

## AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

## Cabin Air Contamination – A Summary of Engineering Arguments

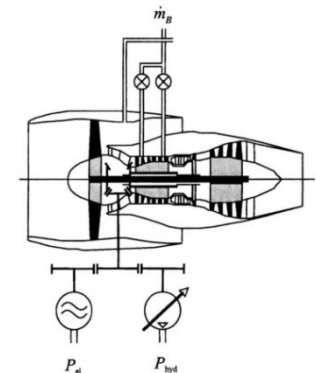
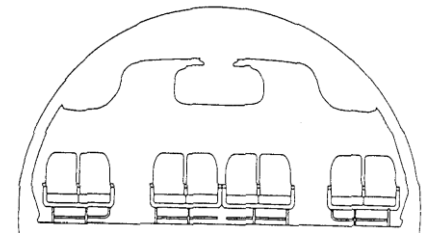
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## International Aircraft Cabin Air Conference

**2019** Imperial College London, 17/18.09.2019

<https://doi.org/10.5281/zenodo.4450241>



## Cabin Air Contamination – A Summary of Engineering Arguments

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# Introduction

## Introduction

### **Definition: Fume Event**

In a fume event, the cabin and/or cockpit of an aircraft is filled with **fume**. Air contamination is due to fluids such as engine oil, hydraulic fluid or anti-icing fluid. A Fume Event includes a Smell Event. Note: Other reasons for fume in the cabin are possible. The term "fume event", however, is generally used as defined here. Definition adapted from (Wikipedia 2019)

### **Definition: Smell Event**

A fume event without visible fume or smoke, but with a distinct **smell** usually described as "dirty socks" from the butyric acid originating from a decomposition of the esters that are the base stock of the synthetic jet engine oil.

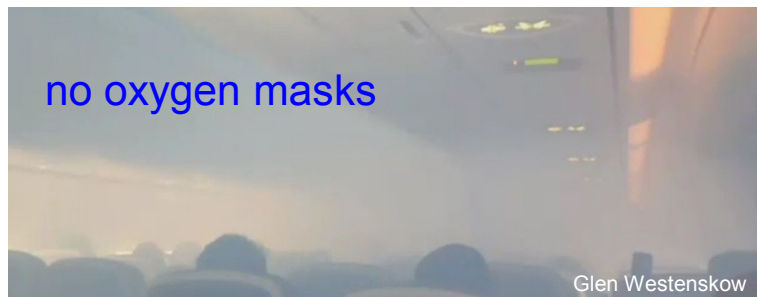
### **Definition: Cabin Air Contamination Event (CACE)**

In a Cabin Air Contamination Event (CACE) the air in the cabin and/or cockpit of an aircraft is contaminated. Sensation of the contamination can be from **vision** (fume/smoke), **olfaction** (smell/odor), a combination of typical **symptoms** experienced by several passengers and/or or crew or by related **measurements** of CO, CO<sub>2</sub>, ozon or other "harmful or hazardous concentrations of gases or vapours" (CS-25.831).

## 2019-08-22: Hawaiian Airlines, A321neo Emergency Landing and Evacuation; Smoke on Board

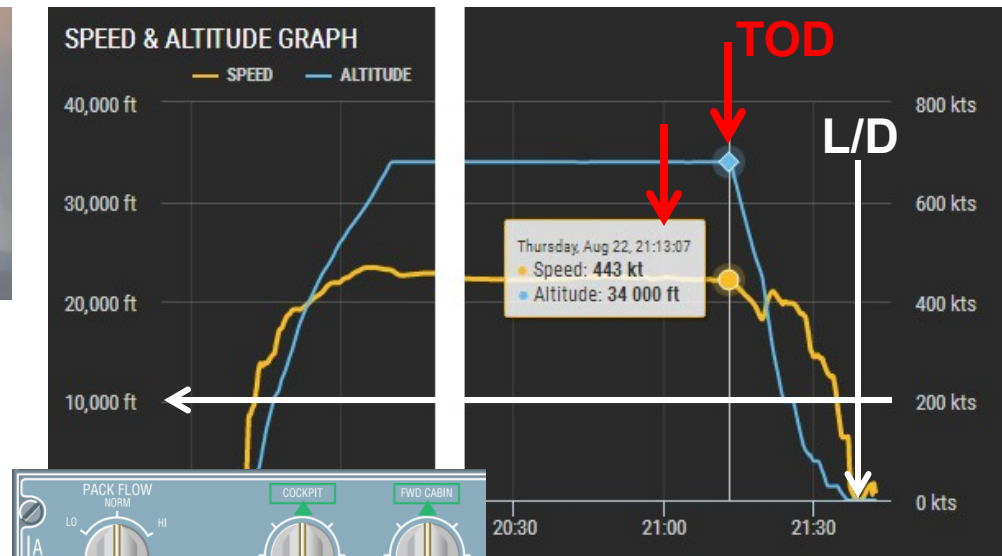
Oakland to Honolulu, Flight HA47, A321neo, N218HA

21:13: Top of Descent: Smoke starts to fill cabin i.e. when thrust setting changed.

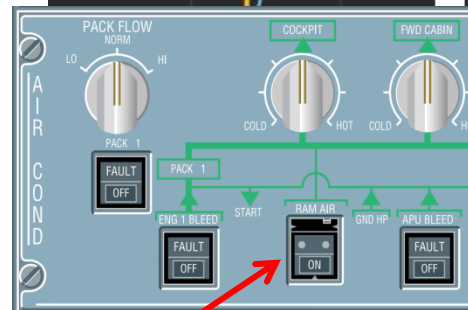


21:16: Pilots received a fire warning from the cargo compartment and declared an in-flight emergency.

21:36: Landing. After landing there was "no visible evidence of fire, no visible flames" said Snook. "We have since determined that a seal failed in the aircraft's left engine" said Da Silva.



