Bearing chamber sealing and the use of aircraft bleed air

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ABSTRACT

Reports of contaminated bleed air remain ongoing. Master of Science (MSc) research [1] was undertaken to assess whether there is any gap between the certification requirements for the provision of clean air in crew and passenger compartments, and the theoretical and practical implementation of the requirements using the bleed air system. Low level oil leakage into the aircraft cabin in normal flight operations is a function of the design of the engine lubricating system and bleed air systems, both utilising pressurised air. The use of the bleed air system to supply breathing air has regulatory and certification implications that require changes to be implemented.

Keywords: cabin air quality; bleed air contamination; oil leakage, lubrication, gas turbine, oil seals

NOMENCLATURE

AMC	Acceptable Means of Compliance
APU	Auxiliary Power Unit
CS	Certification Standard
EASA	European Aviation Safety Agency
/efh	per engine flight hour
FAA	Federal Aviation Administration
/fh	per flight hour
/APUoh	per APU operating hour
CS	Certification Standard
CS E	Certification Specification Engine
CS APU	Certification Specification APU
FAR	Federal Aviation Regulation
MSc	Master of Science
nm	nanometer
μm	micrometer

1.0 INTRODUCTION

There are extensive reports regarding concerns about contamination of the aircraft bleed air supply (fume events) extending back to the early 1950s [2–4]. This coincided with the introduction of synthetic jet oils that replaced mineral oils and the introduction of higher performing, higher temperature and pressure turbine engines[5]. Varying types of reports have continued to the present day, such as military, airline, manufacturer and crew reports. Furthermore, there have been airworthiness directives, regulator initiatives, legal and insurance claims, scientific committee studies, published literature and media reports. There have been in excess of 45 key recommendations and findings from nine bureaus of air safety between the mid 1990s and 2018, related to incidents involving reported contaminated air[6].

The vast majority of fume events are associated with an abnormal leakage of engine or Auxiliary Power Unit (APU) oil[7]. Compressor bearing seals have long been seen as the main source of small leakages of oil into the cabin air supply [8,9].

Frequency of exposure to engine oils, are suggested to range from rare and infrequent to frequent, with seals leaking as a normal function of their design and operation, with oil seals reliant upon compressed air for their sealing functionality. Recent suggested frequency rates include events reported to the regulator at 2.1 events per 10,000 departures, 0.87 incidents per day and oil fumes reported in 1% of flights [10–12]. However, under-reporting is commonly recognised [13–15]. Alternatively, the current design of the majority of commercial airliners guarantees this continual background exposure because all oil seals weep small amounts of lubricant in normal operation [1,16,17]. Impairment has been highlighted in around 30% of the reported events[1,13,18–20].

Exposure to a range of hazardous substances and pyrolysis by-products, from engine oils and hydraulic and deicing fluids contaminating the aircraft air supply, is increasingly recognised as potentially adversely impacting flight safety[21,22]. Despite no real time monitoring to detect compressor bleed air contamination, a growing number of studies have confirmed the presence of low levels of oil substances in the air supply system in normal operations between 25% and 100% of flights[23–25]. While the significance of exposure continues to be questioned, an increasing number of global initiatives continue to be undertaken by the International Civil Aviation organization (ICAO), the International Air Transport Association(IATA), the European Aviation Safety Agency (EASA), The European Commission, The European Chemicals Agency (ECHA) and government and industry initiatives [21,25–31]. While short-term effects associated with exposure to engine oils and other aircraft fluids are becoming more widely acknowledged, it is suggested by the industry that long-term effects are unlikely but cannot be ruled out[31,32]. However there is supporting literature addressing longer-term effects, with a cause and effect link between both acute and long-term effects associated with such exposures reported more recently, based upon epidemiological studies [16,33].

There is general acceptance that aircraft cabin air can be contaminated by compounds released from pyrolysed oil from engines and auxiliary power units (APU) [34–36]. Mobil suggested this is an abnormal event [37]. There are two key ways in which oil leakage outside of the bearing chamber is reported to occur. Outside of the specialist engineering and air/oil sealing community, the wider aviation industry community commonly suggests oil leakage occurs only as a result of seal failure or operational deficiencies, such as seal wear or oil overfilling and as such is very rare [25,38,39]. The alternative view is that oil seal leakage occurs at low levels during normal phases of flight, indicating that all engines leak low levels of oil from the bearings through the seals during transient power changes and while the engines are still achieving optimum temperatures and pressures [1,40–42]. Chronic exposure to vapours that *"continuously leak through the seals in 'tiny'amounts"* are recognized [43], with design improvements called for, as sealing is required over the entire engine operating range including during transient manoeuvres [34,44]. The failure versus normal leakage scenario is highlighted by the suggestion that oil leaking from the bearings can be either *"slowly varying and somewhat continuous or sporadic and quite intermittent"*[45]. The specialist sealing and engineering community tend to support the latter view, however their views are not commonly reported.

The lower level leakage has generally been viewed as normal and safe, associated with minor discomfort only, with the larger events such as seal bearing failure or wear possibly affecting occupant health or flight safety [42].

There are clear regulatory standards and guidelines related to the aircraft air quality and differing views as to how the air can become degraded. It was therefore decided to raise an MSc research question addressing oil leakage out of the bearing chamber to determine if this is an occasional maintenance or failure scenario or a function of normal engine operation.

The aim of this work was to assess if there is any gap between aircraft certification requirements for the clean air in crew and passenger compartments of transport aircraft using the bleed air system and the theoretical and practical implementation of the requirements.

2.0 METHODOLOGY

The research consisted of three elements:

- A review of the certification regulations, standards and guidance/compliance material;
- Assessment of the documented understanding of bleed air contamination of the aircraft cabin air supply;
- Research addressing the real world implementation of the certification requirements requiring clean bleed air.

In order to understand the practical real world implementation of the requirements using the bleed air system, two separate interview processes were utilised:

- Semi-structured interviews undertaken with EASA and FAA airframe and engine/APU airworthiness departments about the process by which they certify and ensure clean aircraft air requirements are met with the use of bleed air;

- Semi-structured interviews undertaken with ten experienced aviation engineering professionals and two seal supplier experts about their professional judgement on how oil may leak past oil bearing seals into the air supply under various flight operational conditions. Ten of the twelve participants had an average of 43 years' experience in their respective fields, with the remaining two averaging 13 years. The areas of expertise included mechanical engineers, gas turbine designers and technicians and licenced aircraft maintenance engineers. The participants were from the UK (6), US (2), Australia (3) and France (1).

For the purposes of this paper, the reviews and assessment of the regulations and standards and contamination of the air supply have been updated slightly since the research was completed.

3.0 RESULTS

3.1 Certification standards, regulations and guidance material

Aircraft certification is essentially the same around the world, with some changes in the binding and non-binding nature of the requirements. For example the US Federal Aviation Regulations (FAR) are of regulatory nature, accompanied by acceptable means of compliance (AMC) and guidance material (GM). The European system utilises binding regulations and implementing regulations, accompanied by non-binding certification standards (CS), AMC and GM, which assist meeting the applicable legislation. The content of the two approaches is however very similar. Where non-binding requirements are provided, it is necessary to look additionally at the binding regulations applicable to the various areas. Use of the AMC set by EASA for example, provides a presumption of compliance with the standards and law, however alternative means of compliance may be used, with the loss of the presumption of compliance.

