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Aircraft Cabin Air Contamination Events – An Engineering View

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CONFERENCE on CABIN AIR QUALITY

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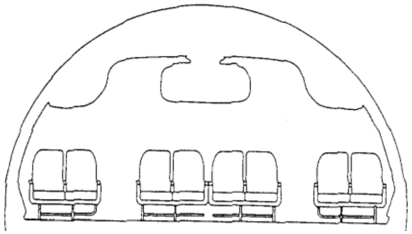
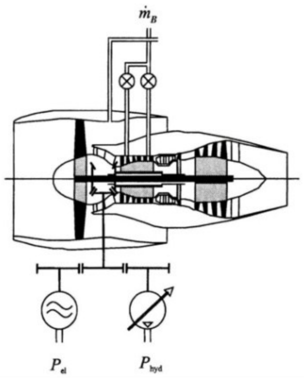
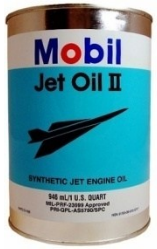




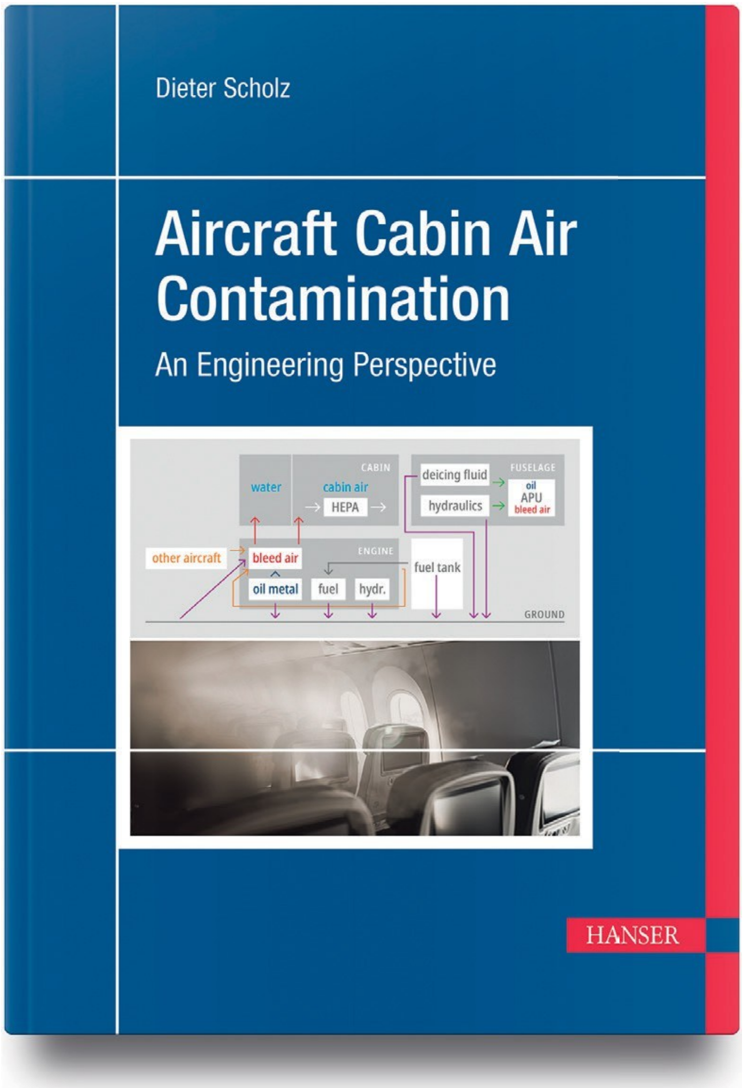


Aircraft Cabin Air Contamination Events – An Engineering View

Abstract

Air conditioning in aviation means temperature control, pressure control and ventilation. The cabin is vented with a certain percentage (e.g. 50%) of fresh outside air. The remaining part of the air for cabin ventilation is provided as air from the cabin, filtered and recirculated back into the cabin. At cruise altitude, ambient pressure is below cabin pressure. Hence, the outside air needs to be compressed before it is delivered into the cabin. The air is compressed in the engine compressor and tapped off as "bleed air" at temperatures reaching 400 °C or more. Hence, bleed air cooling is necessary. The engine shaft is supported by lubricated bearings. They are sealed against the air in the compressor usually with labyrinth seals. It is explained why jet engine seals leak oil by design in small quantities. The amount of oil leakage can be estimated with a new equation. The estimate shows the same order of magnitude as measured in flight (Cranfield study, EASA study). The oil leaking into the compressor contains problematic additives which get pyrolized (burned) at the elevated temperatures in the compressor, leaving more than 100 substances behind, some of them hazardous and some known as Volatile Organic Compounds (VOC). 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 airplanes. Also, certification standards give some guidance, however, more general. In essence, bleed air systems as we see them on today's passenger jet aircraft should not be built the way they are. For immediate action, hints are given: In case of smoke in the cockpit pilots should read the carbon monoxide (CO) concentration from a personal CO detector as an objective indicator in addition to their human senses. The present CO concentration should be compared with values obtained under normal conditions. If pilots are alerted and it is suitable (fuel reserves, terrain clearance), pilots should consider to descend to 10000 ft, reduce speed and ventilate the aircraft by means of the ram air inlet. This 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. Cabin crew should consider wearing a personal breathing mask in such cases. 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, the physics are such that filters in the recirculation path cannot remove substances fully. It is only possible to reduce the concentration down to a value depending on filtration rate and recirculation rate. With typical values the incoming VOC concentration can be reduced to about 60%. In case of full filtration (including ducts from the bleed air sources) incoming VOC concentration can be reduced to about 18%. Aircraft from the beginning of the jet age (B707, DC-8) used turbocompressors keeping bleed air and outside air compressed for cabin ventilation separate. Based on past experience, turbocompressors cannot be considered a solution for future aircraft. A final solution to the problem of contaminated cabin air is seen in electric (bleed free) cabin air supply architectures. Here, outside air for cabin ventilation is compressed separately in dedicated clean compressors. Bleed free cabin air architectures have the additional advantage of much improved fuel economy. So far, the Boeing 787 is the only passenger aircraft in service with a bleed free cabin air architecture. Airbus could follow with related technology already available and checked in test flights.

Contents



500 pages

coming soon

HANSER

Solutions to a Hotly Debated Problem

Abstract

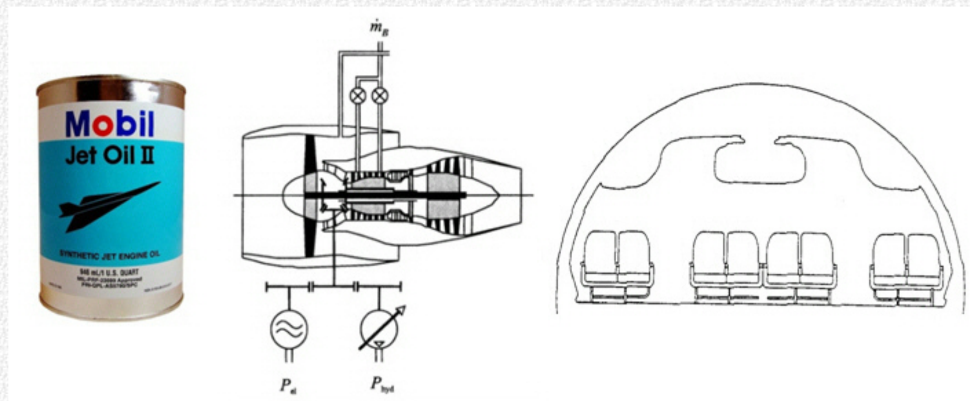
Purpose – This text is written to bring the engineering explanations of aircraft cabin air contamination together in one place and on another level of detail. Explanations go into technical detail, but all interested parties and people from all disciplines should benefit. --- **Methodology** – It is a review of the evidence combined with own contributions to the field. --- **Findings** – At a closer look, the aircraft is anything else but a glamorous polished machine. For technical reasons, dangerous chemicals are in use. These substances leave their intended places and get distributed everywhere. As such they just follow the law of nature: entropy. Unfortunately, while spreading, the substances also arrive in the human body with health and flight safety consequences. All occupants are potentially affected, but predominantly the crew, who spend much more time in an airplane than even a frequent flyer. In this way low dose exposures accumulate and are potentially topped by a high dose exposure in a failure case. --- **Research Limitations** – Focus is on cabin air contamination from engine oil in transport category airplanes. Contamination due to hydraulic fluid, deicing fluid, and even ozone is also considered. --- **Practical Implications** – People who suffer from consequences of aircraft cabin air contamination may find answers to the main question: Why? Others may find hints on how to get protected. --- **Social Implications** – This text can prove evidence of the engineering fundamentals in court. **Originality** – No comparable text seems to be published.

Aircraft Cabin Air

The air you breathe on an aircraft may not be as good as you had hoped for. Coming to this page, you probably know already. However, if it is all new to you, read my German Memo or watch this Video in English.

Abstract

A detailed look at the design of jet engines with their bearings, lubrication and sealing reveals that jet engines leak small amounts of oil by design. This oil gets into the engine compressor and the bleed air. Almost all passenger jet aircraft today use this potentially contaminated bleed air for cabin ventilation.



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My webpage: http://CabinAir.ProfScholz.de

FAKULTÄT TECHNIK UND INFORMATIK
Department Fahrzeugtechnik und Flugzeugbau

HAW HAMBURG

Technical Analysis of the Accident: Swiss Flight LX1885 with an Airbus A220 – From Uncontained Engine Failure via Smoke on Board, A Dead Flight Attendant to Alleged Cover Up at Austrian's Federal Safety Investigation Authority (SUB)

Air conditioning systems of all large passenger aircraft (except the Boeing 787) take the air unfiltered from the compressor of the engine (bleed air)! Any contamination in normal operation and in failure cases (as in LX1885) goes straight into cockpit and cabin. Such a system design is inadequate as stated for decades in SAE AIR 1168-7A [1]: "... the risk of obtaining contaminated air from the engine may preclude its use for transport aircraft, regardless of other reasons [like financial advantages]."

Why is smoke on board after a severe engine failure? The air conditioning system takes air from the engine!
Why a dead flight attendant? Oil fumes are toxic, and aircraft do not offer adequate breathing protection!
Why is the Austrian Air Accident Investigator (SUB) providing an intermediate report below standards?
Why is the Austrian Air Accident Investigator (SUB) prosecuted? Why is the case transferred to the STSB in Switzerland?
Aircraft manufacturers / airlines do not have an interest that the answers given above get into an (intermediate) report!

Poster DLRK 2025: https://doi.org/10.48441/4427.2885

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)

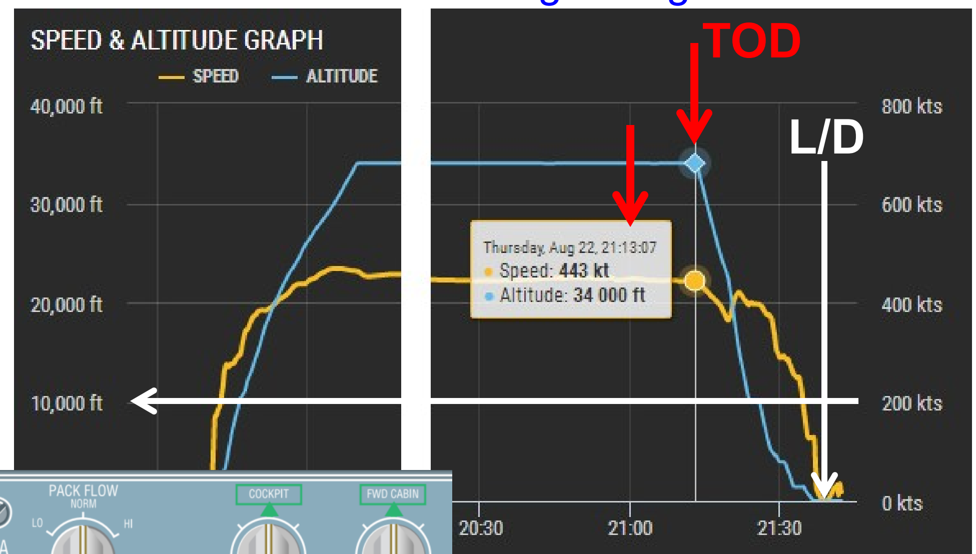
In a Cabin Air Contamination Event (CACE) the air in the cabin and/or cockpit of an aircraft is contaminated. Sensation of the contamination can be from vison (fume/smoke), olfaction (smell/odor), a combination of typical symptoms experienced by several passengers and/or or crew or by related measurements of CO, CO2, ozon or other "harmful or hazardous concentrations of gases or vapours" (CS-25.831).

Introduction

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

Oakland to Honolulu, Flight HA47, A321neo, N218HA

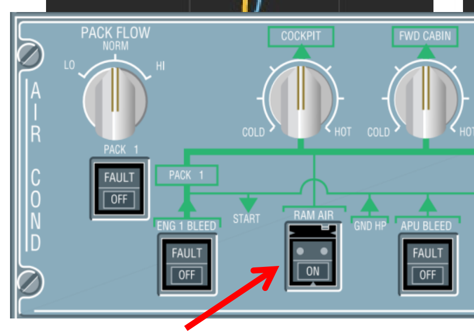
21:13: Top of Descent: Smoke starts to fill cabin i.e. when thrust setting changed.



based on Flight Radar 24

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.



guarded pushbutton

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

Introduction

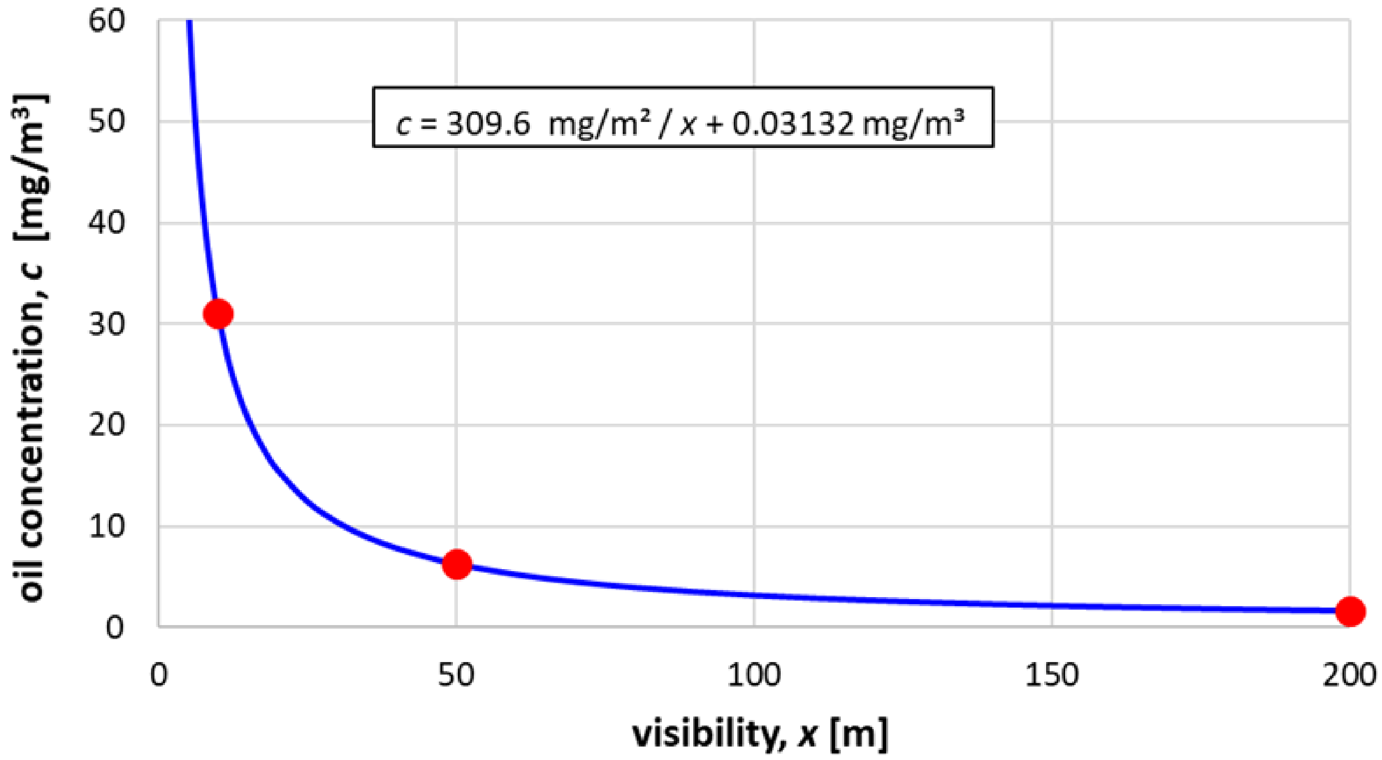
Cabin Air Contamination Event Due to Engine Oil After Technical Fault

Top:2019-08-22, Hawaiian Airlines HA47, A321neo.
Bottom: 2019-08-05, British Airways BA-422, Airbus A321 (https://youtu.be/tFsN0h09gAI).

Cabin Air Contamination Event Due to Engine Oil After Technical Fault

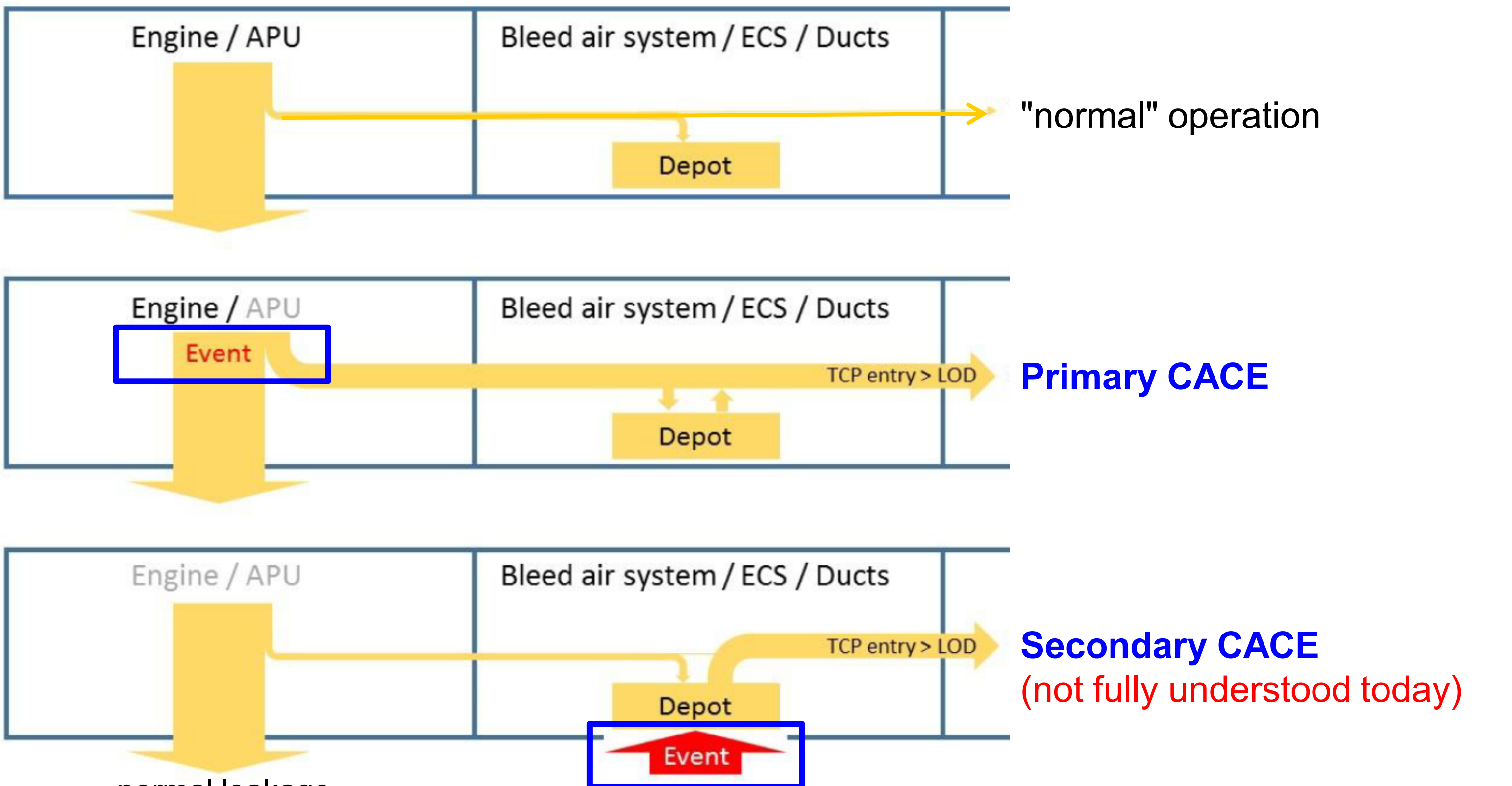
Top: 2010-09-17, US Airways US-432, Boeing 757-200 (https://youtu.be/AZqeA32Em2s).
Bottom: 2018-12-10, Indigo flight 6E-237, Airbus A320neo (https://youtu.be/TO_FZ3L4yus).

