Aircraft contaminated air: a brief outline

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Abstract: Aircraft bleed air supplies contaminated by engine oil dates back to the early 1950s. Aircraft and engine/APU design utilising unfiltered bleed air to supply the breathing air in aircraft explains the mechanism by which the air supply routinely becomes contaminated with low levels of a complex mixture of jet oils and hydraulic fluids in normal operation. Exposure to these contaminants is increasingly recognised as a flight safety issue as well as an occupational health problem, with impairment in flight not uncommon. Maintenance investigation techniques are less effective in identifying the more frequent low level oil leakage events with repeat events occurring. Over the last two decades, there have been an increasing number of international activities looking into bleed air contamination. It is necessary for the aviation industry to take a closer look at fume events linked to the supply air and introduce mitigating strategies.

Keywords: bleed air; oil leakage; fumes; cabin air contamination; synthetic lubricants; cabin air quality; CAQ.

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1 Background

Concerns regarding aircraft air supplies becoming contaminated extend back to the early 1950s and continue to the present day. The higher performing turbine engines introduced in the early 1950s required the use of newly developed synthetic lubricants. This corresponded with both civilian and military reports about contamination of the air, which was reported to be associated with the oil lubricants leaking into the air supply. Such reports have continued to the present day but have considerably increased in the last two to three decades. The main focus of these concerns relates to the air supply becoming contaminated with synthetic engine oils and hydraulic fluids. The air supply for all modern transport aircraft, except for the Boeing 787 Dreamliner, is drawn unfiltered from the engine or auxiliary power unit (APU) compressor stages. This air is known as 'bleed air' and it is recognised to become contaminated with the oils and hydraulic fluids from either external or internal sources.

There is extensive documentation from various sources highlighting the ongoing nature of these fluids contaminating the air supplies in aircraft. These include oil, parts, airframe and engine/APU manufacturers and airline documentation, aviation regulator and bureau of air safety incident reports, measurements, scientific studies, published literature, air crew and union reports, medical and legal documentation, government and industry reviews and committee findings and academic studies. An extensive review by Michaelis (2010) is available highlighting the history up to 2010. However, the problem of aircrew and passengers breathing air contaminated by these fluids remains unresolved necessitating more to be done to address this. Across the board, there is limited understanding of the various factors relevant to this topic, which prolongs adequate resolution.

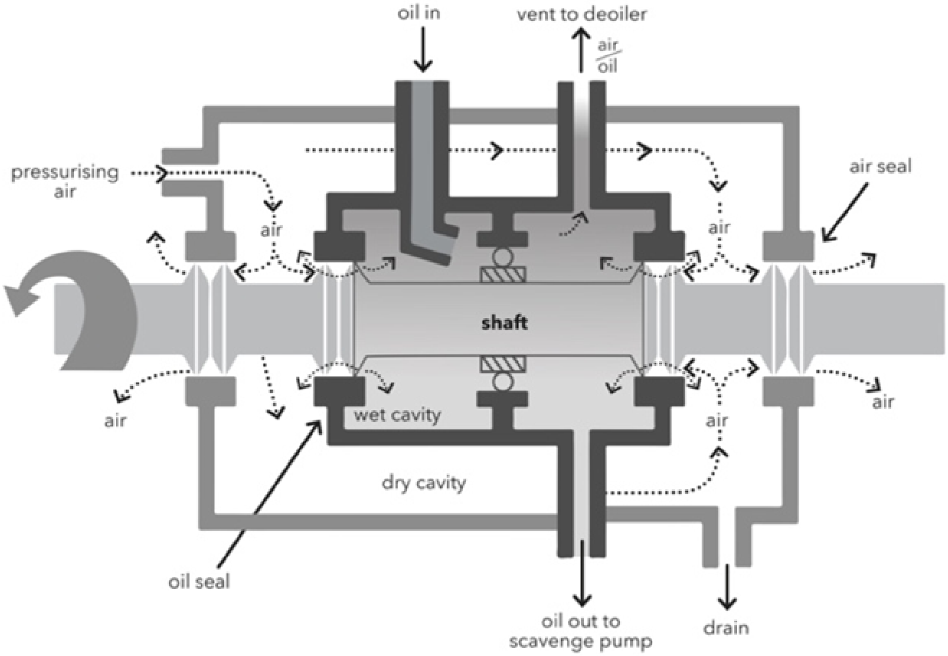
2 Discussion

The oil system within the engine (including APU) explains how leakage of the fluids into the air supply may occur. As shown in Figure 1, the oil-bearing chamber is sealed with the use of pressurised air drawn from the compressor into the bearing chamber. The turbine engines "lose some lubricant under normal operating conditions and the oil lost is replenished on a regular basis. These procedures maintain the additive packages at acceptable levels" (Johnson, 2018).