Key relevant airworthiness certification standards/regulations and guidance/compliance material relate to the following areas. A complete list can be found in the original research [1].

3.1.1 Airframe level

- CS/FAR 25.1309 – Equipment and systems design 'hazardous' and 'major' failure conditions must be extremely remote and remote respectively under the EU certification standards (CS) as shown in Table 1. The acceptable means of compliance (AMC), an established way of meeting the CS standards, outline that 'hazardous' failure conditions occur not more than 1×10^{-7}/flight hour (/fh) or a few times during the total life of all the aeroplanes of type. These include failure conditions causing pilots to be unable to be relied upon to perform their jobs accurately or completely or for a few other occupants to sustain serious injury. AMC 'major' failure conditions should not occur more than 1×10^{-5}/fh and are unlikely to occur to each aeroplane but may occur several times during the total life of a number of aircraft of type. These include impaired crew efficiency, discomfort to the pilots and physical distress or injuries to other occupants. The US Federal Aviation Regulations (FAR) are a little different (see Table 1), apart from terminology based on major failure conditions reducing the capability of the crew to cope with adverse conditions being improbable ($\leq 1 \times 10^{-5} - > 1 \times 10^{-9}$/fh). Minor or probable failure conditions listed under the EU AMC are those occurring above 1×10^{-5}/fh causing a slight increase in pilot workload or some inconvenience to other occupants and may occur one or more times during the entire operational life of each aeroplane.
- CS and FAR 25.831 relate to the airworthiness ventilation and heating for the cabin. They require that each crew compartment has enough fresh air enabling crew to perform their duties without undue discomfort or fatigue. The FAR is very similar but requires a sufficient amount of uncontaminated air and references reasonable passenger comfort. Crew and passenger compartments must be free of harmful or hazardous concentrations of gases or vapours. Only

carbon monoxide (CO), carbon dioxide (CO_2), ozone (O_3) levels and fresh airflow rates are listed.

- Warning systems must be provided to alert the crew to unsafe system operating conditions and to enable them to take corrective action under FAR and CS 25.1309c.
- An unsafe condition includes events that occur more frequently than the safety objectives allow, or that may reduce the ability of the crew to cope with adverse operating conditions, impair crew efficiency or cause discomfort/injuries to occupants (EASA AMC 21. A.3Bb).
- There are various other voluntary standards or recommended practices that have been published over the years. The original Military specification (MIL-E-5007) used for certification compliance defined that oil leakage within the engines should not cause oil contamination of the bleed air. However contaminant levels were to be within specified limits.

3.1.2 Engine/APU level

- CS E (engine) 510 and CS APU 210 engines and APU safety analysis require that 'hazardous' engine/APU effects are extremely remote, $<10^{-7}$/engine flight hour (/efh) or APU operating hour (APUoh) up to 10^{-9}/efh or /APUoh. This includes toxic products in the engine or APU bleed air intended for the cabin sufficient to incapacitate crew or passengers. Degradation of oil leaking into the compressor airflow is listed as toxic products under the AMC. The safety analysis must include compressor bleed air systems. 'Major' engine/APU effects must not be greater than remote ($<10^{-5}$/efh or /APUoh) under the CS. The AMC 'major' effects includes toxic products in the bleed air sufficient to degrade crew performance. Further details can be seen in Table 1. The US FAR, CFR 14 33.75 engine safety analysis and related guidance material is very similar. A US APU Technical Standing Order (TSO- C77b) requires that failures do not generate an unacceptable concentration of toxic products in the bleed air. In dealing with such low probabilities, absolute proof is not possible with reliance placed on good engineering judgment, previous experience, sound design and test philosophies.
- CS E-690 requires contamination or purity tests of the bleed air when it is directly used in the cabin and an analysis of defects that could cause this to occur. CS-APU 320 and TSO-C77b require that characteristics of bleed air contaminants are listed for APUs providing compressor bleed air.

Table 1
Airframe and engine/APU regulations, standards, AMC and GM relevant to clean air requirements (see reference 1 for complete table or original material).

Airframe Level

FAA	EASA
Regulation/standard	
CFR 14 25.1309 - Airworthiness standards – equipment: Failure condition: 1. Reducing ability of crew to cope with adverse operating conditions. • Improbable	CS 25.1309 - Equipment, systems … design requirements – Failure condition: 1. Major • Remote 2. Hazardous • Extremely remote
Guidance Material (Advisory Circular - CS AMC)	
AC 25.1309-1A – Failure conditions **1. Minor**: Crew actions well within capabilities - slight increase in workload - some inconvenience to occupants. • **Probable** o > 1x 10^{-5} /fh **2. Major**: - Conditions impairing crew efficiency or some discomfort to occupants;	**AMC 25.1309 – Failure conditions** **1. Minor**: Crew actions well within capabilities - slight increase in workload - some physical discomfort to cabin crew or passengers. • **Probable** o > 1x 10^{-5} /fh **2. Major**: -Conditions impairing crew efficiency or discomfort to flight crew;

- Higher workload or physical distress such that crew can’t be relied upon to perform tasks accurately or completely. • **Improbable** o $\leq$ 1x 10^{-5} – > 1x 10^{-9} /fh	- Physical distress to cabin crew or passengers, possibly including injuries. • **Remote** o $\leq$ 1x 10^{-5} - > 1x 10^{-7} /fh. **3. Hazardous** - excessive workload or physical distress such that flight crew can’t be relied upon to perform tasks accurately or completely - serious or fatal injury to a small number of occupants other than flight crew. • **Extremely remote** o $\leq$ 1x 10^{-7} – > 1 x 10^{-9} /fh
Anticipation of failure conditions • Probable: One or more times during entire operational life of each aeroplane; • Improbable (FAA): Will not occur during entire operational life of a single random aeroplane - may occur occasionally during life of all aeroplanes of type; • Remote (EASA): Unlikely to occur to each aeroplane during its total life, but may occur several times during life of a number of aircraft of type; • Extremely remote (EASA): Will not occur to each aeroplane during its life but may occur a few times during total life of all aeroplanes of type.	

Engine - APU Level

FAA	EASA
Regulation/standard	
CFR 14 33.75 - Safety analysis-Engines **1. Hazardous engine effects:** • **Extremely remote** • 10^{-7} to 10^{-9}/efh • Concentration of toxic products in engine bleed air intended for the cabin sufficient to incapacitate crew or passengers **2. Major engine effects** • **Remote** • 10^{-5} to 10^{-7}/efh	**CS-E 510 & CS-APU 210 - Safety analysis - Engines & APU** **1. Hazardous engine/APU effects:** • **Extremely remote** • <10^{-7}/efh or /APUoh • Concentration of toxic products in engine/APU bleed air intended for the cabin sufficient to incapacitate crew or passengers **2. Major engine effects** • **Remote** • <10^{-5}/efh or /APUoh
Safety analysis: must include compressor bleed systems.	
Guidance Material (FAA Advisory Circular – EASA CS AMC)	
FAA - AC 33.75-1A (engines) / CS AMC E 510 & CS –APU 210 (engines & APU) **1. Hazardous Engine effects: Toxic products:** • Generation and delivery of toxic products caused by abnormal engine operation sufficient to incapacitate crew or passengers during flight. • Degradation of oil leaking into compressor airflow. Intent is to address relative concentration of toxic products in bleed air delivery. No assumptions including cabin air mixing/dilution. **2. Major engine effects:** Concentration of toxic products in engine/APU bleed air for the cabin sufficient to degrade crew performance.	