based on Flight Radar 24



guarded pushbutton

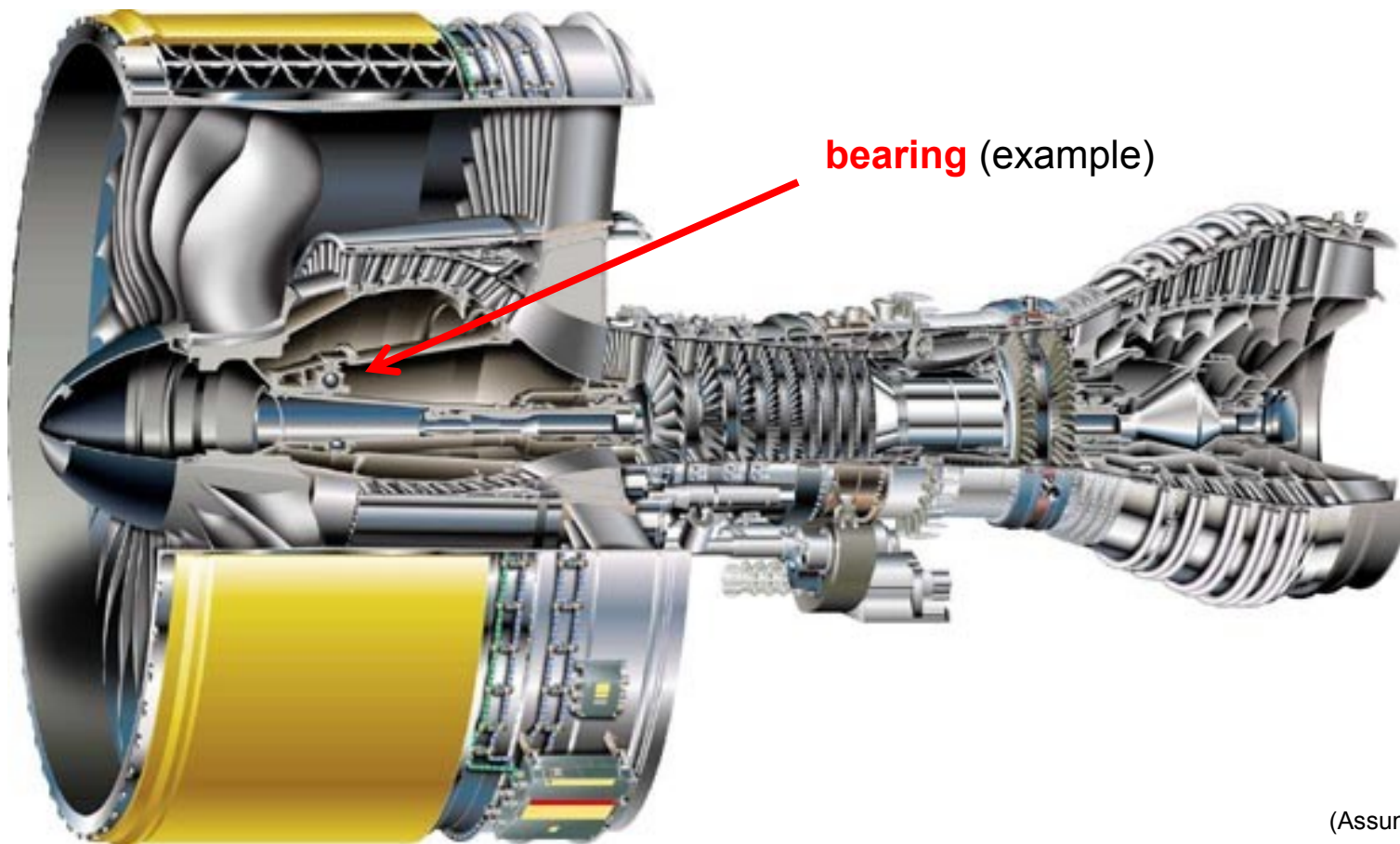
**Direct** (emergency) **venting with ram air** (independently of bleed air) is possible **below 10000 ft**, but was **not used**.

# Jet Engine Technology

## Jet Engine Technology

### Engine Overview

#### Engine Alliance GP7000



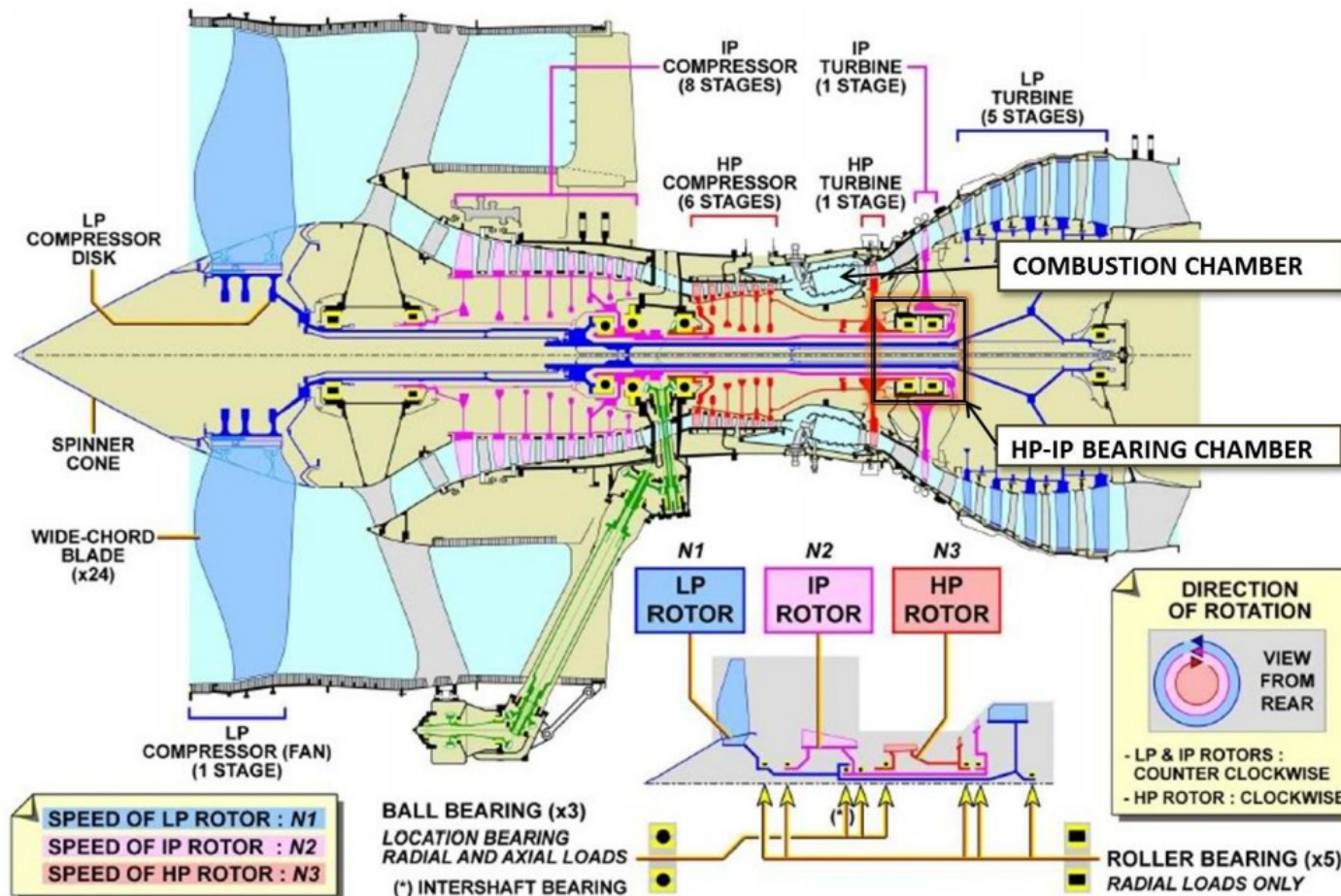
(Assuntos Militares 2013)



