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What are the main factors related to aircraft air quality?

Sources of aircraft air supply – Introduction.

Air in most commercial aircraft is supplied via the engines or Auxiliary Power Unit (APU), while the Boeing B787 Dreamliner (B787) sources its air direct from outside using an electric compressor. This air entering the aircraft cabin is sometimes called fresh air by the industry. On most aircraft approximately 50% of the cabin air is then recirculated. Therefore, approximately 50% of the air provided to the aircraft cabin is outside air and 50% is recirculated air. Although HEPA filters are often utilised to filter the recirculated air, the air from the outside is not filtered.

During flight, the cabin represents an environment that exposes passengers (and crew) to environmental conditions different from those on ground: hypobaric hypoxia, relative low humidity and relative proximity to fellow passengers (1).

We are all hearing the aviation industry telling us that the air in aircraft is safe and cleaner than homes and offices, and as good as in operating theatres due to HEPA filters; with clean outside air and complete air renewal in 2 to 3 minutes as well as air moving only from top to bottom in the cabin. Unfortunately, these statements are inaccurate. The key factors of aircraft air conditioning are briefly highlighted below.

1. **Ventilation:** The aircraft cabin is ventilated with an outside airflow to dilute contaminants, bioeffluents and particulates. The air needs to be compressed, because the outside pressure at cruise altitude is much lower than cabin pressure. It takes energy to compress the air. As such the airflow rate is limited for economic reasons. The required minimum airflow rate per person is given in the certification requirements: minimum of 7.5 -10 cubic feet per minute (cfm) / at least 0.55 lbs of fresh (outside) air per minute. This is in many cases lower than ground based environments (15-20 cfm). Some aircraft may provide higher rates of outside air than the required minimum rate. Recirculated air is then often utilised to increase the total airflow rate per person to levels similar to other indoor environments. Airflow rates vary between aircraft. The flight deck receives more outside air per person as the additional ventilation rate is utilised for cooling of equipment, control of smoke and fumes, smoke removal and windshield defogging. The concentration of any contaminant in the cabin is impacted by several factors: 1) any contamination of the air intake (e.g. contaminants from the engine compressor, APU or a polluted airport environment on the ground); 2) contaminants generated in the cabin (e.g. from people in the airplane exhaling CO_2); 3) strength of an environmental sink in the airplane (e.g. a filter taking out contaminants in recirculated cabin air) and 4) the airflow rate used for ventilation.

2. **Air exchange rate:** The air exchange rate is only of importance when looking at single events (like a single sneeze). The air in an aircraft is reported to be exchanged every 2-6 minutes (10-30 times per hour). However, due to the mixing of the air entering the cabin with the air already within the aircraft and due to limited ventilation efficiencies, it is estimated that it takes up to 10 times longer until the aircraft air is fully purged and replaced (see Q3), (2,3). The air exchange rate in aircraft is high not because the rate of air supplied is high, but because the cabin volume per passenger is small (2 m^3) compared to other indoor spaces (2).

3. **Recirculated air & HEPA filters:** Approximately 50% of the air supplied to the cabin is recirculated to provide a performance benefit in terms of reduced fuel consumption. The remainder of the air is exhausted overboard. High Efficiency Particulate Air (HEPA) filters are commonly utilised in the recirculated air to remove dust, fibres, allergens and microbes (‘microbes’ includes viruses and bacteria) at an efficiency rate of around 99.99% for 0.3 micron particle size (4). Smaller particles (such as the sizes of viruses) are removed by a combination of

inertial impact and diffusional impact. Their efficiencies are shown to improve with particles both smaller and larger than the 0.1-0.3 micron range (4). The efficiency of these filters as they age in use, is unclear. These filters do not remove gases and volatile organic compounds (VOC) from the recirculated air. Additionally, there are no requirements to install HEPA filters and no requirement on when to maintain or replace these filters, except for the manufacturer's recommendations. Some aircraft now use a combination HEPA/carbon filter in the recirculated air line to additionally help remove odours and volatile organic compounds (VOCs) e.g. Advanced Cabin Air Filter (A-CAF).