Oil Concentration, c (mg/m³) in the Cabin versus Visibility, x (m) in the Cabin



The three points are given in NRC (1997). Source: D. Scholz.

Primary and Secondary Cabin Air Contamination Events (CACE)



Event Mechanism:

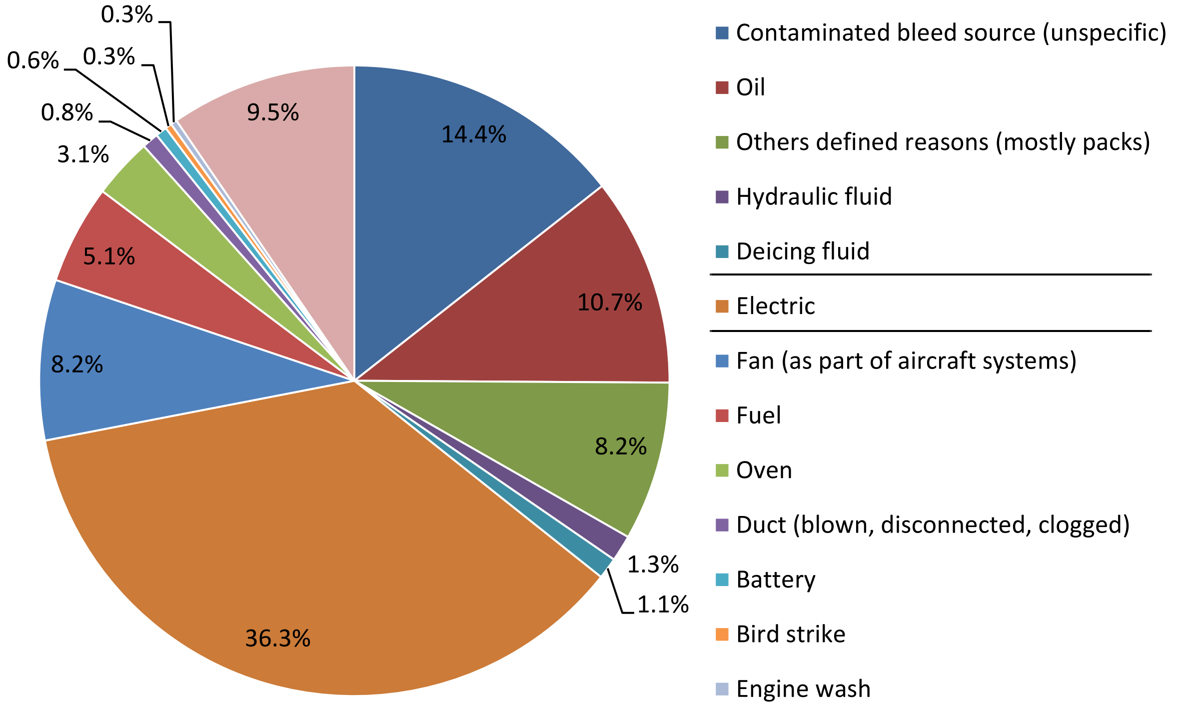
- normal leakage
- seal failure
- neg. Δp in bearing chamber
- transients

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

Based on EASA 2017a

Introduction

Reasons for Cabin Air Contamination Events (CACEs)



The objectionable "classical" cabin air contamination from "contaminated bleed source", "oil", "hydraulic fluid", and "deicing fluid" accounts together for 35.7% (roughly 1/3). Cabin air contamination from electrics is responsible for 36.3% (roughly 1/3). Other reasons from "fan" via "oven" to "engine wash", and "sources unknown" make up the last 1/3 of the cabin air contamination events with 28.0%. Source: D. Scholz. Data: Anderson 2019.

Introduction

How Often are Cabin Air Contamination Events (CACEs)?

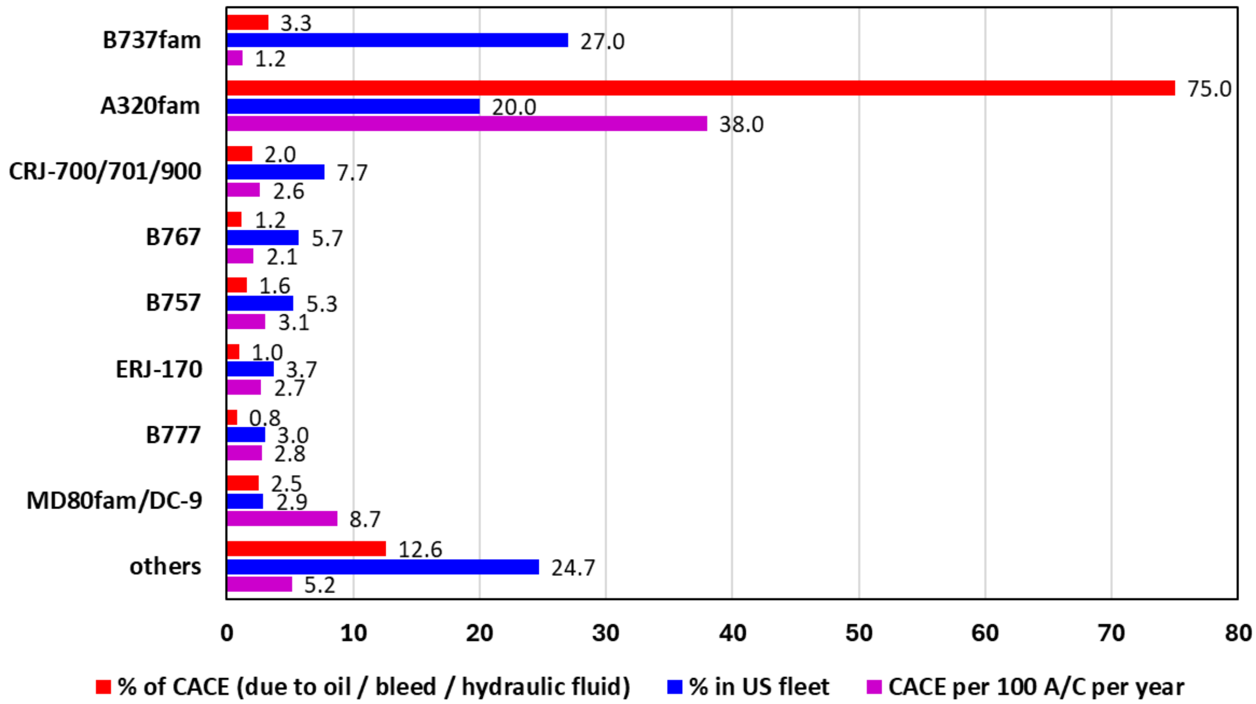
According to Michaelis (2010) **no (exact) figure can be given** to the question of how many cabin air contamination events occur. Neither manufacturer, nor airline, union or government agency knows it. There is tremendous underreporting.

Author:	Anderson 2019	Shehadi 2016
database	SDRS	several
interval (from – to)	2002 – 2011	2007 – 2012
average year of interval	2007	2010
number of years	10	6
area or country	USA	USA
number of events	**4459**	11563
events per year	446	1927
events per day	1.22	5.28
events in 2020 per day	2.30	8.60
events in 2020 per day globally	6.29	23.5
events per 100000 flights	**5.6**	**21.0**

Michaelis (2003) reports about a survey done with UK pilots flying Boeing 757 airplanes. Underreporting here was at about 4%. In other words, there were 25 times more cases than being reported.

5.6 events per 100000 flights can be estimated (Anderson 2019). This is more than one event in 20000 flights. If underreporting is considered with 10% (instead of 4%), we would need to **expect one cabin air contamination event every 2000 flights**.

Distribution of Cabin Air Contamination Events (CACEs) over Aircraft Types



Number of CACE due to oil, bleed air, or hydraulic fluid retrieved from FAA's Service Difficulty Reporting System for four (non-COVID) years 2018, 2019, 2022, and 2023 per aircraft type (in total 3167 CACE) in percent, compared to the number of aircraft of the type in the US fleet (in total 7808 aircraft) in percent. Listed are the top eight aircraft types (and others). Also given the number of CACE for each aircraft type per 100 aircraft per year. The A320 family is highly overrepresented. Among the other aircraft types the MD80 family shows an elevated number of CACE. Based on data from Anderson (2024).

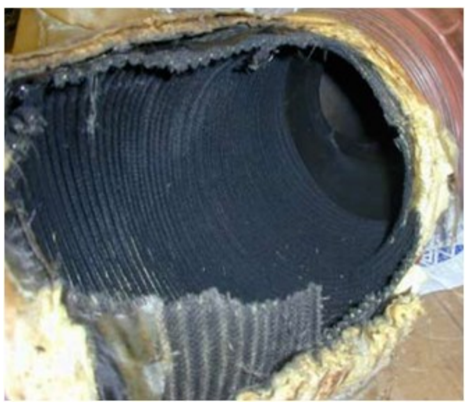
How Do We Know about Oil in the Cabin?

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 carbron concentrations in the cabin can be calculated and agree with measurements

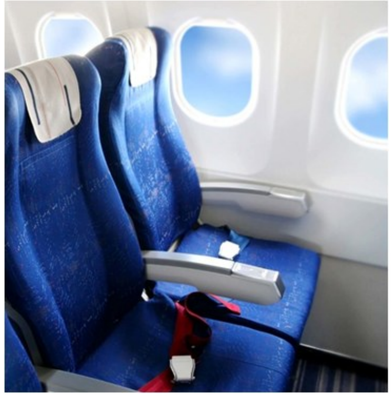
Evidence collected in Scholz 2017 and Scholz 2019 summarized here:

1. (GCAQE 2017)



2. (CAA 2004)

3. (Eckels 2014)

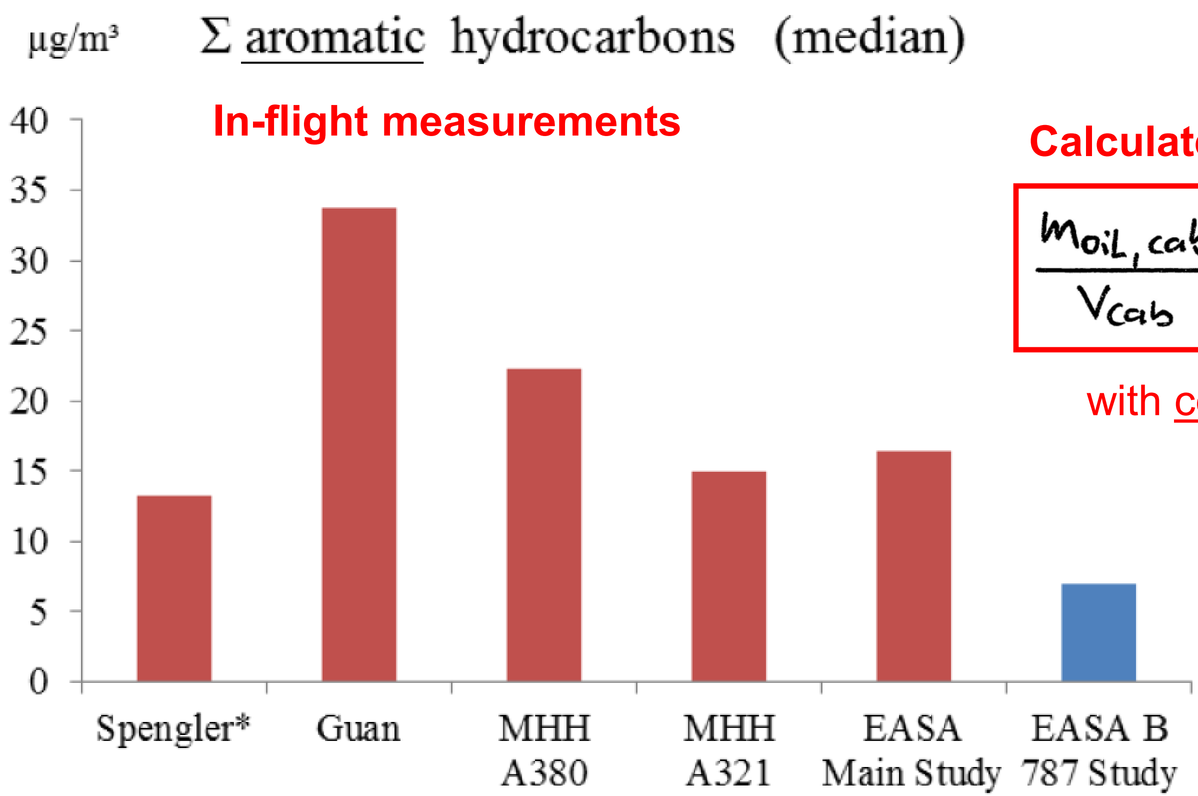


4. (Lamb 2012, Solbu 2011)

5. (Scholz 2017)

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

Example Calculation Compared with Measurements



Calculated:

$$\frac{m_{oil,cab}}{V_{cab}} = 17 \ \mu g/m^3$$

with <u>conservative</u> estimate:

x_{seal} = 1 %

Σ aromatic hydrocarbons, comparison of different studies (median);
* highest values from three investigated airlines

(EASA 2017)

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**."

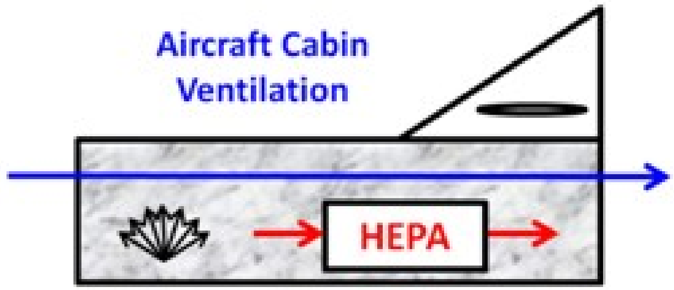
Introduction

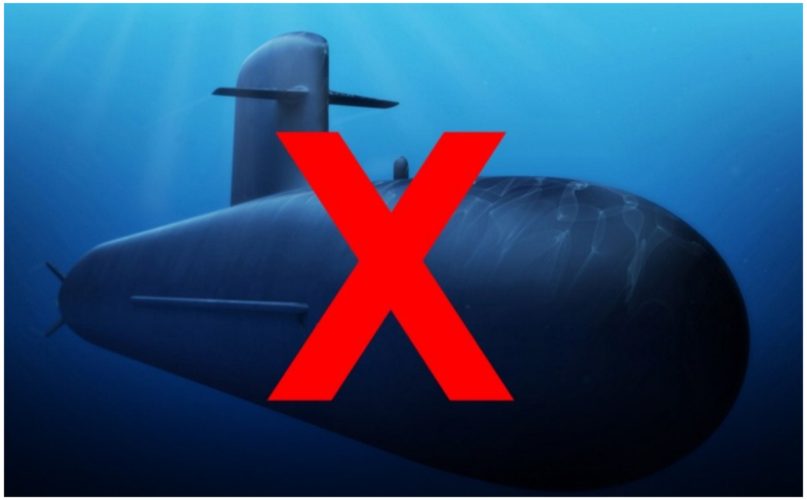
Nevertheless,
it is claimed:

https://perma.cc/686X-X9AZ

Air Conditioning System

Boundary Conditions





- **Atmospheric conditions**
  - Oxygen content: 21%; independent of altitude.
  - Pressure: 22% of sea level pressure.
  - Temperature: -56 °C.

- **Aircraft is not a submarine.**
  Aircraft is open to the environment to draw air.
  - Outside ("fresh") air can be used, but needs to be compressed. This requires energy.
  - Compression delivers very high temperatures (based on thermodynamics).
  - Cooling is necessary
    1.) to get the temperature down to normal levels
    2.) to cool the cabin, because the cabin experiences net heating due many passengers, system inefficiencies converted into heat, ...

Requirements

- **Ventilation**
  - "the ventilation system must be designed to provide a **sufficient amount** of uncontaminated air" "to provide each occupant with an airflow that contains at least **0.25 kg of fresh air** [outside air] **per minute**" CS-25.831(a) "i.e. 10 cubic feet per minute of air at 8000 feet pressure altitude and at a cabin temperature of 24 °C" AMC 25.831(a)(1)
  - "Where the air supply is supplemented by a **recirculating system**, it should be possible to stop the recirculating system and –
    a. Still maintain the fresh air supply prescribed, and
    b. Still achieve 1 [avoid contamination]." AMC 25.831(c)
  - "Each passenger and crew compartment must be ventilated ... to enable crewmembers to perform their duties **without undue discomfort or fatigue**." CS-25.831(a)
  - "Crew and passenger compartment air must be **free from harmful or hazardous concentrations of gases or vapours**." CS-25.831(b)
  - CO, CO2, ozone concentration limits are given, but not for other substances. This does not mean that other substances are allowed in any concentration (BFU 2014) "The BFU is of the opinion that a product [aircraft] which has received a type certificate by EASA should be designed in a way that neither crew nor passengers are harmed or become chronically ill." (BFU 2014)

Requirements

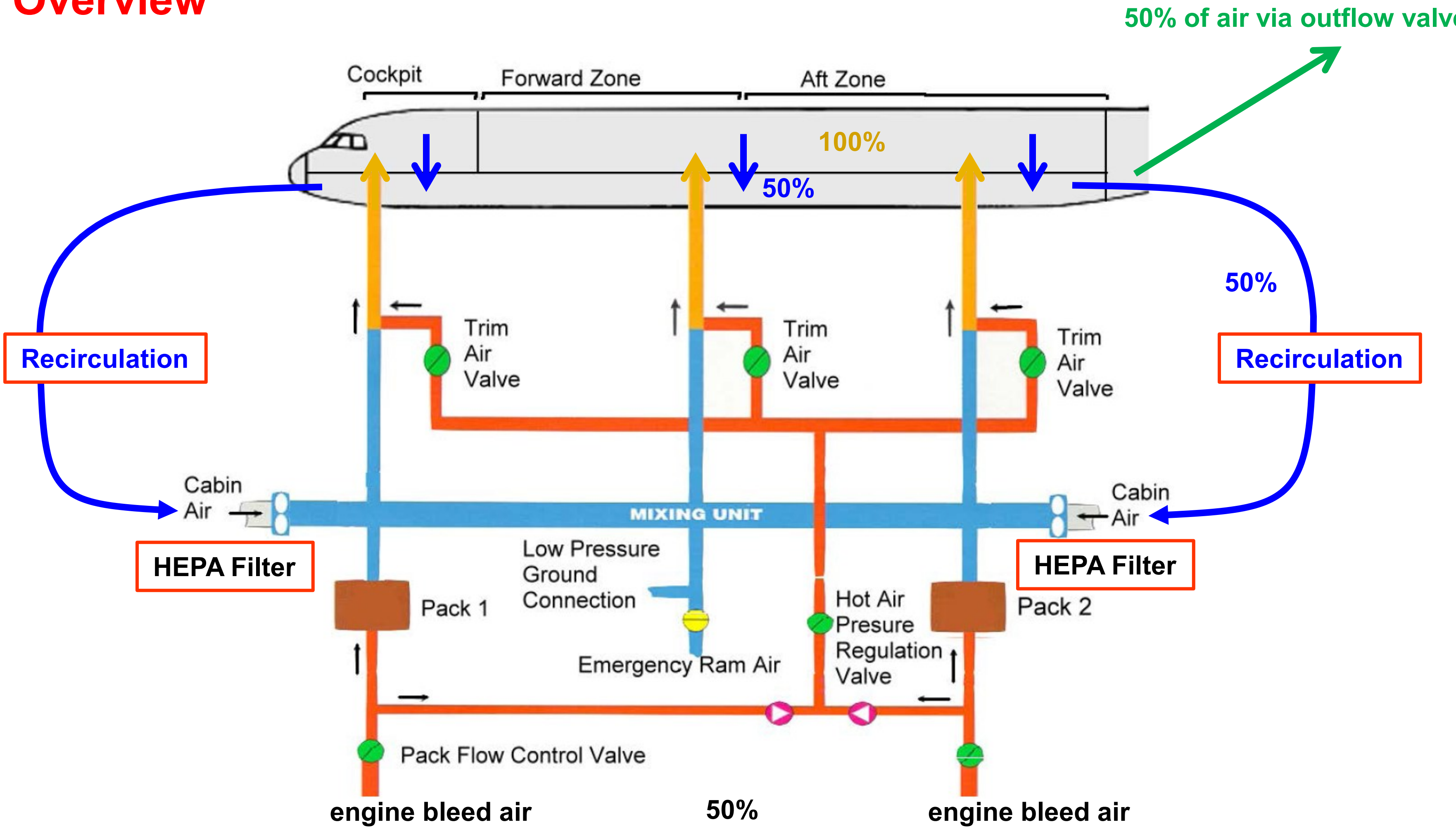
- **Temperature Control**
  - Cabin air temperatures are not defined in CS-25.
  - Temperature control is done by ventilation with (in most cases) cold air.
  - Recirculation allows to use "more air" at temperatures "not as cold" as required with less air.
  - Hence, recirculation
    - allows a more even temperature distribution in the cabin,
    - avoids cold drafts near passengers and increases cabin comfort.
  - "More air" (than required) could also be obtained from outside, but ...
    - outside air needs to be compressed (to cabin pressure), which requires more energy.
    - recirculated air only needs to be pumped (against pressure losses in tubes); it saves engergy.
  - Recirculated air spreads air among all passengers (unlike outside air), hence need of filtration.
- **Pressure Control**

