Aero

Hochschule für Angewandte Wissenschaften Hamburg
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AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Agence Nationale de Sécurité Sanitaire (ANSES) – **Hearing on the Operation of Air Conditioning in Aircraft Cabins and the Associated Air Quality**

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ANSES

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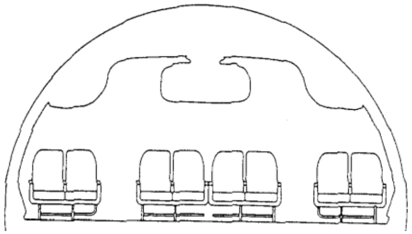

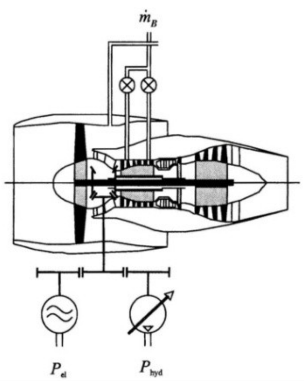

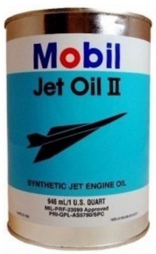

Abstract

Passenger aircraft occasionally encounter a Cabin Air Contamination Event (CACE). When these events make themselves know with a distinct smell they are called Smell Events. When they are evident even by smoke (and smell), they are called Fume Events. The objectionable classical cabin air contamination from "bleed", "engine oil", "hydraulic fluid", and "deicing" accounts together for roughly 1/3 of the events. Oil has left traces on its way from the engine to the cabin interior: In bleed air ducts, air conditioning ducts, in recirculation filters, on cabin surfaces (wall panels, seats ...). Hydro carbon concentrations in the cabin can be calculated and agree with measurements. SAE has highlighted the risk of obtaining contaminated air from the engine compressor. It may preclude its use for transport aircraft, regardless of other good reasons. Nevertheless, aviation organizations like IATA claim that "Cabin air is as clean as a hospital operating theatre". Cabin air ventilation in passenger aircraft is done with outside air. 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 most economic system principle simply uses the air that is compressed in the engine compressor anyway and taps some of it off as "bleed air". The engine shaft is supported by lubricated bearings. They are sealed against the air in the compressor usually with labyrinth seals. Unfortunately, the jet engine seals leak oil by design in small quantities. The oil leaking into the compressor contains toxic additives. Furthermore, the oil includes toxic metal nanoparticles – normal debris from the engine. 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 in much the same way. Compressed air from the engine is also used to pressurize the potable water. It has been observed that the potable water on board can also be contaminated. Fan air and bleed air ducts at the interface between engine and wing carry outside compressed air. The inside of the ducts shows differences. The brown stain in the bleed air duct appears to be engine oil residue. In comparison, the fan air duct is clean. This shows that oil leaves the compressor bearings. Ducting further downstream shows a black dry cover. The reason for the change in color seems to result from the different air temperatures: 400 °C at engine outlet and 200 °C further downstream behind the precooler. The water extractor is a part of the air conditioning pack. The inlet of the water extractor is covered with black oily residue, because the temperature is even lower at this point. The air conditioning air distribution ducts in the cabin are black inside from contaminated bleed air. New ducts are clean. Air duct are even clean inside at the end of the aircraft's life, in areas where they are used such that no bleed air flows through them. Flow limiters have been found in ducts of the air conditioning system that are clogged from engine oil. Also riser ducts feeding the cabin air outlets are black inside from engine oil residue.

