An update on aircraft oil bearing chamber sealing

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On board aircraft, the common use of engine compressor, pressurised air to seal the oil bearing chamber and as a source for the cabin bleed-air supply provides a mechanism for low-level oil leakage in routine engine operations. This is of great concern and was discussed previously in this newsletter in a feature entitled 'Oil bearing seals and aircraft cabin air contamination' (*Sealing Technology* April 2016, pages 7–10). Further to this article, Dr Susan Michaelis has now been awarded an MSc for her extensive work in researching the issue of oil leakage past seals in aircraft gas turbine engines.[1] An update on this research and associated initiatives is provided by this article.

Wide ranging reports regarding concerns about contamination of the aircraft bleed-air supply (fume events) have remained ongoing since the 1950s. There has been particular concern raised with regard to oil, hydraulic and de-icing fluid leakage entering the aircraft air supply, with it long recognised that the main source related to small amounts of oil leakage from the engines and auxiliary power unit (APU) into the cabin environment.

Numerous initiatives that are currently ongoing are addressing this issue, including a major study by the European Aviation Safety Agency (EASA) in conjunction with the European Commission, EU standardisation, ECHA chemical review and government care pathways. Various international bureaus of air safety have put forward a range of findings and recommendations related to fume events and the International Civil Aviation Organization (ICAO) has published fumes guidance material.

More recently, a number of papers have been published addressing the health aspects related to exposure to aircraft contaminated air, suggesting there is a cause and effect relationship between exposure to oil fumes, hydraulic and other fluids.[2]

It is suggested that exposure to low-levels of engine oil emissions on a chronic repeat basis, combined with acute exposure, provides a pathway for increased vulnerability for aircrew or those flying regularly.[3]

Varying degrees of in-flight crew impairment related to contaminated air have been identified in around 30% of reported events, despite under-reporting clearly recognised to be occurring. This rate went up to 93% impairment for crew involved in a review of specific incidents of which 87% were positively sourced to oil contamination of the breathing air.[2]

Whilst a growing number of ad-hoc air monitoring studies, including those by EASA,[4] have repeatedly identified oil substances in normal flight, simulated oil leakage studies[5] have identified that oil contamination in the compressor will result in a fog of very fine droplets (less than 10–150 nm) in the bleed air under "most normal operating conditions".

The hazards associated with the lubricants and fluids are recognised under the EU chemical classification regulations,[6] in the material safety data sheets, hazards databases and elsewhere.

Many within the aviation industry routinely suggest that bleed-air contamination by oil fumes is a very rare event, only occurring under failure scenarios, such as seal failures or operational factors such as seal wear or oil over-servicing. Others suggest fume events are a lot more frequent, are a design factor and part of normal engine operation.

Therefore MSc research was undertaken to look at how oil may pass the seals, with the potential to leak into the air supply. The aim of the work was to assess if there is a 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. The results of the three areas of research are briefly set out in the sections that follow below.

Aircraft certification regulations, standards and guidance

There are a variety of airworthiness certification standards, regulations and associated guidance material related to the requirement for clean ventilation air at both the airframe and engine/APU level.

For example 'major' airframe failure conditions must be remote under the EU standard (CS 25.1309) and not expected to occur more than 1×10^{-5}/flight hour under the Acceptable Means of Compliance (AMC). 'Major' failures under the AMC include impaired crew efficiency or physical discom-

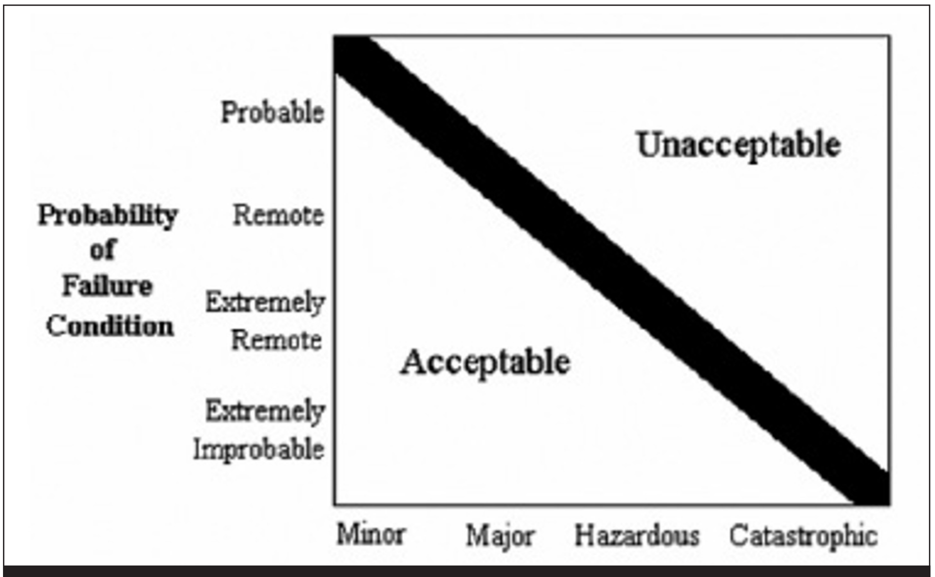

Figure 1. EASA Acceptable Means of Compliance 25.1309: probability versus severity.

fort for the pilots and physical distress to others, as shown in **Figure 1**. Such failures are not expected to occur in each aeroplane, but may occur several times during the total life of a number of aircraft of type.