3.2 Oil sealing

Around 25% of the engine core airflow is extracted and utilised to supply engine internal air and air for the various aircraft systems. This secondary air, also known as bleed air, is primarily tapped off the compressor and used for cooling the engine, and accessory components, bearing chamber oil cooling and sealing, control of turbine tip clearances, cavity ventilation bearing load controls, cabin pressurisation, ventilation, anti-icing and other services. The extracted secondary/bleed air is controlled and minimised as it reduces power and efficiency of the engine. To do this a number of oil and air seals are required.

A recirculatory oil system provides oil under high pressure for various purposes including lubrication, cooling and sealing. The minimum amount of oil performs these duties taking into account the permissible consumption of oil, usually around 0.1-0.5 US quarts per engine per hour or up to 1.0 US quart in some older engines.

Main shaft bearings grouped together in bearing chambers require a continuous supply and removal of oil. Pressurised air from the compressor is used to prevent oil leaking though the bearing seals and to cool and ventilate the bearing sumps. Pressurised air is used to maintain the bearing compartment at a lower pressure than the surroundings, causing an inward flow and preventing an outward leak. Oil seals have various functions including to prevent moisture and dirt entering the chamber, prevent outward leakage of oil (prevents fumes in cabin, fires, loss of performance), control air leakage in (improves performance) and reduce oil consumption.

Military jet aircraft commenced using compressed bleed air for ventilation and pressurisation in the late 1940s. There were early concerns raised about the thermal degradation or the ‘cracking temperature’ of the oils rapidly increasing at elevated temperatures [46]. It was soon recognised that engine bleed air used for the ventilation was increasingly subject to unacceptable contamination, with the compressor bearing seals being the main source of oil leakage [8,9]. Early commercial jet aircraft, such as the Boeing 707, Douglas DC8 and Convair 880/990 drew air from outside the aircraft using separate blowers or compressors. One of the first civilian aircraft to use bleed air directly for ventilation was the French SE210 Caravelle in 1955. There was continuing high awareness of oil contamination of the bleed air supply in the 1950s and early 1960s, however with the desire to reduce the costs associated with an extra compressor for the air supply, bleed air was accepted as of similar quality to outside air [47]. This led to the general acceptance of using bleed air to supply the ventilation air required for the cabin in all further commercial aircraft except for the recent B787 Dreamliner. Various steps were taken to reduce the temperature to which the oil would be exposed, such as taking the air from the lower stage pressure port when able. Bleed air cleaners were recommended if the bleed port design features could not achieve sufficient particle separation and requirements for bleed air quality were recommended to be imposed on the engine manufacturers [48]. Noxious and toxic substances were recommended to be prevented from entering the cabin or flight deck air, with special attention given to lubricants and hydraulic fluids [49].

Aero bearing seals are required to operate at high speeds necessitating either a well lubricated seal or one that operates with a clearance [50]. There are various factors affecting seals as shown in Figure 1, with all dynamic seals designed to leak. How much they leak depends on many factors including the style / type of seal, the hydrodynamic effects, the balance ratio or tooth patterns, the variabilities of the lubricating regime, general operating conditions (speed, temperatures and pressures), wear and distortion [51,52].

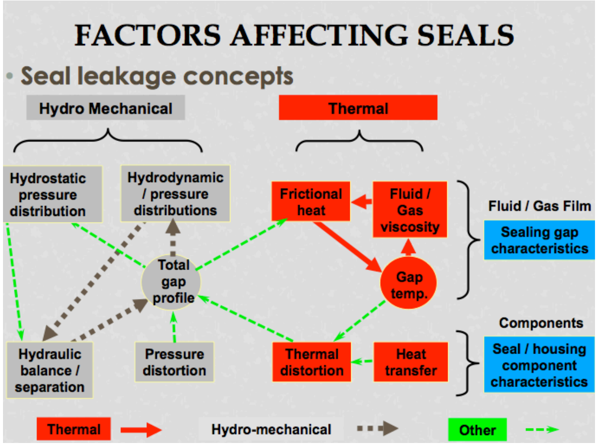


Figure 1 –Factors affecting seal leakage [51]

There are two main types of seals used in aero engines. Compressor sealing air flowing across the seal into the bearing compartment is utilised regardless of the type of seals [53] and is responsive to variations in engine operating conditions [54]. Sealing bearing compartments containing oil and gas mixtures at near ambient pressure is difficult [55]. The pressure difference between the inside and outside of the chamber is very small, allowing a much greater chance of pressure reversal in transient modes.

3.2.1 Labyrinth seals

Labyrinth seals or non-contacting clearance seals (see Figure 2) operate with tight clearances often in the range of 200-400nm (0.0002-0.0004mm) [52]. The controlled leakage of air or liquid over restrictions reduces pressure over the seal. Fluid can flow in either direction depending on pressure, momentum and design. Performance deteriorates with time, wear and change in operating conditions, with clearances increasing for example with *'rubs'*. Labyrinths are renowned for being low cost and simple. They are subject to high air leakage, loss of engine performance and do not in isolation provide a complete barrier to leakage [56]. While good at restricting the airflow, they do not respond well to dynamics, with permanent increases in seal clearances from shaft excursions on stop/start operations and other transient conditions [55].

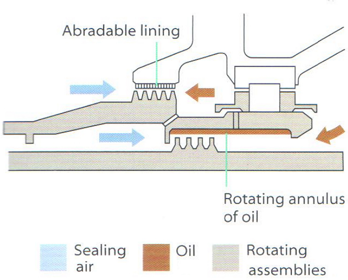


Figure 2: Labyrinth seal [57]

3.2.2 Mechanical seals

Mechanical (face, positive contact) carbon seals (see Figure 3) operate with a micro seal face separation (typically 0.25-1μm), providing (non visible) low leakage [51,52]. The faces have a high degree of flatness to form a good seal and must be lubricated so as to operate at a reasonable speed and provide a long life [50]. The oil film in the face separation is a factor of the hydrodynamic effects acting on the seal, and is a design compromise between being thick enough to provide lubrication and long seal life, but as thin as possible to minimise leakage [56]. Pressure and temperature distortion during operation can impact the parallelism of the flat seal faces, thereby reducing or increasing leakage. Seal surface material or surface roughness can influence the oil film condition, while gradual wear of the sealing faces will occur. This type of seal is more complex and expensive. It is accepted that a normal seal will leak a very small amount of oil vapour from a few ppm to 10cc/min [58].

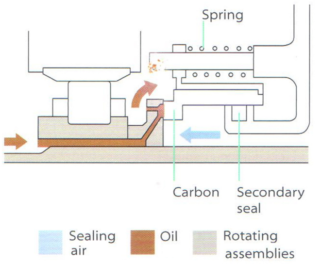


Figure 3. Carbon seal [57]

3.2.3 Common assumptions

Common assumptions regarding oil leakage include:

- Higher pressure in the gas path than in the bearing chamber will keep the oil in the bearing chamber;
- Seals leak only when a failure occurs;
- Reverse pressures are to be avoided so as to prevent leakage.