## Jet Engine Technology

### Engine Bearings

### Rolls-Royce Trent 1000

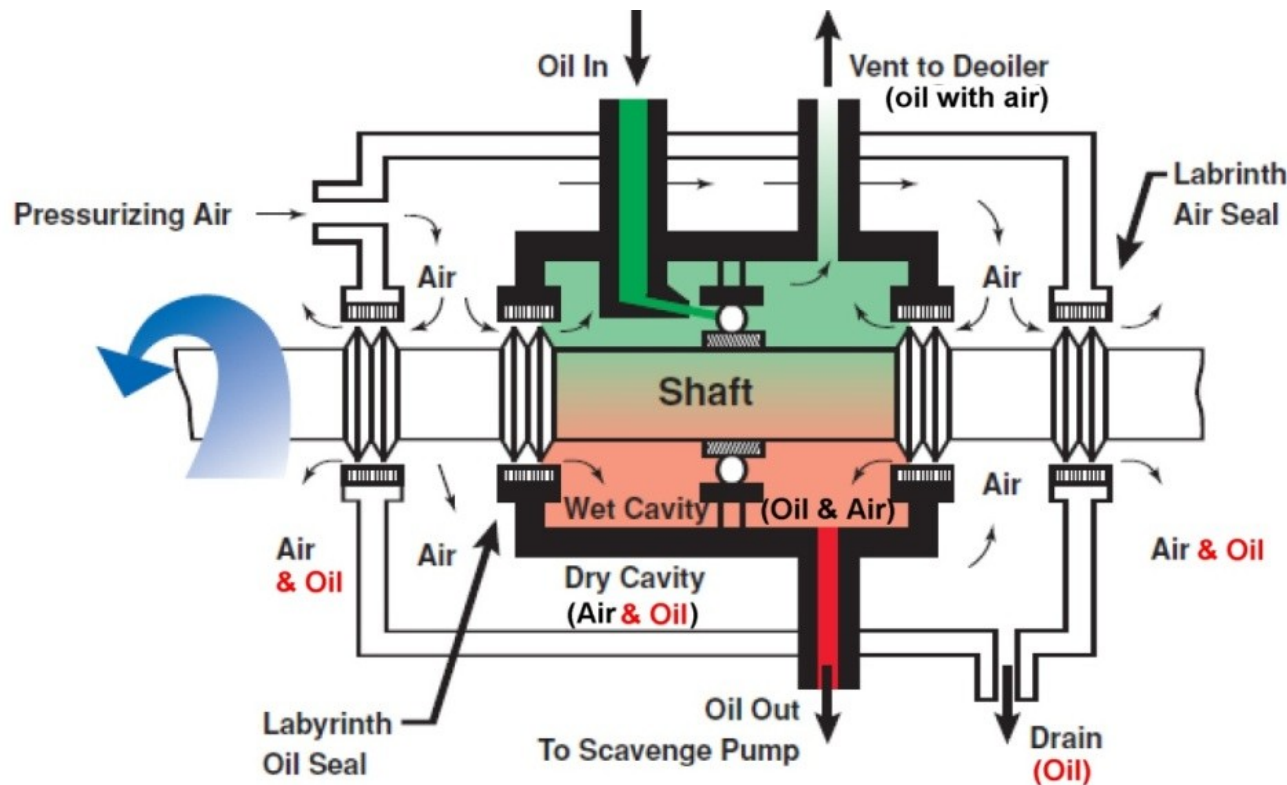


(Ademiya 2015)



## Jet Engine Technology

### Lubrication and Sealing of Engine Bearings

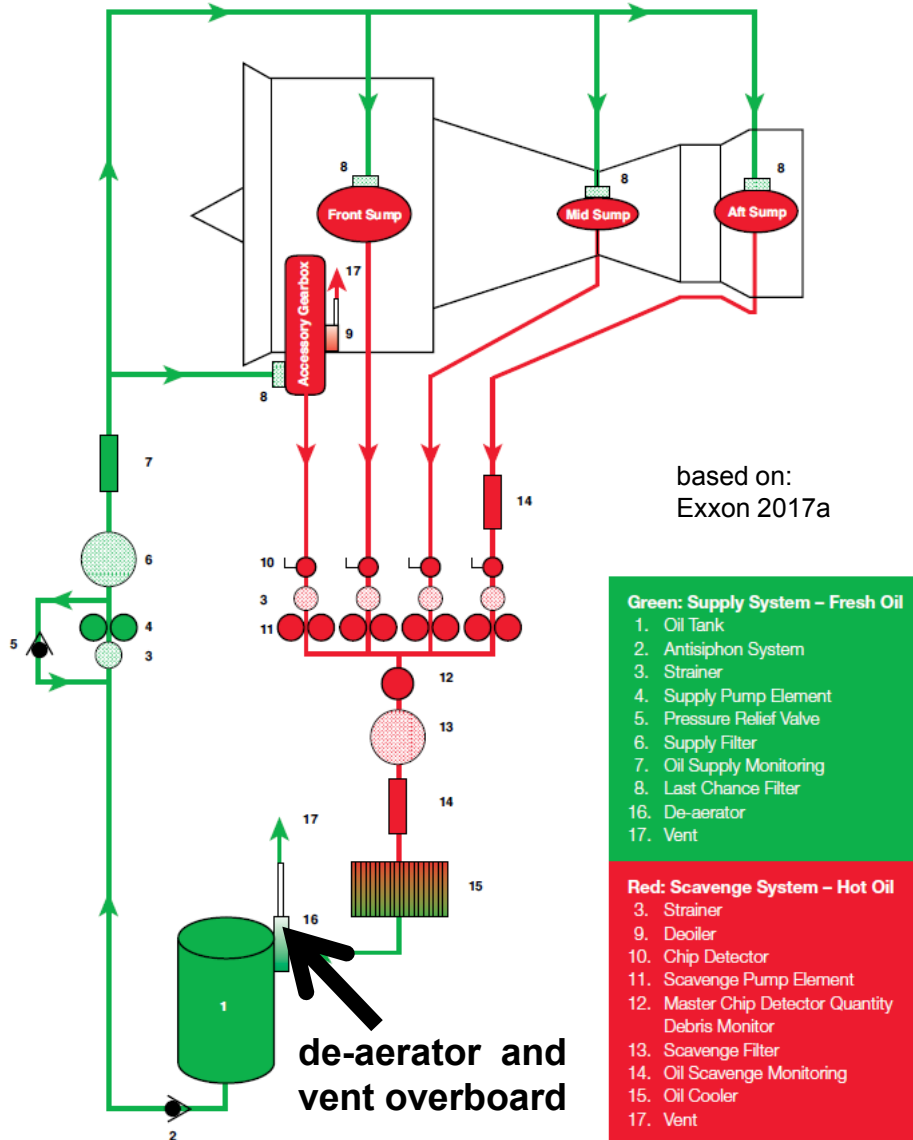


Based on (Exxon 2017b)

**Normal operation of engine seals:**

1. The "**drain**" discharges **oil**.
2. The "**dry cavity**" contains **oil**.
3. Air and **oil** leak from bearings **into** the **bleed air**.

