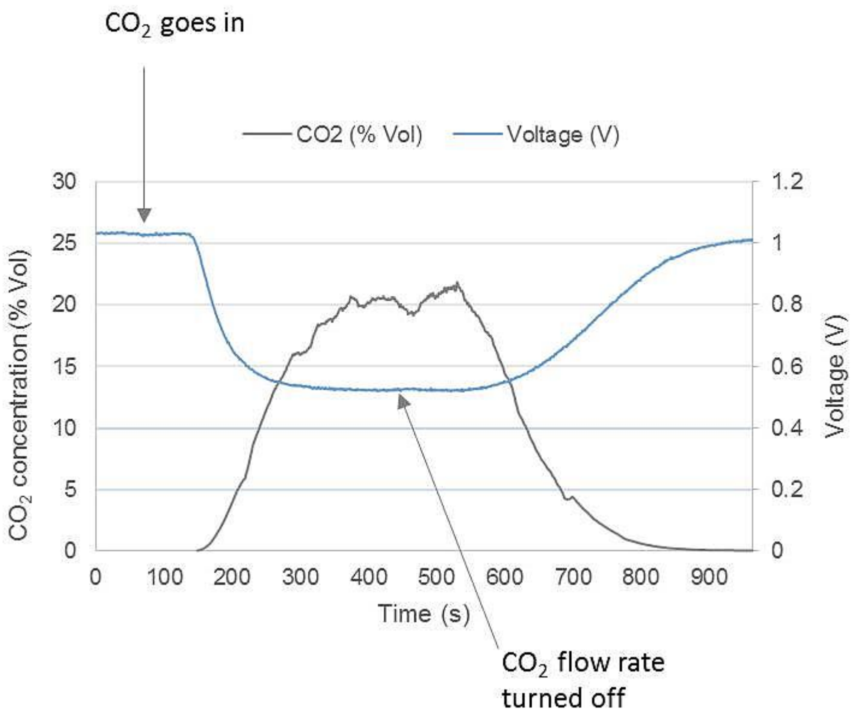

Figure 8 Response of CO_2 sensor to a standard concentration of 20% CO_2 at a flow rate of 1 litre / min.

As an example, Figure 9 represents the response of the PID sensor to the volatile emissions generated through the heating process from room temperature (22 °C) up to 150 °C, at a heating rate of 5 °C min^{-1}.

A volatile content of 0.01% was released at the end of the heating period (150 °C).