  "provide a cabin pressure altitude of not more than 8000 ft" CS-25.841(a)
- **Moisture Control**

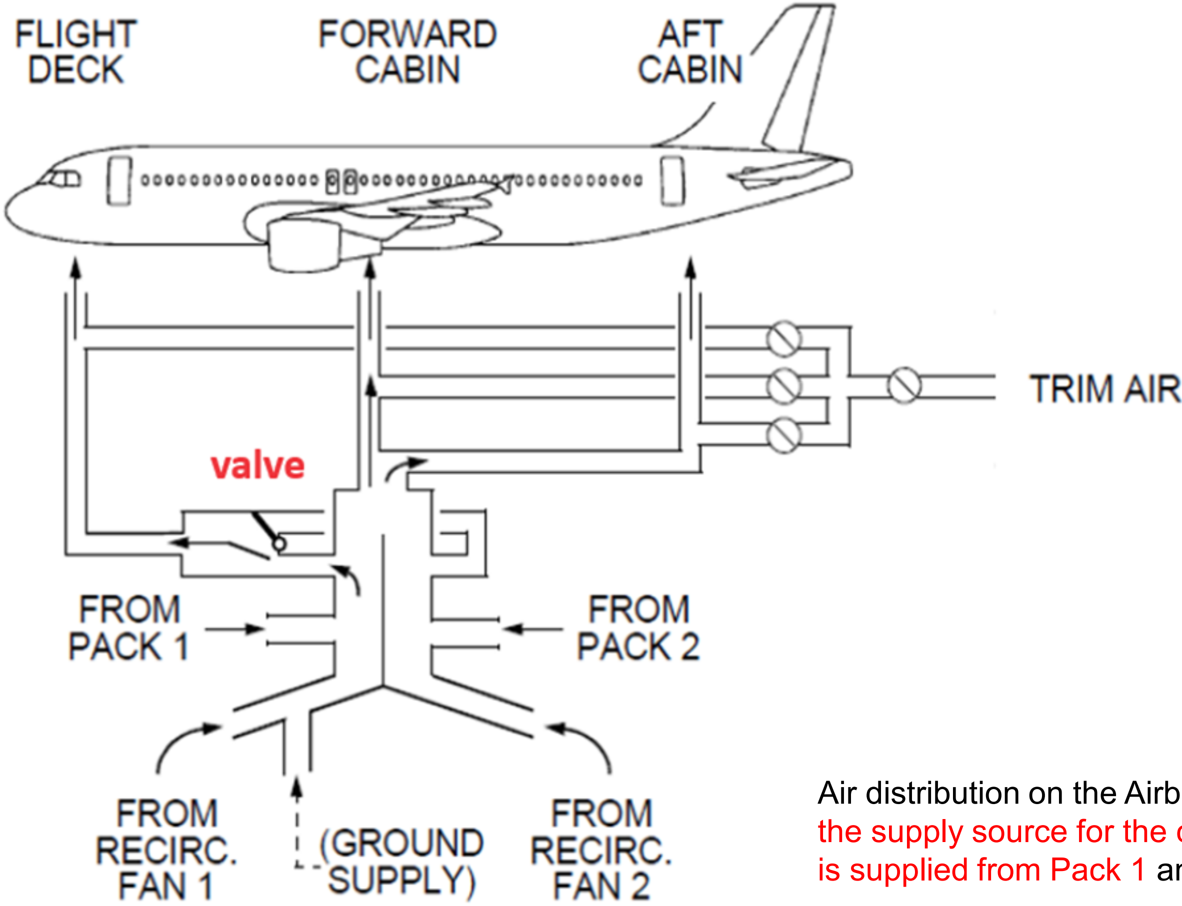
  No requirements

Requirements related to pressure and moisture control are not further detailed.

Overview

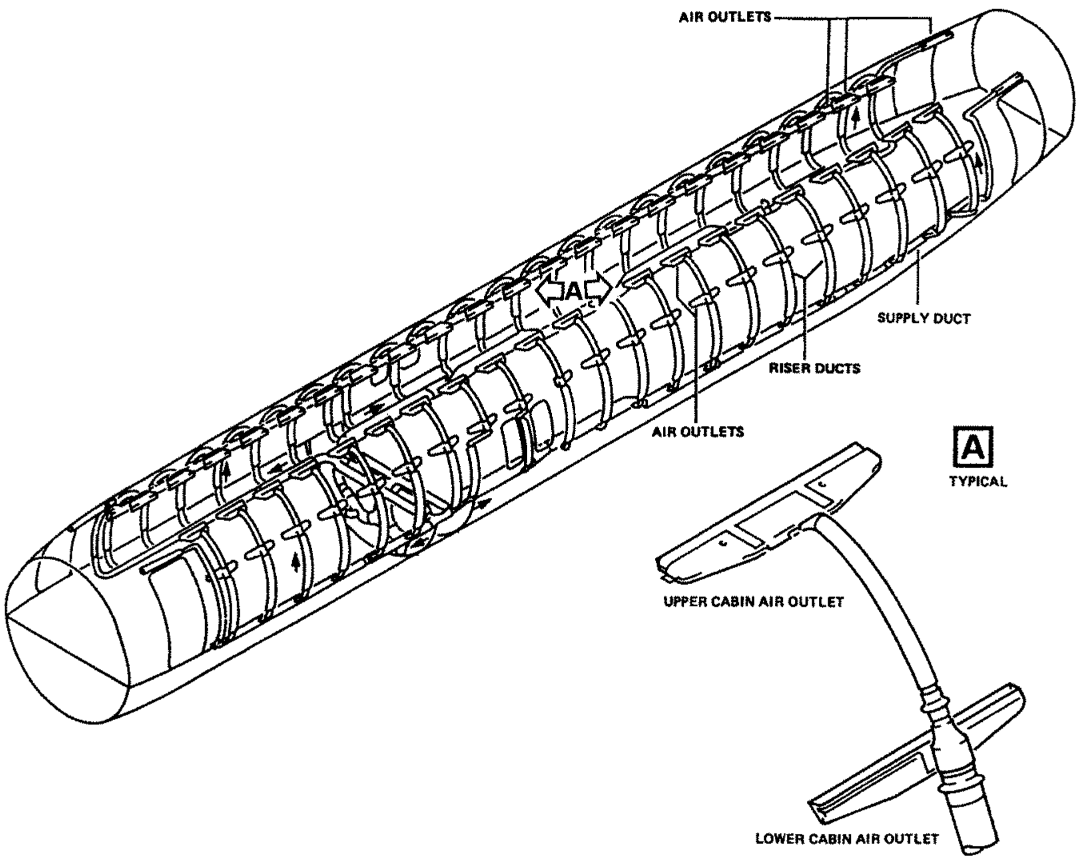

50% of air via outflow valve
Cockpit
Forward Zone
Aft Zone
100%
50%
50%
Recirculation
Recirculation
Trim
Air
Valve
Trim
Air
Valve
Trim
Air
Valve
Cabin
Air
Cabin
Air
MIXING UNIT
HEPA Filter
HEPA Filter
Low Pressure
Ground
Connection
Pack 1
Pack 2
Hot Air
Presure
Regulation
Valve
Emergency Ram Air
Pack Flow Control Valve
engine bleed air
50%
engine bleed air

Air Distribution Into the Cockpit on the Airbus A320: From Pack 1



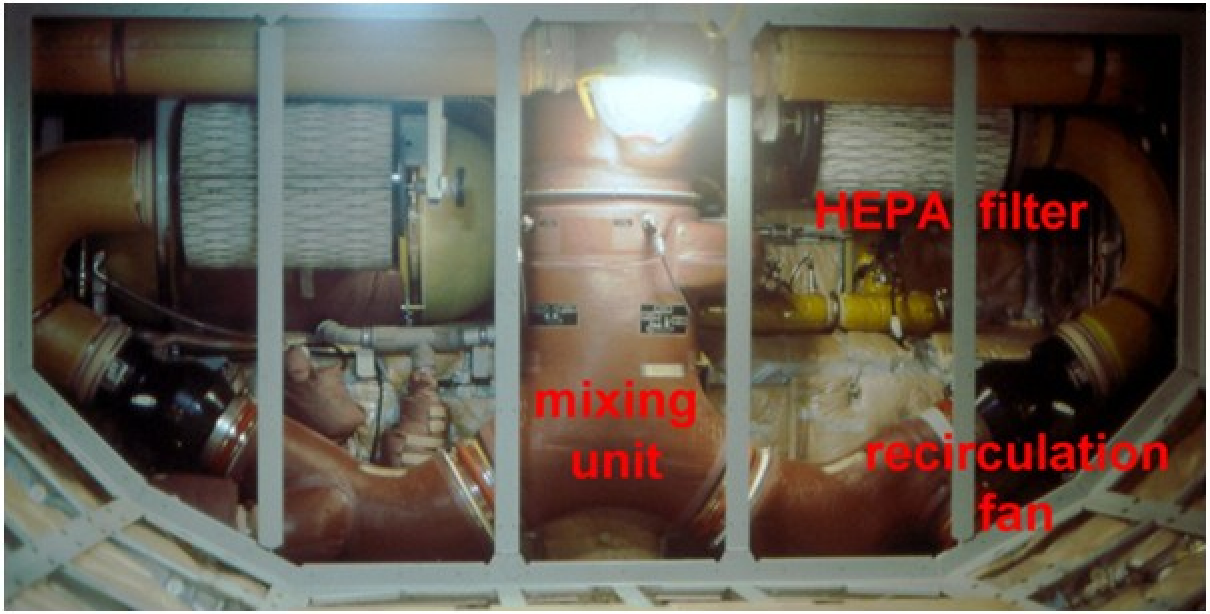
Air distribution on the Airbus A320 (Stein 2019). A valve selects the supply source for the cockpit. In normal operation the cockpit is supplied from Pack 1 and Recirculation Fan 1.