Air Conditioning in Aircraft Cabins and the Associated Air Quality

Cleaning on top of the overhead bins brings to light dirt that is clearly more than dust. The black residue known from the ducts settles also on the bin surface. Deicing fluid and hydraulic fluid can find their way into the air conditioning system via the APU air intake. A fence and a deflector around the air intake cannot fully prevent contaminants from entering the APU. Traces of contamination tend to be visible on the lower part of the fuselage. Contaminants are carried by the air flow in flight, from the landing gear bay to the APU inlet. Hydraulic systems are never leak free. A hydraulic seal drain system tries to collect hydraulic fluid leaving the system with partial success. It is impossible to catch all leaking hydraulic fluid. If the containers of the seal drain system are not emptied they spill over. In old aircraft, 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 hydraulic bays, but continues its journey on the lower side of the fuselage towards the APU. Deicing fluid if applied in the winter to the aircraft and can leak from the tail into the APU inlet. Fuel and oil also leak down onto the airport surfaces. These fluids can be ingested by the engine from the ground and can enter the air conditioning system from there. Entropy is the law of nature that states that disorder always increases. This is the reason, why it is impossible to confine engine oil and hydraulic fluids to their (predominantly) closed aircraft systems. This is why engine oil with metal nanoparticles hydraulic fluids, and deicing fluids eventually go everywhere and finally into the human body. Filtration can help to avoid cabin air contamination. HEPA filters are in use with most passenger aircraft that work with recirculated air. Only HEPA carbon filters can also filter some of the Volatile Organic Compounds (VOCs). They are available for only some aircraft types and only lead to about 40% reduction of the concentration of VOCs in the cabin. Necessary would be to filter the incoming air from the engine compressor. Filter manufacturer Pall has worked on such a total air filtration option for the Airbus A320 for several years, but is so far not able to offer the new system. For this reason, we are left with a situation, where engines are longer and longer on the wing without the chance to replace engines seals that get worn out more the longer the engine is operated. This leads to an increasing number of CACEs. Airbus duct cleaning maintenance procedures after a CACE are ineffective. 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, and most of the deposit are firmly attached to the surface and cannot be removed. This situation leaves the passengers in a situation for which the degree of contamination is unknown but real. Strictly, the amount of oil in the cabin cannot be determined from the oil consumption of the engine. For legal benefit of the aviation industry, sensors are missing on board and deprive passengers and crew from data that could be used in court.

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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)**

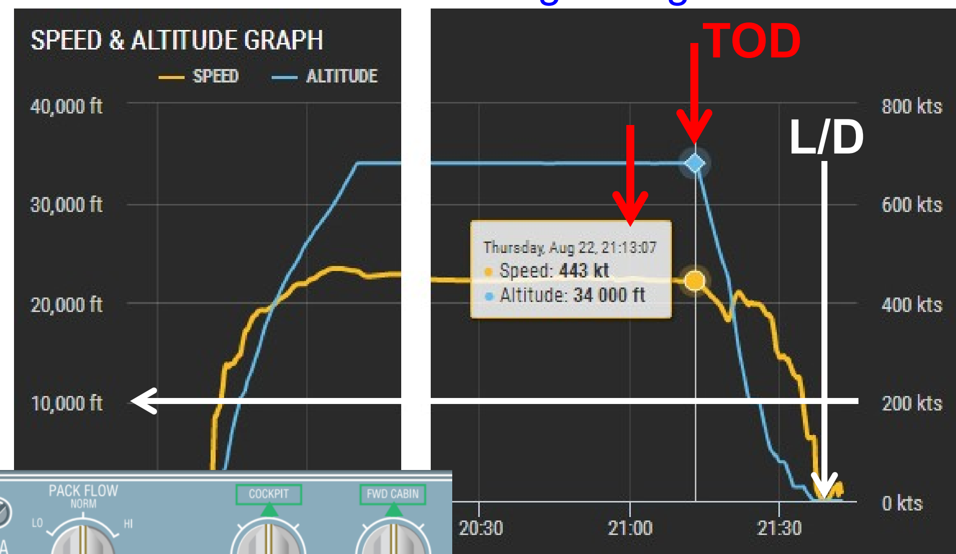
In a Cabin Air Contamination Event (CACE) the air in the cabin and/or cockpit of an aircraft is contaminated. Sensation of the contamination can be from vison (fume/smoke), olfaction (smell/odor), a combination of typical symptoms experienced by several passengers and/or or crew or by related measurements 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 ()

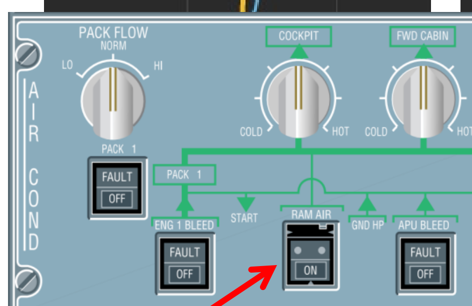
21:13: Top of Descent: Smoke starts to fill cabin i.e. when thrust setting changed.