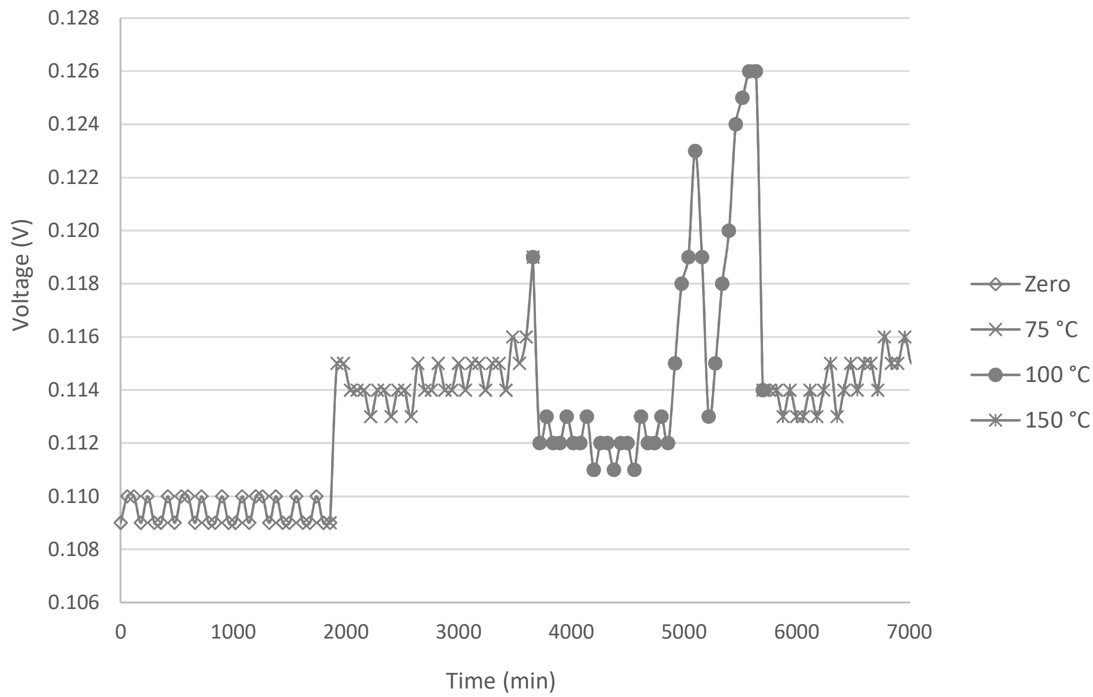

Figure 9 Example response of the PID sensor to volatile emissions (furnace temperature controller programmed to warm up from 22 °C to 150 °C at 5 °C min^{-1}).

4.5.5. Concluding remarks

- The information gained throughout this preliminary investigation will allow to identify technology capable of detecting potentially hazardous emissions, and the limitations encountered,
- Several issues and their solutions associated with the test methodology have been investigated,
- The sensors have demonstrated a good performance to real-time detection of gases, working consistently over long periods of time (≤ 8 hours),
- There is cross-response of sensors to a range of volatiles, and this needs to be taken into account while investigating and implementing gas sensors into a certain environment,
- Modelling is needed to link the emission rate in such tests with a possible concentration in the ECS and elsewhere in the cabin. In the laboratory tests, concentrations are enhanced in order to be easily measurable,
- Information would also be required about what temperature the materials experience during normal operations.

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4.6. Methodological guidelines to assess cabin air quality

This section highlights a few challenges to the in-situ assessment of cabin air quality that the WP7.3 team came across during literature study and own development work. In addition to the challenges, guidelines are given to address these challenges. The WP7.3 team considers these guidelines as valuable to share even though their innovation potential is limited.

The first challenge is that usually cabin air quality is assessed as part of a larger study with a specific target. The definition of cabin air quality assessment needs to be aligned with the target of the larger study. Studies involving cabin air quality assessment may have quite different purposes, such as related to regulatory purposes (including certification), medical purposes (such as treatment of individuals that link their health concerns to cabin air quality), increase of scientific understanding and business case development.

Regulatory purposes are governed by global, European, and national treaties, laws, regulations, etc., whereas for specific medical purposes certain requirements and protocols may apply. Cabin air quality assessment for regulatory purposes and specific medical purposes are not addressed here.

To increase scientific understanding and business case development there are still different types of research, such as exploratory research, hypothesis testing, and research for falsification. Each of these types of research may put different requirements on the definition of the cabin air quality assessment. For example, hypothesis testing will require an agreed hypothesis and the size of the data set should be large enough to draw statistically significant conclusions. Also, the main interest for cabin air quality assessment may vary: for example, just measuring concentrations, identifying sources of substances in the cabin air, and/or investigation of the impact on humans. This detailed definition of the purpose of the study should be made with the relevant stakeholders to gain their acceptance of the conclusions and with the relevant experts (including aircraft and sensor experts, but more disciplines will be needed) to ensure the feasibility of cabin air quality assessment in line with the purpose of the study.

Guideline: the common purpose of the cabin air quality assessment should be identified in detail with relevant stakeholders and experts.

Defining the assessment methodology for cabin air quality, several options are available as described in this chapter. Sensor-based methods have the advantage of providing objective information, but may be costly, depending on the purpose of the study. Human-based information, if readily available, may be cheaper, however such information may be subjective and influenced by many unknowns (e.g., human perception, variation, pre- and/or post-conditions). Nevertheless, human-based information can reveal unexpected circumstances that were not measured.

Guideline: sensor-based methods are preferred for cabin air quality assessment, supported by human-based information. For preliminary exploratory research human-based information can be more cost-efficient.

