

Aircraft Cabin Air and Engine Oil— An Engineering View

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KEYWORDS

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ABBREVIATIONS

CO	Carbon monoxide
L/D	Lift to drag ratio
VOC	Volatile organic compounds

ABSTRACT

Almost all passenger jet aircraft today use potentially contaminated bleed air for cabin ventilation. A detailed look at the design of engine bearings, their lubrication and sealing reveals that jet engines leak small amounts of oil by design and not only in failure cases. An equation is derived to calculate the concentration of a possible cabin air contamination. Results show good agreement with measured concentrations of hydrocarbons in aircraft cabins under normal conditions. The solution to the problem of cabin air contamination is a bleed free design. Other partial remedies are briefly discussed.

INTRODUCTION

Passengers like short trip time, but even more they demand inexpensive tickets, which are only possible at aircraft costs low enough to allow for airline profits. Aircraft must have a price sufficiently high to allow for aircraft manufacturer profits. If aircraft fly fast, their productivity is high and their price depreciated each year is shared among more passengers. Also fuel costs have to be low. Therefore, drag has to be low, and thrust to

overcome drag has to be produced efficiently.

The aerodynamic efficiency of an aircraft is expressed with the lift to drag ratio (L/D). L/D is called glide ratio. In cruise, aircraft lift equals aircraft weight, and drag is low when L/D is high. The *maximum* glide ratio is independent of density and as such altitude. However, a favorable *actual* glide ratio depends on a favorable (medium) lift coefficient. As we have seen, cruise speed needs to be high (but should be below the speed of sound for economic and legal reasons). This means that (at given wing area selected for approach and landing) optimum aircraft performance requires flight at low density (high altitude) to achieve the favorable lift coefficient. When flying at high cruise altitude (≈ 11 km), engines will have lost much of their thrust due to the low density. This has to be compensated during aircraft design with a larger (heavier) engine. This drawback is only partially compensated by the lower temperatures at altitude that make the engine a little more efficient.

At cruise altitude humans cannot survive. This is due to the atmospheric pressure which is only 20% of that at sea level and as such much too low for breathing. The low atmospheric temperature adds to the problem. For obvious comfort reasons, passengers are not asked to wear an oxygen mask throughout the flight. Instead the cabin is pressurized to a sufficient 74% of sea level pressure (which is equivalent to an altitude of 8000 ft).

A jet engine consists of a compressor, a combustion chamber and a turbine. Since the 1950s, outside air is brought to the higher pressure required for the cabin by means of the engine's compressor of passenger jets. Air is simply taken away from within the compressor. This air is called bleed air. A separate compressor could be used, but a compressor already in place does not add costs and hence does not add to the aircraft's price. Why and how much cabin air can potentially be contaminated by bleed air is discussed in this paper.

In summary, the potential problem of contaminated cabin air is due to financial reasons:

1. To be economic, aircraft have to fly fast and hence high. This requires pressurizing the cabin.
2. For inexpensive cabin pressurization, engine compressors on each engine are used. The engine compressor is an available commodity. Any other design consists of more components and is therefore more expensive.

Air conditioning

Air conditioning in aviation means temperature control, pressure control and ventilation.¹

The cabin is vented with a certain percentage (e.g. 50%) of fresh outside air. CS-25.831 details how much fresh air is required for each passenger and pilot – in normal case and in failure cases.² The remaining part of the air for cabin ventilation is provided as air from the cabin itself – filtered and recirculated back into the cabin. Recirculating cabin air gives additional ventilation (beyond certification requirements) without the need of new (expensive) compression. In addition, recirculated air contains some passenger exhaled humidity – much in contrast to ambient air, which is almost dry at cruise altitude.

If outside air is compressed only up to cabin pressure (753 hPa) – which means setting the cabin to an equivalent maximum allowed altitude of 8000 ft (CS-25.841) – it will have about 70°C. This is more than the typical 21°C in a cabin and needs cooling. Cooling is done in the air conditioning system with further compression, with heat exchange to the environment and with expansion to regain at least some energy in a so-called air cycle process. At the heart of this process is the air cycle machine, consisting of a compressor coupled to a turbine. Traditionally, the process runs on energy taken with even higher bleed air pressure (more than 3000 hPa) from the engine compressor. This results in air temperatures reaching 400°C or more. Hence, bleed air cooling is even more paramount. Clearly, any cooling means dumping heat overboard and results in a low efficiency of the process.