Air Distribution – Supply and Riser Ducts

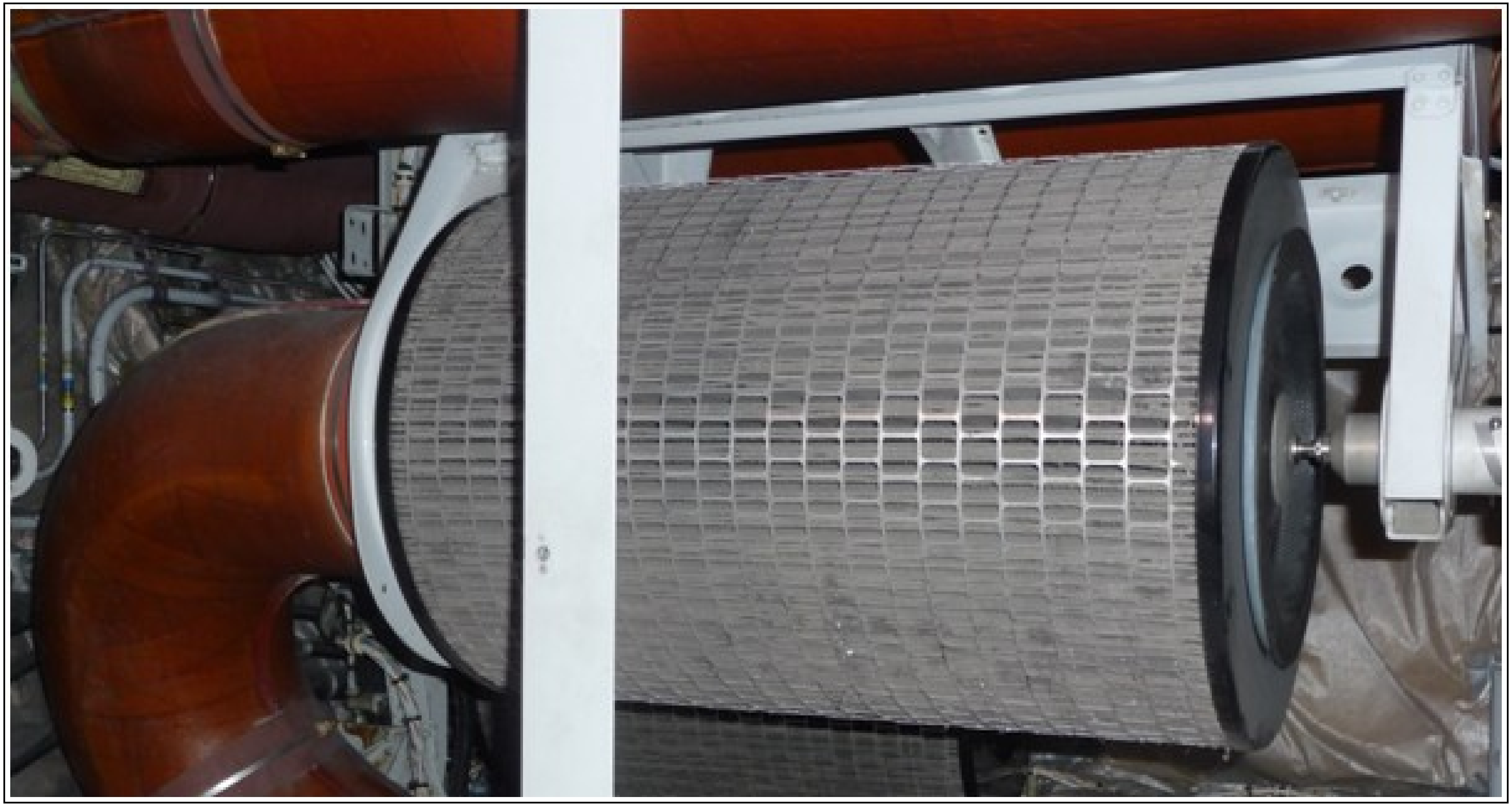


Scholz 2000

Mixing Unit, HEPA Filters, Recirculation Fan



HEPA Filter



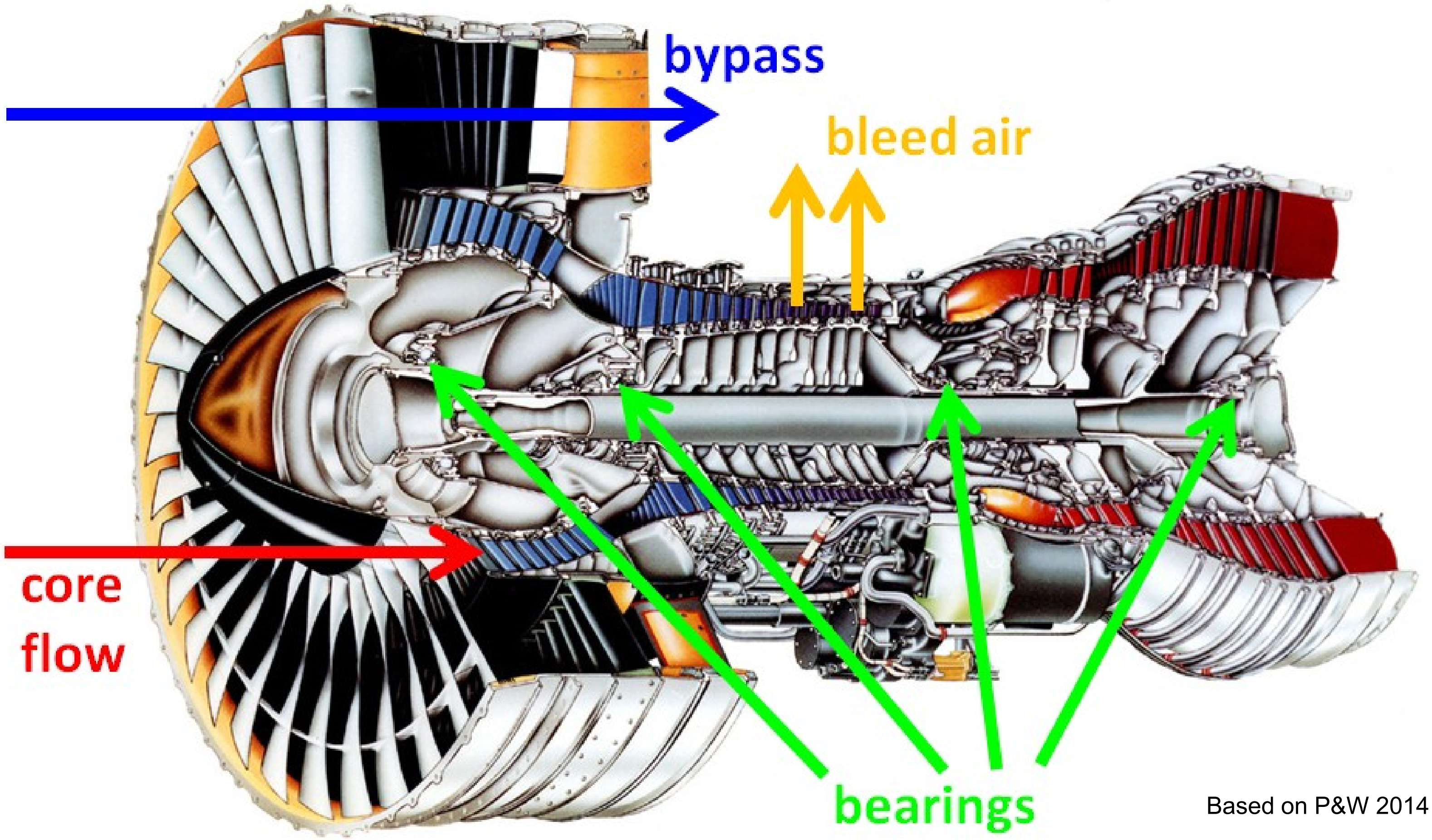
Air Conditioning System

HEPA Filter

A380, Emirates

Jet Engine Technology

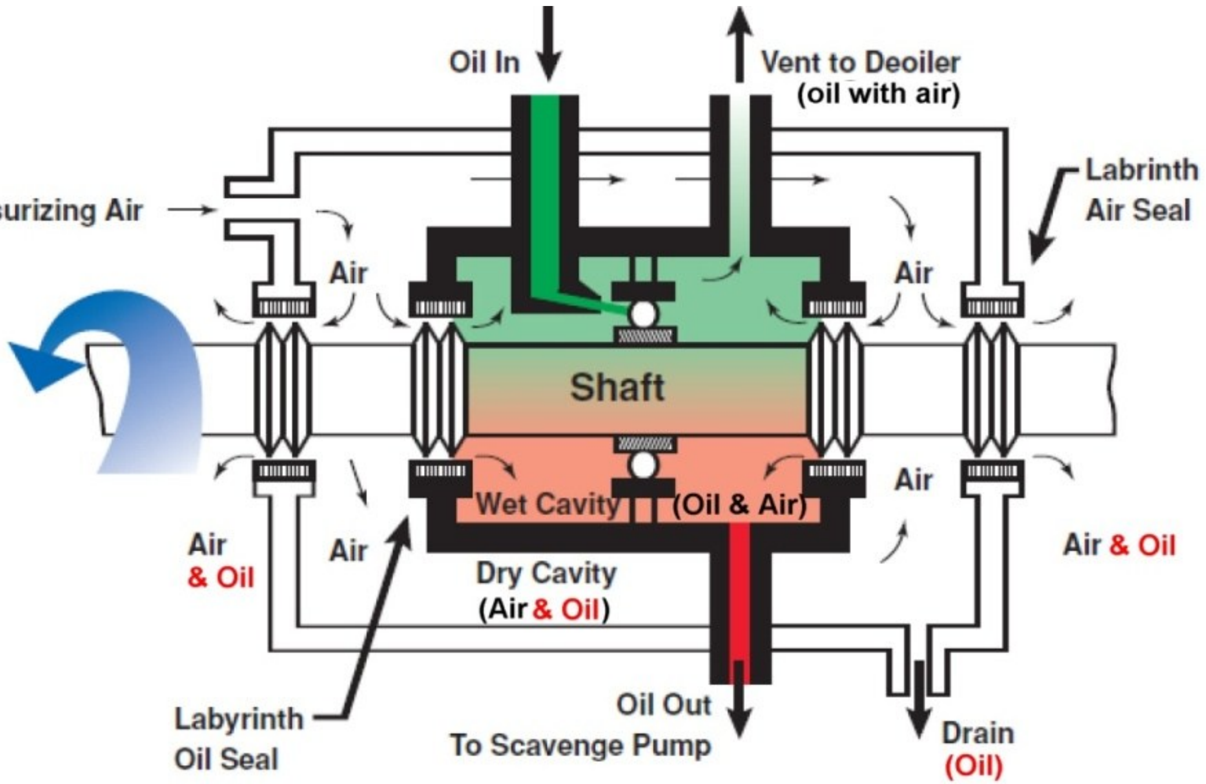
Engine Bearings and Bleed Air



Based on P&W 2014

Jet Engine Technology

Lubrication and Sealing of Engine Bearings



Based on Exxon 2017

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!**

Metal Particles

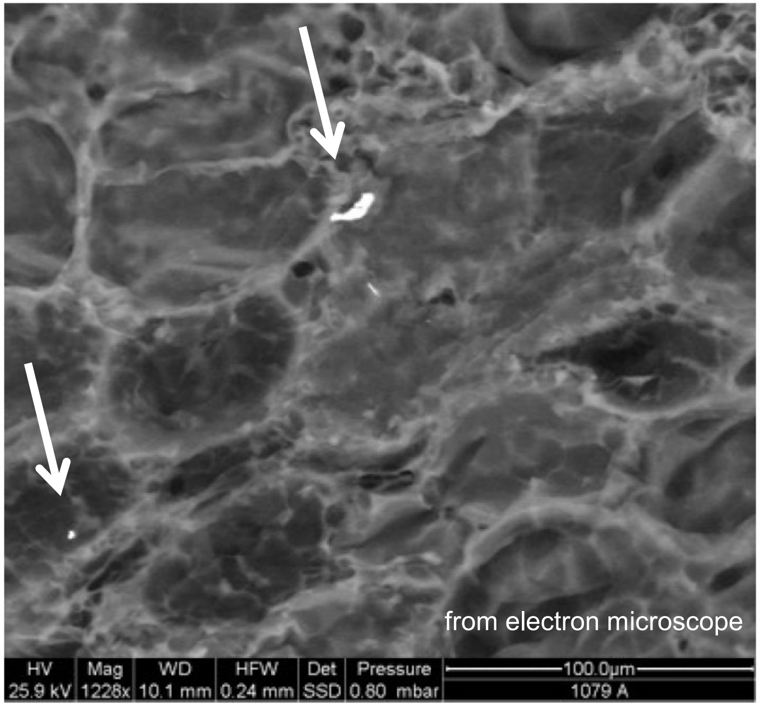
Used Oil Analysis for Metal Particles

- 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:
- Catastropic 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 μm and 5 μm.
- 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.

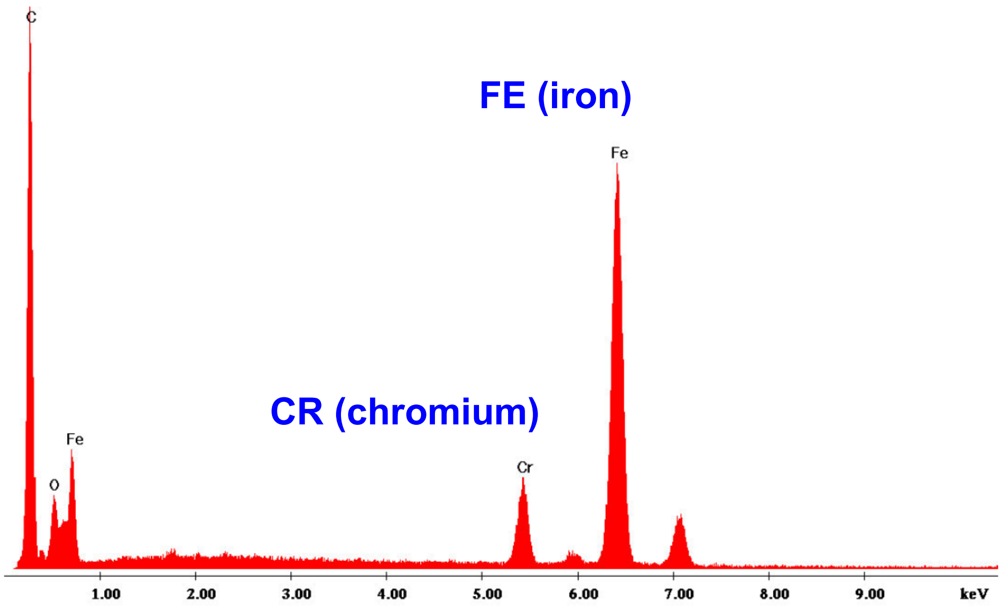
- **Metal micro and nano particles can leave the engine together with the oil into the cabin!**

Partially based on Exxon 2016b

Metal Nanoparticles in the Oil – Finally in Human Fatty Tissue of Aviation Employees



(Gatti 2019, report written for client)

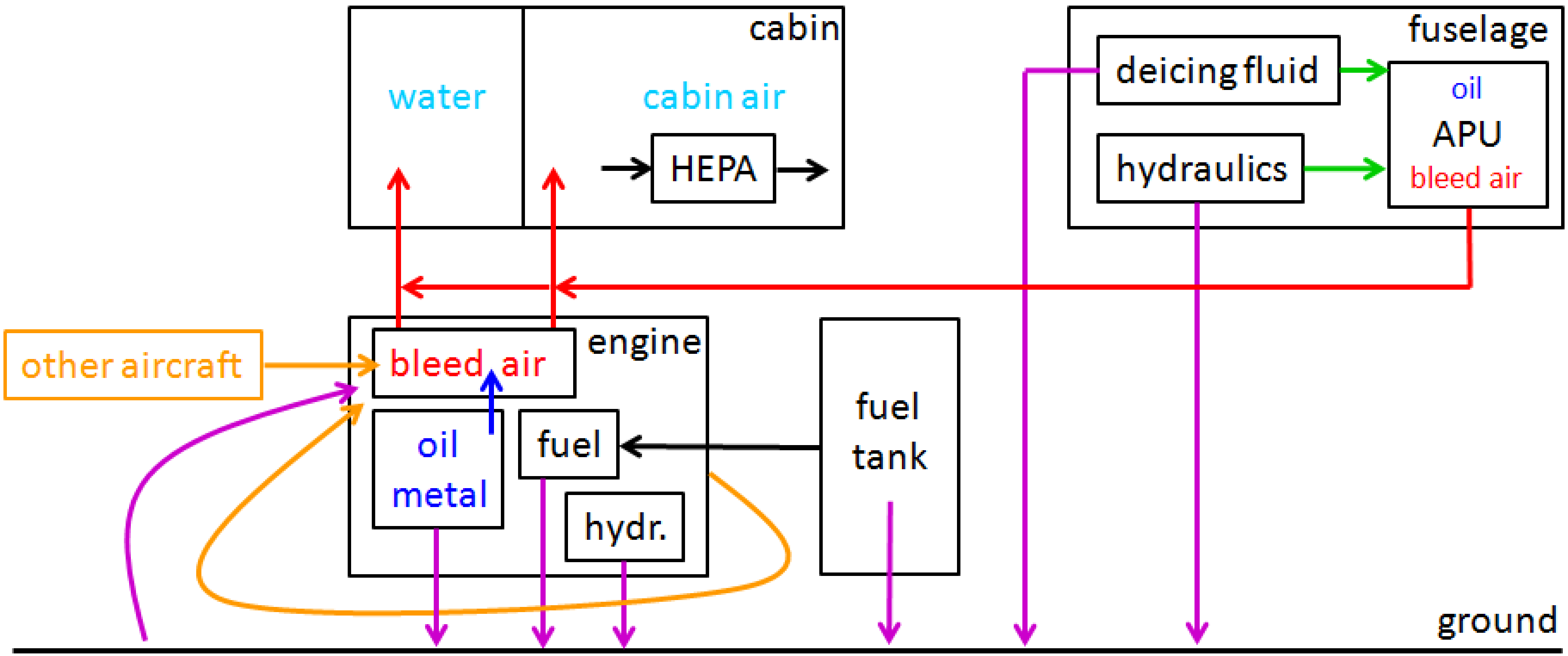


Analysis 8 of Table I. High-magnification image (1228x) and EDS spectrum of 10-micron and 1-micron brighter-looking particles composed of Carbon, Iron, Chromium and Oxygen: a stainless-steel composition. EDS: Energy-Dispersive X-ray Spectroscopy.

Distribution of Engine Oil with Metal Nanoparticles

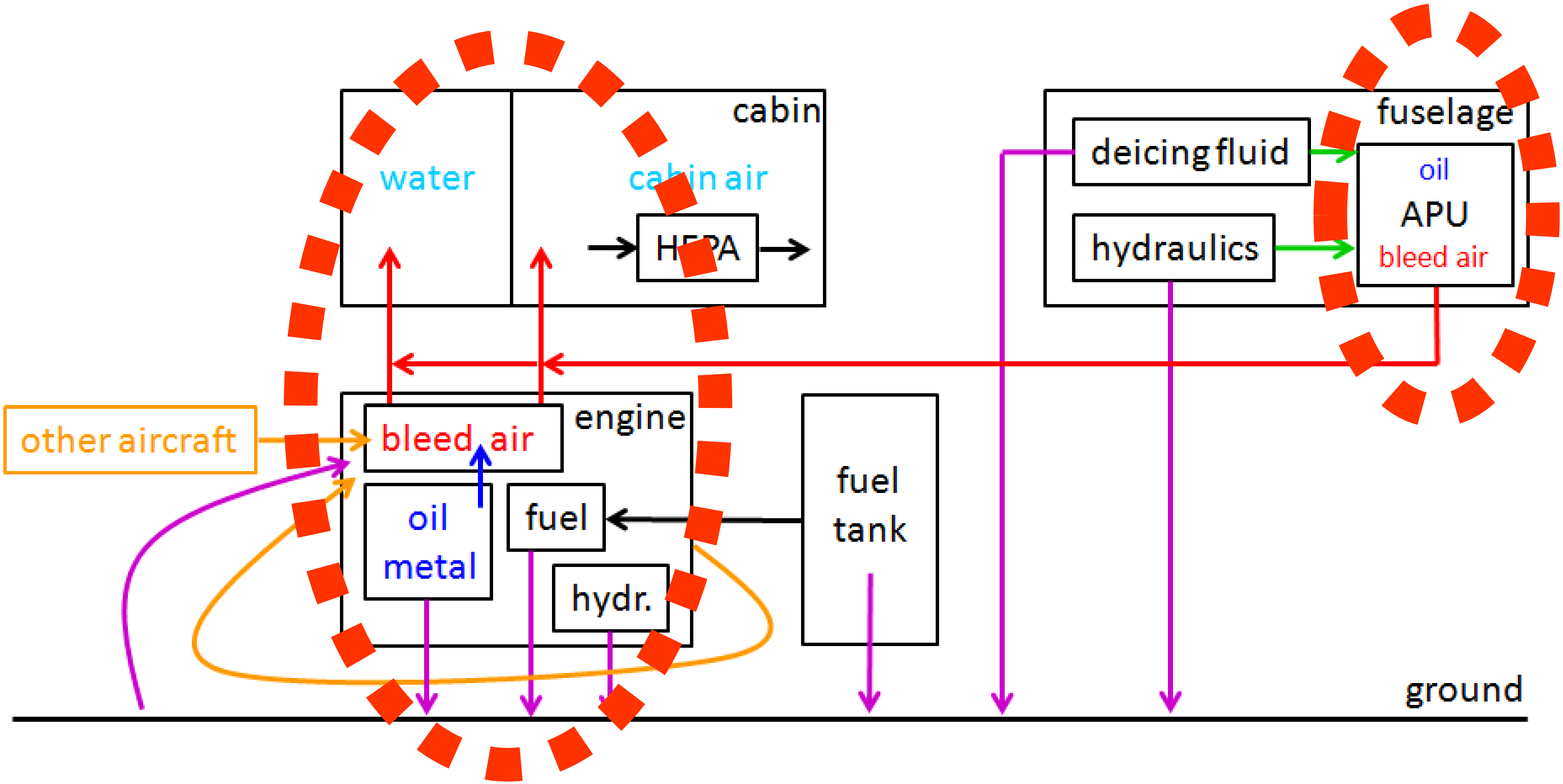
Distribution of Engine Oil with Metal Nanoparticles

Contaminants and Their Routes Into the Cabin



Distribution of Engine Oil with Metal Nanoparticles

The Route of Engine Oil Into the Cabin



Distribution of Engine Oil with Metal Nanoparticles

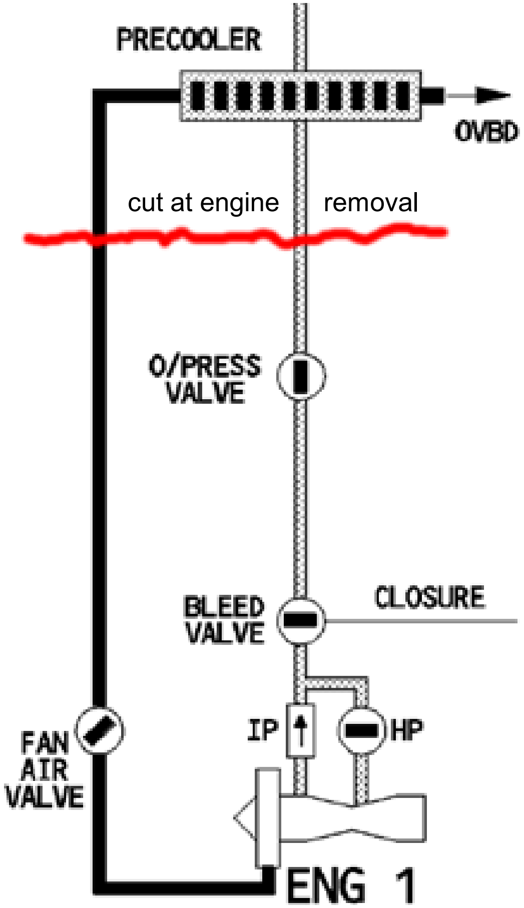
Engine Oil in the Potable Water

Potable water contaminated by bleed air on an Airbus A320. The last water extracted from the tank before it is empty is black, probably from engine oil residue.

Picture source:
Video: https://youtu.be/dlPOeudTTCI.
The video explained:
https://purl.org/CabinAir/WaterContamination.

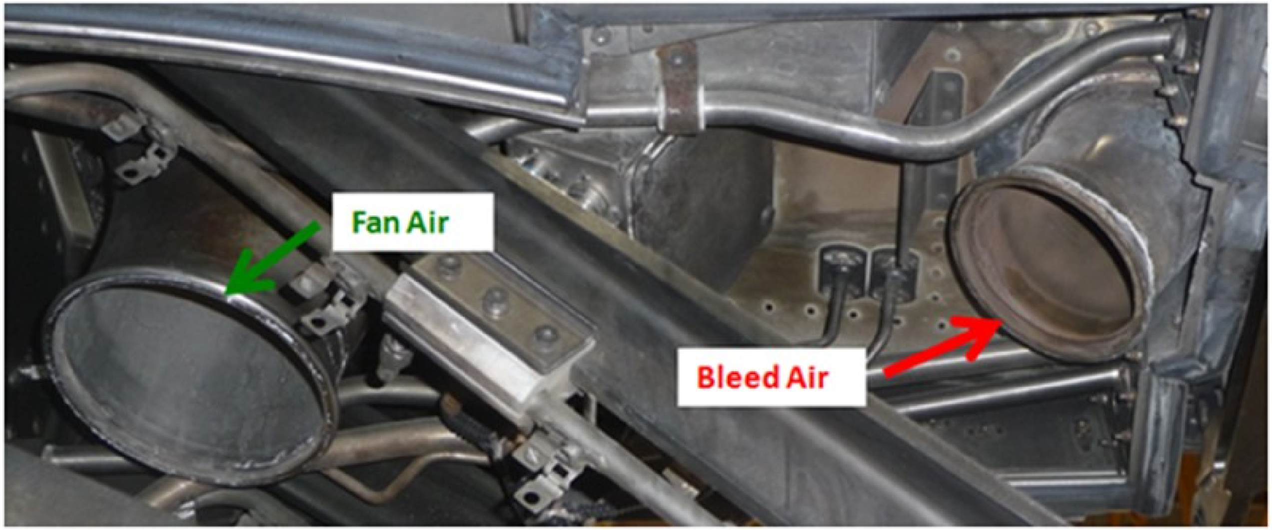
Distribution of Engine Oil with Metal Nanoparticles

Engine Oil Colors Bleed Air Duct Brown



Airbus A320 FCOM

Fan air and bleed air ducts at the interface between engine and wing on an Airbus A320. The brown stain in the bleed air duct appears to be engine oil residue. In comparison, the fan air duct is clean. Air temperature in the bleed air duct about 400 °C.