**=> Engines leak small amounts of oil by design!**



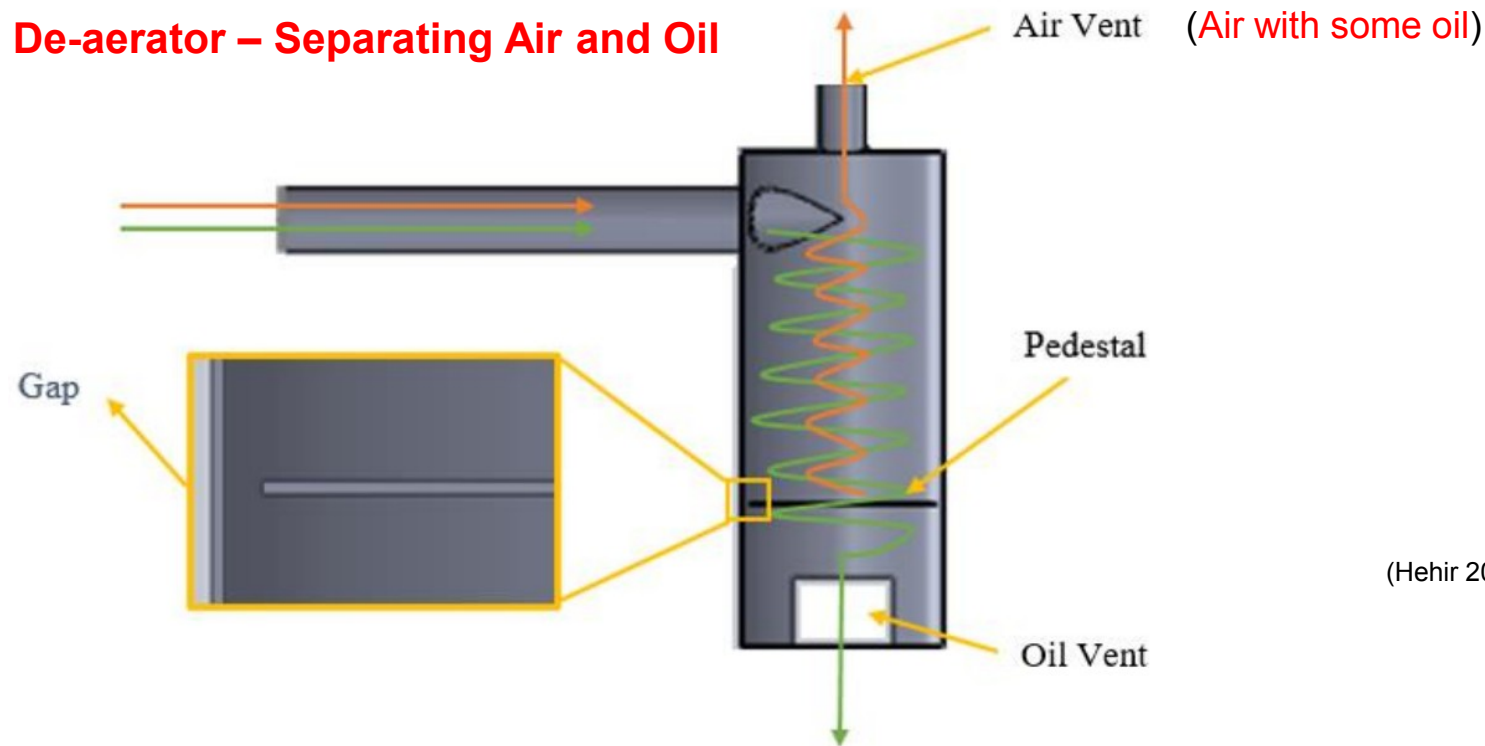
## Engine Air and Oil System

Quotes from: Exxon Mobile (2017a):  
**“Jet Engine Oil System – Overview”**  
*with remarks:*

- "The scavenged oil flow is slightly lower than the supply flow due to normal oil consumption through the deoiler, oil seals, and oil leaks." (Remark: *Oil escapes also from the seals*)
- "Therefore, a large amount of air is carried by the scavenge oil and must be removed through a de-aerator when entering the tank." (Remark: *Seals do not seal but allow large amounts of air to enter the seals. If pressure in the compressor is low compared to pressure in the oil system i.e. low  $\Delta p$ , oil can escape from the seals.*)

## Jet Engine Technology

### De-aerator – Separating Air and Oil



(Hehir 2016)

- Air leaving the de-aerator still **contains some oil** (sometimes visible on the engine as white smoke).
- Amount of oil depends on the **oil separating efficiency of the de-aerator**.
- Oil leaving de-aerator determines (almost exclusively) the oil consumption of the engine.
- **Oil leaving through engine seals** is only a very **small portion  $x$**  of the engine's oil consumption (1%?).
- **Hence: Oil entering cabin depends more on this portion  $x$  than on the absolute engine oil consumption!**

## Jet Engine Technology

### Engines Longer on Wing

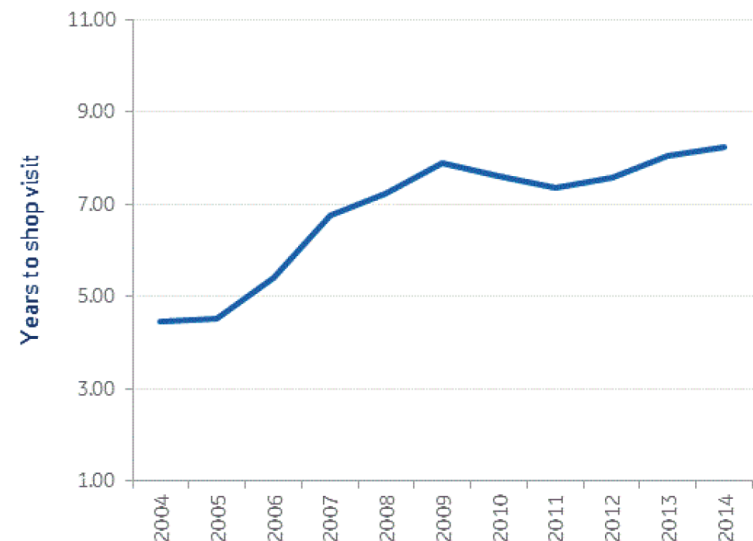
### Labyrinth-Seal Clearances Increase as Engines Age

"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" (Exxon 2016a) and hence leakage into the bleed air.

The figure shows increasing time to first shop visit of CFM56-7B engines. It follows:

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.

CFM56-7B time to first shop visit (years)



Source: FDM TOW data, CFM56-7B

(AviationWeek 2016)