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**.

Cabin Air Contamination Event Due to Engine Oil After Technical Fault

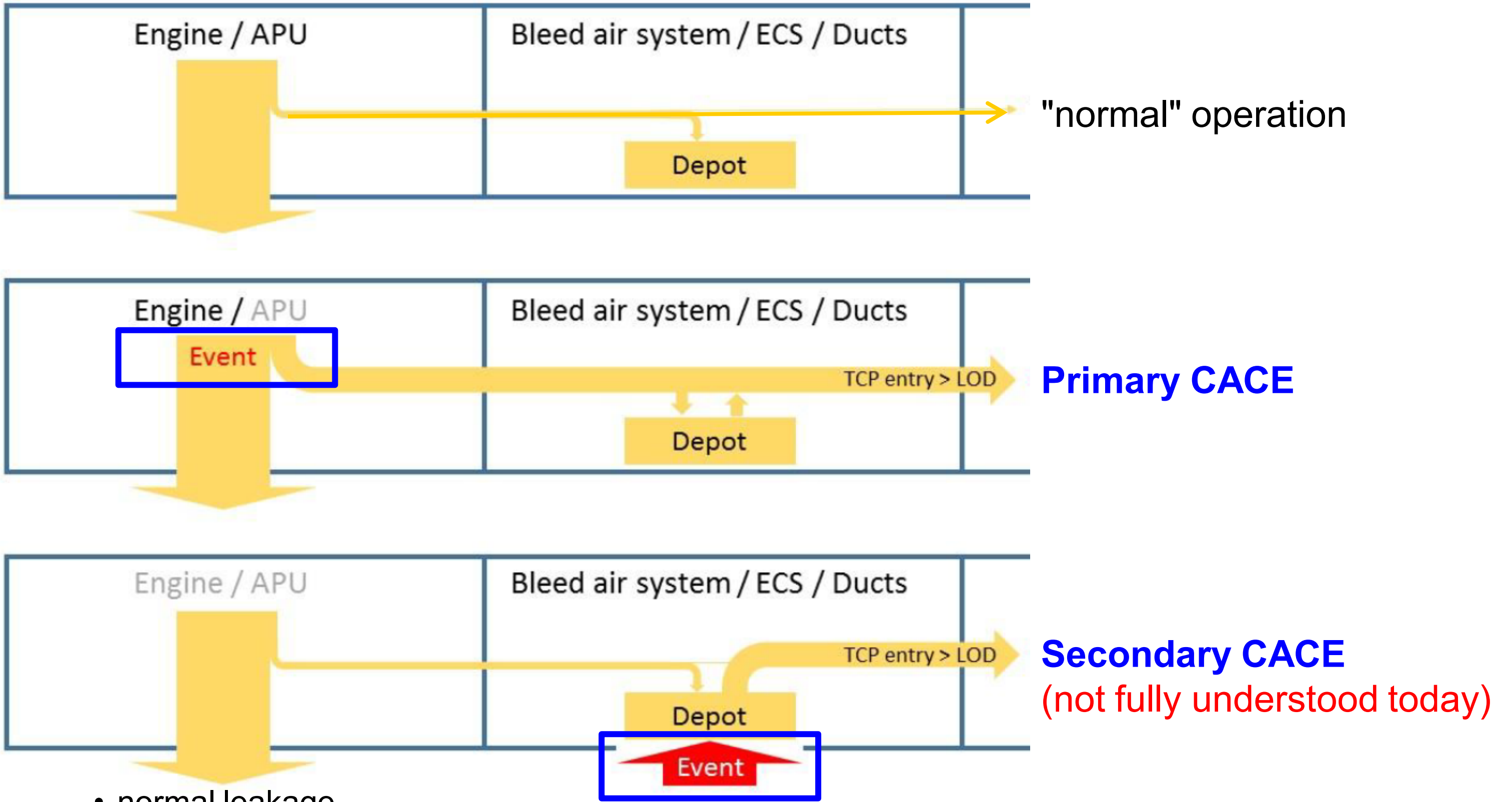
Top:2019-08-22, Hawaiian Airlines HA47, A321neo.
Bottom: 2019-08-05, British Airways BA-422, Airbus A321 (https://youtu.be/tFsN0h09gAI).