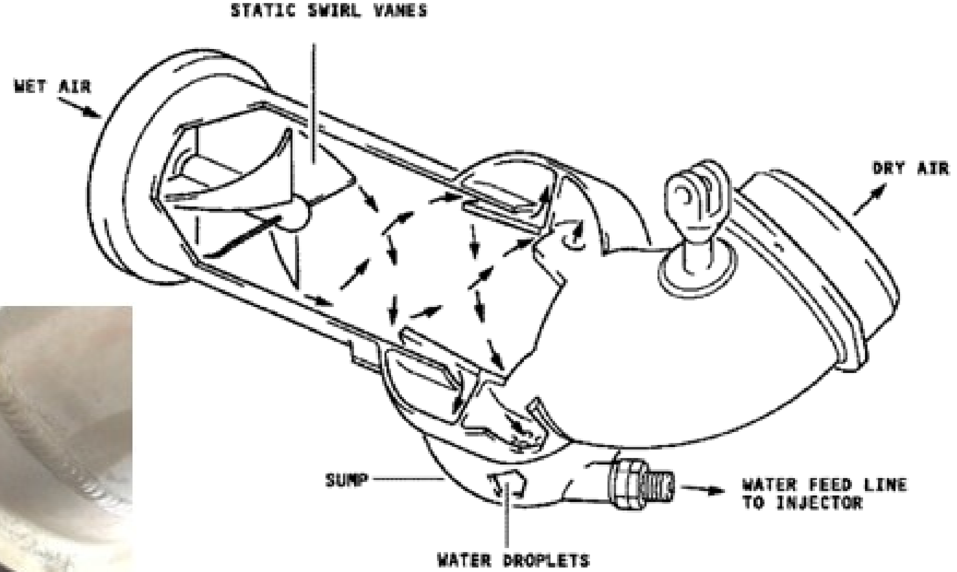
Distribution of Engine Oil with Metal Nanoparticles

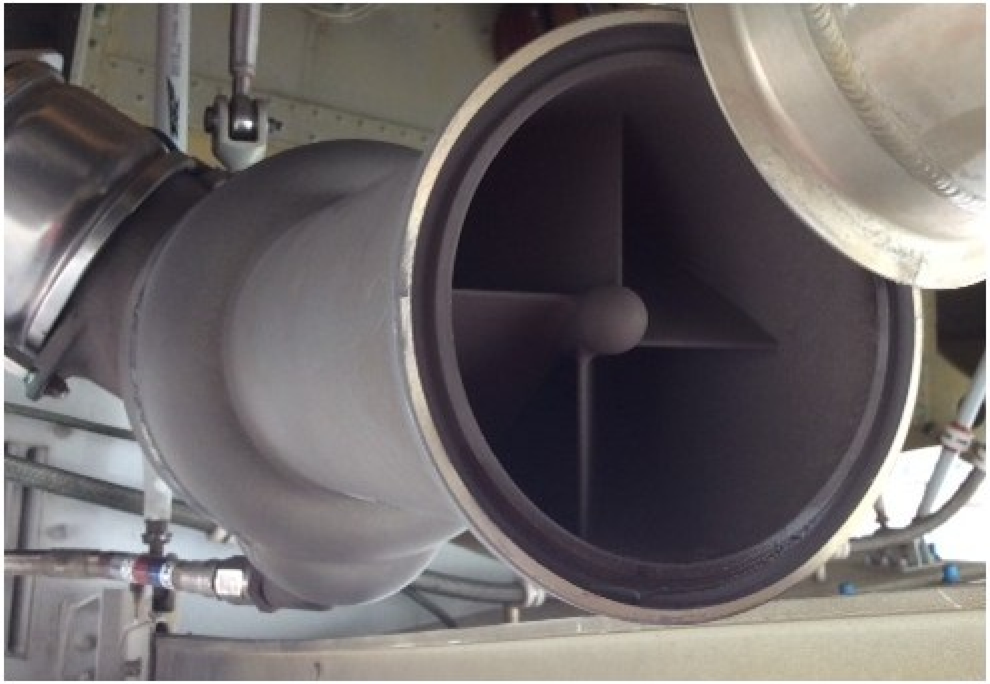
Engine Oil Colors Bleed Air Duct Black

Bleed air duct of a Boeing 737 with black oil residue inside. Air temperature of about 200 °C.
Picture source: **Video**: https://vimeo.com/groups/617439/videos/345959025

Distribution of Engine Oil with Metal Nanoparticles

Engine Oil Residue Accumulates in Water Extractor





The Airbus A320 water extractor (Airbus 1999), is a part of the air conditioning pack. The inlet of the water extractor is covered with black oily residue.

Distribution of Engine Oil with Metal Nanoparticles

Engine Oil Colors Cabin Air Duct Black

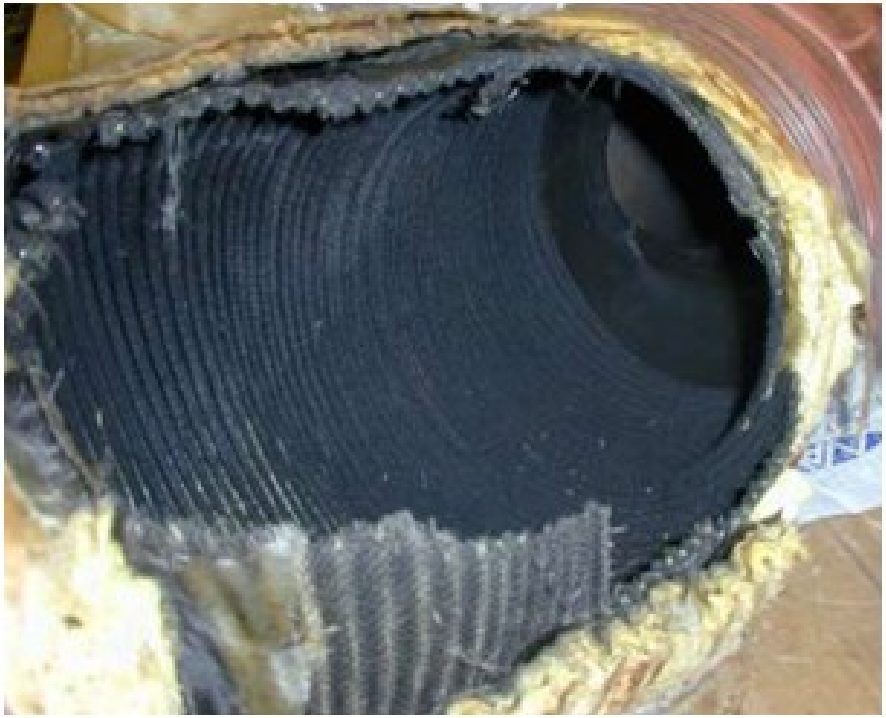
Airbus A320 air conditioning air distribution duct in the cabin. The inside is black from contaminated bleed air.

Air Duct Is Clean at End of Life of an Aircraft, if Not Fed With Bleed Air

The inside of the air extract duct (located near the extract fan) is clean at the end of life of an Airbus A320, because the duct is normally not fed with bleed air.

Distribution of Engine Oil with Metal Nanoparticles

Engine Oil Colors Cabin Air Duct Black



Left: An unused duct supplied new.
Right: A ducts that had been installed downstream of the environmental control system air conditioning packs on a BAe 146 passenger aircraft after 26061 flight hours (CAA 2004).

Distribution of Engine Oil with Metal Nanoparticles

Flow Limiter in Air Conditioning Ducts

Flow limiter clogged from pyrolysed engine oil in ducts of the air conditioning system of Boeing 757 aircraft with Rolls-Royce RB211-535E4 engines operated by Icelandair (Hansen 2019) compared to a clean flow limiter (top).

Distribution of Engine Oil with Metal Nanoparticles

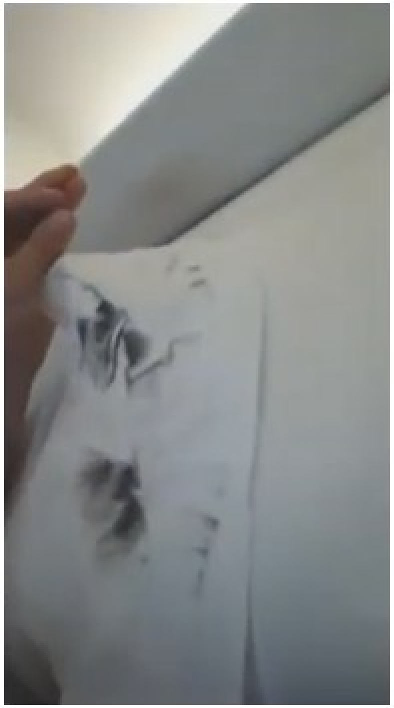
Engine Oil Colors Riser Ducts Black

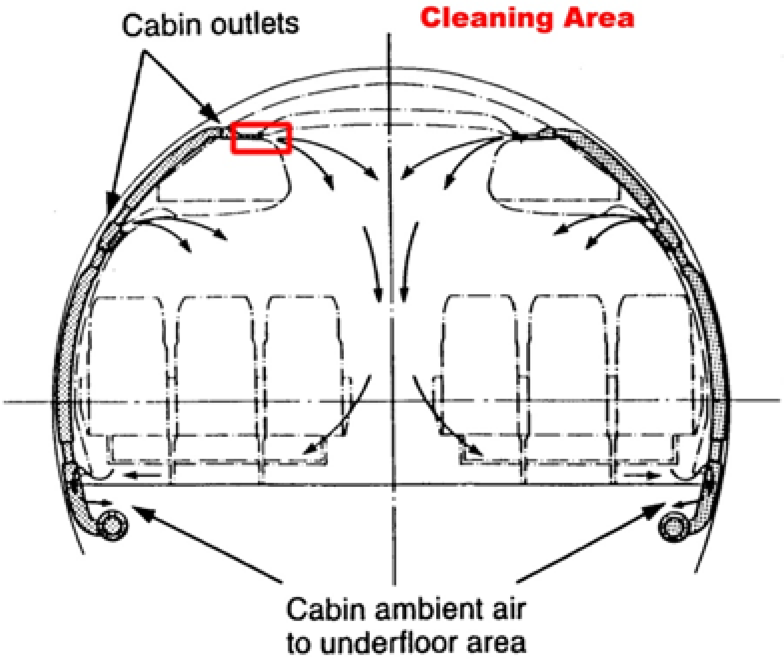
Video: https://bit.ly/2YXcL3a

Riser ducts and lower cabin air outlet on an Airbus A320 aircraft. The red line close to the cabin floor shows, where the duct was separated and opened. It is black inside from engine oil residue.

Distribution of Engine Oil with Metal Nanoparticles

Black Residue Settles on the Overhead Bin's Surfaces



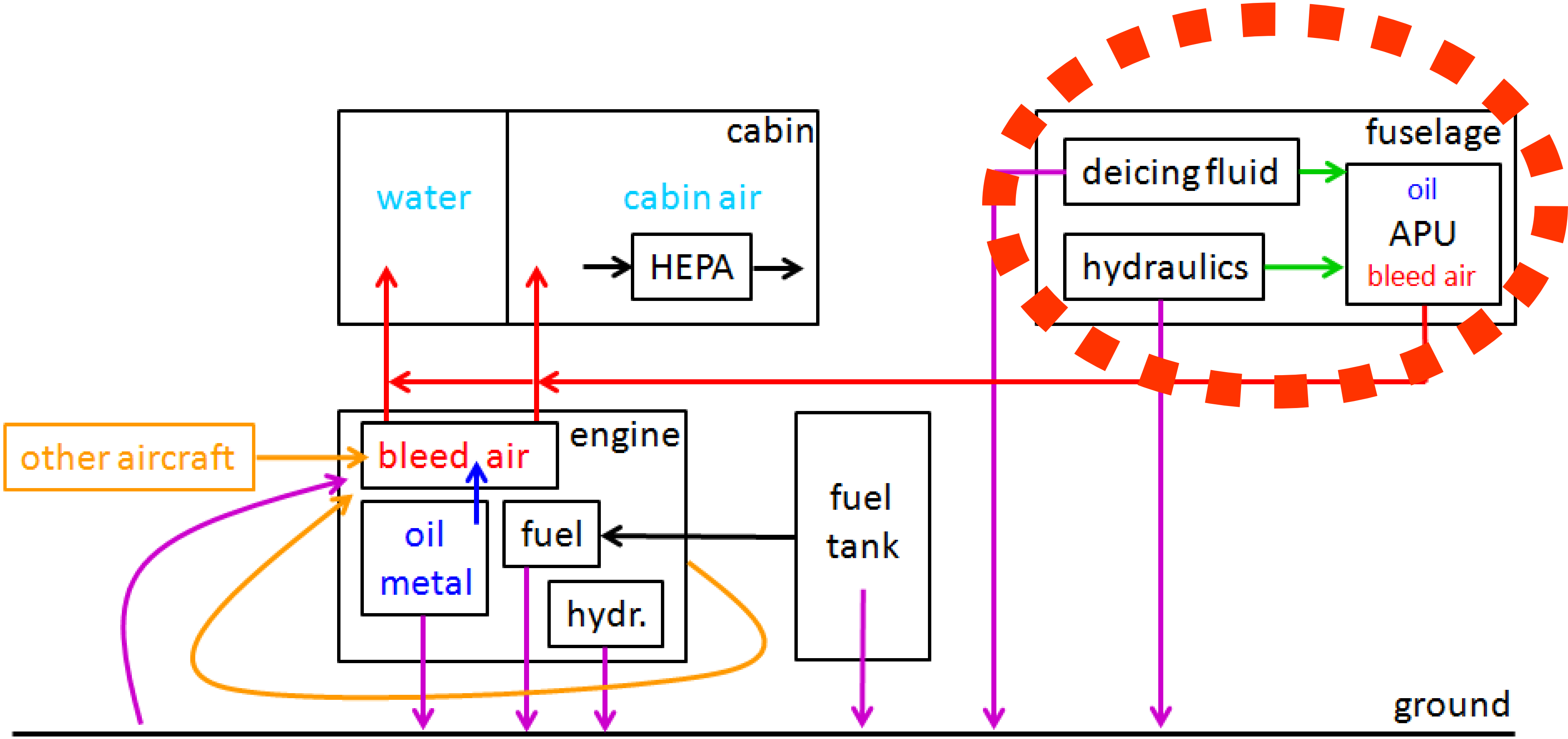


Left: Cleaning on top of the overhead bins of an Airbus A320 brings to light dirt that is clearly more than dust. The black residue known from the ducts settles also on the bin surface. Picture source: **Video**: https://youtu.be/uQfA_DiMBS8
Right: Airbus A320 cabin cross section with the upper cabin air outlet releasing potentially contaminated air on top of the overhead bins (Airbus 1999).

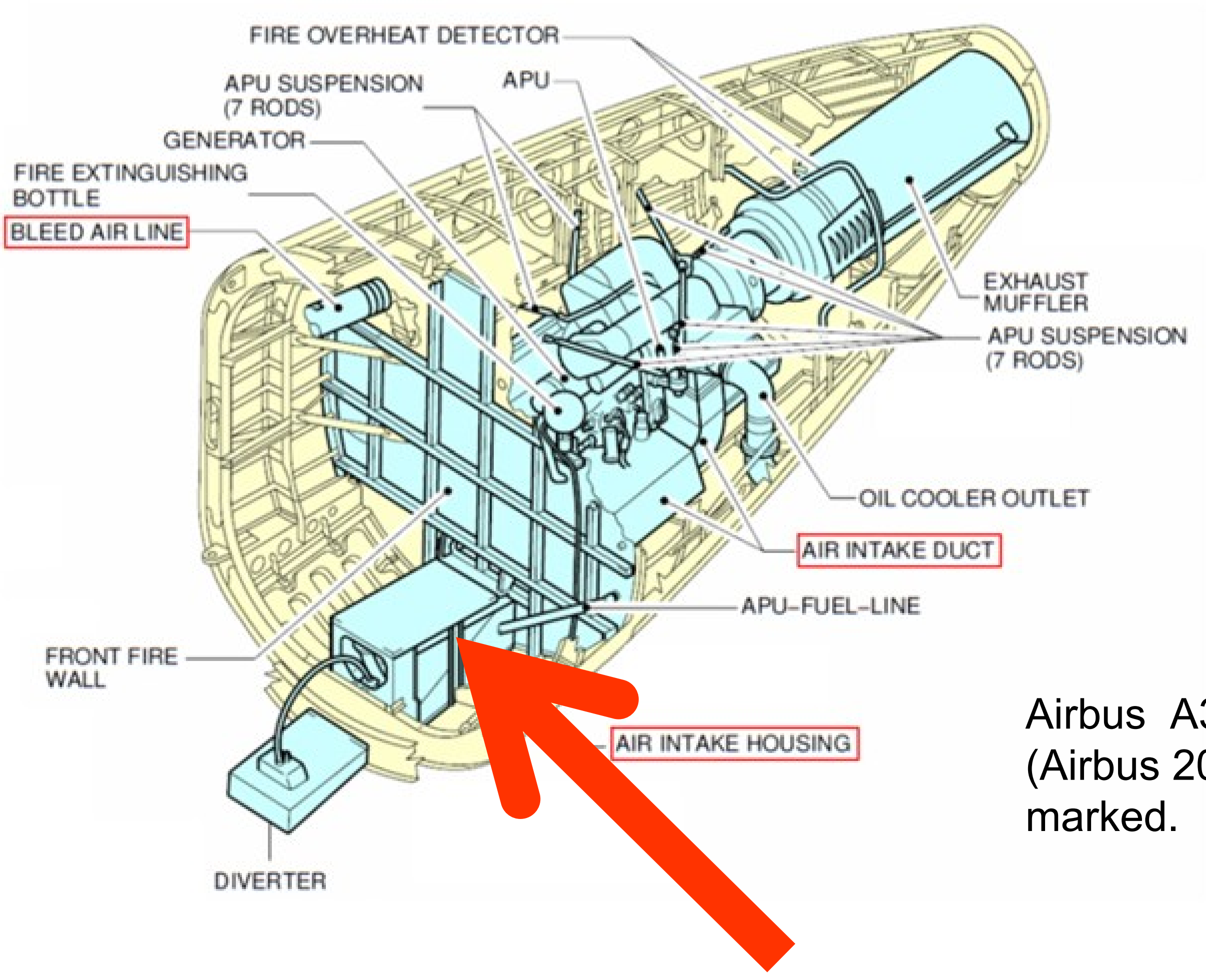
Distribution of
Hydraulic and Deicing Fluid

Distribution of Hydraulic and Deicing Fluid

The Route of Hydraulic and Deicing Fluid into the Cabin



APU Air Intake – Entry Point for Hydraulic and Deicing Fluid into the Cabin



Airbus A320 APU installation (Airbus 2020). The air intake is marked.

Distribution of Hydraulic and Deicing Fluid

APU Air Intake – Entry Point for Hydraulic and Deicing Fluid into the Cabin

Left: Air intake of the A320 APU. Fence and deflector around the APU air intake are clearly visible. These measures cannot fully prevent contaminants from entering the APU. Right: Traces of contamination are clearly visible on the lower part of the fuselage. Carried by the air flow in flight, the contaminants reach the APU inlet. Source of picture on the right: Airbus 2019.

Distribution of Hydraulic and Deicing Fluid

"Zero Leakage" of Hydraulic Systems Has Not Been Achieved

Mekanikong 2019b

Aft collector tank of the A320 hydraulic seal drain system. In this old Airbus A320, **all surfaces** in the landing gear bay **are covered with a layer of hydraulic fluid**. Dirt accumulates on the sticky surface. The hydraulic fluid is not confined to the inside of the hydraulic bay, but continues its journey on the lower side of the fuselage towards the APU inlet (previous page).