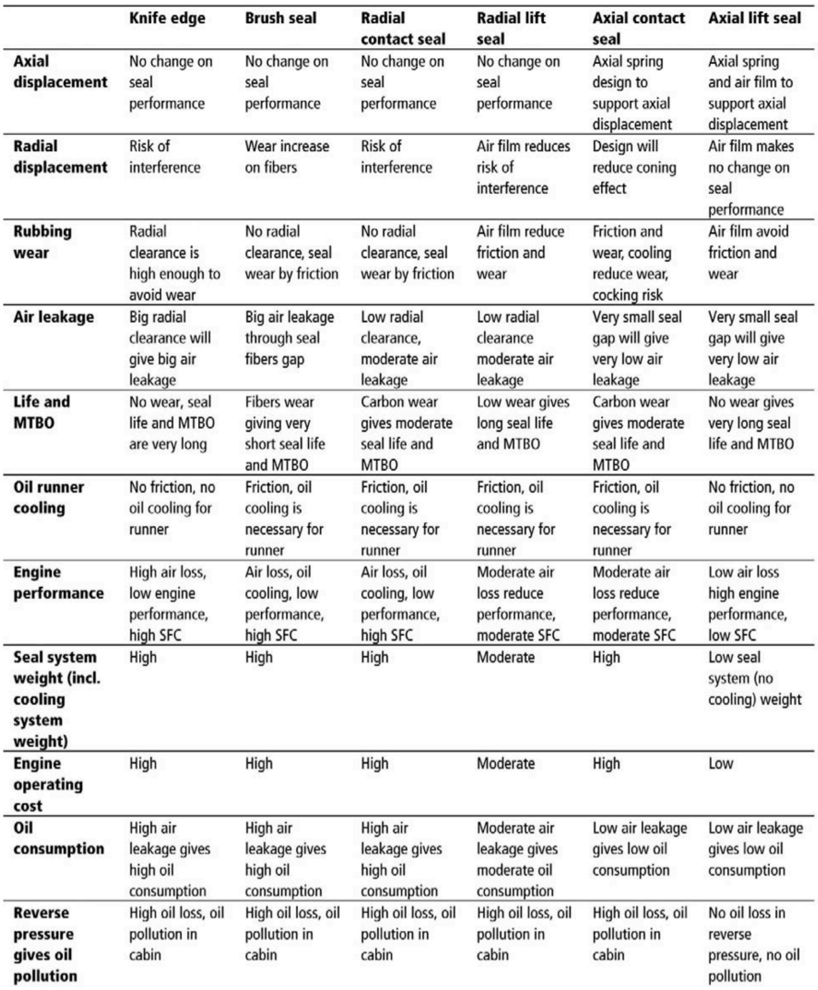
However, oil may flow both with and against the positive pressure gradient with both types of seals. Positive pressure gradients are difficult to attain at near ambient pressures that are used in sealing bearing chambers. Reverse pressures over the seals, unless designed for, allow oil to flow in the opposite direction with both types of seals. It is accepted that such seals will leak a very small amount of oil vapour during normal service. Labyrinths operate with a clearance, while the mechanical seal faces operate with a lubricated face, with both types of seals designed to limit sealed product migration and therefore limiting emissions, rather than preventing them [52].

Upon closer review, specialist sealing and aero industry awareness of oil seal leakage is well established. Manufacturers have differing views on which seals offer greater advantages and disadvantages, with sealing technology in this industry suggested to not have kept pace with other major engine component advances [59]. For example, Allied Signal reported the need for improvements in face air/ oil seal reliability regarding high temperatures, tracking, oil coking, high oil consumption and wear with the need for research in the transient behavior of seals [60]. Carbon face seals are suggested to be the industry workhorse but have problems with face blisters [61]. Labyrinth seals are associated with higher leakage rates and ignorance around transient effects. While some suggest labyrinth usage are converted to other types of seals, [44,58] OEMs (original equipment manufacturers) are suggested to remain satisfied with labyrinths for main shaft sealing [62]. However there is clear recognition that *"shaft seals- must function as SEALS-NOT flow restrictors"* [63]. Advancements in sealing technology are being developed [55], however these styles of conventional seals will be around for a long time [64]. Overall the major part of oil consumption is made up of permissible oil loss past certain seals, escape of mist or aerosol through the breather and losses incurred during inspections [65]. More recently an aircraft manufacturer advises that it is expected that that reports of oil fume odours *"would be associated with changes in engine speed or bleed system configuration (switching from IP to HP or visa-versa)"* [35].

The problems associated with conventional oil sealing have been clearly highlighted [59]. Seal design was therefore recommended to be thoroughly integrated into the engine design process [59]. Further pros and cons associated with seals are outlined in Table 2 [66]. The difficulty in access to seals with on condition maintenance has been noted unless there is complete seal failure or obvious damage [67]. The difficulty in identifying lower-level oil leakage with current maintenance practices and air monitoring has been more recently acknowledged [25,35,68–70]. However improved maintenance practices allowing easier and more cost effective seal maintenance has been identified [71].

Control measures in part depend on how leakage is regarded. Hendricks suggests the aviation industry is unique in that environmental aspects drive sealing requirements, rather than emission limits as occurs in critical industries and the general environment [62]. Customer satisfaction and cabin air free of smells and performance parameters are said to drive seal technology [55,62]. Few limits are suggested to apply to the aviation industry where leakage may be defined as 10,000ppm or as a visible mist [62.] A Maintenance Repair Organization (MRO) reported that an aircraft with ongoing repeat fume events and adverse effects recorded, showed normal engine wear and tear, oil consumption within normal limits and that the findings would not cause significant oil smell in cabin complaints [70]. However it is noted that only a few drops of oil are required to generate a detectable odour in the cabin [69,72] and most events involve fumes only rather than mist or smoke [33,35]. The literature strongly refers to leakage paths in terms of performance penalties related to airflow leakage, with minor references to the oil leakage out of the bearing chambers.