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).

Introduction

Primary and Secondary Cabin Air Contamination Events (CACE)



Event Mechanism:

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

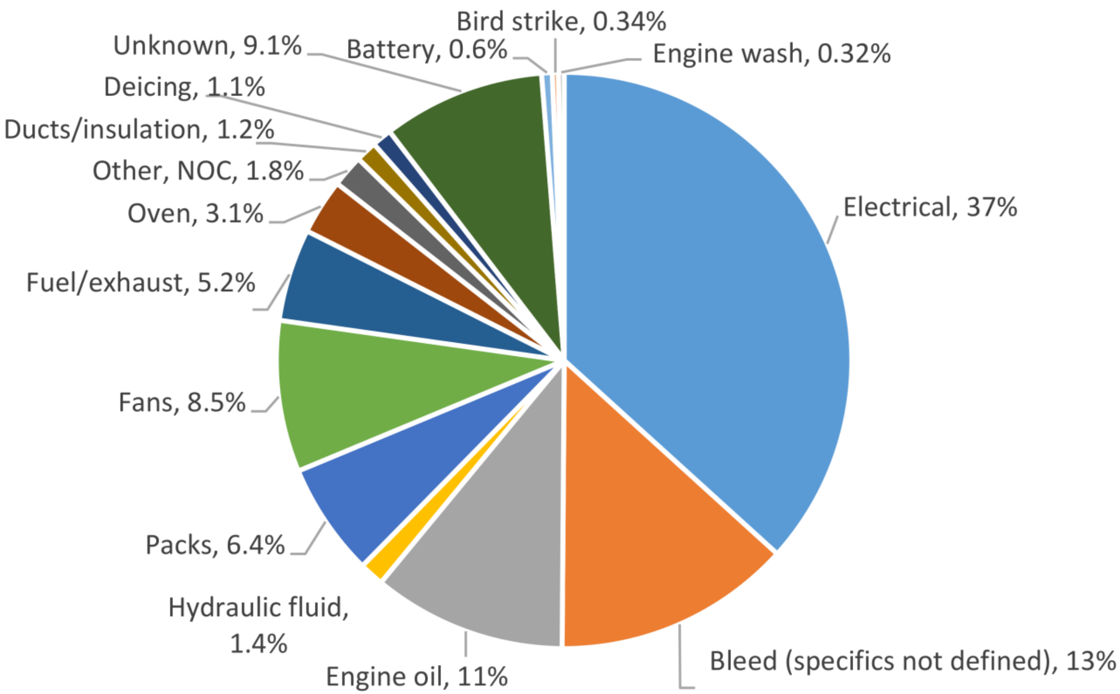
- mechanical stress?
- thermal stress?
- solvents (water, de-icing fluid, ...)?

Based on EASA 2017b

Introduction

Reasons for Cabin Air Contamination Events (CACEs)

Anderson (2019 and 2021) lists the **reasons for cabin air contamination events**.



Anderson 2021

Onboard Fumes/Smoke Reported by U.S. Airlines total 12452 events of different source. The objectionable classical cabin air contamination from "**bleed**", "**engine oil**", "**hydraulic fluid**", and "**deicing**" **accounts together for roughly 1/3** of the events. Industry often quotes "oven" as the main reason, but it only accounts for 3.1%.

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**.