Distribution of Hydraulic and Deicing Fluid

Deicing Fluid Leaks from the Tail into the APU Inlet

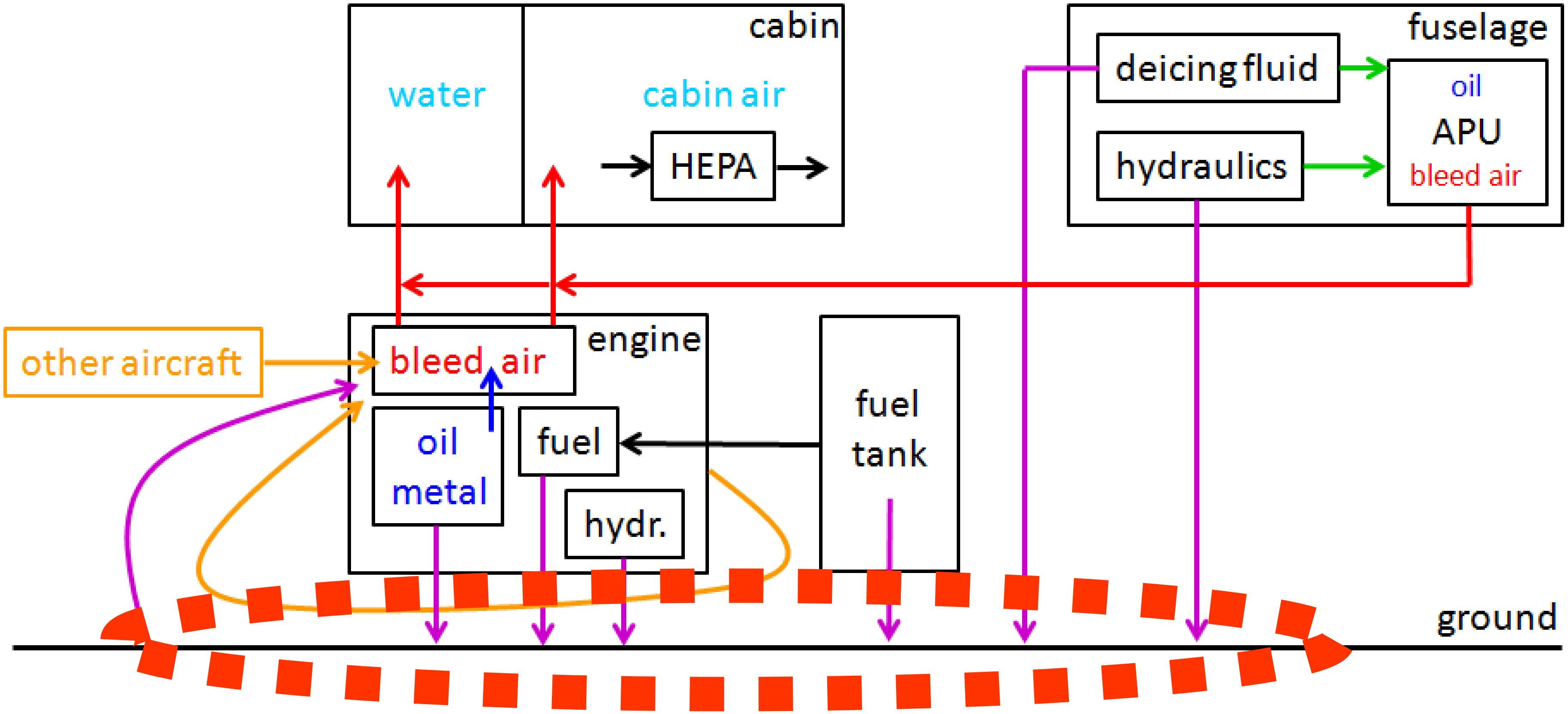
Vera-Barcelo 2013

Petchenik 2015

Distribution of
Fluids via the Airport Surface

Distribution of Fluids via the Airport Surface

The Route of Fluids Down to the Ground and Back into the Engine



Leak Limits of Aircraft Equipment (Example)

INSPECT/CHECK	MAXIMUM SERVICEABLE LIMITS
Oil	
The starter pad	7 drops/min
The AGB rear hydraulic pump pad	7 drops/min
The AGB fuel pump pad	7 drops/min
The lube unit pad	No leaks allowed
The main oil/fuel heat exchanger	7 drops/min
The AGB/IDG pad	7 drops/min
The forward sump	20 drops/min
The Aft sump (flooding drain)	Any amount, less than 20 drops/min after engine shutdown.
The Aft sump area	No leak allowed
INSPECT/CHECK	**MAXIMUM SERVICEABLE LIMITS**
Fuel	
The fuel manifold shroud	No leaks allowed
Fuel pump at the AGB drive pad	60 drops/min (up to 90 drops/min allowed for 25 cycles)

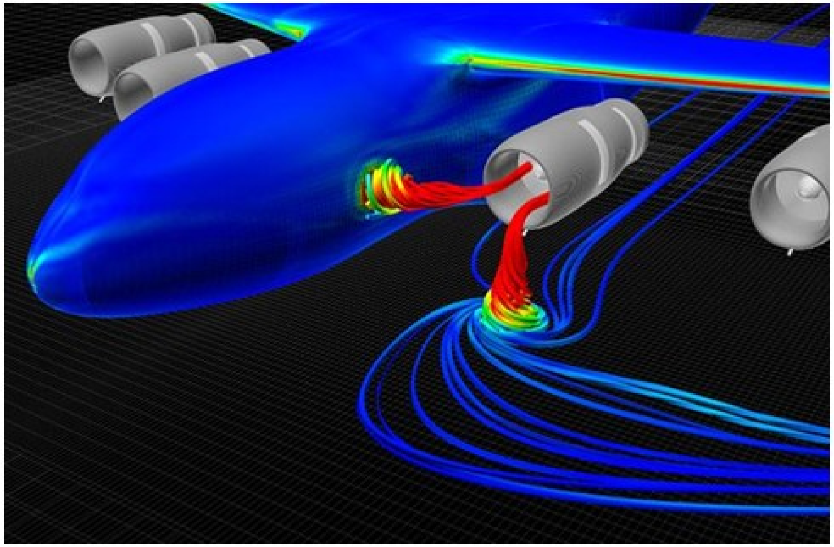
■ ■ ■

A320 leak limits for the CFM56-5B engine in drops per minute. Drops add up over time (Mekanikong 2019e).

AGB: Accessory Gearbox

Fluids Can Be Ingested by the Engine from the Ground

The ground vortex can also form between the ground and an engine on a high wing (Childs 2017).



Simulation of two intake vortices, one of them as a ground vortex. The rotation of the vortex is visible (https://perma.cc/VH99-87XS).

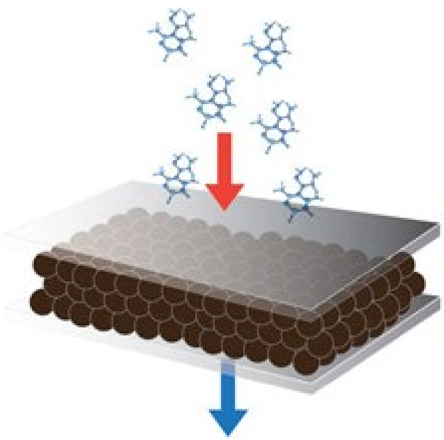
Filtration Systems

Filtration Systems

Filter in the Recirculation Path

Pall offers Odour/VOC Removal Filters

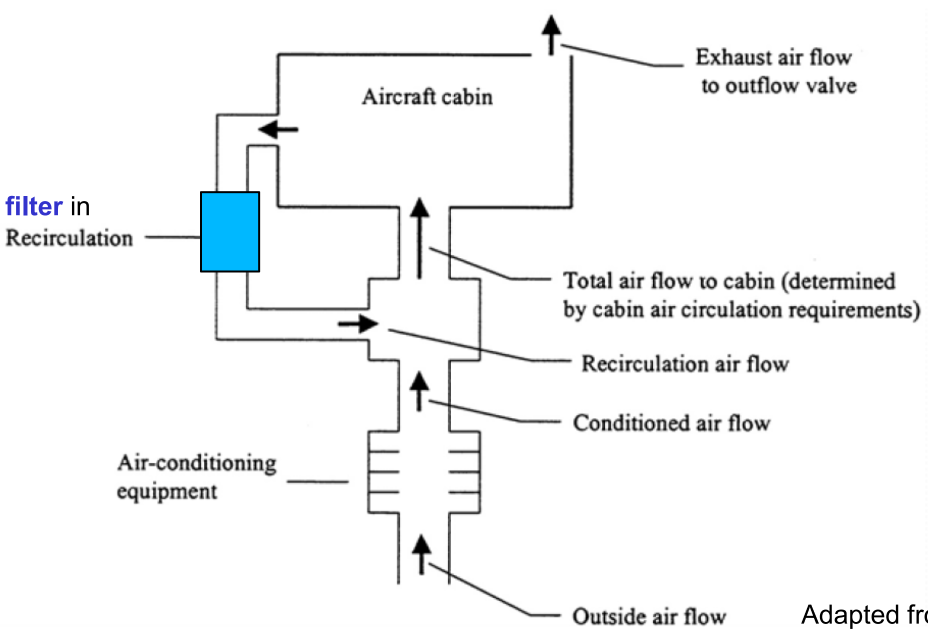
- "The carbon adsorbent is effective at adsorbing volatile organic compounds (VOC). Test results have shown a removal efficiency of 65% ... 73% when challenged with TCPs in the gaseous phase." (Pall 2011)



Schematic of carbon filter (Pall 2011)

Application of Carbon Filters

- HEPA-Carbon filters have been added to 33 A321 aircraft at Lufthansa Group so far. (Lufthansa 2017)
- These filters are located in the recirclulation path of the cabin air.

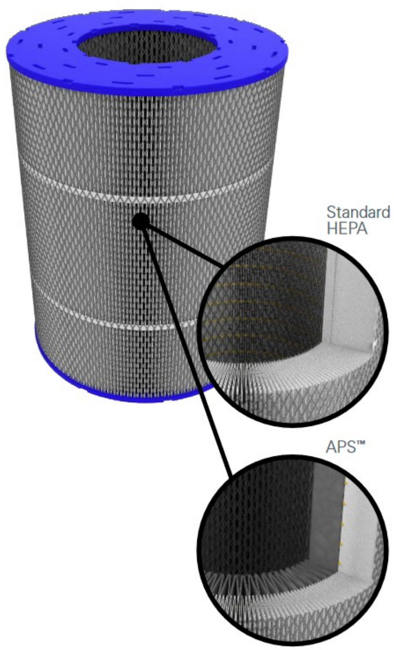


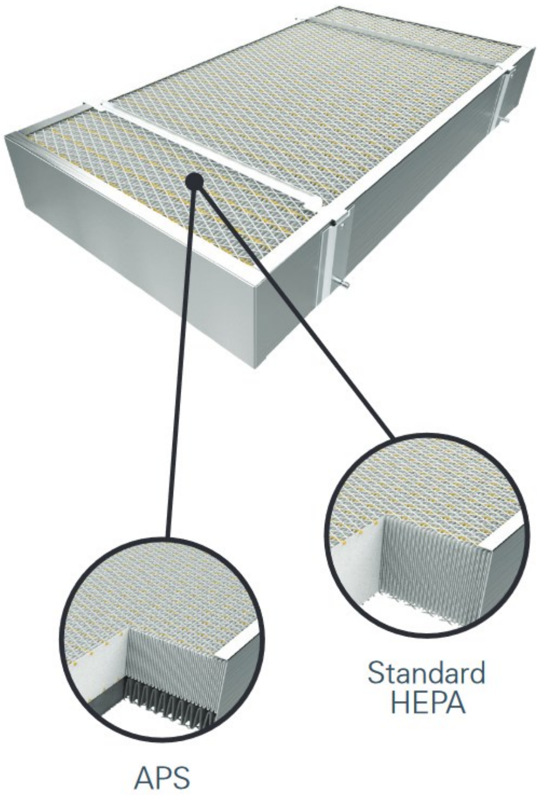
Adapted from (NRC 2002)

(Lufthansa 2017)

Filtration Systems

HEPA-Carbon Filters





Left: The HEPA-Carbon filter for the Airbus A320 from Pall (Pall 2024a). Right: The standards HEPA filter compared to the HEPA-Carbon filter "Air Purification System" (APS) for the Airbus A320 from Donaldson (2022).

The standard HEPA filter compared to the HEPA-Carbon filter "Air Purification System" (APS) for the Airbus A330/A340 from Donaldson (2024).

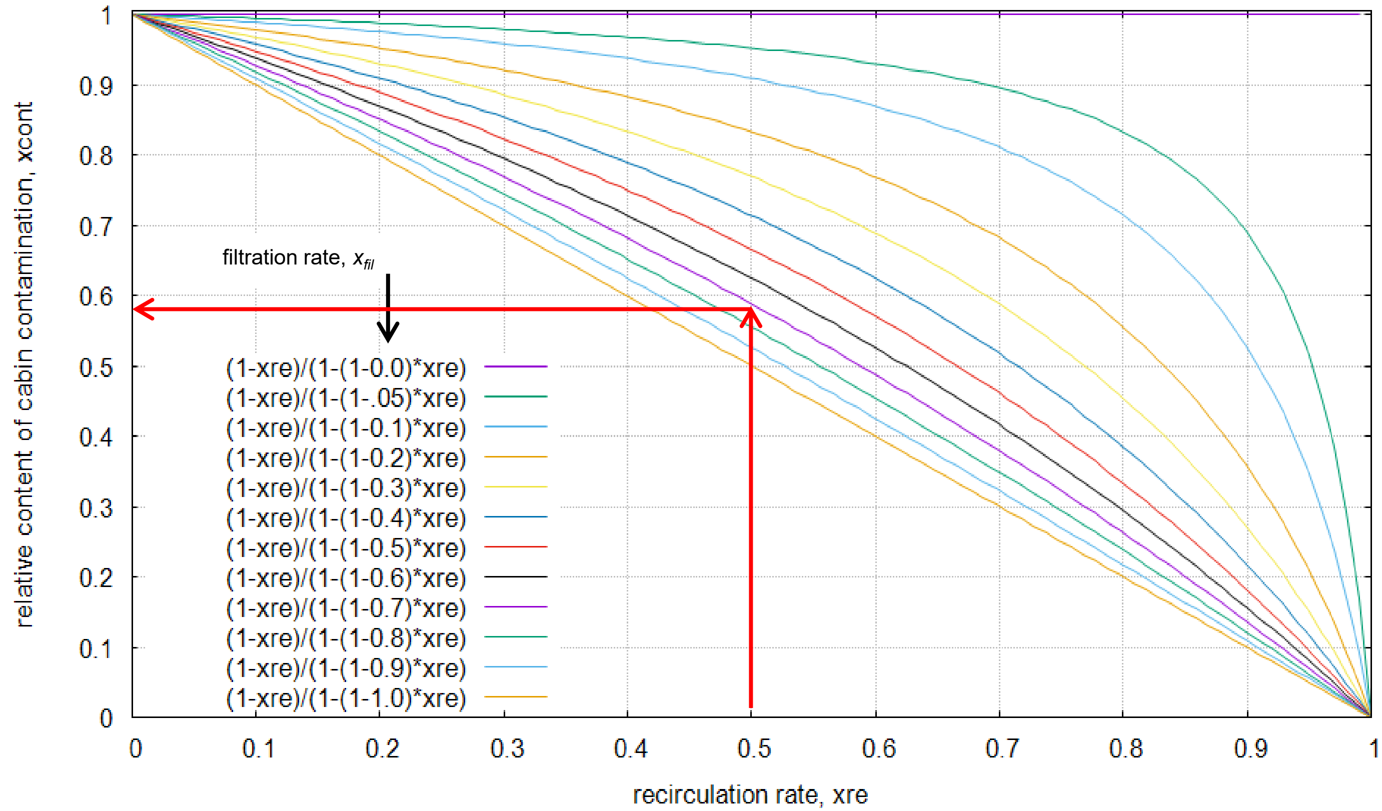
Filtration Systems

Efficiency of Filter in the Recirculation Path

Example calculation:

- With a filtration rate, x_{fil} = 0,7 (Pall 2011) and a recirculation rate, x_{re} = 0,5 (A320) the **filter** in the recirculation path **reduces the incoming concentration to 58,9%.**

$$\frac{x_{cont,cab}}{x_{cont,in}} = \frac{1 - x_{re}}{1 - (1 - x_{fil})x_{re}}$$



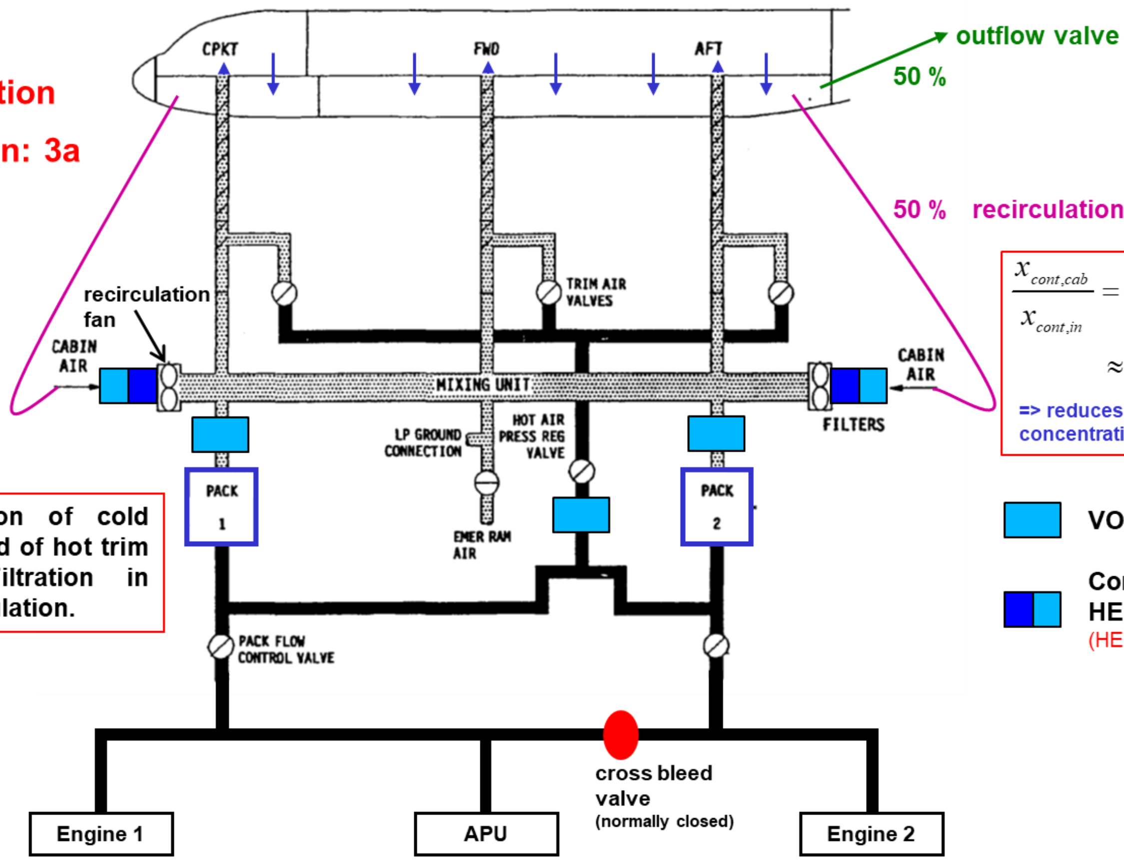
for $x_{fil} = 1$:

$$\frac{x_{cont,cab}}{x_{cont,in}} = 1 - x_{re}$$

Filtration Systems

Total Air Filtration

Filtration Option: 3a



$$\frac{x_{cont,cab}}{x_{cont,in}} = (1 - x_{fil}) f_{recirc}$$

$$\approx 0.3 \cdot 0.6 = 0.18$$

=> reduces incoming pollutant concentrations to ≈ 18%

Filtration of cold air and of hot trim air. Filtration in recirculation.

VOC Filter

Combined HEPA & VOC Filter (HEPA-Carbon Filter)

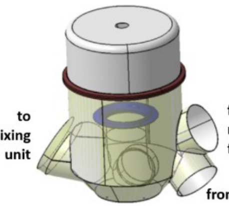
The air is filtered between PACK outlet and MIXING UNIT inlet. The hot trim air is filtered separately.

Filtration Systems

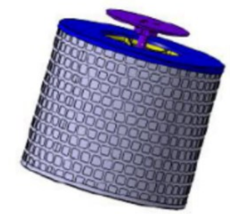
Pall Aerospace Total Air Filtration "PUREcabin"

(a)

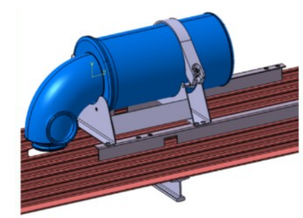
(b)



(c)



(d)

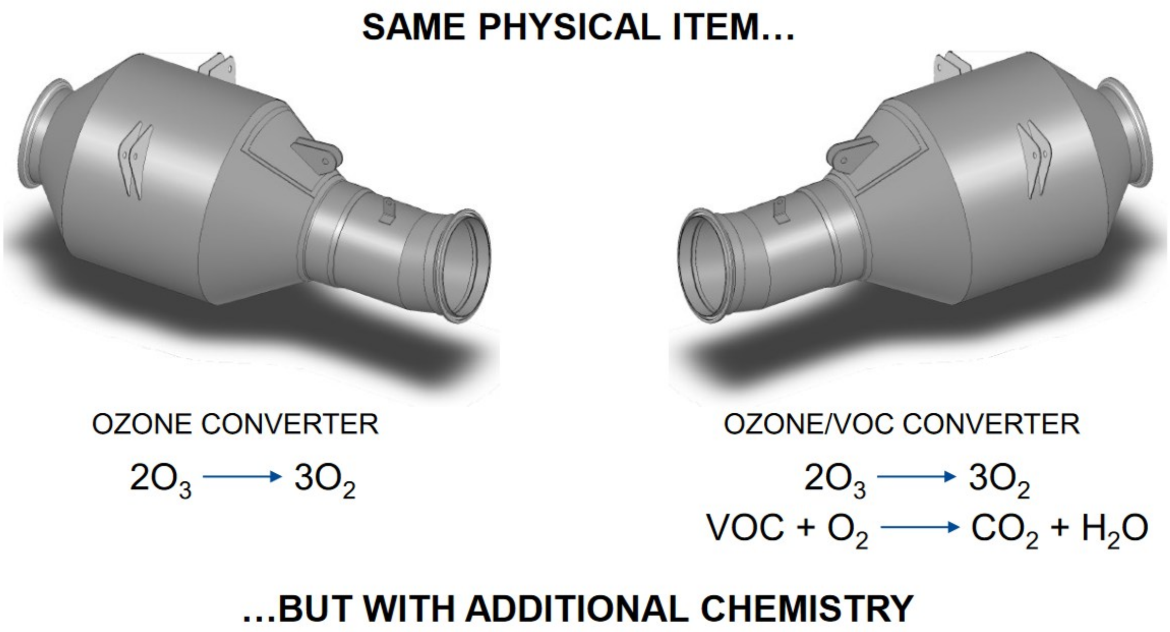


Total cabin air filtration solution "PUREcabin" for the Airbus A320Fam (Stein 2019). View: aft. (a)(b) Details of the filter units. (c) Filter element for the filter units with open By-Pass Valve (BPV). (d) High temperature element to remove particulate and VOC from the trim air.