4. **Cabin air contamination:** The air supplied in all current transport aircraft except the B787 is sourced from the compressor section of the engines or APU. This air is not filtered. The compressor generated pressurised air is used to seal the lubricated areas within the engines/APU. Additionally, the aircraft pressurisation and ventilation air supply ("bleed air") is sourced from the compressor stage of the engine or APU. Despite the manufacturers utilising various designs to limit oil leakage through the engine/APU oil seals, seals limit leakage rather than prevent it occurring. Therefore, very low levels of the heated oil and a complex mixture of contaminants that are generated internally within the engine/APU, migrate out of the oil bearing chamber back into the compressor air. That is, the standard oil sealing design enables a very small oil leakage rate through the seals during normal operation. The oil and associated contaminants are then are able to enter the bleed air supply in normal operations. This becomes more noticeable during transient engine/APU power and air supply changes and other low pressure conditions such as start up, taxiing, descent. This odour is often characterized as a temporary dirty sock smell, which is a sign of oil exposure. Under certain system degradation conditions increased leakage of oil can enter the aircraft air supply. Other contaminants that can enter the ventilation supply air (outside air) include hydraulic or de-icing fluids, aircraft and airport exhaust emissions, airport electrical faults, fuel and engine compressor wash. As such the outside air cannot be claimed to be clean or fresh. A variety of cabin or flight deck sourced fumes can also contaminate the air supply including pesticides, cleaning products, carpet or upholstery, carry on baggage and human bioeffluents. Some of these contaminants may be a nuisance, while others are known to be hazardous and toxic. Contaminants that have been repeatedly identified in air monitoring studies include the organophosphate oil antiwear agent tricresyl phosphate (TCP), a known neurotoxin, tributyl phosphate, a primary ingredient in hydraulic fluids and an excess of 300 other compounds, including carbon monoxide. There are no detection systems fitted to aircraft to identify when the air supply is contaminated.

5. **Reduced oxygen environment:** Most aircraft cabins are pressurised to the equivalent of up to 8000 feet. Newer aircraft such as the B787 and Airbus A350 are pressurised up to 6000 feet. This reduced pressure environment provides a reduced amount of oxygen in the air, compared to being on the ground. This could have implications for people with adverse conditions and for workers at altitude who may not be obtaining enough oxygen for their physiological requirements (5).

6. **COVID-19:** The aviation industry and other professional bodies are publishing information on aircraft air supply systems and health and safety measures to address the COVID-19 problem that is a global current issue. The GCAQE will not repeat these measures here. Selected questions and answers are however set out below.

Questions related to COVID-19

Q1. Are the statements made by manufacturers and industry in general correct?

Answer: No. The GCAQE does not agree with the generalised statements made by manufacturers and many within the industry (6–8) that the air is safe and healthier than other environments as outlined in the various questions below. The statements are simplistic and designed to generate public confidence in air travel at a difficult time. This applies to both the COVID-19 as well as general air quality statements.

Q2. Will HEPA filters prevent transmission of COVID-19 in an aircraft?

Answer: No. HEPA filters are in the recirculated air path. They will obviously not prevent transmission of COVID-19, but reduce it. The importance of the HEPA filters is their role in helping prevent the distribution the viruses throughout the whole cabin by filtering the recirculated air. HEPA filters cannot be 100% effective, are not required to be inspected and changed at a specific interval. HEPA filters will also not prevent direct transmission between people who are in close proximity to others in the aircraft high density enclosed environment. Preliminary studies have shown that virus particles can remain in the air for up to 3 hours in a hospital environment and that SARS-CoV-2 provides an efficient form of exposure by way of aerosols (9,10). Additionally, 50% of the air entering the cabin is outside non-filtered air and 50% recirculated air that may be filtered. Therefore, the spread of airborne infectious agents in the passenger cabin can occur before the air is directed to the HEPA filters in the recirculated air system (11). The spread of airborne infectious agents in the passenger cabin is constantly generated by sick people and not from a single event. A survey undertaken by the GCAQE identified that 25% of aircrew reported a range of COVID type symptoms in April/May 2020 (12).

Q3. Will the high air exchange rate prevent transmission?

Answer: No. While the air exchange rate is high on aircraft, it is the volume flow per passenger that is the important factor and this is small compared to other ground based settings. Every few (2-6) minutes a cabin volume of fresh air enters the cabin, but due to mixing and limited ventilation efficiency, the air takes considerably longer (up to 10 times) to be fully renewed (2,3). The effective airflow (ventilation) rate in aircraft is comparable to office spaces and therefore does not provide a lower virus concentration (2). When considering only a single cough, studies have shown that the airborne droplet fraction reduced to 12% within 4 minutes, but was not fully eliminated in this time (13).

Q4. Is the air fully renewed every 2-6 minutes?

Answer: No, see Q3.

Q5. Does the air flow from top to bottom and subsequent removal prevent air movement between adjacent seat rows or to rows further up or down the cabin?

Answer: No. The aircraft airflow is more complex than purely vertical movement and other movements of air should also be taken into account. In addition, air flows horizontally, laterally and to a substantially lesser extent longitudinally through the cabin. The mixing of the cabin air in the longitudinal direction also occurs due to (air and human generated) turbulence and dilution (2). Mixing of air between passengers in adjacent rows is possible (2), while airborne aerosols and airborne exposure that can transmit via air currents has recently been highlighted as an important consideration rather than purely droplet exposure (14). Studies related to other airborne infectious diseases have identified that airborne exposure is not limited to the individual row only (9,13,15,16). The aircraft is a unique environment in that a lot of people are in the environment sitting in very close proximity for a long period of time, with relatively little volume of air per passenger (17). There are a variety of other factors that should be considered related to pathogen inhalation in aircraft, with long-haul flights identified as the highest risk compared to other ventilated environments (11). Other factors such as low relative humidity in aircraft, turbulence of air due to people movement and airflow beyond the individual row (11), individual gasper use and body heat creating increased air turbulence and greater aerosol movement should also be considered.