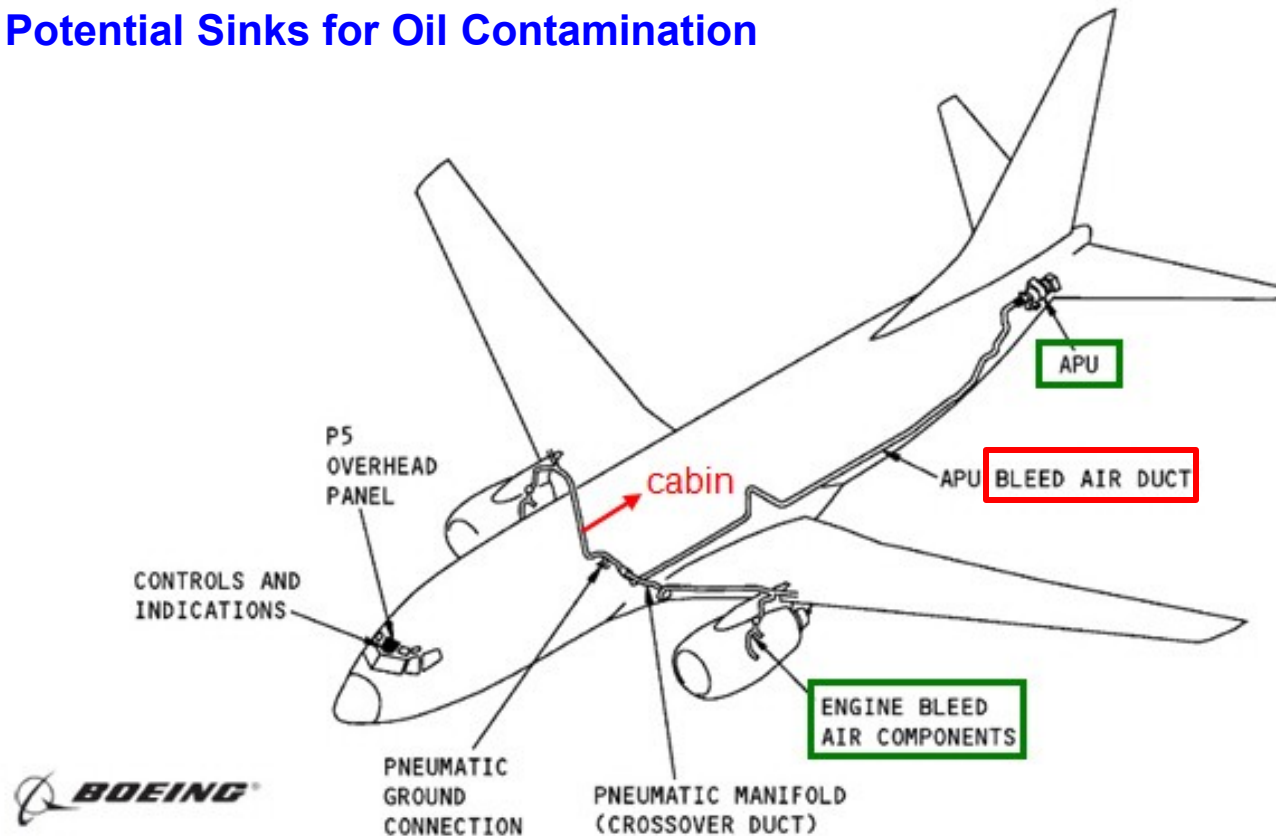
# Aircraft Systems Technology

## Aircraft Systems Technology

B737

### Bleed Air Ducts

### Potential Sinks for Oil Contamination



737-600/700/800/900 AIRCRAFT MAINTENANCE MANUAL

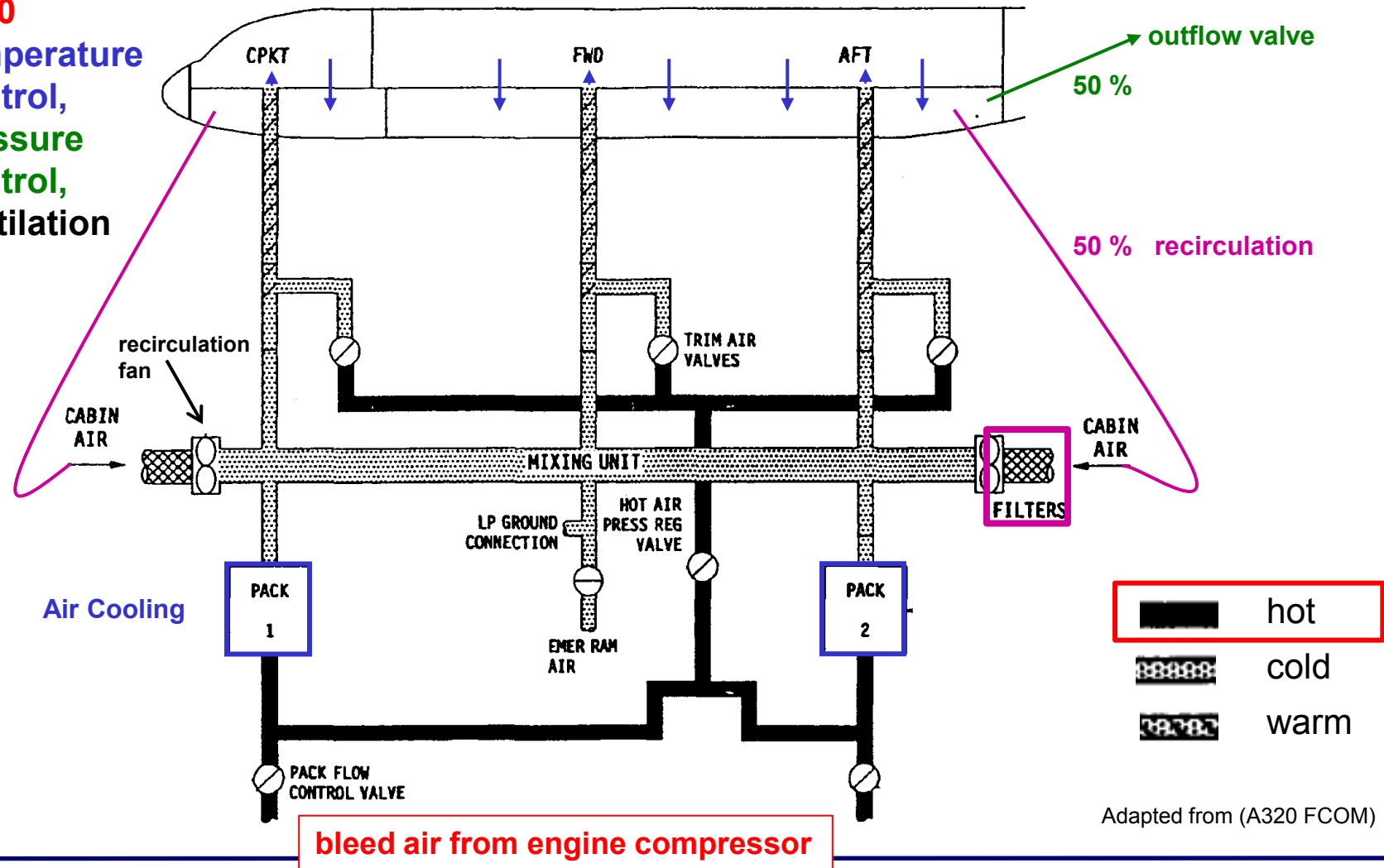
PNEUMATIC - COMPONENT LOCATIONS

Adapted from (AMM B737)