In terms of what sensor-based methods to use, the WP7.3 team sees much need for continuous air quality sensing. This need is specifically addressed in Chapter 5, in which the concept architecture for an industrial framework for such sensing as well as associated considerations and guidelines are presented.

Limitations on the availability of sufficient and representative human-based data often complicate cabin air quality assessment studies that involve humans (e.g., sparse events, wide spectrum of symptoms). Conclusions to be drawn from the cabin air quality assessment study should therefore be coupled with factors and events outside the cabin, even if a significant part of human life is spent in the cabin (e.g., by cabin crew). Taking into account the hostile environment in which aircraft are operating and the high level of aviation safety compared to other transport modes, it is also useful to compare the findings with air quality in other environments.

Guideline: Conclusions drawn about the human aspect of the cabin air quality assessment should be placed in the perspectives of other factors and events outside the cabin and of air quality in other environments

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5 INDUSTRIAL FRAMEWORK FOR CONTINUOUS AIR QUALITY SENSING

5.1. Trends addressing complex issues

State of the art research indicates that there is a large and increasing interest in assessment of cabin air quality during events with one or more of the following characteristics:

- The events happen irregularly with low frequency,
- There is a spectrum of potential effects of the events,
- Potential effects of the events may be in the long term,
- There is human variability in the potential effects and there is human perception of the potential effects.

Due to these characteristics, large-scale, continuous, on-board measurement of cabin air quality is one of the assessment methods to address this interest. This aligns with developments in sensor technology (see Chapter 0).

The interest in cabin air quality can find an overlap with the trend of the self-quantified individual. This trend, based on the increasing availability of low-cost sensors and other data-record technology, can allow the use of data based approaches to correlate the individual's state with life events to which they have been exposed. Such functionality, if existing, coupled with a holistic approach to the self-quantified individual, could provide new business streams for the benefit of the individuals: e.g., individual tailoring of local cabin conditions; increase of knowledge to develop improvement on jet lag effects; etc. Similar big data trends are observed in different areas in aviation. Several pilot projects aim to harness the gains of availability of big data sets for operational efficiency or, even, safety. In that regard, Future Sky Safety P4 "Total system risk assessment" [107], can be considered one of the first steps to understand how such future data repositories can be put in place and managed for the aviation systems. EASA is also leading the project BigData4Safety [108], with a similar purpose and is a partner of project SafeClouds.eu [109], also under H2020. In another aeronautical area, the consistent management of aircraft and engine (geometrical and behavioural) design data in the supply chain during aircraft and engine development is mastered with further big data challenges ahead.

5.2. Concept for continuous air quality sensing

WP7.3 proposes the "**I**ndustrial cabin air quality **F**ramework based on **C**ontinuous **A**ir quality **S**ensing" (**IFCAS**), see Figure 10. The core of IFCAS is a network of distributed low power, low weight sensors that is distributed across the cabin. This network constitutes a big cabin air e-nose. The sensors can be clustered also around small concentration hubs for data and initial post-processing. Data that has been initially post-processed will be made available for downloading during turn-around. Post-processing of the data could be completed during turn-around or later. Specific data may be fed to the pilots during flight, whenever this is not compromising safety.

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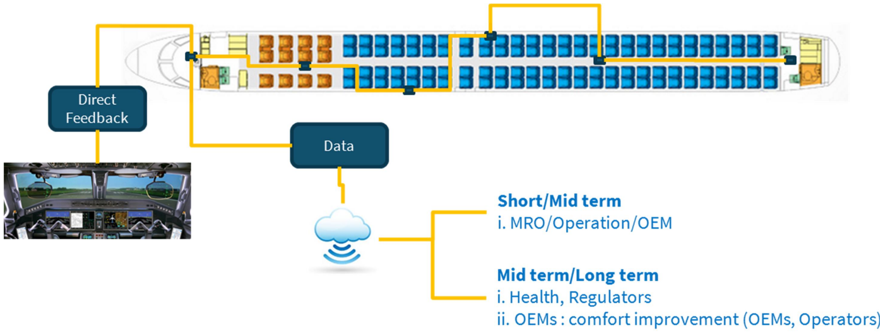

Figure 10 Concept architecture for an Industrial cabin air quality Framework based on Continuous Air quality Sensing (IFCAS) (with cabin and cockpit pictures from Embraer)

In line with current trends of using commercial off the shelf sensors and lowering costs, the system architecture should be open. Defining a standardized interface with the airplane would allow for an IFCAS “black box” type of equipment to encapsulate different sensors and allow for fast replacement of sensors. Wireless communication and power by energy harvest [110] are technologies to be explored for efficient integration in aircraft, especially for installation during refit of existing aircraft.