Table 2 Seal technology comparison [66**]**



	Knife edge	**Brush seal**	**Radial contact seal**	**Radial lift seal**	**Axial contact seal**	**Axial lift seal**
Axial displacement	No change on seal performance	No change on seal performance	No change on seal performance	No change on seal performance	Axial spring design to support axial displacement	Axial spring and air film to support axial displacement
Radial displacement	Risk of interference	Wear increase on fibers	Risk of interference	Air film reduces risk of interference	Design will reduce coning effect	Air film makes no change on seal performance
Rubbing wear	Radial clearance is high enough to avoid wear	No radial clearance, seal wear by friction	No radial clearance, seal wear by friction	Air film reduce friction and wear	Friction and wear, cooling reduce wear, cocking risk	Air film avoid friction and wear
Air leakage	Big radial clearance will give big air leakage	Big air leakage through seal fibers gap	Low radial clearance, moderate air leakage	Low radial clearance moderate air leakage	Very small seal gap will give very low air leakage	Very small seal gap will give very low air leakage
Life and MTBO	No wear, seal life and MTBO are very long	Fibers wear giving very short seal life and MTBO	Carbon wear gives moderate seal life and MTBO	Low wear gives long seal life and MTBO	Carbon wear gives moderate seal life and MTBO	No wear gives very long seal life and MTBO
Oil runner cooling	No friction, no oil cooling for runner	Friction, oil cooling is necessary for runner	Friction, oil cooling is necessary for runner	Friction, oil cooling is necessary for runner	Friction, oil cooling is necessary for runner	No friction, no oil cooling for runner
Engine performance	High air loss, low engine performance, high SFC	Air loss, oil cooling, low performance, high SFC	Air loss, oil cooling, low performance, high SFC	Moderate air loss reduce performance, moderate SFC	Moderate air loss reduce performance, moderate SFC	Low air loss high engine performance, low SFC
Seal system weight (incl. cooling system weight)	High	High	High	Moderate	High	Low seal system (no cooling) weight
Engine operating cost	High	High	High	Moderate	High	Low
Oil consumption	High air leakage gives high oil consumption	High air leakage gives high oil consumption	High air leakage gives high oil consumption	Moderate air leakage gives moderate oil consumption	Low air leakage gives low oil consumption	Low air leakage gives low oil consumption
Reverse pressure gives oil pollution	High oil loss, oil pollution in cabin	High oil loss, oil pollution in cabin	High oil loss, oil pollution in cabin	High oil loss, oil pollution in cabin	High oil loss, oil pollution in cabin	No oil loss in reverse pressure, no oil pollution

3.3 Research

The following responses were given as a result of the two interview studies undertaken**.** Full responses can be seen in the original research [1].

3.3.1 Engineers

- Oil leakage from the bearing chamber can be both internal and external to the engine/APU. Leakage may be a part of the normal oil consumption out via the oil system breather or may enter the core airflow with the potential to enter the cabin bleed air.
- Leakage past the seals can occur as a function of the seal design as they are not an absolute design. Leakage occurs with changing pressure differentials, thermal, axial and radial (mechanical) changes in engine structures; changes in engine speed and power and design parameters not taking account of all engine conditions. Operational factors such as seal wear, installation and maintenance can also affect leakage.
- Various phases of flight affect leakage such as changes in engine performance - changing pressure differentials and balances over the seals with differing transient engine power, application and ambient conditions affecting seal efficiency and leakage rates; mechanical variations in structures over the engine operating range and low power settings such as start, taxi, spool up, top of descent, descent.
- Both carbon face and labyrinth seals leak for varying reasons with some leakage inevitable, as it is inherent in the design. Labyrinth seals rely more so on pressure differentials, while mechanical seals require lubrication between the sealing surfaces allowing for leakage across the faces and are more subject to wear, and are temperature critical. Leakage occurs both with and against the pressure drop with both types of seals.
- There are no specific published limits for oil contamination and there are differing views on when action is required to be taken. Some regard action is required only if oil leakage is above permissible limits, while others regard low level leakage is part of the system design and fails to meet the published design requirements. Regulatory enforcement is regarded as a low priority with available standards ignored.
- Oil leakage is seen in two differing ways: oil leaving the intended areas, loss over the seals or residing in greater amounts than intended. Alternatively leakage is seen as leakage above the permissible consumption limits and pressure differentials, with lower-level leakage or emissions ignored.
- Under reporting of oil leakage is generally accepted as occurring.
- Mitigating oil leakage should be given high priority including improved maintenance, better designs, filtration, electric systems and real time monitoring.

3.3.2 Regulators

- With regards to engine/APU certification, there is no specific process that the manufacturers must follow to demonstrate compliance. Bleed air quality compliance under CS E510 and FAR 33.75 addresses hazardous engine effects, including toxic products, such as oil in the bleed air capable of incapacitating crew or passengers at an ‘extremely remote’ rate of $<10^{-7}$ - >10-^{9}/efh. There are no specific regulatory limits provided, however EASA references SAE recommended practice ARP 4418 as a means to demonstrate compliance. Bleed air purity testing is required under CS E 690 and CS APU 320, however no specific guidance is given, while the FAA lists oil leakage into the compressor airflow as a toxic product, with no further guidance given.
- With regards to the airframe certification, the regulators require enough fresh air or sufficient uncontaminated air to avoid discomfort, fatigue, a minimum airflow, with CO, CO_2 and O_3 considered only. The FAA requires more recent certification programs to address the 2002 National Research Council’s (NRC) cabin air quality recommendations and to consider a range of other optional standards and guidelines and sources of data to show that incapacitation will not occur. EASA reports there is

an interactive process between the regulator and the manufacturers, but provided no details.

4.0 DISCUSSION

4.1 General

Regulations, standards and guidance material related to cabin air quality exist which ought to be acceptable in demonstrating compliance. There are however limitations in the descriptive terminology and the presentation of the requirements between the standards and guidance material. This could enable the compliance requirements and AMC to be interpreted in a number of ways or with lesser priority. For example, the engine safety analysis standard refers to toxic products in the bleed air sufficient to incapacitate, while oil leakage into the airflow causing degraded crew performance is listed in the AMC non mandatory guidance material. This may well explain why a lesser focus is placed on oil causing impairment. The specific details relating to what is considered toxic products sufficient to incapacitate or degrade performance, the air requirements not causing adverse effects or failing to refer to substances other than CO, CO_2 and O_3 and further details on warning systems are absent. This allows room for interpretation and failure to adhere to the standards, AMC and GM. Additionally, the non-binding nature of the European CS, and AMC and GM under both the US and European systems may allow further room for interpretation, however the regulations are also not being given the priority they require either.

There is a clear discrepancy in the understanding of oil contamination of the bleed air supplied to the cabin. The general understanding within and outside the aviation industry, primarily supports leakage due to failed bearing seals, operational factors such as worn seals or overfilled oil reservoirs. There is a less well known view that oil leaks at background levels as a function of the design using the pressurised bleed air system. The literature involving the seals and aero experts is not widely available, but clearly shows oil leakage at lower levels occurs in two key ways: 1) background very low-level leakage across the seals; 2) increased leakage with changed engine and operational conditions. Pressurised compressor air is used to seal the bearing compartment, but is responsive to variations in engine operating conditions. Both types of commonly used bearing compartment seals, allow low level oil leakage across the seal, with various operating factors effecting levels further.

The engineering and sealing experts identified a variety of factors allowing low-level oil leakage to enter the compressor air and the bleed air system in normal flight including:

- Changes in pressures and balances during different engine operating and ambient conditions/transient performance changes reduce seal efficiency;
- Thermal, axial and radial changes in engine structures cause changes in gaps needing to be sealed over whole engine operating range;
- Low internal pressures at various phases of engine operation;
- Standards and designs modeled on steady state conditions, not transients;
- Seals are not an absolute design, enabling leakage;
- Seal wear/component degradation.

Based upon the responses given by the engineering and seals experts and the regulators, there is a discrepancy between the design standards and their implementation using the bleed air system. 'Major' engine/APU effects should not occur greater than remote or 10^{-5}/efh or /APUoh. Under the AMC or guidance material, these include oil leakage into the compressor airflow sufficient to degrade crew performance. The emphasis by the regulators is placed on the regulatory or standard component addressing 'hazardous' effects of toxic products able to cause incapacitation, while almost ignoring the AMC and guidance component and 'major' effects.