Converters

Converters

Ozone/VOC Converters



Bleed air
+Air contaminants
+Hydraulic fluid leaks
+Lube oil leaks
+De-icing leaks

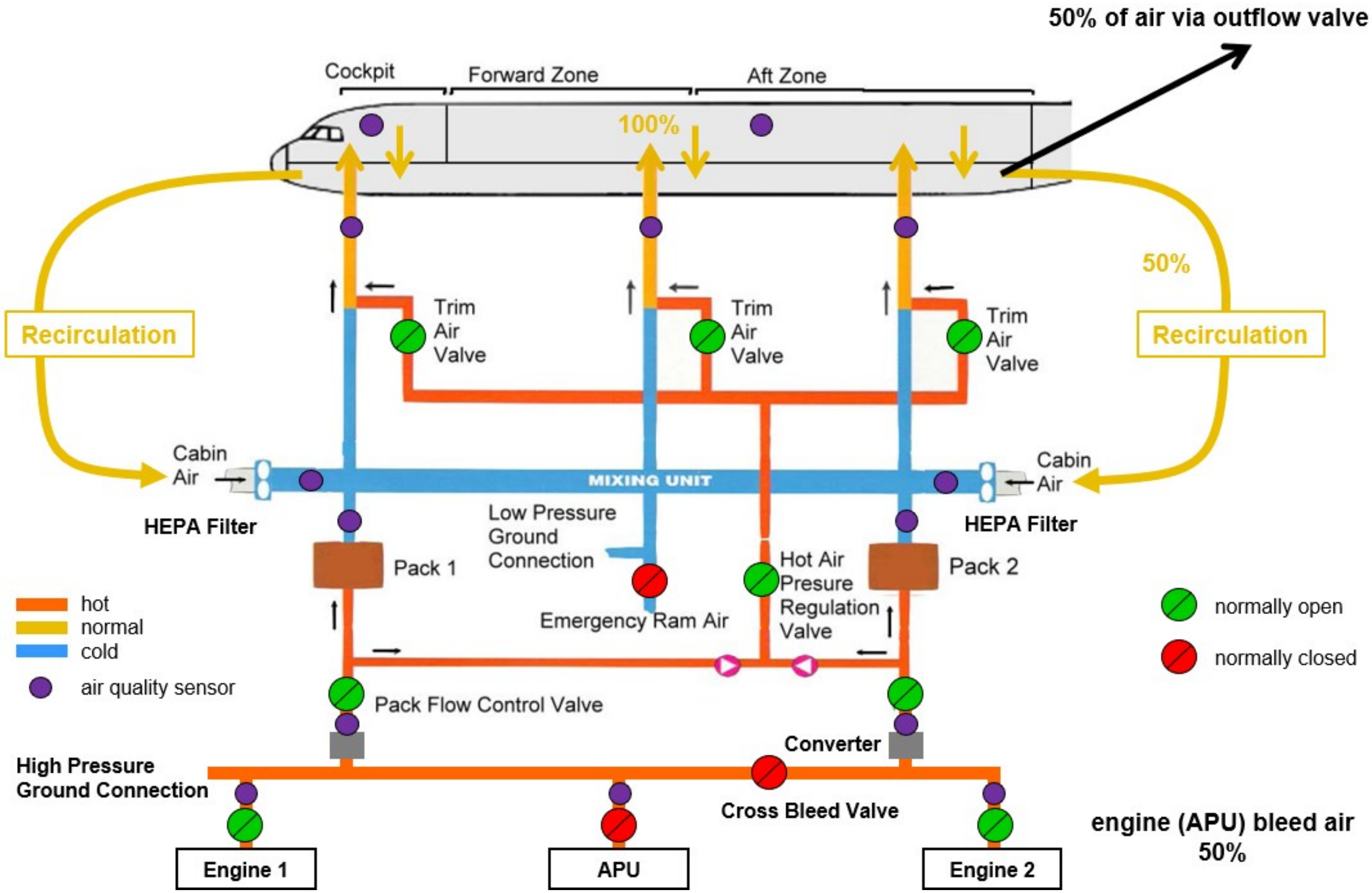
Bad for catalyst

The ozone converter and the ozone/VOC convert are interchangeable and look the same. The difference is in the catalyst and the chemistry. The performance of ozone converters is compromised by polluted bleed air. BASF calls this the "intrinsic problem". (Leung 2019)

Sensors

Sensors

Potential Air Quality Sensor Locations



Potential air quality sensor locations (purple dots). Picture source: D. Scholz.

Sensors

Sensor Summary

Picture source: Optiknv, https://bit.ly/40nV0KU, CC BY-SA.

Canaries were used as sentinel animals in the British mining industry starting from the end of the 19th century for a period of nearly 100 years. They were used to warn especially of CO gas. Picture source: Optiknv, https://bit.ly/40nV0KU, CC BY-SA.

Summary of marker (i.e. sensor) suitability from literature (+++ to 0) and reliability rating (A, B, C) to detect main cabin air contamination sources. Added information: Electronic sensor technologies as well as marker's background level in cabin air and in urban (or airport) ambient air.

Marker[a] / Sensor	Electronic Sensor[b] Technology	Engine Oil	Hy-draulic Fluid	Engine Exhaust	Fuel	De-Icing Fluid	Cabin / airport back-ground level
UFP	CPC, ...	+++/B	0	C		0	yes
FP	CPC, ...		++			0	yes
Formaldehyde	EC	++/B	B	B		++	low
Acetaldehyde	EC	++/B	B	C			low
TVOC	PID/EC	?/C	?/C	C	B	+[c]	yes
CO2	IR/EC	0/-	-	++/C			yes[d]
CO	CBS/EC	0/C	0/C	?/C		0/C	nil
Benzene	CBS/IR/PID			C	C		
Toluene	CBS/IR/PID	B		C	C		
NOx (NO/NO2)[e]	EC			A			airport: yes
Kerosene	IR/PID				yes		airport: yes
O3	EC					++	yes[d]
Carboxylic acids	(EC)	B					
TCP	(EC)	A					
TBP	-		A				
Propylene glycol	-					A	
Ethylene glycol	-					A	

Sensors

Abbreviations Explained from Previous Page

[a] Marker details:

Formaldehyde	CH_2O	UFP/FP (Chapter 6.5)	Ultrafine particles / Fine particles
Acetaldehyde	$CH_3CHO = C_2H_4O$	TVOC (Chapter 6.5)	Total volatile organic compounds
Benzene	C_6H_6 (only traces in kerosene)	CO2 (Chapter 2.2)	Carbon dioxide
Toluene	$C_6H_5CH_3 = C_7H_8$	CO (Chapter 2.2)	Carbon monoxide
Kerosene (jet fuel)	CAS-No.: 8008-20-6	NOx (Chapter 2.2)	Nitrogen oxides (NO and NO_2)
Carboxylic acids	$CH_3(CH_2)_nCOOH$ (Table1.1)	O3 (Chapter 2.2, 11)	Ozone
Propylene glycol	$CH_3CH(OH)CH_2OH = C_3H_8O_2$	TCP (Chapter 6.3)	Tricresyl phosphate (in engine oil)
Etylene glycol	$(CH_2OH)_2 = C_2H_6O_2$	TBP (Chapter 6.6)	Tributyl phosphate (in hydraulic fluid)

[b] Electronic Sensor Technology (allocation of sensor to maker by Dräger 2025f and other sources):

CBS	Catalytic Bead Sensor (not sensitive enough for "Tox")	CPC	Condensation Particle Counter
EC	Electrochemical sensor	-	no practical electronic sensor available
IR	Infrared sensor		
PID	Photoionization Detector		

[c] Little TVOC downstream of a VOC converter.

[d] Background level, CO2 is known: Outside on the ground and outside in flight: ≈400 ppm. In the cabin during flight: ≈1400 ppm. Background level, O3 is known: Determine from Chapter 11.1.

[e] NOx is just the shortcut name. Two separate sensors for NO and NO2 measure both. If in doubt, take an NO sensor.

Marker evaluation:

+++, ++, +, ?, 0:	According to literature (see text) markers are qualified with: very good, good, helpful, questionable, no indications.
A, B, C:	Reliability rating (prEN 17436, Table B.2) as defined in the text (A is best).
"-":	Marker is not mentioned for this contaminant in prEN 17436.

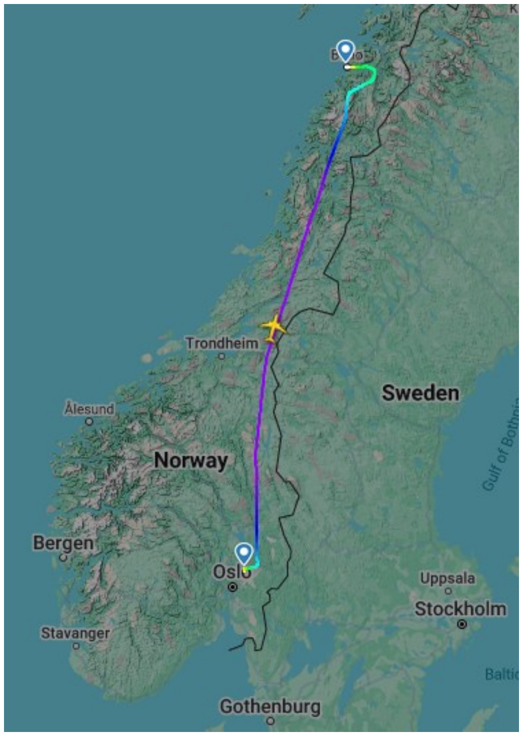
Sensors

An Affordable Sensor for Cabin and Cockpit: BLATN BR-SMART-128s

The BLATN BR-SMART-128s combines measurements of particles (number concentration and mass concentration), formaldehyde, VOC, and CO_2. This is an interesting combination for aircraft cabin air quality measurements. (Blatn 2025)

Sensors

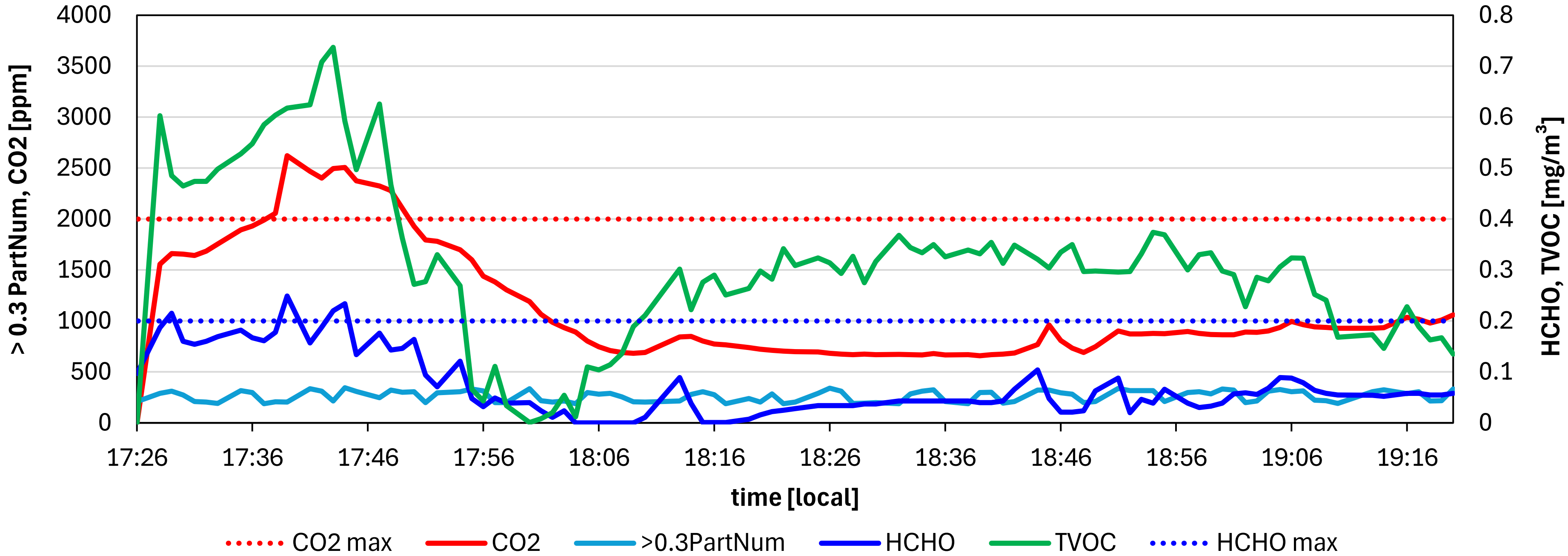
Measurements with BLATN BR-SMART-128s on Flight to Bodø



DATE	FROM	TO	A/C	FT	STD	ATD	STA	STATUS	A/C
07. Apr 25	Oslo (OSL)	Bodo (BOO)	B738 (LN-ENM)	01:23	17:45	17:55	19:15	Landed 19:18	B737-8JP

Sensors

Measurements with BLATN BR-SMART-128s on Flight to Bodø

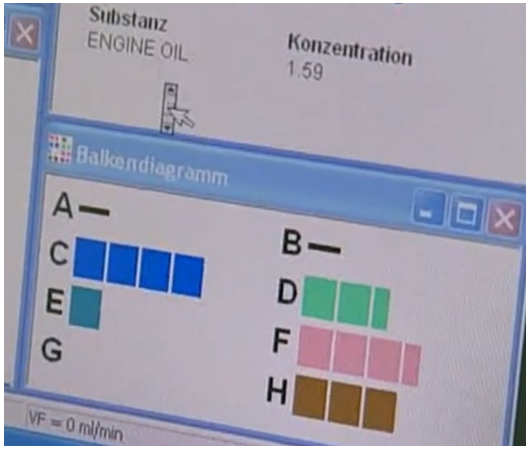


"Hazardous" according to BLATN: CO_2 > 2000 ppm; HCHO > 0.2 mg/m³. This is indicated by the dotted line.
EASA CS 25.831: CO_2 < 5000 ppm; DIN EN 13779: CO_2 < 1400 ppm or cognitive degradation

DATE	FROM	TO	A/C	FT	STD	ATD	STA	STATUS	A/C
07. Apr 25	Oslo (OSL)	Bodo (BOO)	B738 (LN-ENM)	01:23	17:45	17:55	19:15	Landed 19:18	B737-8JP

Sensors

Airsense: Aerotracer – Sensing for Maintenance



The Aerotracer is an electronic nose for pattern recognition (Airsense 2014). The Aerotracer detects 15 substances, among them are grease, liquid, engine oils, de-icing fluids, hydraulic fluids, shock strut fluids, corrosion inhibitors, glue, heat transfer fluid, and kerosene. It can indicate 8 different substance groups A to H for alcohol, ester, ketone and others. The strength of the smell is categorized using 7 levels on a smell scale

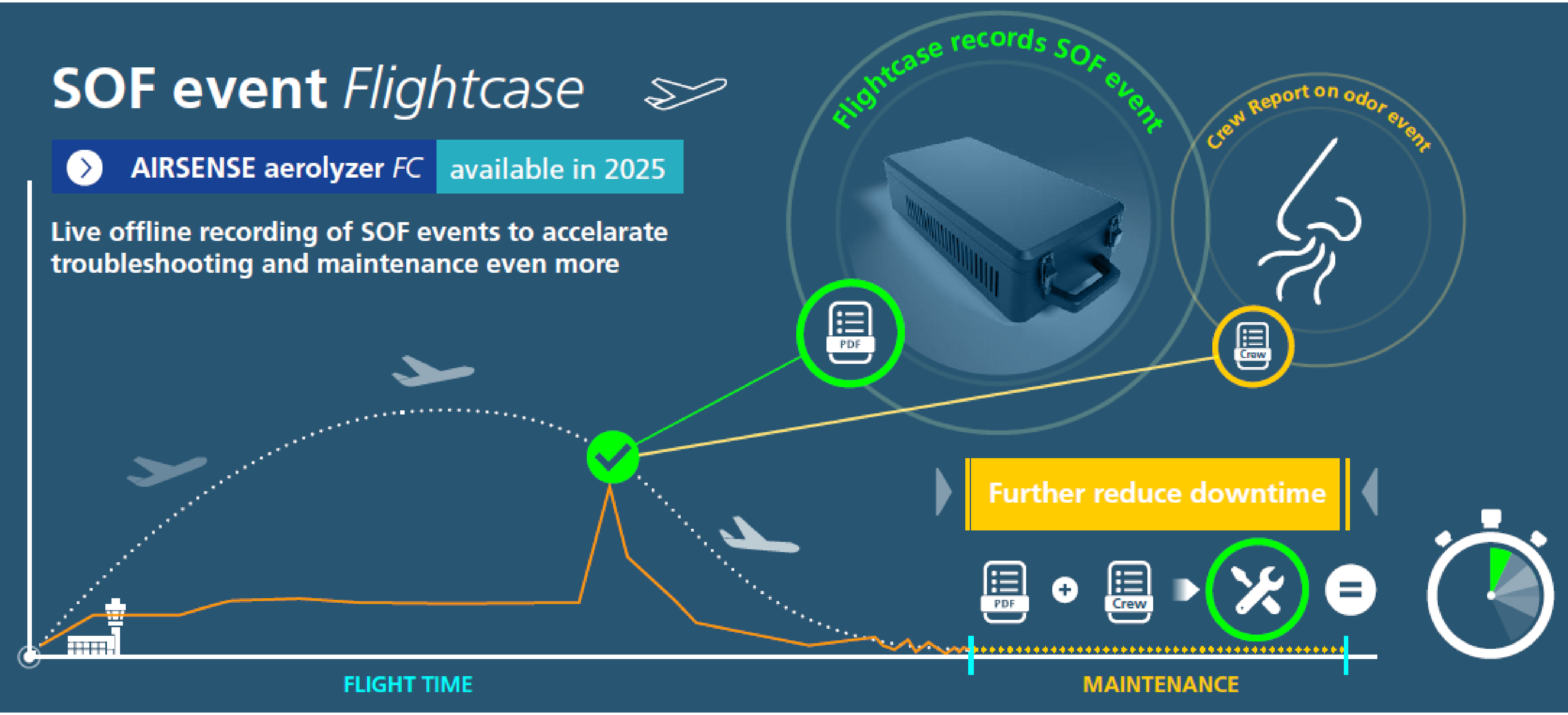
Sensors

Airsense: Aerolyzer – Sensing in Flight

Distinguish in real time / in flight between Engine Oil / APU Oil, Deicing Fluid, VOC, Hydraulic Fluids & Phtalic Anhydride. The measurement analysis is easy to use on Windows based PCs and Tablets. (Airsense 2026)

Sensors

Airsense: Aerolyzer – Sensing during Flight



SOF events that require technical attention are usually caused by bleedair from engine or APU, deicing system, hydraulics or the ECS as well as electrical burning in general (VOC). (Airsense 2026)

Maintenance

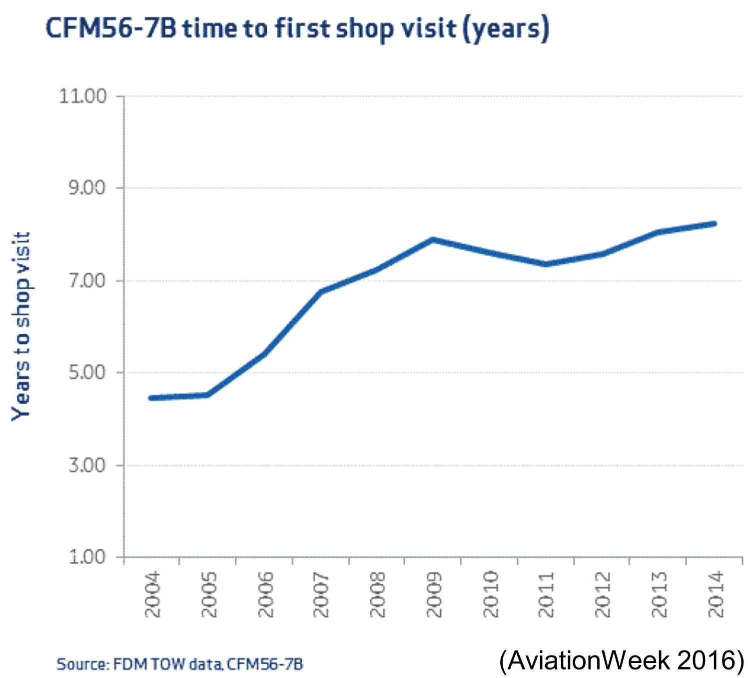
Engines Longer on Wing

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.