Applications of the sensed IFCAS data are envisaged in multiple ways, on different time horizons with respect to the actual flight in which data is sensed:

- During flight, specific data directly fed to the pilots can increase safety, e.g., by reducing false fire alarms,
- In the short/mid-term the data may be used for further enabling Prognostics Health Management (PHM) and Condition Based Management (CBM) as it can be used to forecast, in a probabilistic sense, time for possible equipment failures. Furthermore, if the data is stored, in case of incidents, it would allow for an improved knowledge in real, operational, context, of air degradation (e.g., fire scenario),
- In the mid-term the correlation of databases of on-board conditions with the state of individuals provides a possibility to give more extensive, evidence-based answers, to concerns expressed by individuals,
- In the mid/long-term the data can be used for more methodical, engineered approaches, to improve comfort and even better be able to design the air inside the cabin.

This list indicates that a rich set of applications of IFCAS can be envisaged for the benefit of different stakeholders. The next section elaborates on the effective use of the sensed data.

5.3. How the sensed data is used effectively

Following our own methodological guidelines, see Section 4.6, to assess cabin air quality, the effective use of the sensed data has some challenges, which are in common with many big data projects.

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Considering our guideline "Identify the common purpose of the cabin air quality assessment in detail with relevant stakeholders and experts" it may seem that the purpose of the proposed continuous cabin air quality sensing is only to measure and to store the (post-processed) measurement data. However, the sensed data will be used later in studies. In the definition of these studies the relevant stakeholders and experts have to confirm the applicability of the sensed data. Therefore, the sensed data need to be managed upfront and the continuous cabin air quality sensing needs to be supported by the potential stakeholders and experts. This demands further research to understand opportunities of value creation and governance in data sharing among stakeholders.

The study [8], which was carried out in the USA, gives a summary overview of the different stakeholders' concerns regarding the presence of cabin air quality sensors in aircraft, see Table 5. As can be seen, an ample space of convergence and common interest exist (also some local goals can be at odds among some stakeholders, demanding discussion and convergence).

Stakeholder	Sensor-Related Issues
Regulatory agencies	Compliance with FARS and ASHRAE Standard
Aircraft manufacturers	Safety, low cost, simplicity, maintenance alerts, aircraft ECS design improvements. 'level playing field'
Airlines[a]	Revenue, passenger comfort, minimal complaints, 'level playing field'
Crew	Documenting exposures to contaminants (hydraulic fluids, pyrolysis products, pesticides); health risks; chemical sensitivity; compliance with standards; discomfort; access to data
Passengers	Health risks, comfort, access to data
Researchers	Exposure data related to health research and aircraft design improvements; access to data

Table 5 Stakeholder and sensor use interest, taken from [8]

In more fundamental research it could be an interesting use case to consider a citizen-based observatory for cabin air quality. The research question would be how incumbent stakeholders (regulators, operators, manufacturers) can harness these new social initiatives for improvement of the industry value chain.

The IFCAS flight data could also be used effectively in conjunction with other cabin air quality data. Such data may concern sensing-based data from research facilities and simulators and/or human-based data, both from flight and from research facilities and simulators. For example, full-size cabin simulators, including cabin air quality, are in Fraunhofer IBP, in Holzkirchen, Germany, using a A310-200 [111] and, in USP Polis, São Paulo, in Brazil, using Embraer 190 and 175 aircraft cabins and set-up in 2011 [112], [114].