Alternative (electric) cabin air cooling compresses air

to only 753 hPa (8000 ft cabin altitude) or for additional comfort to 812 hPa (only 6000 ft cabin altitude). The reduced compression saves about 1 kW per passenger.³ A separate compressor is used with oil-free air bearings. The air is taken directly from the outside via air inlets on the fuselage. The air cycle machine is powered by electric motors. The electricity comes from generators connected to the aircraft's engines.⁴ Shaft power to drive the generators can be obtained from an aircraft engine with an efficiency of amazing 70%.⁵ This is due to the fact that shaft power off-takes increase the engine's turbine inlet temperature towards the design maximum and hence increase the efficiency of the engine while producing thrust. Shaft power off-takes are about twice as efficient compared to bleed air extraction. An electric air conditioning system can be economical at a high fuel price because it trades higher depreciation (from a higher aircraft price due to more components) against reduced fuel costs. The described alternative air conditioning solution flies today only on the Boeing 787. Airbus could follow. The technology is already available at Airbus and was checked in test flights. As of today, Airbus is still undecided about a bleed versus a no-bleed decision for an air conditioning system of a possible all-new aircraft.

Engine seals and oil

The engine shafts are supported by lubricated bearings. They are sealed against the air in the compressor often with labyrinth seals. Subsequently, it will be explained why these jet engine seals leak oil by design in small quantities. Leakage of carbon seals is only 10% of the amount experienced with labyrinth seals.⁶ However, leakage should not occur – no matter how small – because the oil contains problematic additives. Three percent of the engine oil usually consists of tricresylphosphate (TCP). Some TCP isomers are known for causing nervous system effects among other symptoms. The oil gets pyrolyzed (chemically modified) at the elevated temperatures in the compressor, leaving more than 100 substances behind, some of them are hazardous and among them are various Volatile Organic Compounds (VOC).⁷

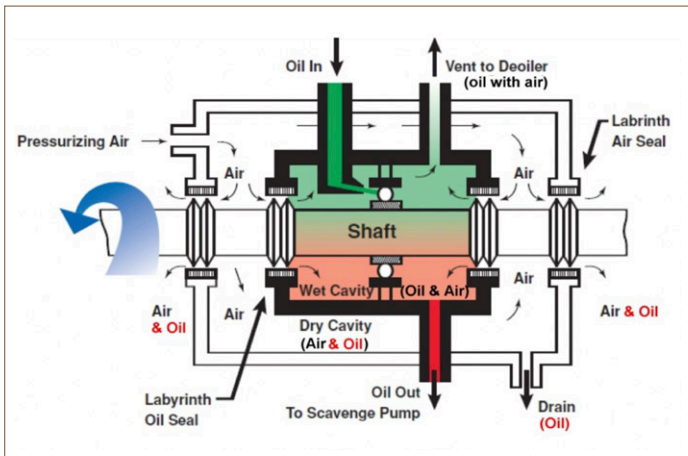


Figure 1— Typical bearing lubrication and sealing in a jet engine. The Figure is based on Exxon (2017).⁸ Shown is a double walled seal design.

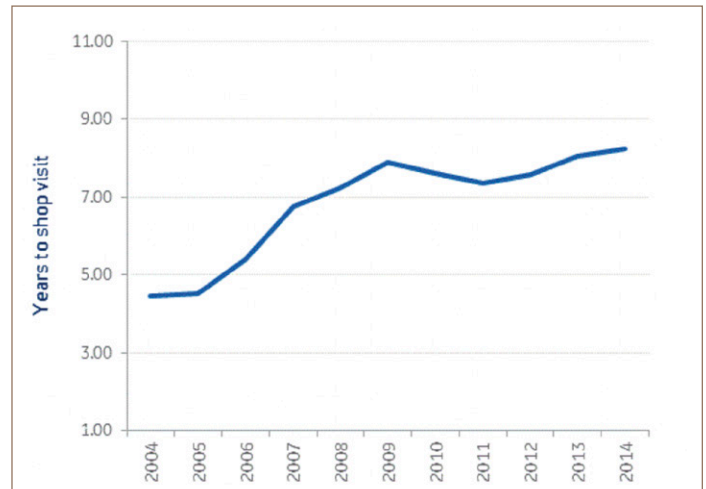


Figure 2 — CFM56-7B Time to first shop visit.¹⁰

Labyrinth seals require bleed air going from the dry cavity to the wet cavity. The airflow should keep the oil back, which has a normal tendency to scatter and to flow out of the wet cavity (through the seal in the inner wall). As can be expected, the air cannot fully keep the oil back from flowing into the (so called) “dry cavity”. This is indicated in Figure 1 by an (oil) drain. The oil drain allows the “dry cavity” to be continuously emptied from accumulating oil. Now that it is understood that the “dry cavity” contains some oil, it is also clear that the air flowing through the seal in the outer wall (from inside towards the outside) will carry some oil out into the engine compressor. In the engine compressor the oil mixes with compressed air, of which a small portion is bled off into the cabin. When only a single wall design is used, air and oil leak directly through the seal into the compressor.