# Aircraft Systems Technology

A320

**A320**  
Temperature  
Control,  
Pressure  
Control,  
Ventilation



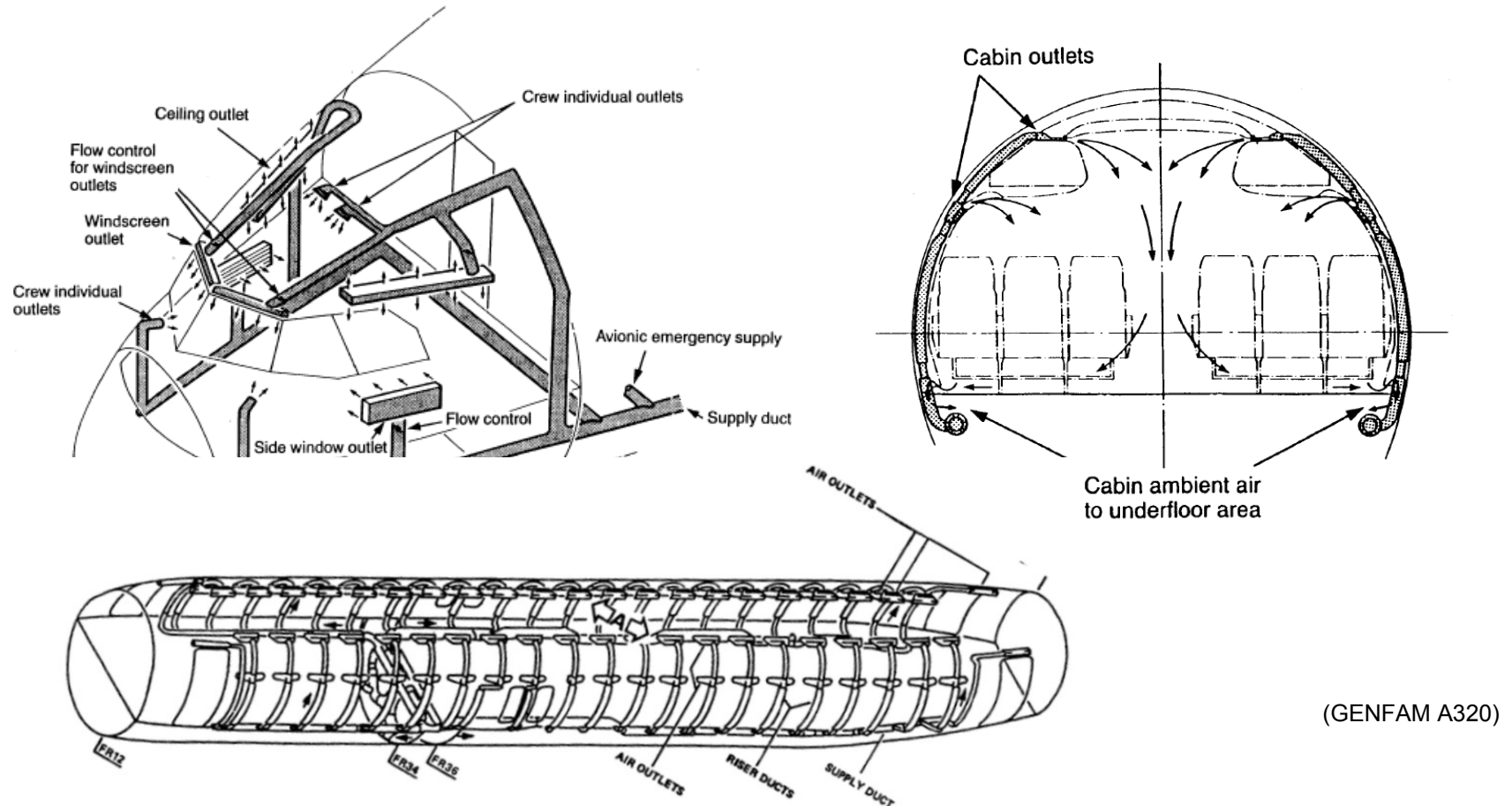


## Aircraft Systems Technology

A320

### Cabin Air Ducts

### Potential Sinks for Oil Contamination



(GENFAM A320)

## Aircraft Systems Technology

### Cabin Air Ducts

#### Insufficient / Impossible Duct Cleaning

In the case of heavy contamination, this being assumed  
when there are visible traces of oil on the internal surface of the ducts, it is necessary to  
manually clean the affected ducts using rags and an appropriate degreasing agent.

(Airbus 2013)

***Aircraft released back into service over night***

***after an (oil based) CACE***

***are not cleaned as instructed by Airbus, because***

- ***ducts cannot be removed from behind the panels in this short time,***
- ***the inside of ducts is not accessible in the first place.***

## Aircraft Systems Technology

### How Do We Know about Oil in the Cabin?

#### Oil has left traces on its way from the engine to the cabin interior:

1. Oil traces in bleed air ducts
2. Oil traces in air conditioning ducts
3. Oil traces in recirculation filters
4. Oil traces on cabin surfaces (wall panels, seats, ...)
5. Hydro carbon concentrations in the cabin can be calculated and agree with measurements

**Evidence** collected in Scholz 2017a and Scholz 2017b summarized here:



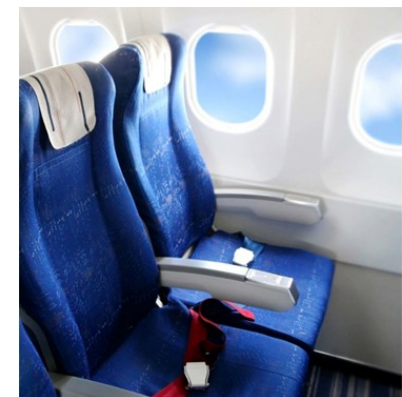
1. (GCAQE 2017)



2. (CAA 2004)



3. (Eckels 2014)



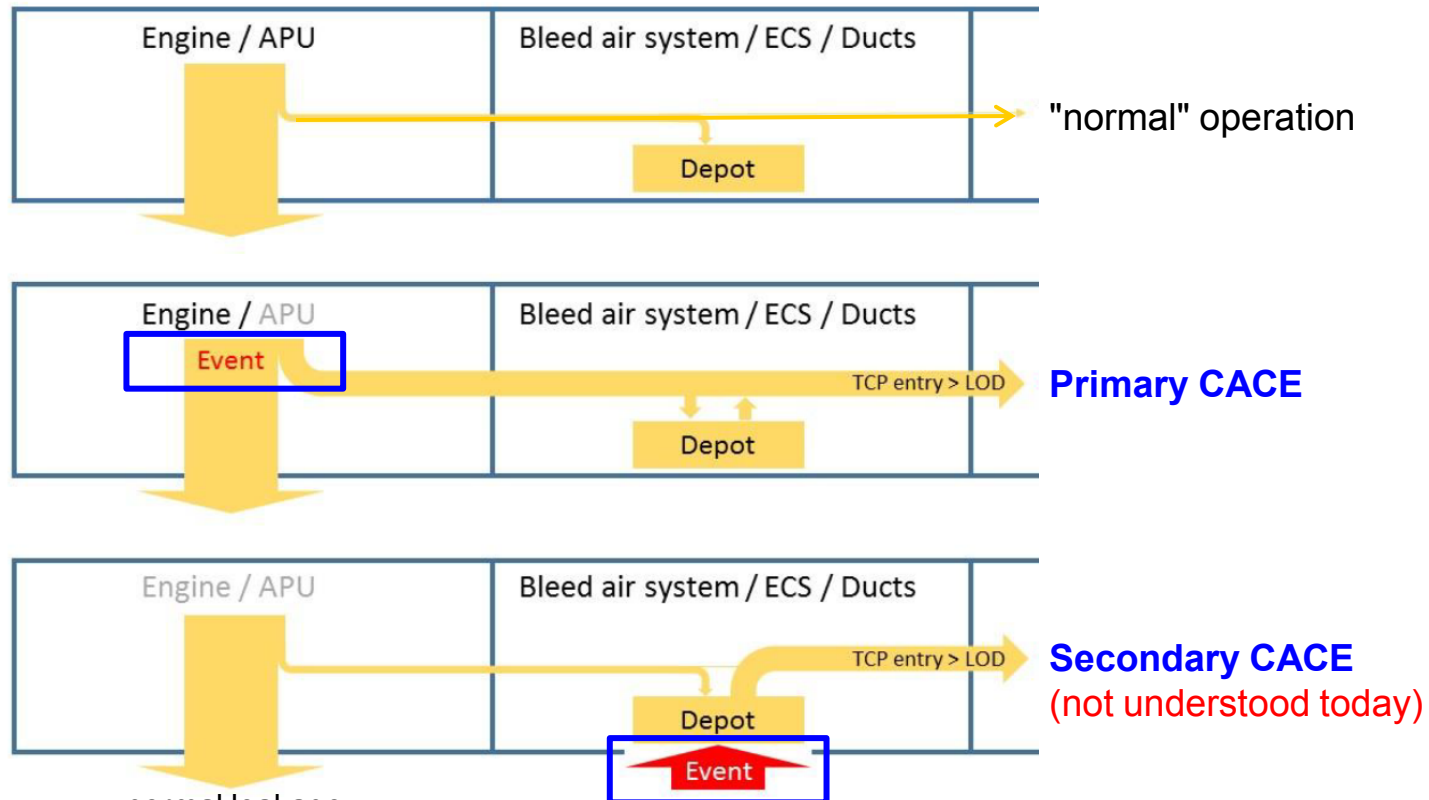
4. (Lamb 2012, Solbu 2011)