Airframe regulations/standards do not allow failure conditions which reduce the ability of the crew to cope with adverse operating conditions to be more than improbable or 'major'/remote. Under the guidance material, these include impairment to crew efficiency, discomfort to flight crew (pilots) or physical distress to other occupants and should not be more frequent than $1x10^{-5}$/fh or /APUoh. Such failure conditions may occur several times during the total life of a number of aeroplanes of type, but unlikely to occur to each aeroplane.

The literature associates the lubricants and their substances with adverse effects [1,13, 16–21,31-33,42,44,74–82]. These can be expected to occur more frequently than remotely or improbably (10^{-5}/fh, /efh or /APUoh), based on 1) the design, 2) hazard recognition under the various chemical databases and literature and 3) frequency reported. Impaired crew efficiency or degraded crew performance can and is expected to occur with exposures. The frequency based on the design meets the definition of 'probable' (10^{-3}-10^{-5}/fh) or above which allow no adverse effects on the flight crew or discomfort to others only through to no effect on flight crew or inconvenience on others only. Exposure to oils via the bleed air system does not meet this. Major effects are expected which must be improbable or remote, yet they are probable or above and not infrequent.

CS 25.831 requires the air supply to have sufficient fresh or uncontaminated air so as to not cause undue discomfort or fatigue and must be free of harmful or hazardous concentrations of gases or vapours. However adverse effects are expected and occurring. The regulator emphasis is placed on the ventilation rates and CO, CO_2, while ignoring the discomfort component and all other chemical substances. More recently, reliance on selected industry actions, studies and standards have been regarded as acceptable means of compliance.

The lack of detection systems and warning indicators to identify oil fumes in flight fails to meet CS/FAR 25.1309c addressing unsafe system operating conditions. There are conflicting views on how low-level oil leakage in normal operations is regarded and it is clear the problem remains unaddressed. Oil related effects meet the definition of an unsafe condition (AMC 21.A.3B(b)) due to the exposure to oils being associated with impaired crew efficiency at a rate higher than the safety objectives allow. The system design enabling oil leakage as a part of its function, cannot meet the stipulated airworthiness requirements.

4.2 Developments

There are a number of developments that have been implemented or are underway. A few of these include:

- Bleed free design used on the Boeing B787 Dreamliner; Electric ECS in development [83];
- Bleed air filtration – in development [84];
- Cabin and bleed air monitoring sensors – In development [85];
- Enhanced checklists for fume events - Several airlines only;
- Regulator alert for operators to improve procedures [86];
- On-going development of air quality standards, recommended practices… - CEN, SAE, ASHRAE [34];
- Other industry actions: Reporting; medical guidance – [21,26];
- Maintenance: Aerotracer, (useful for higher level oil fume events) [87]; Bearing and seal replacement [71].

5.0 CONCLUSIONS

Low-level leakage of oil fumes containing hazardous and harmful substances occurs in normal flight via the aircraft bleed air supply. Resulting adverse effects are occurring and creating a risk to flight safety. There is a gap between the aircraft certification requirements for the provision of clean air in crew and passenger compartments using the bleed air system and the documented theoretical and practical implementation of the requirements. The use of the bleed air system to supply the required air quality standards is not being met. Key conclusions are summarised below.

1. Regulations and standards: Low-level oil leakage over the bearing seals into the bleed air is an expected normal condition with engine/APU operation increasing at various phases of flight. The required bleed air quality is not being met, as the standards and compliance material are not specific enough to ensure suitable bleed air quality, or application. The focus is placed almost entirely on the prevention of incapacitation, while ignoring impairment, with the clean air requirements open to interpretation. The non-binding nature of some certification aspects creates additional problems.
2. Design*:* Although many suggest the certification requirements for clean air supplies are being met, careful review and research shows this not to be the case. Oil leakage past the bearing seals associated with impaired or degraded performance occurs more frequently than the 'major' remote or improbable regulatory, standards and compliance criteria allow. Oil leakage associated with impairment is probable or above and is an 'unsafe condition.'
3. Compliance: The lack of detection systems to identify the air quality in flight causes ongoing compliance problems. Additionally the ventilation requirements are not specific enough to ensure occupants will remain free of adverse effects.
4. Preventative control measures*:* Low-level and transient oil emissions are not adequately taken into account when considering acceptable leakage levels. The designs are based on steady state conditions, there are no filtration or detection systems to identify and prevent exposure with rigorous controls lacking.
5. Retrospectively: Previous certification requirements were not specific enough to prevent oil leakage into the air supply.
6. Expertise and communication: Oil contamination of the air supply is a highly specialist area, with inadequate communication between all relevant parties to ensure compliance and airworthiness.

5.1 Recommendations:

Recommended future research and activities should include:

- Review of regulations, standards, AMC and guidance material;
- Preventative measures, normal & abnormal operations: Implement detection systems and flight deck warning, filtration, improved sealing, maintenance investigation protocols for lower levels of oil leakage and other actions to prevent oil leakage into the air supply, particularly in normal operations;
- Improved operational protocols to address oil fumes rather than primarily a smoke focus only;
- Review reasons why the industry is reluctant to address prevention of in-flight exposure to lubricants in normal/abnormal operations;
- Oil leakage not to be related to rare failure conditions or maintenance factors only;
- Oil leakage to include emissions, not just leakage above permissible consumption level or outside set limits;
- Frequency of oil leakage explained by design factor;
- Retrospective certification for bleed air quality;
- Future aircraft – bleed free designs;
- Far greater emphasis placed on clean air regulatory compliance including low-level oil emissions in normal flight.

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REFERENCS

1. Michaelis S. Implementation Of The Requirements For The Provision Of Clean Air In Crew And Passenger Compartments Using The Aircraft Bleed Air System. (MSc thesis) Cranfield University; 2016 : http://www.susanmichaelis.com/caq.html

2. Gutkowski G, Page R, Peterson M. D-14766-2. B-52 Decontamination Program. Seattle: Boeing; 1953.

3. Loomis T, Krop S. MLSR No. 61 - Cabin Air Contamination In RB-57A Aircraft. Maryland: Army Chemical Center; 1955.

4. Treon J, Cappel J, Cleveland F, et al. The Toxicity Of The Products Formed by The Thermal Decomposition Of Certain Organic Substances. Ind Hyg Q. 1955;(September):187–95.

5. Johnson R, Swickert M, Bisson E. NACA TN 2846. Effective Lubrication Range for Steel Surfaces Boundary Lubricated at High Sliding Velocities by Various Classes of Synthetic Fluids. Washington: National Advisory Committee for Aeronautics; 1952.

6. Loraine T. Air Accident Investigation Findings and Recommendatons. In: International Aircraft Cabin Air Conference, Imperial College, london 19-20 September, 2017. 2017.

7. EASA. A-NPA-2009-10. Cabin Air Quality Onboard Large Aeroplanes. Cologne: European Aviation Safety Agency; 2009.

8. Reddall HA. Elimination Of Engine Bleed Air Contamination - SAE paper 1955 - 550185. Warrendale: Society of Automotive Engineers; 1955.