(AviationWeek 2016)

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,***
- ***most of the deposit cannot be removed.***

Maintenance

Pack Burn

Task 21-00-00-615-001-A
Decontamination of the Environmental Control System (ECS) when the Temperature is below 24 deg.C (APU)

WARNING : MAKE SURE THAT THERE IS A GOOD FLOW OF AIR THROUGH THE WORK AREA WHEN YOU USE SPECIAL MATERIALS.
IF YOU GET ONE OF THESE MATERIALS ON YOUR SKIN, IN YOUR MOUTH OR IN YOUR EYES :
- FLUSH IT AWAY WITH A FLOW OF CLEAN WATER FOR BETWEEN 10 AND 15 MINUTES.
- GET IMMEDIATE MEDICAL AID IF IRRITATION OCCURS.

DO NOT BREATHE THE FUMES FROM THE MATERIAL.
DO NOT SMOKE WHEN YOU USE THE MATERIAL.
DO NOT USE THE MATERIAL NEAR A FLAME, SPARKS OR SOURCES OF HEAT.
THESE MATERIALS ARE DANGEROUS : THEY ARE POISONOUS, FLAMMABLE AND SKIN IRRITANTS.

1. Reason for the Job

To decontaminate the ECS if oil has gone into it from the APU.

Warning related to engine oil released during the decontamination procedure of the Environmental Control System (ECS) of the A320 Family according to the Aircraft Maintenance Manual (Airbus 2011). The warning "DO NOT BREATHE THE FUMES" also true, if smoke from a Cabin Air Contamination Event (CACE) due to oil is released into the cabin.

Airbus A320 family "Pack Burn". The ECS pack is heated so much with air from the APU that oil deposits get partially vaporized. It is necessary to remove the pack outlet duct behind the condenser of the pack and to blank the downstream ducting to prevent downstream contamination. The air with smoke from evaporating oil is released into the environment. The picture is a screenshot from the video https://youtu.be/d7ZfIFYcYV8.

Flight at 10000 ft
to Vent the Cabin with Outside Air

Flight at 10000 ft to Vent the Cabin with Outside Air

Checklists

SMOKE/FUMES/AVNCS SMOKE

LAND ASAP

IF PERCEPTIBLE SMOKE APPLY IMMEDIATELY :

- BLOWER .... OVRD
- EXTRACT .... OVRD
- CAB FANS .... OFF
- GALLEY .... OFF
- SIGNS .... ON
- CKPT/CABIN COM .... ESTABLISH

• IF REQUIRED :
  - CREW OXY MASKS .. ON/100%/EMERG

• IF SMOKE SOURCE IMMEDIATELY OBVIOUS, ACCESSIBLE, AND EXTINGUISHABLE :
  - FAULTY EQPT .... ISOLATE

• IF SMOKE SOURCE NOT IMMEDIATELY ISOLATED :
  - DIVERSION .... INITIATE
  - DESCENT (FL 100 or MEA, or minimum obstacle clearance altitude) .... INITIATE

• AT ANY TIME of the procedure, if SMOKE/FUMES becomes the GREATEST THREAT :
  - SMOKE/FUMES REMOVAL ... CONSIDER
  - ELEC EMER CONFIG .... CONSIDER
  Refer to the end of the procedure to set ELEC EMER CONFIG

• At ANY TIME of the procedure, if situation becomes UNMANAGEABLE :
  - IMMEDIATE LANDING .... CONSIDER

SMOKE/FUMES REMOVAL

Use the smoke removal procedure if there is dense smoke, toxic fumes (smell), or if smoke generation cannot be stopped.

- EMER EXIT LIGHT .... ON

...

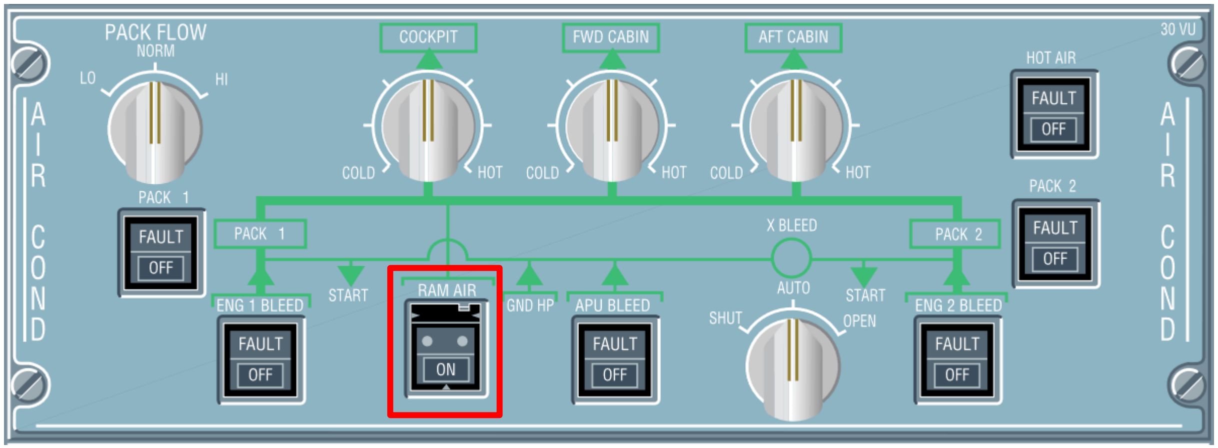
- LDG ELEV .... 10000 FT/MEA
- DESCENT (FL 100, or MEA, or minimum obstacle clearance altitude) ...... INITIATE
- ATC .... NOTIFY
- SMOKE/FUMES/ AVNCS SMOKE PROC .... CONTINUE
  While descending, continue applying the appropriate steps of the SMOKE/FUMES/AVNCS SMOKE procedure depending on the suspected smoke source.

• At FL100 or MEA :
  - PACK 1+2 .... OFF
  - MODE SEL .... MAN
  - MAN V/S CTL .... FULL UP
  - RAM AIR .... ON

In case of smoke and fumes on an Airbus A320 the "Smoke/Fumes/Avionics Smoke" checklist is applied. If smoke/fumes become the greatest threat, the "Smoke/Fumes Removal" checklist is used. Important steps are shown. If the steps do not show sufficient effect, cockpit windows could be opened as a next step. Based on Smart Cockpit (2020).

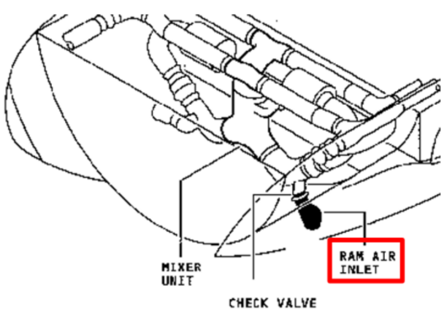
Flight at 10000 ft to Vent the Cabin with Outside Air

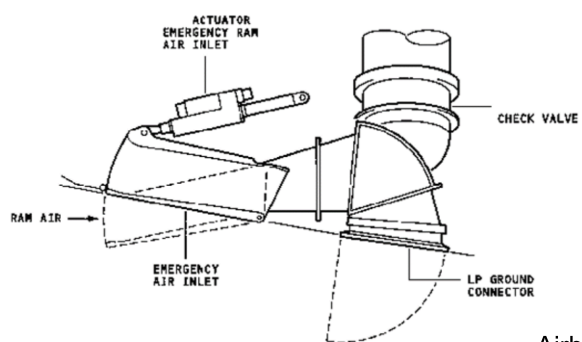
Activating the Guarded RAM AIR Switch on the Airbus A320



Airbus A320 air conditioning (AIR COND) part of the overhead panel. The air conditioning packs (PACK 1 and PACK 2) can be switched "OFF". The guarded RAM AIR switch is covered to prevent inadvertent use. By pressing RAM AIR "ON", the ram air inlet is opened.

Airbus A320, ECAM System Display (SD) cabin pressurization (CAB PRESS).Flight in FL 100 with the emergency ram air inlet open. Both packs are shown in amber, because they are switched off. The outflow valve is halfway open. Cabin pressure control is set to manual (MAN). The cabin altitude (CAB ALT) is 9850 ft. Vertical speed is now at 0 ft/min and differential pressure, Δp = 0.1 psi.





Airbus 1999

Load Reduction Device, LRD

Load Reduction Device

A bird strike can cause heavy engine vibration due to imbalance in the rotating parts. This can happen, when a fan blade breaks off. A Load Reduction Device (LRD) is a feature on the LEAP engine. The CFM International LEAP is a high-bypass turbofan engine produced by CFM International, a joint venture between GE Aerospace (USA) and Safran Aircraft Engines (France). It is the successor of the CFM56 to power the new generation of narrow-body aircraft (B737 MAX, A320neo, C919). **The LRD disconnects the fan from the engine core**. This allows the fan to spin freely. The fan's unrestricted axial rotation brings fan blade tips into contact with surrounding components, slows the fan's rotation, and minimizes vibration. Unfortunately, LRD activation opens the oil sump **which allows oil to enter** the core compressor and **the bleed valves**. This LRD behavior is as it is designed and certified. CFM says: "Load reduction devices have been widely used across the industry for more than 20 years and operated as designed."

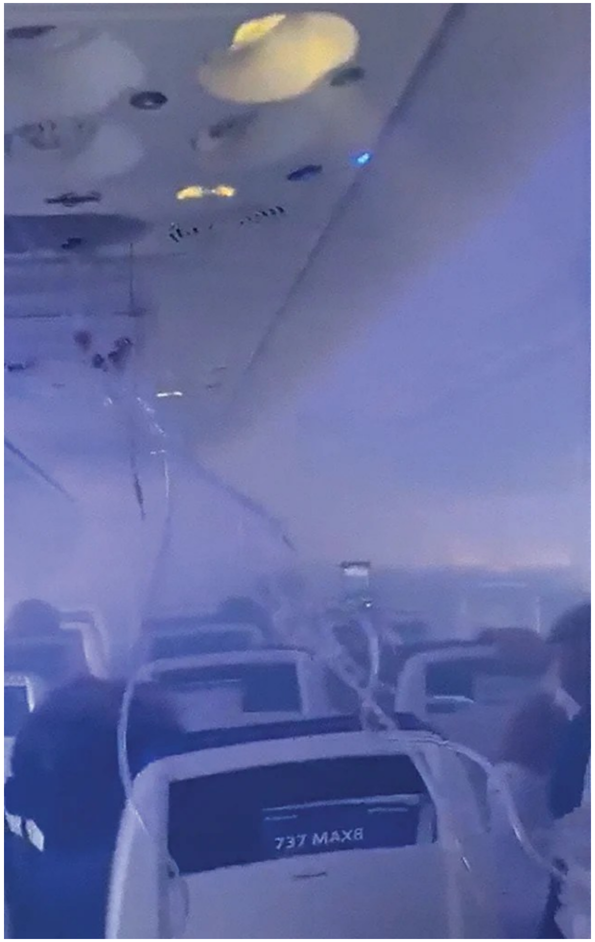
If the valves from the left engine air flow are not closed, ingested smoke on the B737 MAX will **reduce visibility in the cockpit to 5 in within 30 s** according to a Boeing analysis. The FAA report adds that after just 39 s, concentrations of **noxious fumes** (acrolein and formaldehyde) in the confines of the cockpit may exceed acute exposure thresholds, described as **potentially lethal**. According to the FAA report, Boeing had calculated the probability of LRD activation as about **one incident per year**.

In the case of LRD activation pilots initiate an **engine shut down**. This needs to be done carefully to avoid a shut down of the wrong engine. In the meantime smoke pours into the cockpit, so that pilots need to don their oxygen mask. Together with the engine shut down the **bleed air is cut off** automatically.

If the failure happens after take-off pilots must return to the airport to land while handling a failure, close to the ground, under an oxygen mask, and almost without visibility in the cockpit. This is certainly a **very difficult flying task**. In addition, pilots were so far not aware of the LRD, because the LRD was not described and became known to pilots only in the wake of the two Southwest 737 MAX incidents.

Load Reduction Device and the ECS – Bottom Line

The Load Reduction Device (LRD) can cause cabin air contamination because a wrong principle is applied using bleed air from the engines. The LRD and resulting oil release would have no effect on the cabin air if the air would be taken from an inlet on the fuselage.

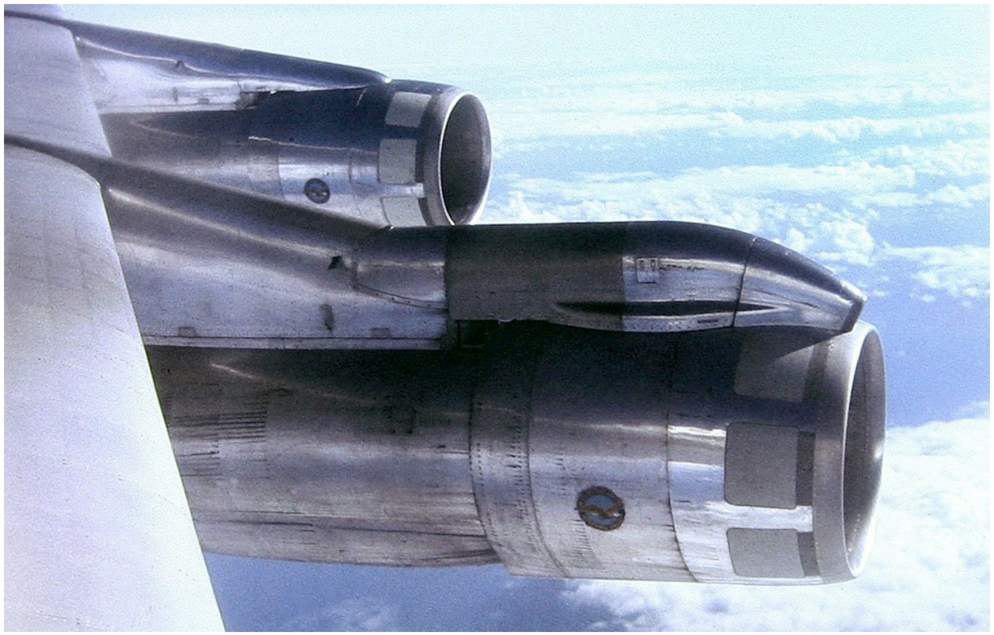


2023-03-05, Southwest Airlines WN-3923, Boeing 737-8 MAX climbing out of Havana. Bird strike and **smoke in cabin due to activation to the Load Reduction Device, LRD**. More: AvHerald 2023. Picture source: Video: https://youtu.be/DlgBcqlY7-c.

Bleed-free ECS Design

Bleed-free ECS Design

Boeing 707: Turbocompressor



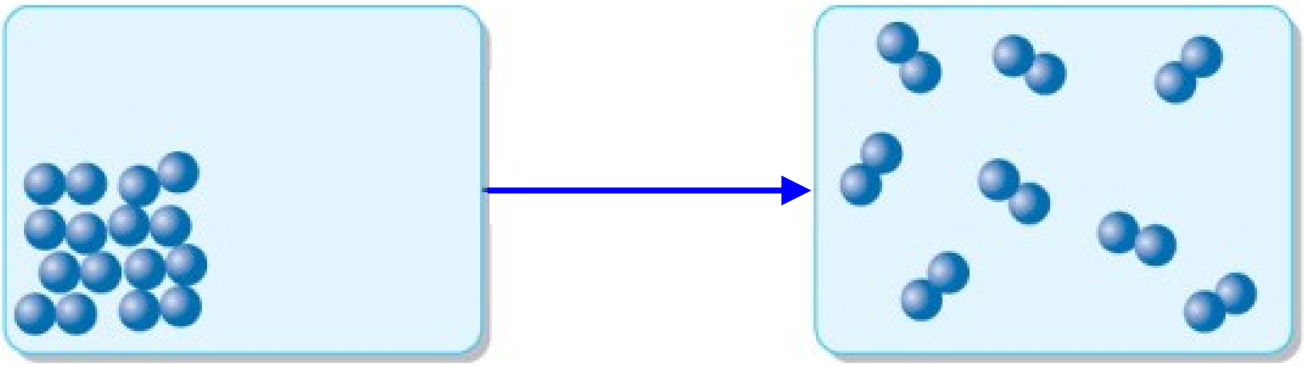
The B707-320C with Pratt & Whitney JT3D engines. One of the turbocompressors is located on top of engine number 2. Engine one is in any case without turbocompressor. Source: John, https://bit.ly/40IcfaE, CC BY-SA. Left: Air conditioning and pressurization panel on the B707 flight engineer's station with RPM indication and controls of turbocompressors on engine 2, 3, and 4. Source: D. Scholz. Own modification (detail) of original. Courtesy of Alegren (2024a). Right: Boeing 707, Royal Australian Air Force, 2006. Turbocompressor on the engine with cabin air inlet and turbine exhaust duct for the bleed air. Source: Jeff Gilbert, https://bit.ly/3DlMoLW, GNU FDL.

Entropy – Distribution by Law of Nature

Entropy – Distribution by Law of Nature

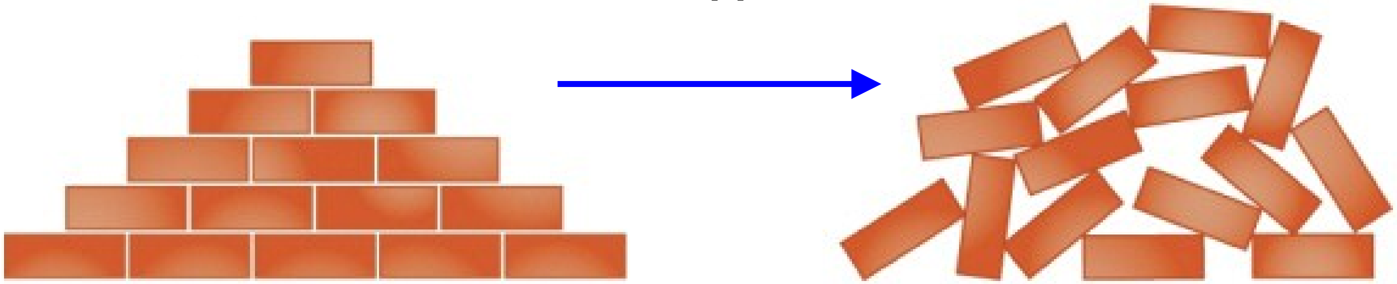
Contaminants Spread Everywhere

Gas spreads to fill space over time



Entropy (Disorder) Always Increases!

Pile of bricks dropped from a truck



based on https://perma.cc/A6KL-XS9R

Contaminants Spread Everywhere

Entropy is the law of nature by which ...

- **engine oil with metal nanoparticles**
- **hydraulic fluid**
- **deicing fluid**

goes everywhere and finally into the human body.

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