The permissible oil consumption (0.1–1 litre per hour) or losses of oil during normal operation occurs with the air/oil mist being extracted via the vent or deoiler system, or with migration of oil over the seals or other leakages during normal operations (ExxonMobil, 2014). The oil system design will ensure the majority of the oil is recirculated through the system with air and oil mist exiting to the environment via the vent system through the gearbox, exhaust system or a separate vent pipe. However, some of the permissible oil consumption will be due to oil migrating over the oil seals, particularly during changes of pressures and balances over the seals or when the sealing pressure is inadequate (Michaelis, 2016, 2018; Michaelis and Morton, 2019). This is most likely to occur during changes of engine power and air supply configuration changes. Some of the oil passing over the seals into the compressor may then enter the bleed air supply, for the cabin, if the bleed air off-take point is downstream of where the oil leakage has occurred.

While many continue to suggest that oil would only enter the air supply during rare bearing seal failure events, this is incorrect. Of course, various engine/APU design features are utilised to minimise oil leakage past the seals and to prevent oil entering the bleed air offtake. However, seals are used to minimise rather than prevent leakage of the fluids, in this case oil. Therefore, as acknowledged by ExxonMobil (2014) and elsewhere, oil leakage past the seals during normal operations is expected. Some of this oil leakage is therefore able to enter the breathing air supply system. Long ago, Rolls-Royce recognised evaporation loss of oil "constitutes only a minor part of the oil consumption in Rolls-Royce gas turbines, the major part of the consumption representing loss of liquid oil arising from permissible leakage past certain seals, escape of mist or aerosol through breathers" and losses incurred during inspections (Edge and Squires, 1969). More recently, EASA (2017a) reported that "most engines might have a certain turbine oil leak rate", which they also described as a "permanent engine oil (contaminant) entry into the cabin." A more detailed discussion on how oil leakage past seals and into the cabin air can occur is available for review (Michaelis, 2016, 2018; Michaelis et al., 2021).

Figure 1 Typical oil-bearing chamber



Engine manufacturers advise that oil will not leak over the seals when an engine is operating normally and that the oil loss occurs via the vent system and oil drain, which is confirmed during engine certification. However, this fails to consider that certification is based upon steady state operations and does not address transient power changes and changing pressures over the seals, when the majority of the more frequent transient fume events occur. Additionally, this approach fails to consider that all dynamic seals are designed to leak. "How much they leak depends on many factors including the style of seal, the balance ratio or tooth pattern, the lubricating regime, operating conditions (speed, temperatures and pressures), compartment condition, wear life and distortion" (Howard et al., 2018). The impact of seals on engines and aircraft includes engine efficiency, bearing damage, dirt ingestion into the engine and contamination of the bleed air supply (Shabbir et al., 2019).

In summary, oil leakage past seals is known to occur in three distinct ways:

1 Leakage past seals at very low levels as seals are flow restrictors, rather than an absolute prevention technology.

2 Low level leakage past seals during transient changes of power or air supply configuration, specifically with changes of pressures and balances or low pressures over the seals during certain operating conditions, start-up, taxiing, take off, climb, top of descent, descent, approach and landing (Michaelis, 2016, 2018; Howard et al., 2018).