5. (Scholz 2017a)

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

## Aircraft Systems Technology

### Primary and Secondary Cabin Air Contamination Events (CACE)



#### Event Mechanism:

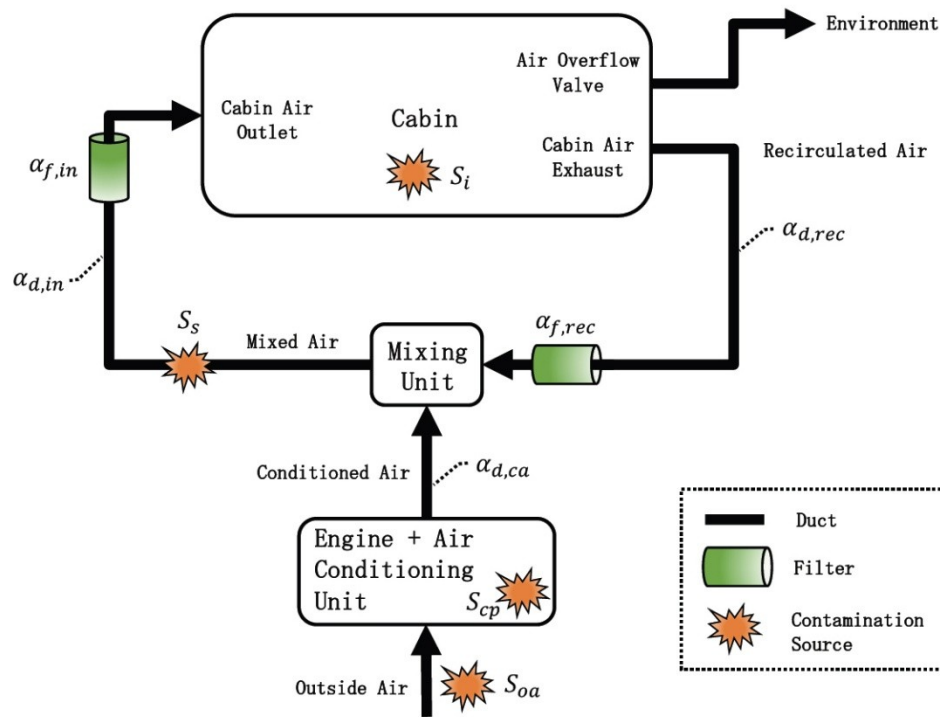
- normal leakage
- seal failure
- neg.  $\Delta p$  in bearing chamber
- transients

- mechanical stress?
- thermal stress?
- solvents (water, de-icing fluid, ...)?

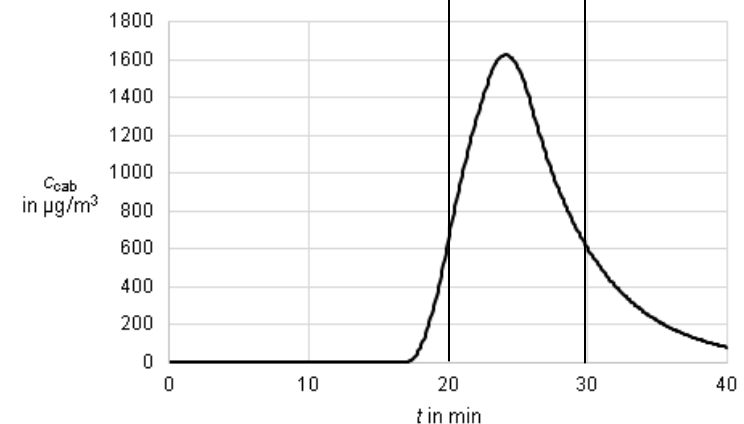
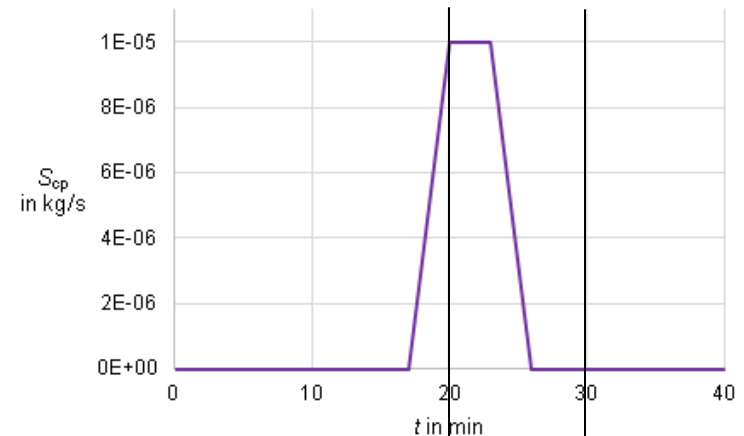
Based on EASA 2017b

## Aircraft Systems Technology

### Dynamic Cabin Air Contamination Calculation Theory



It takes about **20 minutes** for a discrete cabin air contamination event (CACE) **to be washed out** by the air conditioning system ("**thinning effect**").



$$\frac{d}{dt} c_{cab} + a \cdot c_{cab} = b_1 + b_2 \cdot t$$

Lakies 2019 at HAW Hamburg

Download of project report: <https://doi.org/10.15488/4543>

# Aircraft System Design Principles

## Aircraft System Design Principles

### Interpretation of CS-25.1309 with respect to Bleed Air from Jet Engines

#### CS-25 (AMC 1309, 6. Background, b. Fail-Safe Design Concept)

The CS-25 airworthiness standards are based on ... the **fail-safe design concept** ...

(2) The fail-safe design concept uses the following design principles:

- (i) **Designed Integrity and Quality** including **Life Limits**, to ensure intended function and prevent failures.
- (v) **Failure Warning** or Indication to provide detection.
- (xi) **Error-Tolerance** that considers adverse effects of foreseeable errors during the aeroplane's design, test, manufacture, operation, and maintenance.

- *The probability of CACEs must not be compared with the **effect-probability relationship of CS-25.1309** which is for statistical errors.*
- *Errors of the bleed air-based air conditioning system are well known, permanent and non-statistical.*
- *The system's error-tolerance (e.g.: two pilots, autopilot, cockpit crew oxygen masks) is compromised, if it has to cope with already known design errors that are not rectified out of negligence.*
- *In case of bleed air used for cabin ventilation: **Known problems need to be rectified!***

#### CS-25.1309 Effect-Probability Relationship

<u>Effect</u>	<u>Probability</u>
Minor	$< 10^{-3}$ 1/ FH
Major	$< 10^{-5}$ 1/ FH
Hazardous	$< 10^{-7}$ 1/ FH
Catastrophic	$< 10^{-9}$ 1/ FH



## Aircraft System Design Principles

### Engineering Design Principles for Air Conditioning from SAE

#### SAE AIR 1168-7: Aerospace Pressurization System Design (first edition: 1991, A in 2011)



“Compressor bleed from turbine engines is attractive because of the mechanical simplicity of the system.” However, “**oil contamination ... can occur in using compressor bleed air from the main engines.**” “Popular opinion regarding the risk of obtaining contaminated air from the engine **may preclude its use for transport aircraft, regardless of other reasons.**”