Q6. Is it a good idea to put the overhead air gasper outlet facing you?

Answer: No. The gasper airflow creates turbulence of the air and therefore entrains some of the breathing air from the people sitting next to you. It is better to either leave the gasper flow off or point it between the seats and face it downwards.

Q7. Is all the aircraft air filtered?

Answer: No. Approximately 50% of the air provided to the aircraft cabin is outside air and 50% is recirculated air. Only the recirculated air is filtered if the aircraft is equipped with HEPA filters. There is no requirement to have HEPA recirculated air filters. The air sourced from outside entering through the engines or APU flows through the entire system totally unfiltered (all aircraft including the B787). Approximately 50% of the air provided to the cabin may then be recirculated and HEPA filters may be installed to filter this portion of the air being recirculated.

Q8. Is the air that enters the cabin fresh and clean as claimed?

Answer: No. The outside air utilised as the source for the aircraft ventilation system is not filtered at all. It is known to contain a range of contaminants generated from both the external environment as well as within the engines and APU that enter the compressor air, from where the aircraft air supply is sourced. Some of these contaminants such as engine oil will enter the aircraft air during aircraft normal operations. This air is not filtered. Filtration is only applied to the recirculated air. Therefore any contaminated outside air will circulate throughout the aircraft, before it has a chance to be filtered (not always) to remove a range of contaminants, but not all.

Q9. By using HEPA filters on the recirculated air, does the air in aircraft become as clean as an operating theatre?

Answer: No. An operating theatre is a clean room following recognised standards. It is ventilated by air filtered in several stages. Ventilation of an aircraft cabin is by no means controlled by comparable standards. The HEPA filter is the only part in common, but is used in a totally different way. The air in an aircraft is sourced from the engines or APU and this air is not filtered before being supplied to the aircraft cabin. Operating theatre HEPA filters do not use air sourced from engines or recirculated air and are replaced far more often, based on a pressure check and are not as heavily polluted (17). Additionally, a plane and a hospital operating theatre are not comparable for a variety of other reasons including that, 1) the air circulates in differing ways: the pathogens are not swirled around in an operating theatre, rather they are displaced, whereas in an aircraft, the air mass is circulated or mixed, leading to air turbulence; 2) larger particles are 95% filtered out in an operating theatre before reaching the HEPA filter (17).

Q10. Is wearing masks in the cabin enough to prevent transmission of SARS-CoV-2?

Answer: The GCAQE believes that while there is a lot to learn about the transmission of SARS-CoV-2, that in addition to the standard air supply/ventilation system utilised in aircraft, the policy of wearing masks (FFP2/3), social distancing, improved sanitisation and prevention of localised transmission via aerosols should all be undertaken (9).

Other questions related to cabin air quality

Q11. Is the airflow ventilation rate high enough to flush out/dilute contaminants?

Answer: No. A wide range of low levels of contaminants have been identified in aircraft air. Contaminants related to engine and APU oils and aircraft hydraulic fluids have been routinely identified in ad-hoc aircraft air monitoring studies and swab testing. The majority of these studies have been undertaken during normal aircraft operation and are not limited to failure events.

Q12. Is the air fully sanitised when the engines are started and before the air reaches the cabin?

Answer: No. The air supplied via the engines or APU or ground power source (outside air) at the airport is not filtered or sanitised at all. This air is provided to the cabin and the occupants unfiltered. Once this unfiltered air has been circulated through the cabin one full time, 50% of this air is then recirculated and sometimes filtered using HEPA filters for selected particles but not VOCs and gases.

Q13. Does more need to be done to protect aircraft occupants from chemical compounds/contaminants?

Answer: Yes. All aircraft should be fitted with filtration or air cleaning systems to remove contaminants from the outside air supply that is known to generate contaminants, both from outside the aircraft that then enters the supply air and within the aircraft engines and APUs. Future aircraft designs should no longer source the air from the engine or APU compressor. The B787 is one such design as detailed in Q16.

Q14. Are there any aircraft detection systems to identify when the aircraft air supply is contaminated?

Answer: No. There are no sensors or flight deck warning systems to identify when the aircraft air is contaminated. This is despite regulatory requirements to identify when the air supply is contaminated and strong evidence identifying that the air is becoming contaminated in both routine normal aircraft operations, as well as the less frequent failure conditions.

Q15. Where are filtration, detection system and alternate air supply in their development?