As can be seen from the wide range of applications in Section 5.2 the IFCAS flight data are mostly applied when used together with IFCAS flight data from other flights. This implies the use of IFCAS database(s). Other aviation big data projects (see at the end of Section 5.1) can help to establish an understanding of how data can be collected, shared, and managed across different entities and stakeholders. In this regard, they pave the way to understand governance of enlarged data pools of the type proposed, see also Section 5.5.4.

Considering our guideline “Prefer sensor-based methods for cabin air quality assessment, supported by human-based information” it should be investigated how analysis of IFCAS data can take into account human-based information such as incident reports or questionnaires, if available. IFCAS data may include information that makes it easier to identify associated human-based information.

The guideline “Conclusions drawn about the human aspect of the cabin air quality assessment should be placed in perspective.” will be addressed through the recommendations in Chapter 6.

In the next subsection, high-level requirements on IFCAS are identified to enable its efficient use.

5.4. High-level requirements on the industrial framework

The WP7.3 team went one step further in defining IFCAS. The outcome of this work is summarised in a number of high-level requirements, in preliminary conclusions on the feasibility of IFCAS and in recommendations on the way forward. Whereas the conclusions and recommendations are presented in Chapter 6, this section indicates the high-level requirements.

The IFCAS sensing system shall be easily installable and replaceable on-board aircraft. The IFCAS sensing system should be like a black-box of equipment. This “black-box” concept also provides the best flexibility to provide the system for different aircraft and to interface with different systems, where needed.

The IFCAS system shall require minimum maintenance on-board. There will be requirements on the calibration validity of the individual sensors in order to be aligned with maintenance schedules. Three months of calibration validity is estimated to be a minimum. Self-calibrating technology is favoured.

The IFCAS data shall be used in conjunction with other data, where needed. For example, synchronised aircraft condition data are relevant to correlate cabin air quality data of aircraft on ground with the ambient air quality. This may also extend to other flight phases and to other data (e.g., number of passengers and crew). It requires further investigation with the stakeholders how such conjunctions can be supported.

The quality of the sensed data is a major area for requirements. At least, the quality of the IFCAS data shall be known in detail for later studies based on these data. Depending on the purpose of such studies different IFCAS data will be relevant and will have their specific requirements. For example, the use of IFCAS data that is relevant for fire-related purposes may require higher sensor output rates than for comfort or health purposes.

There will be generic performance requirements for the IFCAS system of sensors (e.g. on accuracy) and specific performance requirements for each sensor. Such performance requirements for sensors concern what they are able to detect, how accurately and at what concentration, how much cross-responsivity can be tolerated, their range of temperature, pressure and humidity, how quickly they respond, their

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approximate size and weight restrictions, and how they should communicate with other systems. For example, the WP7.3 team already considered accurate measurements with respect to Permissible Exposure Limits (PELs), which are often expressed in time-weighted average for time intervals, which are typically 8 hours, but also Short Term Exposure Limits (STELs) for 15 minutes and ceiling limits appear. For such applications accuracy requirements may go beyond the generally stated requirements in [22], (see Section 4.3).

The IFCAS system shall be compatible with the aircraft, in particular the cabin. In accordance with the regulation, different environmental requirements shall be satisfied to ensure that the aircraft environment is not disturbed by the IFCAS system. In addition, the IFCAS system shall be such that its operation is not influenced by the aircraft environment. It is noted that these requirements are applicable for the IFCAS system as a whole. Casing will in many cases determine the environmental properties of the system, often more than the isolated sensor. Besides environmental requirements there are interface requirements for IFCAS. Mechanical and electric power interface requirements will apply. In addition, IFCAS data format shall be compatible with available aircraft buses. This interface for recording is further elaborated in Section 5.5.1.

5.5. Supporting methodologies

5.5.1. Overview

This section synthesizes the results from the WP7.3 on a number of methodologies that are supporting the IFCAS framework.

5.5.2. Data recording on-board aircraft

The IFCAS framework relies on cabin air quality recording on-board aircraft. If aircraft condition data, such as on-ground or in-flight, APU on/off, etc., is available this will help maximise the potential of the measurements and also help interpret any unusual readings. This section provides information on how the recording on-board aircraft is performed at present for aircraft condition data and how the existing recording facilities could be used for IFCAS cabin air quality data.