9. Walker P. SAE-E31. Discussion Paper. Discussion On The Specification Limit For Total Organic Material In Cabin Bleed Air. Rolls-Royce; 1990.

10. Shehadi M, Jones B, Hosni M. Characterization Of The Frequency And Nature Of Bleed Air Contamination Events In Commercial Aircraft. Indoor Air. 2015;26:478–88.

11. Murawski J, Supplee D. An attempt to characterize the frequency, health impact, and operational costs of oil in the cabin and flight deck supply air on US commercial aircraft. J ASTM Int . 2008;5(5):1–15.

12. COT. COT Statement 2007/06. Statement On The Review Of The Cabin Air Environment, Ill-health In Aircraft Crews And The Possible Relationship To Smoke/Fume Events In Aircraft . London: Committee Of Toxicity; 2007

13. Michaelis S. Health and Flight Safety Implications from Exposure to Contaminated Air in Aircraft- . (PhD Thesis) UNSW, Sydney; 2010. :http://handle.unsw.edu.au/1959.4/50342

14. EASA. Comment Response Document (CRD) To Advance Notice Of Proposed Amendment (A-NPA) 2009-10 - Cabin Air Quality Onboard Large Aeroplanes . Cologne: European Aviation Safety Agency; 2011 May.

15. FAA. FSAW 06 -05A. Guidance For Smoke/ Fumes In The Cockpit/ Cabin. Vol. 1, Flight Standards Information Bulletin For Airworthiness. Washington: FAA; 2006.

16. Howard C, Michaelis S, Watterson A. The Aetiology of ‘ Aerotoxic Syndrome ’ - A Toxico- Pathological Viewpoint. Open Acc J Toxicol. 2017;1(5):1–3.

17. Michaelis S. Aircraft clean air requirements using bleed air systems. Engineering . 2018;10:142–72. : http://www.scirp.org/Journal/PaperInformation.aspx?PaperID=83906

18. Michaelis S. Contaminated Aircraft Cabin Air. J Biol Phys Chem. 2011;11(4):132–45.

19. CAA. Mandatory Occcurrence Reports: Engine Oil Fume Events: January 2006 - March 2011. Gatwick: Civil Aviation Authority; 2011.

20. BFU. BFU 803.1-14. Study Of Reported Occurrences In Conjunction With Cabin Air Quality In Transport Aircraft. Braunschweig: Bundesstelle für Flugunfalluntersuchung; 2014.

21. ICAO. Cir 344-AN/202. Guidelines on Education, Training And Reporting Practices related To Fume Events. Montréal: International Civil Aviation Organization; 2015.

22. IFALPA. Safety Bulletin 13SAB006. Cabin Air Quality. Montreal: IFALPA; 2013.

23. Crump D, Harrison P, Walton C. Aircraft Cabin Air Sampling Study; Part 1 and 2 of The Final Report. Cranfield: Institute of Environment and Health, Cranfield University; 2011.

24. Rosenberger W, Netz-Piepenbrink S, Wrbitzky R. Untersuchungen Zum Vorkommen Von Mono- Und Diortho-Trikresylphosphaten In Der lnnenraumluft Von Flugzeugen. Gefahrstoffe - Reinhaltung der Luft. 2013;73(4):138–43.

25. EASA. Research Project : CAQ Preliminary Cabin Air Quality Measurement Campaign. Final report EASA_REP_RESEA_2014_4 . Cologne: European Aviation Safety Agency; 2017.

26. IATA. IATA Guidance for airline health and safety staff on the Medical Response to Cabin Air Quality Events: Smoke, fumes/odours. Montreal: IATA; 2015.

27. EASA. Research Project: AVOIL. Characterisation of the toxicity of aviation turbine engine oils after pyrolysis. Final Report EASA_REP_RESEA_2015_2 . Cologne: European Aviation Safety Agency; 2017.

28. EASA-EU Commission. FACTS- Aircraft air quality study . 2017.

29. ECHA. DECISION ON SUBSTANCE EVALUATION PURSUANT TO ARTICLE 46(1) OF REGULATION (EC) NO 1907/2006. For Tris(methylphenyl) phosphate, CAS No 1330-78-5. . Helsinki; 2016 Jul.

30. CEN. European Committee for Standardization. CEN/TC 436. Project Committee - Cabin air quality on civil aircraft - Chemical agents. Brussels; 2015.

31. CAA. Civil Aviation Authority - Information For Health Professionals On Aircraft Fume Events. 2017

32. COT. Position Paper On Cabin Air . London: Committee Of Toxicity; 2013.

33. Michaelis S, Burdon J, Howard C. Aerotoxic Syndrome : a New Occupational Disease ? Public Heal Panor. 2017;3(2):198–211.

34. ASHRAE. Standard 161-2013. Air Quality Within Commercial Aircraft. Atlanta: ASHRAE; 2013.

35. Airbus. Environmental Control System Decontamination. Reference 21.00.00018. First issue date 07 November, 2013. A318;A319;A320;A321. Toulouse: Airbus; 2013.

36. AAIB. EW/G2012/10/12. AAIB Bulletin: 5/2013 D-AIRX. Aldershot: Air Accidents Investigation Branch; 2013.

37. Mackerer C, Ladov E. Mobil Submission (14a): In: Inquiry Into Air Safety - BAe 146 Cabin Air Quality Vol 3. Canberra: Parliament Of The Commonwealth Of Australia; 2000.

38. House of Lords. Evidence given by Boeing to the House Of Lords Science And Technology Committee. Air Travel And Health: An Update. London: House of Lords. 2007.

39. Suppelsa M. WGN Investigates The Boeing Papers: How Safe Is The Air Up There? - FAA And Boeing Statements. WGN-TV. 2016.

40. BAe Systems. Operational Notice: NO.OP 16 (Issue 1) Manufacturers Operations Manual - AVRO 146-RJ - Notice To Aircrew. BAe Systems; 2001.

41. Michaelis S. Oil bearing seals and aircraft cabin air contamination. Seal Technol. 2016;4, April(4):7–10.

42. SAE. AIR 4766/2- Airborne Chemicals In Aircraft Cabins. Development. Warrendale: Society of Automotive Engineers; 2005.

43. de Boer J, Antelo A, van der Veen, I. et al. Tricresyl phosphate And The Aerotoxic Syndrome Of Flight Crew Members - Current Gaps In knowledge. Chemosphere.

2015;119:S58–61.

44. Peitsch D. Developments In Modern Aero-Engines To Minimize The Impact Of Bleed Air. In: Air Quality In Passenger Aircraft - Royal Aeronautical Society, London, 16-17 October 2003 . London: Rolls-Royce Deutschland; 2003. :http://projects.bre.co.uk/envdiv/cabinairconference/presentations/Dieter_Peitsch.pdf

45. Overfelt R, Jones B. RITE-ACER-CoE-2013-02. Proposed Test Plans For A Study Of Bleed Air Quality In Commercial Airliners. Auburn: Airliner Cabin Environment Research; 2013.

46. Waddock R. Report No. SM 15195. Engine Compressor Bleed Air Contamination Study. XC-132 Project,. Santa Monica: Douglas Aircraft Company; 1954.

47. NRC. The airliner cabin environment and the health of passengers and crew. 2002.

48. SAE. ARP 1796: Aerospace Recommended Practice - Engine Bleed Air Systems For Aircraft. Warrendale: Society of Automotive Engineers; 1987.