Answer: As of August 2020, a number of companies are said to be developing sensors and filters (e.g. Safran, Pall). It is understood that Pall Aerospace who have developed a Cabin Air Quality Sensor (CAQS) will soon have a portable part for companies to order. The sensor detects the signature of either: engine oil, hydraulic fluid, de-icing fluid or other. Their total cabin air filtration system (18) (filtering the bleed air), also known as a MAVE filter is still in ground test evaluation mode. Airbus has a patent for a system and method for determining the origin of oil leakage in the aircraft bleed air supply system, while Boeing has patented a method for reducing aircraft engine oil leakage which includes an oil leak detection sensor (19,20). Other patents relating to real time air monitoring systems are available (21–24). An alternate method of pressurising air via a fan inlet separate from core air supply, using separate clean air auxiliary compressor has been patented (25), as well bleed air sourced from a secondary power unit (not engines) using air lubricated bearings (26) and an ECS that draws in outside air for the air supply which is not exposed to bleed air (27). It is unknown whether any of the above patents have been implemented.

Q16. Is the Boeing B787 air cleaner than aircraft using engine/APU sourced bleed air?

Answer: The B787 should be applauded, as it does not source the air from the engines or APU. Therefore it is not subject to engine or APU internally generated oil fumes that are known to contaminate other aircraft in all flights. However, the B787 sources the air via an air inlet sourced at the wing route and the body of the aircraft and this air is not filtered. Therefore while on the ground, the externally supplied air will contain contaminants (aircraft exhaust emissions, oil, airport environment and vehicle emissions), however the electrical air compressor system itself will not generate oil fumes as other aircraft do when using bleed air. Therefore the B787 supply air will be cleaner than the regular bleed air aircraft.

Q17. Is any of the engine bleed air filtered?

Answer: Yes. The engine bleed air is not currently filtered before it enters the aircraft cabin and cockpit. However there are 2 known exceptions. Bleed air is also used to pressurise some fuel tanks as part of the Fuel Tank Inerting System (FTIS). This bleed air is pre-filtered to remove particulate, oil and water mist contamination, VOCs and ozone from the engine bleed air utilised in the fuel tanks to protect the air separation module used in the FTIS (28,29). An advanced VOC carbon adsorbent is utilised as part of the 4 stage FTIS pre-filter process (28). Similar technology has also been used since about 2010, when activated carbon filters were installed on DHL Boeing 757 aircraft with Rolls-Royce engines. This 'Cockpit Filter Unit (CFU)', made by Pall Aerospace, filters the bleed air supply to the cockpit (30). It is also understood these filters are being introduced on other DHL aircraft.

Q18. Have the various industry studies that suggest the air quality in aircraft is better than other environments been adequately undertaken to address health and flight safety concerns?

Answer: No. Various ad hoc studies have been undertaken to identify contaminants in the aircraft cabin air and on the surfaces. These have routinely identified low levels of contaminants related to oil and hydraulic fluid exposure. Most of the studies were undertaken during normal operations and therefore not during fume events. The studies incorrectly show the low levels of the identified substances to be below government set exposure standards, and suggest the levels are below those identified in other environments, such as offices, homes and kindergartens. These conclusions are made knowing that exposure standards are not available for all chemicals, apply to individual substances, do not apply to the general public and should not be applied to the aircraft environment (31).

Q19. Are the aviation standards and regulations met using the aircraft bleed air system?

Answer: No. The aviation regulators and industry of course suggest all standards and regulations are met related to the aircraft ventilation air supply, cabin air quality and the use of the bleed air system. However, this is incorrect. The air supply must provide a sufficient amount of uncontaminated air to allow the crew to perform their duties without undue discomfort or fatigue, must not supply harmful concentrations of gases or vapours and must not cause impairment greater than 1 in 100,000 flight/engine/APU hours. However, the use of supply air without filtration and more specifically the use of the bleed air system cannot meet these requirements (32,33).

GCAQE September 2020

Further information:

1. GCAQE: https://www.gcaqe.org/

2. susanmichaelis.com: https://www.susanmichaelis.com/about

3. 2017 air quality conference proceedings:

https://www.journalhealthpollution.org/doi/10.5696/2156-9614-9.24.191201 (journal)

https://zenodo.org/communities/aircraftcabinair/?page=1&size=20 (individual papers)

4. 2019 air quality conference videos: (GCAQE members ask for discount code):

https://vimeo.com/ondemand/aca2019

5. Free videos on cabin air by Fact Not Fiction Films

https://vimeo.com/groups/617439/

6. Professor Dieter Scholz: Information on flying during the corona pandemic.

http://corona.ProfScholz.de

https://www.youtube.com/playlist?list=PLwaZT943QwlHbtRl1_xTUH-PcLzNmGNyB

7. Global Cabin Air Reporting System: https://gcars.app/

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