Smaller clearances in the seal require less air flow, but eccentricity and relative movement between components requires designing the seal with some minimum clearance. If clearances are too small labyrinth seals can be damaged. For a given clearance, sealing will be better with larger air flow, but pressurized air comes at a cost due to increased fuel consumption and therefore air flow will be limited.

“Labyrinth-seal clearances naturally increase as an engine ages. As this occurs – due to rubbing under vibration, gyroscopic torque, rough landings or any g-load factor, the engine air flow increases, resulting in even higher oil consumption” and hence leakage into the bleed air.⁶ In addition, during a period of 10 years (2004 to 2014) maintenance practice changed such that engines stay on the wing almost twice as long without shop visit and seal replacement (Figure 2). This means that the aviation industry accepts increasingly higher oil leakage and as such higher contamination levels in the cabin. Once again we are back to economics. For other aspects of jet engine seal design and operation see also Michaelis (2016).⁹

An alternative source for the compressed air is the Auxiliary Power Unit (APU). Like the aircraft’s jet engine, it is a gas turbine, built much in the same way when it comes to bearings and seals. For this reason, also compressed air from the APU is potentially contaminated.

Engineering standards from SAE contain guidance about sound engineering design principles for air conditioning systems of air planes.³ Also certification standards give some guidance, however, more general. In essence,

bleed air systems used to supply the air conditioning system as we see them on today's passenger jet aircraft should not be built the way they are.

Cabin air and oil

The amount of oil leakage and the resulting concentration of pyrolyzed engine oil in the cabin air can be estimated from first principles. These are the steps, thoughts and example parameters:

- Oil is mixed with air in the bearing chamber (Figure 1). If this mixture would be vented, the oil consumption would be extraordinary. In order to retain most of the oil, an air/oil separator also called deoiler or deaerator is used. The device separates air and oil with rotation and centrifugal force. Nevertheless, some oil escapes with the vented air overboard.
- All calculations are done for the whole aircraft.
- Consider the number of engines: $n_{eng} = 2$
- Determine the engine oil consumption per flight hour from airline maintenance records: \dot{m}_{oil}
- Oil consumption is a minimum of 0.3 l/h per engine. Here two engines: $\dot{V}_{oil} = 0.6$ l/h
- $\dot{m}_{oil} = 0.1673$ g/s with an oil density of 1.0035 kg/l
- Estimate the ratio of oil out of all seals versus the total oil out (including especially that oil leaving the air/oil separator, also called deoiler or deaerator): $x_{seal} = 1\%$ (conservative estimate)
- Determine number of all bearings or seals: $n_{bear} = 5$ (CFM56)
- Determine number of bearings or seals upstream of first bleed port: $n_{bear,up} = 3$ (CFM56)
- Calculate upstream bearing ratio:
 $x_{bear,up} = n_{bear,up} / n_{bear} = 3/5 = 0.6$

- Get the Bypass Ratio (BPR) of the engine: $\mu = 5.7$ (CFM56-5B1)
- Get engine frontal area from engine inlet diameter or fan diameter: $S_{eng} = \frac{4}{\pi} D_{eng}^2$, $D_{eng} = 1,73$ m
- Get aircraft cruise Mach number: $M_{CR} = 0.76$ (A321)
- Get aircraft cruise altitude: $h_{CR} = 11$ km
- Get speed of sound at cruise altitude (from ISA Table or calculated): $a(h_{CR}) = 295$ m/s
- Get density at cruise altitude: $\rho_{CR} = 0.364$ kg/m³ and in the cabin (at 8000 ft): $\rho_{cab} = 0.963$ kg/m³
- The steady state oil concentration in the cabin is equal to the oil concentration of the inflow.
- Finally, we have the equation of the oil concentration in the cabin (derivation in Scholz 2017³):

$$\frac{m_{oil,cab}}{V_{cab}} = \frac{\dot{m}_{oil} x_{bear,up} x_{seal}}{S_{eng} n_{eng} M_{CR} a(h_{CR})} \cdot \frac{\rho_{cab}}{\rho_{CR}} (1 + \mu)$$

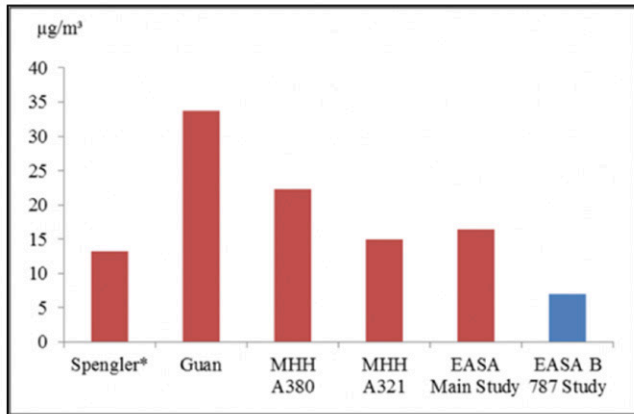
with sample data: $\frac{m_{oil,cab}}{V_{cab}} = 17$ $\mu\text{g}/\text{m}^3$

The estimate shows the same order of magnitude as measured in flight (Figure 3).