49. SAE. ARP 85E: Aerospace Recommended Practice: Air Conditioning Systems For Subsonic Airplanes. Warrendale: Society of Automotive Engineers; 1991.

50. Flitney R. A Description Of The Types Of High Speed Rotary Shaft Seals In Gas Turbine Engines And The Implications For Cabin Air Quality. J Biol Phys Chem. 2014;14(4):85–9.

51. Michaelis S, Morton J. Mechanisms of Oil Leakage into the Cabin Air Supply & the Regulatory Implications. In: International Aircraft Cabin Air Conference, Imperial College London, 19-20 September 2017. 2017.

52. Howard C, Johnson DW, Morton J, Michaelis S, Supplee D, Burdon J. Is a Cumulative Exposure to a Background Aerosol of Nanoparticles Part of the Causal Mechanism of Aerotoxic Syndrome ? Nanomedicine Nanosci Res . 2018;139. https://gavinpublishers.com/admin/assets/articles_pdf/1537165462new_article_pdf69025564.pdf

53. Linke-Diesinger A. Systems of Commercial Turbofan Engines: An Introduction to Systems Functions. Hamburg: Springer; 2008.

54. Palsulich J, Riedel R. SAE 560171. Dynamic Seals For Aircraft Gas Turbine Engines. Warrendale: Society of Automotive Engineers; 1956.

55. Chupp R, Hendricks R, Lattime S et al. NASA/TM-2006-214341. Sealing In Turbomachinery . NASA. Cleveland; 2006

56. Flitney R. Seals And Sealing Handbook. 5th ed. Burlington: Butterworth-Heinemann; 2007.

57. Rolls-Royce. The Jet Engine. 5th ed. Derby: Rolls-Royce; 2005.

58. Boyce M. Gas Turbine Engineering Handbook (4th Edition). Butterworth-Heinemann; 2012.

59. AGARD. Seal Technology in Gas Turbine Engines. In: AGARD Coference Proceedings No 237- Seal Technology In Gas Turbine Engines. London: NATO-AGARD; 1978.

60. Ullah R. Seals Research At Allied Signal. In: NASA 10181 Seals Code Development Workshop, June 14-15, 1995. Cleveland: NASA; 1995.

61. NASA. NASA/CP-1999-208916/Vol 1. 1999 NASA Seal/Secondary Air System Workshop. In: In 1998 NASA Seal/Secondary Air System Workshop. Cleveland: NASA; 1999.

62. Hendricks R. Environmental And Customer-Driven Seal Requirements. In: Seals Flow Code Developmnet-93, NASA CP 10136. Cleveland: NASA; 1993.

63. Bill R. NASA/CP-10070. Army Research Concerns In Engine Sealing. In: Seals Flow Code Development, 26 March, 1991. Cleveland: NASA; 1991.

64. Hendricks R. Turbomachine Sealing. In: Seals Code Development workshop NASA CP/10181. Cleveland: NASA; 1995.

65. Edge R, Squires A. SAE 690424. Lubricant Evaluation And Systems design For Aircraft Gas Turbine Engines. Warrendale: Society of Automotive Engineers; 1969.

66. Tran H, Haselbacher P. High-Performance Lift Augmentation Dynamic Seals For Turbine Bearing Compartments. Seal Technol. 2004;(1):5–10.

67. Smith C. American Airlines Operational And Maintenance Experience With Aerodynamic Seals And Oil Seals In Turbofan Engines. In: AGARD Coference Proceedings No 237- Seal Technology In Gas Turbine Engines. London: NATO-AGARD; 1978.

68. CAA. CAA: Health Information for Passengers/Cabin Air Quality . 2017 [cited 2017 Oct 22].

69. Occupational Health and Safety Tribunal Canada. 2015 OHSTC 14 - Case No.: 2011-62 and 2012-06 - Air Canada V CUPE. 2015-08-27. Occupational Health and Safety Tribunal Canada; 2015 Aug 27.

70. AAIU. AAIU Report No: 2016-013. Serious Incident Report: Boeing 737-8AS, EI-EFB, 18 September 2014. Dublin: Aircraft Air Accident Investigation Unit Ireland; 2016 Sep.

71. Lufthansa Technik. Smart Idea Cuts Repair Time. 2017.

72. Vera-barcelo L. A Clean APU Means Clean Cabin Air. Airbus, FAST 52. 2013 Aug.

73. Guerzoni F. Presentation to SAE E34 Propulsion Lubricants Conference Cardiff, 1999. The Debate Over Aircraft Cabin Air Quality And Health: Implications For Aviation Turbine Lubricants. Shell Global Solutions; 1999.

74. Boeing. Boeing MSDS No. 138541. Material Safety Data Sheet- MIL-PRF-23699. Rev 08/09/2007. Seattle: Boeing; 2007.

75. ExxonMobil. Material Safety Data Sheet: Mobil Jet Oil II . ExxonMobil MSDS. 2017

76. European Commission. Regulation (Ec) No 1272/2008 Of The European Parliament And Of The Council Of 16 December 2008 On Classification, Labelling And Packaging Of Substances And Mixtures (CLP) . 2009. http://echa.europa.eu/web/guest/information-on-chemicals/cl-inventory-database

77. ICSC. International Programme On Chemical Safety . Geneva: WHO; 2016

78. Harrison R, Murawski J, Mcneely E et al. OHRCA: Exposure To Aircraft Bleed Air Contaminants Among Airline Workers - A Guide For Health Care providors . San Francisco: occupational Health Research Consortium in Aviation; 2009. http://www.ohrca.org/medical-protocols-for-crews-exposed-to-engine-oil-fumes-on-aircraft/

79. Murawski J. Case Study: Analysis Of Reported Contaminated Air Events At One Major US Airline in 2009-10. AIAA 2011-5089. In: 41st International Conference on Environmental Systems 17 - 21 July 2011, Portland. AIAA; 2011. p. 1–11.

80. Winder C. Hazardous Chemicals on Jet Aircraft : Jet Oils and Aerotoxic Sydrome. Curr Top Toxicol. 2006;3:65–88.

81. ExxonMobil. Jet Oil Chemistry and Composition- Considerations for odor Formation and Risk Assessment. ExxonMobil; 2018.

82. Eastman. Oil can Label: Eastman 2197. 2017.

83. Liebherr. Liebherr-Aerospace & Transportation SAS. Electrical Environmental Control System of Liebherr successful during first flight of Clean Sky/Airbus flight lab. July, 2016 . Press Release. 2016

84. Stein D. Moving Towards Complete Cabin Air Filtration. In: International Aircraft Cabin Air Conference, Imperial College London, 19-20 September 2017. Pall Aerospace; 2017.

85. Savage C. Moving Towards Complete Cabin Air Filtration - Real Time Monitoring. In: International Aircraft Cabin Air Conference, Imperial College London, 19-20 September 2017 . Pall Aerospace; 2017.

86. FAA. FAA SAFO: Safety Alert For Operators . Washington DC: Federal Aviation

Administration; 2018.

87. Airsense Analytics. OSIC Oil smell in cabin: Aerotracer- a new method for the detection of lubricating oils in the bleed air. 2011.