For the purpose of IFCAS use, aircraft condition data is available:

- on aircraft data buses in the aircraft and,
- in the Aircraft Condition Monitoring System (ACMS).

IFCAS cabin air quality data for (possible) fire detection should be made available as quickly as possible for the crew and for aircraft systems. Putting these signals on an appropriate aircraft bus seems the most logical solution for this purpose.

For all other non-real time purposes, several solutions are available for the recording of IFCAS air quality data:

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- Solitary recording in the IFCAS blackbox or in a dedicated data recording system, together with time stamps such that correlation with aircraft data can be made using time information. An interface or a common time source like GPS time is needed for time synchronisation.
- Recording of air quality data together with aircraft condition data in the IFCAS blackbox. An interface with the aircraft is needed to provide the aircraft data, for instance by connecting the relevant aircraft bus(es) to the IFCAS blackbox.
- Recording of the air quality data on aircraft systems, for instance as additional parameters in the ACMS data. An interface with the aircraft is needed, possibly through an aircraft bus, to provide air quality data to the aircraft as a service.

Modern aircraft often have buses that allow for exchanging data between multiple nodes and in two directions. The IFCAS blackbox could be an extra node on such a bus. Processing power for sensors may even be placed in aircraft systems applying the Integrated Modular Avionics (IMA) principles. On older aircraft, only point-to-point or point-to-multipoint digital links may be available. To receive data, the IFCAS black box can be connected to an existing link. To transmit data additional data links, including wiring, need to be installed. Alternatively, data may be put on a wireless network. A regulatory framework for wireless avionics intra-communication (WAIC), inside aircraft, is under development [113].

For the preliminary feasibility assessment, the WP7.3 team also investigated the digital communication means that can be available in present day aircraft.

5.5.3. Modelling and simulation of the environmental control system

Modelling and simulation of the ECS, including the cabin, can support the identification of the best places for the IFCAS sensors on-board aircraft. Modelling and simulation may also support the analysis of IFCAS data. Such modelling and simulation may involve the whole ECS or relevant parts, for example, in the neighbourhood of the sensor.

Sensors could be placed near potential sources, near humans, or in some remote parts of the ECS. Sources may be unknown yet and remote parts may have practical and organisational advantages. However, the airflows between the points of exposure (the human) and the sensors should be considered. Typically, sensors are not placed at each potential source and hence the air flow between the potential source and the sensor needs to be considered in data analysis, including the time it takes to travel from source to sensor. If there is a prior interest in substance concentrations at specific locations, then the airflow between this location and the sensor needs to be taken into account, as it might not be feasible to place the sensor near the main point of interest, e.g., the passenger or crew.

Sensors placed in turbulent flows require additional local modelling, simulation, and testing with tracer gases or particles.

In view of these considerations and the state-of-the-art in modelling and simulation, two types of models are needed:

- A global ECS model that describes the air flow in terms of physical variables (such as pressure, temperature, mass flow, humidity, substance concentrations) during flight at the different compartments of the ECS, typically by a simple representation of these compartments,
- Local detailed flow models for the 3D flows at critical areas of interest such as near sensor locations.

Global ECS models are commonly applied in the industry to develop the control elements of the ECS. Substance concentrations are not controlled directly and therefore typically not modelled. In WP7.3 a generic method (including model) has been developed and verified to extend such global ECS models with substance concentration models of the compartments, which allow the capture of the main dynamical phenomena involving substances in the simulation.

Local 3D flow is typically modelled with computational fluid dynamics (CFD) models. Specific CFD methods exist for the simulation of flow of gases or particles but are not further addressed here.

ECS models and simulations are also supportive in the analysis of the IFACS data for the applications and as a means to secure that the knowledge gained is also applied later in similar cases.

5.5.4. Big data methods

Continuous air quality sensing can generate significant amounts of data. This can be leveraged using big data analysis. First, a description of the current big data trend is given. Next, the most relevant big data methods for IFCAS will be described in more detail.