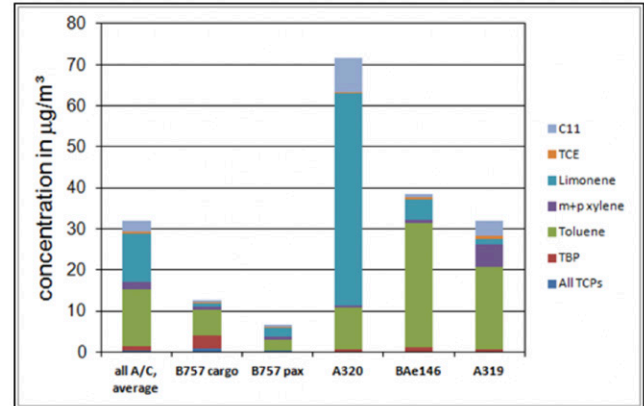
Cranfield and EASA measurements (Figure 3) are not very conclusive when looking for the amount of pyrolyzed oil concentrations (hydrocarbons) in the cabin. However, when asking only for the order of magnitude this is found: A concentration of about 10 $\mu\text{g}/\text{m}^3$ could be considered as background reading present in the cabin and is e.g. due to emissions of VOCs from cabin items and flame retardants. Another 10 $\mu\text{g}/\text{m}^3$... 20 $\mu\text{g}/\text{m}^3$ of hydrocarbons may be explained by oil leaking into the cabin through engine seals.

Solutions to the problem

The problem can only be solved fully by avoiding bleed air for aircraft air conditioning and to select an alternative air conditioning system with a direct intake of ambient



a



b

Figures 3a & b — Left: Sum of aromatic hydrocarbons. Comparison of different studies (median). In-flight measurements. Highest values from three investigated airlines.¹¹ The 10 µg/m³ measured in case of the 787 could be considered background reading from cabin items like furniture that also emit VOCs. Right: Sum of the concentration of measured VOCs. Note: Also other VOCs could have been present, but are not given in the study. Therefore: Sum of VOC concentration could be higher than shown.¹²

air (see section ‘Air conditioning’). The second-best solution is complete cabin air filtration with carbon filters in the supply ducts from the engine. It reduces the concentration of whatever contamination by 80%. Technically the easiest way to install carbon filters to filter VOCs in existing aircraft is in the recirculation path, where HEPA filters are already in use. Unfortunately, air filtration only in the recirculation path is less efficient. It reduces the concentration of whatever contamination by 40%.³

Immediate action should be taken without waiting for the ultimate industry solution of the problem which may not come. Individuals can do something about detection and avoidance. This is especially important during cabin air contamination events (CACE). CACE that manifest themselves as smell event of fume events can be detected by human senses (nose and eyes). Other contaminations may pass unnoticed. For this reason, pilots (or crew in general) should read the carbon monoxide (CO) concentration from a personal CO detector as an objective indicator in addition to the observations from their senses. A measured CO

concentration will always be low. Therefore, it should be compared not against the limit value of 50 ppm (CS 25.831) but rather against values obtained under normal conditions (e.g. 2 ppm). If pilots are alerted of a cabin air contamination and systematic trouble shooting has been done without improvement to the cabin air, pilots should consider to descend to 10000 ft, reduce speed and ventilate the aircraft by means of the ram air inlet (if fuel reserves and terrain clearance allow for it). The ram air inlet is the only source of fresh air in flight, independent of engines or APU. If smoke is present, checklists tell pilots to put on their oxygen mask. In such a case, also cabin crew should consider wearing a personal breathing mask protecting against nerve gas.³

CONCLUSIONS

Aircraft engine seals leak oil by design in small amounts. This already follows from looking at the design of bearing and seals. An equation was derived to calculate the concentration of a possible cabin air contamination. The seal leak ratio may be set to 1% as long as no better values are available. If a certain oil consumption

(given in l/h) is considered troublesome on one aircraft, it may not be considered likewise on another aircraft, which has other parameters of size, BPR and bearing positions relative to bleed ports. Hence, the equation from this paper may be used to compare oil consumption of different aircraft with respect to their cabin air contamination potential. This could be the topic of further research activities.

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