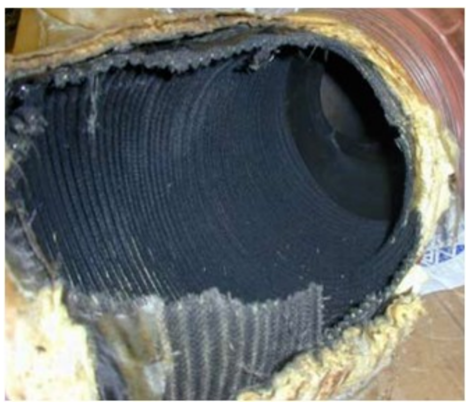
How Do We Know about Oil in the Cabin?

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

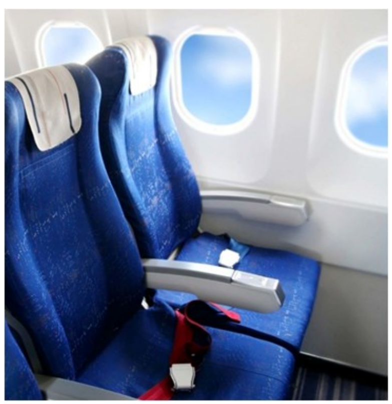
Evidence collected in Scholz 2017 and Scholz 2019 summarized here:

1. (GCAQE 2017)



2. (CAA 2004)

3. (Eckels 2014)

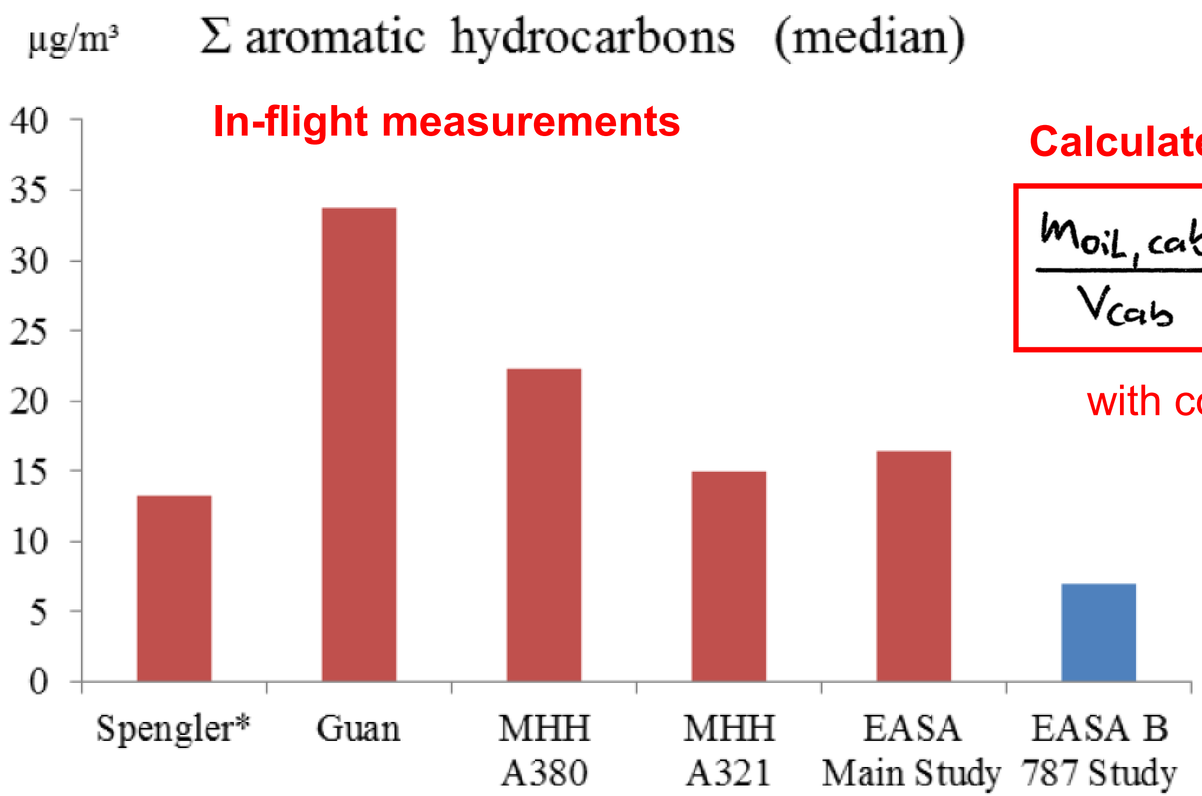


4. (Lamb 2012, Solbu 2011)