As a general trend, the size and variety of data available are increasing. Combined with the high speed at which this data becomes available, new methods and technologies are required to process the data into information. In addition, it is important for the end user to have quick and continuous access to reliable information. For these developments, the term "Big Data" is used.

Gartner [115] defines Big Data as "*High **volume**, high **velocity**, and/or high **variety** information assets that require new forms of processing to enable enhanced decision making, insight discovery and process optimization".*

Developments regarding data production, processing, analysis and visualization are lumped together. New techniques for the processing and analysis of data make existing services more efficient / effective and introduce opportunities for new types of services and products. In that light, 'Big Data' is a generic term for the entirety of data, characteristics of the data and processes to transform these data into intelligent information through processing, analysis and reporting.

Big data may also involve different stakeholders in which case there are specific needs for the coordinated data management between the stakeholders. These needs may cover the whole process from data acquisition to data analytics. A special focus is on the sharing of data with topics such as access, ownership, and governance of the data.

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For data treatment, a distinction can be made between the so-called "*hard*" data (i.e. something that most usually "pops up" in the mind when thinking about data: Excel sheets, databases, sensor measurement stored in a binary format, and so on) and the so-called "*soft*" data (i.e. something that is most frequently not even seen as a data source: logged communication between pilots and technicians/Air Traffic Control, scans of maintenance reports, audio recordings, digitized purchase receipts, and so on). As a rule, the "hard" data can be most easily processed in an automatic fashion. However, a number of approaches exist to extract value from the "soft" data as well (e.g. Text Mining). In some cases, those are of paramount importance, as most of the available data is in the "soft" form.

For IFCAS the following big data areas and their methods are most relevant:

- Data sharing, since the data originates from many flights and may also originate from different stakeholders. IFCAS data sharing encompasses finding appropriate business models, data acquisition, data storage, ownership, and governance,
- Data analytics on the "hard" IFCAS data to discover insight and to support evidence-based decision making,
- Combining the "hard" data methods for IFCAS data analysis with "soft" data methods applied on human-based information about cabin air quality such as incident reports and questionnaires.

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6 CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Aircraft architectures, including propulsion concepts, will change disruptively in response to the increased air traffic projections and the global environmental issues. Safety should not be compromised by these disruptive changes. These changes allow for a thorough review of the aircraft cabin of the future. This includes the cabin air quality of the future, on which this study is focussing.

This study investigates state of the art and developments, including related technologies, in cabin air quality, societal trends in air quality, and competitiveness for industry offered by cabin air quality. It is concluded that:

- Regulation safeguards the introduction of new materials. To ensure safety for new materials (e.g., for nanomaterials) extensive investigation may be needed and this can increase the time needed to introduce new materials into aircraft cabins,
- There is a continuous development of technological innovations in aircraft such as the electrification of propulsive and non-propulsive power and the development of new cabin air filter technology. These innovations can contribute to improvements in cabin air quality,
- There is a growing interest to address complex cabin air quality issues related to comfort, health, and safety.

To address complex cabin air quality, it is concluded that some guidelines (see Section 6.2) should be highlighted regarding assessment of cabin air quality. In addition, continuous cabin air quality sensing could be a pathway. For this pathway, the "**I**ndustrial cabin air quality **F**ramework based on **C**ontinuous **A**ir quality **S**ensing (**IFCAS**)" is proposed. The core of the IFCAS architecture concept is a well-placed network of distributed low power, low weight sensors that is distributed across the cabin. Other elements of the architecture concern the on-board post-processing, storage, and distribution of data during a flight, the storage and sharing of flight data potentially between different stakeholders, and the analysis of the big data that is gathered, potentially combined with modelling and simulations.

Applications of IFCAS are foreseen during flight and on different time-horizons after flight, including prognostic health management and condition-based health management, evidence-based answers to concerns, and methodical, engineered approaches to improve comfort and to better design the air inside the cabin.

Preliminary feasibility of IFCAS has been investigated by deepening the concept. This investigation identified challenges for effective use of the IFCAS data such as:

- Ensure high-level of quality of the IFCAS data, including the human interface, that is used on-board in order not to compromise safety,

- The opportunities offered by common management of IFCAS data and its effective use in further data analysis.