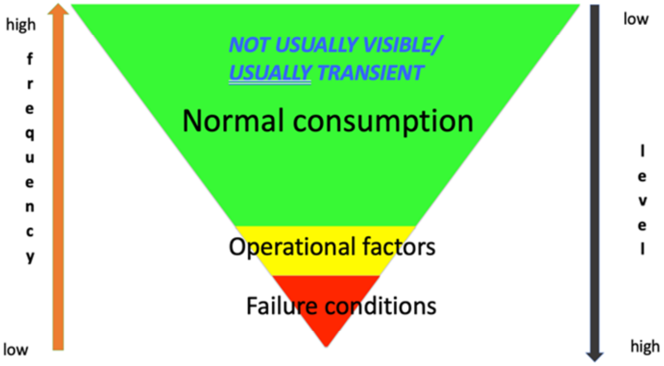
3 Increased leakage as result of a failure in the system such as a failed bearing or seal or other operational factors such as oil overfill/waring seals etc.

Therefore, the common assumption that oil will not leak out of the bearing chamber if there is a higher and positive pressure outside the bearing chamber compared to inside, is also incorrect (Michaelis, 2016).

Ongoing fume events continue to occur on a regular basis. These are most frequently associated with transient events during engine and air supply changes and are usually non-visible. They are often described as a dirty sock type odour, which is associated with the thermal degradation (pyrolysis) of the oil base stock or hydrolysis when moisture mixes with the oil. These carboxylic acids (associated with the oil base stock) have a characteristic smell of dirty socks (ASHRAE, 2012).

Far less frequently, smoke or mist may occur, which is more likely associated with a failure within the system, wearing seals or operational factors, such as oil overfills. The inverse relationship between frequency of operational conditions and level of oil consumption can be seen in Figure 2.

Figure 2 Typical oil consumption (see online version for colours)



However, there is a continual problem with under-reporting fume events at all levels. This has been well recognised (EASA, 2011; FAA, 2006; Michaelis, 2010; Anderson, 2021). In any case reporting of fume events fails to consider the continual chronic background exposure to oil and hydraulic fumes.

There have been more than 40 air monitoring and swab sampling studies undertaken over recent years (Michaelis, 2010; Chen et al., 2021). None of these have been undertaken in real time and most have not been undertaken during fume events. Tricresyl phosphate (TCP) used as the engine/APU oil antiwear additive and tributyl phosphate (TBP) a major component in hydraulic fluids were frequently identified at low levels in many of these studies (EASA, 2017a; Crump et al.,, 2011; CAA, 2004; Rosenberger, 2018).

While it is often suggested that the air quality in aircraft is better than in ground-based environments, including houses, offices and kindergartens, this thinking is erroneously based upon comparing the levels of the substances to government set exposure limits. However, such limits are not available for all substances, and are often based on outdated science, do not apply to passengers, will not protect all workers and should not be applied at altitude or for heated complex mixtures (ACGIH, 2015; Watterson and Michaelis, 2019).

Oil pyrolysis studies have identified that when heated, the oils generate more than 127 differing compounds (EASA, 2017b). This supports the finding that aircraft occupants are exposed to a complex mixture of bleed air contaminants in flight, rather than just the substances in the original oil product.

More recently, ultrafine particles (UFPs) have been identified in a four-part experimental program involving a detailed characterisation of particles generated when the bleed air was deliberately contaminated with engine oils. Oil contamination in the compressor, generated UFP droplets in most normal operating conditions (Jones et al., 2017). UFPs were found at increased concentrations in a small study undertaken on four short-haul flights. The number of UFP particles was shown to increase in association with engine and APU power changes and with changes in air supply configuration (Michaelis et al., 2021). These results correlated with times when APU and engine oil seals are known to be less effective. Michaelis et al. (2021) provides a detailed review of fine particle and UFP studies in aircraft that support these findings.

Chronic background exposure to very low levels of engine oils, in addition to oil fumes during transient power changes or less frequent maintenance or failure conditions, are recognised to impact flight safety (FAA, 2004; Michaelis, 2010; ICAO, 2015; AAIB, 2020). In 2018, the FAA issued a safety alert to operators advising that "Inflight odor, smoke and/or fume events can occur without overt visual and/or olfactory cues. To mitigate adverse health consequences to passengers and crew, prompt and decisive action is critical."

Additionally, acute and chronic exposure to oil fumes and hydraulic fluids are now associated with a range of acute and long-term adverse health effects (Michaelis et al., 2017). These have been increasingly and well documented elsewhere, particularly over the last two decades. A large EU funded study has recently reported that "exposure to engine oil and hydraulic fluid fumes can induce considerable lung toxicity, clearly reflecting the potential health risks of contaminated aircraft cabin air" (He et al., 2021).