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:

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

with conservative estimate:
x_{seal} = 1 %

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

(EASA 2017a)

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

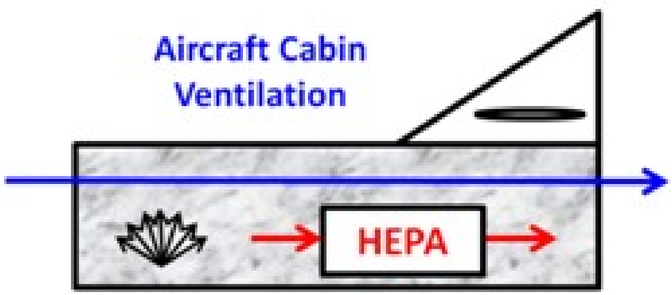
**Nevertheless,
it is claimed:**

https://perma.cc/686X-X9AZ?type=image

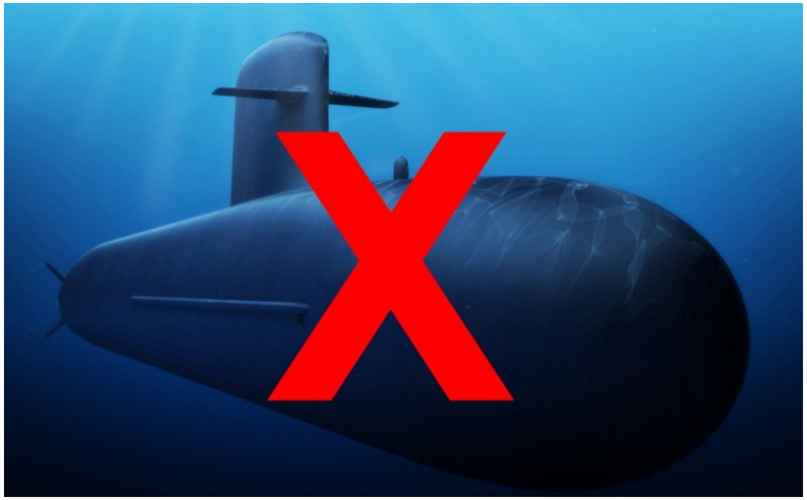
Air Conditioning System

Air Conditioning System

Boundary Conditions



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



- **Aircraft is no 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**

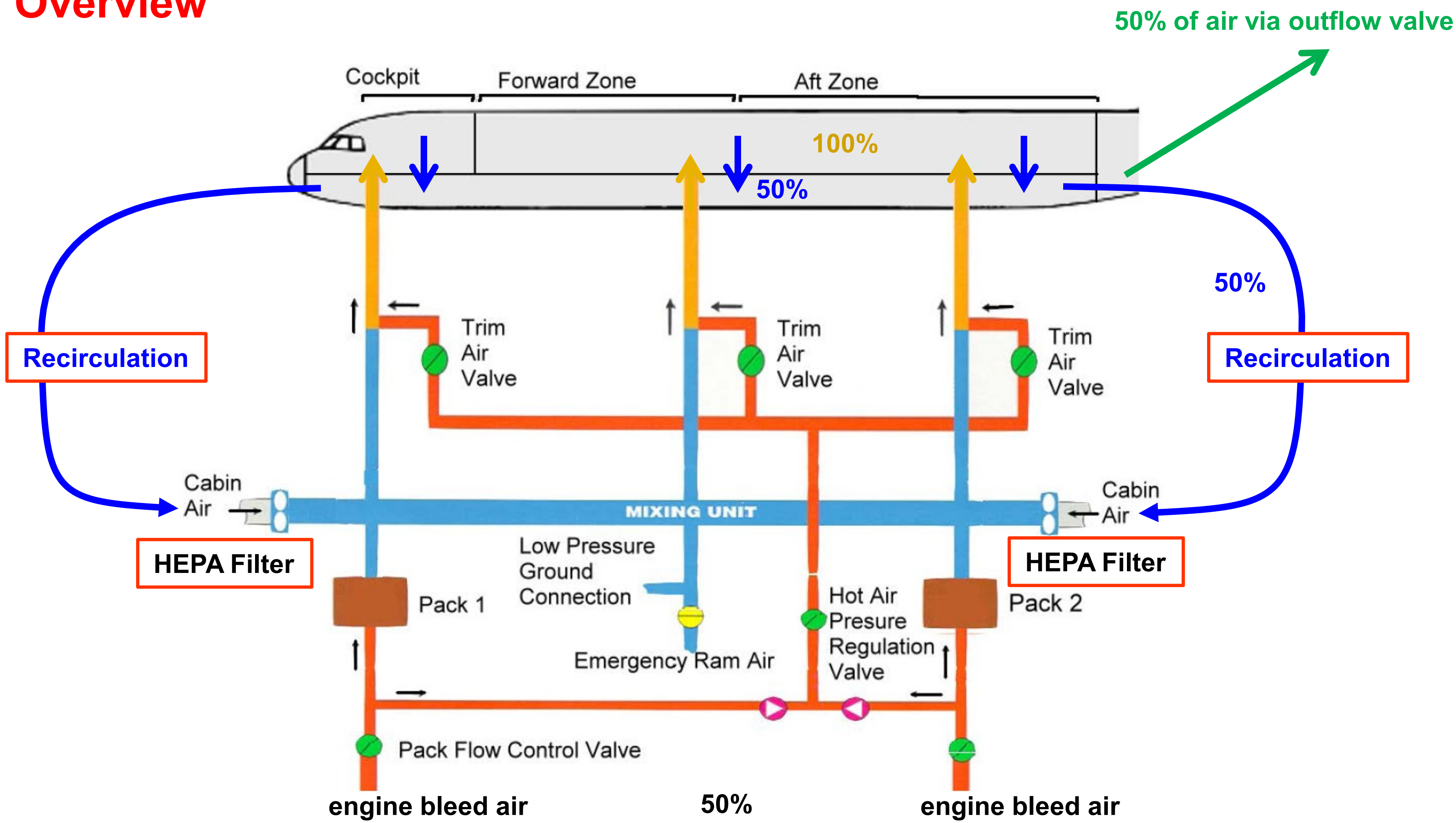
  "provide a cabin pressure altitude of not more than 8000 ft" CS-25.841(a)
- **Moisture Control**