# Engine Metals from the Oil into the Body

## Engine Metals from the Oil into the Body

### Used Oil Analysis for Metal Particles

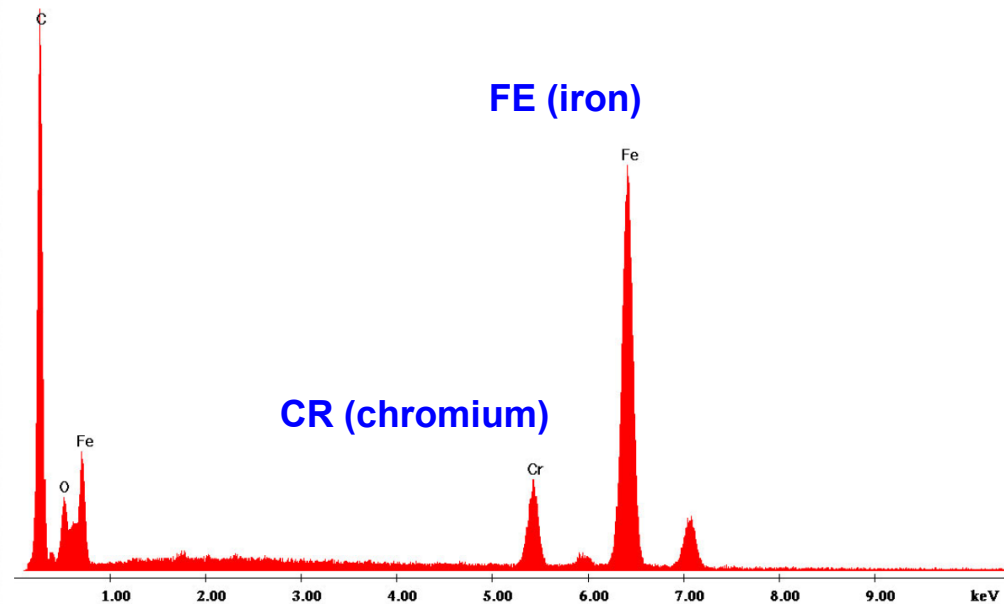
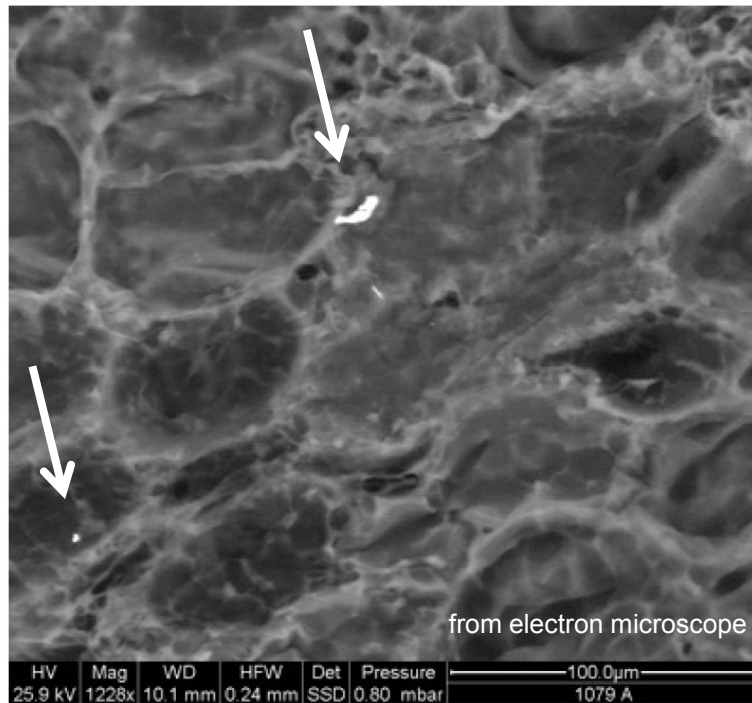
- **Spectrometric Oil Analysis** Program (SOAP) is an analysis of metal particles in the oil.
  - SOAP can be combined with **oil filter inspection** and **magnetic chip detector inspection** which identifies larger metal particles.
  - A monitor program helps to identify the condition of the engine:
  - **Catastrophic** failure of mechanical parts usually generate larger metal particles that can be analysed in magnetic chip detectors.
  - **Slow progressing damage** to gears, bearings and spinning bearing races in the engine case is identified with SOAP. Wear particle size is between 1  $\mu\text{m}$  and 5  $\mu\text{m}$ .
  - **Normal wear** can produce even smaller particles (nano particles).
  - The most important wear metal in the evaluation is **iron** followed by **chromium** – both are present in bearings. If the engine case is **titanium**, increased titanium levels indicate a spinning bearing outer race.
  - Larger metal particles will stay in the engine.
- **Metal micro and nano particles can leave the engine together with the oil into the cabin!**

Partially based on Exxon 2016b

## Engine Metals from the Oil into the Body

### Metal Particles in Human Fatty Tissue

(Gatti 2019, report written for client)



Analysis 8 of Table I. High-magnification image (1228x) and EDS spectrum of 10-micron and 1-micron brighter-looking particles composed of Carbon, Iron, Chromium and Oxygen: a stainless-steel composition. EDS: Energy-Dispersive X-ray Spectroscopy.

## Cabin Air Contamination – A Summary of Engineering Arguments

### Summary (1)

There is a problem with aircraft air conditioning systems based on bleed air. The evidence:

- Engine **bearing seals leak** small amounts of **oil** by design and more so in failure cases.
- Engines are longer under the wing. Therefore seals are worn out more and leak more.
- **Oil residue found** in bleed ducts, air conditioning ducts, recirculation filters and on cabin surfaces.
- **Hydro carbon concentrations** in the cabin **can be calculated** and agree with measurements.
- Hydro carbons are about **two-fold** in standard pax A/C cabins **compared to B787**.
- **"dirty socks smell"** comes from the base stock of the oil. This smell is an indication for oil products in the cabin.
- **Chemicals** and certain **metals** that are common in the workplace are found **in employee's**.

## Cabin Air Contamination – A Summary of Engineering Arguments

### Summary (2)

- There is a "thinning effect" that reduces the contamination concentration, but concentration depends also on the source strength and duration. Accordingly, examples show the cabin constantly full of oil smoke.
- ECS uses bleed air. This design should not be used (SAE).
- Certification rules are violated.
- An aircraft once contaminated with oil cannot be cleaned. Ducts and components would need to be replaced.
- Instead of applying a cautionary proactive attitude, those responsible use too much effort to play things down. We need a change of attitude to the cabin air problem! We need to get back to aviation's proven principle of caution and safety first.

## Cabin Air Contamination – A Summary of Engineering Arguments

### Contact

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<http://CabinAir.ProfScholz.de>



## Cabin Air Contamination – A Summary of Engineering Arguments

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**All online resources have been accessed on 2019-09-18 or later.**

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Quote this document:

SCHOLZ, Dieter, 2019. *Contaminated Aircraft Cabin Air – A Summary of Engineering Arguments*. International Aircraft Cabin Air Conference 2019 (Imperial College London, 17/18.09.2019).

Available from: <https://doi.org/10.5281/zenodo.4450241>.

### See also:

SCHOLZ, Dieter, 2018. *Technical Solutions to the Problem of Contaminated Cabin Air*. German Aerospace Congress (Friedrichshafen, Germany, 04.-06.09.2018). Available from: <https://doi.org/10.5281/zenodo.4072745>.