Adverse health effects associated with exposure to the engine oils and other bleed air contaminants have been termed 'aerotoxic syndrome'. While not widely accepted by the aviation community, this has been highlighted as a possible new occupational disease (Michaelis et al., 2017). The two key exposure scenarios are:

1. acute higher dose (generally non-visible and transient) fume events
2. chronic repeated low-dose exposure to a complex mixture related to the oils and other fluid emissions via the bleed air system (Howard et al., 2017).

The globally harmonised system for chemical classification lists a variety of health hazards associated with exposure to the substances in the oils and hydraulic and de-icing fluids. These statements include: may or suspected to cause damage to fertility or the unborn child, harmful if swallowed, in dermal contact or inhaled, single or repeated/prolonged exposure target organ toxicity, eye, skin and respiratory irritation, may cause allergic skin reaction; may or suspected to cause genetic defects, may cause allergy or asthma symptoms or breathing difficulties if inhaled, may or suspected to cause cancer and may cause drowsiness or dizziness – central nervous system effects (ECHA, 2019; Michaelis et al., 2017).

The oil material safety data sheets (MSDS) report a variety of warning statements including:

- "This product is not expected to produce adverse health effects under normal conditions of use and with appropriate personal hygiene practices. Product may decompose at elevated temperatures or under fire conditions and give off irritating and/or harmful (carbon monoxide) gases/vapours/fumes. Symptoms from acute exposure to these decomposition products in confined spaces may include headache, nausea, eye, nose, and throat irritation." "Contains a substance that may cause damage to organs from prolonged or repeated exposure" (ExxonMobil, 2017).
- "Inhalation of thermal decomposition products may lead to adverse effects including pulmonary oedema…… Do not breathe vapours or spray mist" (Eastman, 2016).

Mobil, however advised that exposure to the oil fumes in aerosol or vapour in aircraft cabins was not considered a normal use of the product (Mackerer and Ladov, 2000). This was clearly acknowledged by Winder Balouet (2002), when saying jet oils "have an appreciable hazard due to toxic ingredients; but are safe in use provided that maintenance personnel follow appropriate safety precautions and the oil stays in the engine."

The common industry practice of looking at the toxicity of the engine oils in terms of the ortho isomer of the TCP additive alone, tri-ortho-cresyl phosphate (TOCP) is inappropriate. This severely underestimates the risks of exposure to the other organophosphate (OP) TCP isomers in the oil and the complex mixture generated (Howard, 2020). Additionally, the OPs that adhere to the surfaces of the particles in the aerosols in the cabin air are of considerable importance when considering the dose and risks associated with exposures in normal operations (Howard et al., 2018; Howard, 2020). These have not been taken into account with the measurement studies to date, which rely on individual substances only.

Certification of aircraft ventilation supplies for the crew and passenger breathing air has been inadequate. The use of bleed air to supply the breathing air for aircrew and passengers fails to meet the aviation air quality related regulations, standards and acceptable means of compliance (Michaelis, 2016, 2018).

There has been little focus on the aircraft bleed air at engine or APU level, with the requirement to ensure that the bleed air supplies do not incapacitate crew or passengers. The requirement to ensure that impairment associated with the air supply happens no more frequently than 10^{-5} is almost ignored. This is clearly outlined in the MSc by Michaelis (2016, 2018). The cabin air certification requirements are almost exclusively seen in light of the ventilation regulation or certification standard (FAR 25.831, CS 25.831). This is despite this regulation/standard referring to three contaminants only, with no requirement by the regulators to monitor these substances in real time to provide the crew with a warning that the air may be contaminated (CS 25.1309c). Additionally, little consideration is given to the design that uses engine or APU generated compressed air to supply the ventilation air, which will be contaminated in normal flight as highlighted above.