CS 25.831 requires that the crew compartments have enough fresh air for the crew to perform their duties without undue discomfort or fatigue, and that air is free of harmful or hazardous concentrations of gasses or vapours.

At the engine/APU level, 'hazardous' engine/APU effects must be extremely remote, at less than 10^{-7}/engine/APU flight hour (/efh), and includes toxic products in the engine or APU bleed-air intended for the cabin sufficient to incapacitate crew or passengers. 'Major' engine/APU effects must not be greater than remote (less than 10^{-5}/efh).

The AMC lists toxic products in the bleed air sufficient to degrade crew performance as a 'major effect'. Toxic products include degradation of oil leaking into the compressor airflow under the AMC. In addition, it is noted that absolute proof is not always possible, with reliance placed on good engineering judgment, previous experience and sound design and test philosophies. The US regulations are similar. The full list of standards can be found in the original research.[1]

Oil sealing – documented knowledge

Turbine engines use air and oil seals to control and minimise secondary/bleed air that is tapped off the core airflow and used for various functions.

Pressurised air from the compressor is used to keep the bearing compartment at a lower pressure than the surroundings – preventing an outward leak through the bearing seals.

Aero bearing oil seals, used to prevent oil leakage outside the bearing chamber, operate at a high speed and, therefore, require a well lubricated seal, or one operating with a clearance. All dynamic seals are designed to leak. With the quantity of leakage depending on many factors, including the style of the seal, balance ratio or tooth pattern, lubricating regime, operating conditions (speed, temperature and pressure), compartment condition, wear life and distortion.[7]

Labyrinth clearance seals and mechanical carbon face seals, are the main aero engine seals that are used – both relying on compressor sealing airflow across the seal and are responsive to varying engine operating conditions.

Regardless of the pressure gradient, fluid can flow in either direction, depending on the design, pressure and velocity. Labyrinth seals operate with a typical clearance of 200–400 nm and do not in isolation provide a complete barrier to leakage. Mechanical face seals operate with a micro-seal face separation (typically 0.25-1 µm), therefore, providing very low leakage under normal operation. It is accepted that such seals will leak a very small amount of oil vapour during normal service.

It is commonly assumed in the aero industry that higher pressure in the gas path than in the bearing chamber (positive pressure gradient) will prevent oil leakage and that seals will leak only when a failure occurs. However, oil can flow with and against the positive pressure gradients, and positive pressure gradients are difficult to attain at near ambient pressures used to seal bearing chambers, allowing a much greater opportunity for reverse pressure in transient engine modes.

The awareness of the pros and cons of the seal types used in aero engines vary widely in the literature, however, this is limited to the specialist sealing community. The broader aviation industry does not seem to be aware that low-level oil emissions outside the bearing compartment will occur in normal flight, with the potential to enter the bleed-air ventilation supply if the leak occurs before the air off-take.

Research

Ten experienced aerospace engine design, lubricant and maintenance experts, along with two seal experts, were asked eight research questions related to their professional understanding of how oil may pass over the seals, and the various implications. The main findings are summarised in the points below.

- Oil leakage past seals will occur as a function of the design, under normal operation, as seals are not an absolute design. Leakage occurs with changing pressure differentials, and thermal, axial and radial (mechanical) changes in engine structures, changing engine speed and power, and because the designs do not take account of all engine conditions. Operational factors such as seal wear, installation and maintenance can also affect leakage.
- Various phases of flight effect leakage, such as changes in engine performance.
- Both carbon and face seals leak for varying reasons, with some leakage inevitable as a function of the design.
- No specific limits for oil contamination have been published, with some suggesting action is required only if leakage is above the permissible consumption rate and others suggesting low-level leakage is contrary to the design requirements. Regulatory enforcement is regarded as low, with available standards ignored.

Both EASA and the Federal Aviation Regulatory Administration (FAA) were asked for their views on the process of engine and aircraft certification related to the ventilation requirements. The main findings are listed below.

- There is no specific process for engine/APU certification that the manufacturers must follow to demonstrate compliance.
- There is a focus on hazardous engine/APU effects, including toxic products (such as oil leaking into the bleed air) not causing crew or passenger incapacitation at a rate greater than 10^{-7}/efh, however, there are no specific limits identified. The AMC is given little priority.
- Airframe standards require enough fresh air or sufficient uncontaminated air to avoid discomfort, fatigue, a minimum airflow and specified levels for CO and CO_2. No further details are provided.

Conclusions

Low-level leakage of oil fumes containing hazardous and harmful substances occurs in normal flight via the aircraft bleed-air supply. This results in adverse effects in flight, 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. Key conclusions include:

1. *Regulations:* regulations and standards, and acceptable means of compliance related to cabin air quality, exist. Low-level oil leakage over the bearing seals into the bleed air is an expected normal condition 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, whilst ignoring impairment, with the clean air requirements open to interpretation.
2. *Design:* although many suggest that 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'