It is finally concluded that, depending upon confirmation of stakeholder interest, the development of IFCAS can be started in the near future, while progressively extending it with the latest sensing technologies.

An experimental methodology has been developed to investigate the potential for new materials to affect cabin air quality via release of gases or volatiles at normal or elevated temperatures. This methodology also offers the ability to test COTS sensors for detection of those volatiles and a number of COTS sensors have been tested in this respect.

6.2. Recommendations

In this section recommendations are given in the form of:

- Highlighted methodological guidelines for cabin air quality assessment,
- Further research and development of IFCAS to increase its maturity.

For cabin air quality assessment to increase scientific understanding and to develop business cases the WP7.3 team wishes to highlight the following methodological guidelines:

- The common purpose of the cabin air quality assessment should be identified in detail with relevant stakeholders and experts,
- Sensor-based methods are preferred for cabin air quality assessment, supported by human-based information. For preliminary exploratory research human-based information can be more cost-efficient,
- Conclusions drawn about the human aspect of the cabin air quality assessment should be placed in the perspectives of other factors and events outside the cabin and of air quality in other environments.

Depending on stakeholders' feedback on the IFCAS concept, the maturity of the IFCAS concept is recommended to be increased, taking into account the direct exploitability of IFCAS data. The recommendations for further research and development are detailed as follows:

- Carry out fundamental research on possible configurations, use and governance of IFCAS as a big data observatory for cabin air quality. This should take into account synergies with other big data initiatives in aviation such as Future Sky Safety's Risk Observatory and EASA's big data initiative. It should also take into account the trends on the Environmental Control System (ECS) and cabin of the future in disrupted aircraft and engine configurations, on the quantified self and on air quality in other environments. This research would help stakeholders, such as OEMs, operators, and regulatory agencies to prepare to exploit IFCAS,

- Study different business models and value propositions for operators and other stakeholders, exploiting, for instance, the use of sensor networks and data sharing for Prognostics Health Management/Condition Based Maintenance (PHM/CBM) or improvement of in-flight cabin management,
- Develop a target specification for gas sensors to operate in the aircraft cabin environment within the proposed IFCAS "black box". This requires cross-industry discussion and agreement. The target specification could be used to allow flexibility between different airlines (for example on which species to detect) and yet provide a common test strategy for sensor providers (for example concerning the environment(s) they should operate in). It would therefore allow sensors to be compared on a consistent basis. This may spur sensor developers to target their efforts towards a solution and act as a focus for research where either needs cannot be met, or where the background conditions are not well-defined (for example how much alcohol vapour builds up in a cabin and therefore how much should be tolerated by sensors without cross-response),
- Stimulate research on high-quality cabin air quality sensors for use in aircraft during flights, including e-nose concepts.

The use of IFCAS data can even be more effective when a wider context is explored. It is therefore recommended:

- To consider a citizen-based observatory for cabin air quality as an interesting use case in more fundamental research. The research question would be how incumbent stakeholders (regulators, operators, manufacturers) can harness these new social initiatives for improvement of the industry value chain,
- To investigate the effective use of IFCAS flight data in conjunction with other cabin air quality data. Such data may concern sensing-based data from research facilities and simulators and/or human-based data, both from flight and from research facilities and simulators. The investigation should be extended to other relevant data such as on-ground ambient data,
- To pursue multi-fidelity cabin air quality modelling and simulation. Models that have been validated against IFCAS data enable OEMs to design better and improved cabins, connecting air flow with systems and human response. The modelling approach in the Future Sky Safety P7 project can be coupled in a large simulation framework to enable this holistic approach.

To enable quantitative investigation of the potential for new materials to affect cabin air quality (if at all), the results of emissions experiments with those materials should be combined with the newly extended Environmental Control System model. Limits on the acceptable concentrations of different substances can also be applied, through the model, to define acceptable limits in these laboratory tests.

The experience of using COTS sensors in these tests should feed into specifications for the sensors in any IFCAS.

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Having established a methodology for potential assessment of materials, a wider range of new materials and testing of an increased number of samples would provide greater detail to inform materials selection and design.

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