There are a variety of occupational health and safety (OHS) regulations and directives addressing hazards in the workplace. However, these are not being applied to aircrew exposed to contaminated air in their workplace. Contaminated air via the aircraft air supply has been seen as an aviation regulatory issue, while the regulators do not have expertise in this area. This was acknowledged clearly by the Civil Aviation Safety Authority (CASA) in Australia during a cabin air quality (CAQ) senate inquiry in 1999–2000. The regulator stated that toxins in the aircraft cabin were more a long-term OHS problem, while they were responsible for short to medium term issues and that CAQ was outside its expertise (PCA, 2000). In the UK for example, despite the OHS directives being applicable to aircrew, a memorandum of understanding (MOU) between the aviation regulator, the Civil Aviation Authority (CAA) and OHS regulator (HSE) gives the lead role to the aviation regulator (CAA et al., 2017). The CAA also admitted such exposures were outside its expertise. The MOU gives the lead to the HSE for non-crew members on the ground.

Another factor that requires consideration is that maintenance troubleshooting investigations are more efficient in the case of heavy oil leakage, with the more common light oil contamination occurrences being more difficult to confirm, particularly the more common transient events only (Howard et al., 2018). Very often, no source can be identified and repeat events occur (Michaelis et al., 2017; AAIB, 2020). Additionally, it takes very little oil to create a fume (Vera-Barcelo, 2013). A handheld maintenance tool has been utilised to investigate reported fume events once on the ground, however this appears more appropriate for the less frequent more significant events only. A careful review of manufacturer documentation related to CAQ and oil fumes should be undertaken. TAP, the Portuguese airline identified the difficulties it had experienced with fume events associated with operating the A330 aircraft (Pavia, 2019). Iceland Air and Air France both undertook a case study reviewing fume events in their airlines (Hansen, 2019; Feuillie, 2020)

Over the last two decades, there have been an increasing number of Aviation Investigation Bureau (AIB) investigations and reports (Loraine, 2019). While most are of a brief nature, some have been more extensive. There are an increasing number of important findings with over 50 recommendations made in 16 reports from ten countries. These recommendations cover a variety of areas including airworthiness, maintenance and certification, protocols during and post FEs, international database, research addressing the oils, contaminants and effects on human health and detection and warning systems. A recent review of a UK AIB report involving a series of fume events on the A320 family of aircraft, identified an insufficient appreciation of the various factors associated with oil fume exposures (Michaelis, 2021).

While studies relating to oil contaminating the air supply have continued since the early 1950s, there has been increasing activity in the last two decades. The more recent activities include inquiries and reviews in Australia, the USA and the UK, US legislative bills, air monitoring and CAQ research studies, scientific studies and literature, chemical reviews, CAQ standards development, extensive air accident department investigations (the UK and Germany) and legal cases.

There are an increasing number of risk mitigation strategies in development to aid in reducing bleed air contamination events. These include sensor and filtration/air cleaning technology developments, patents addressing bleed free designs, following on from the B787 and oil leakage reduction strategies and the development of less toxic oils. There is also a need for better education, training and reporting related to bleed air or supply air contamination (ICAO, 2015). This is relevant for aircrew, maintenance staff, MROs, manufacturer and airline operators, including senior management. A medical guidance document and fume event protocol specific to bleed air contamination and air supply fume events are in development.

3 Conclusions

It is increasingly recognised that there is a permanent low-level leakage of turbine engine oil into the cabin air supply. There needs to be a greater awareness about leakage through the seals, particularly under conditions of changing or reduced air pressure over the seals, which occurs during transient engine operations or low power settings. Improved maintenance troubleshooting and overhaul procedures are urgently required.

While there is extensive documentation supporting and initiatives underway addressing oil leakage into the cabin air supply during normal operations, little tangible improvement has been made to reduce exposures. There is overwhelming and supporting evidence available that real risk mitigation strategies related to all areas of contaminated bleed air exposures must be implemented now.

These risk mitigation strategies include, but are not limited to, bleed free designs for future aircraft, filtration of the bleed air or supply air provided for aircraft ventilation, real-time detection systems to warn crew when the air is contaminated, improved maintenance procedures, fume event education and training and improved reporting systems, fume event medical guidance protocol and post fume event procedures (Michaelis, 2016).

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Abbreviations

AIB	Aviation Investigation Bureau
APU	Auxiliary power unit
CAA	Civil Aviation Authority
CAQ	Cabin air quality
MOU	Memorandum of understanding
OHS	Occupational health and safety
OP	Organophosphate
TCP	Tricresyl phosphate
TOCP	Tri-ortho-cresyl phosphate