  No requirements

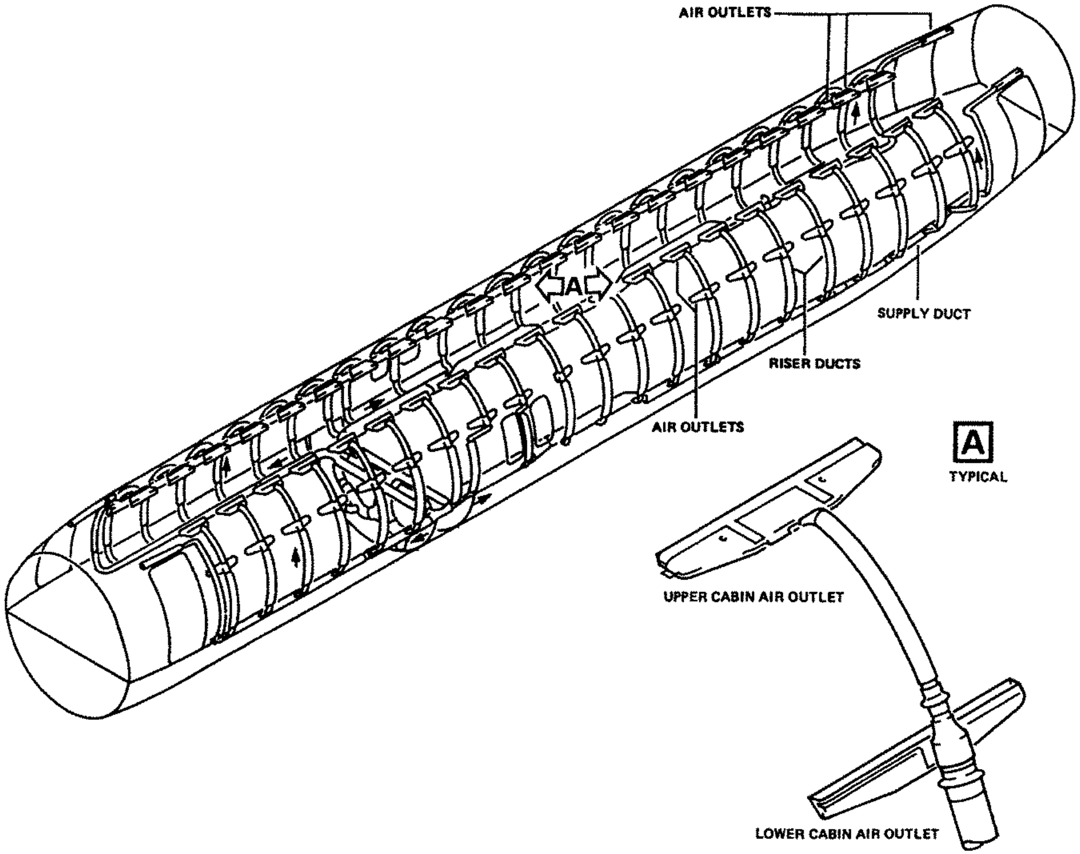
Requirements related to pressure and moisture control are not further detailed.

Air Conditioning System

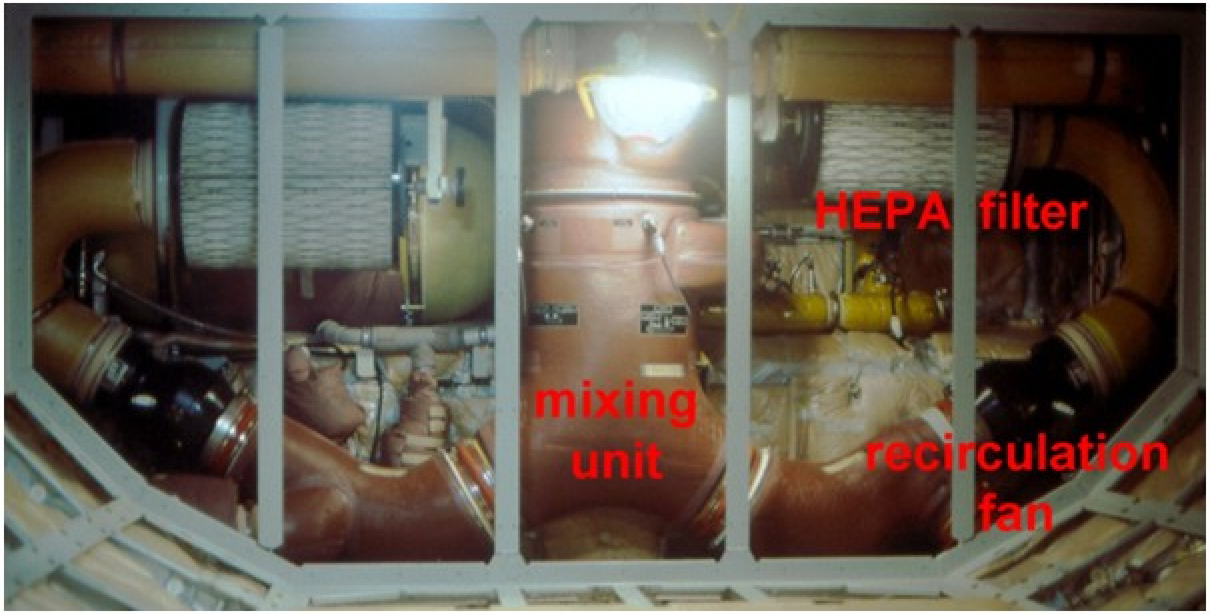
Overview



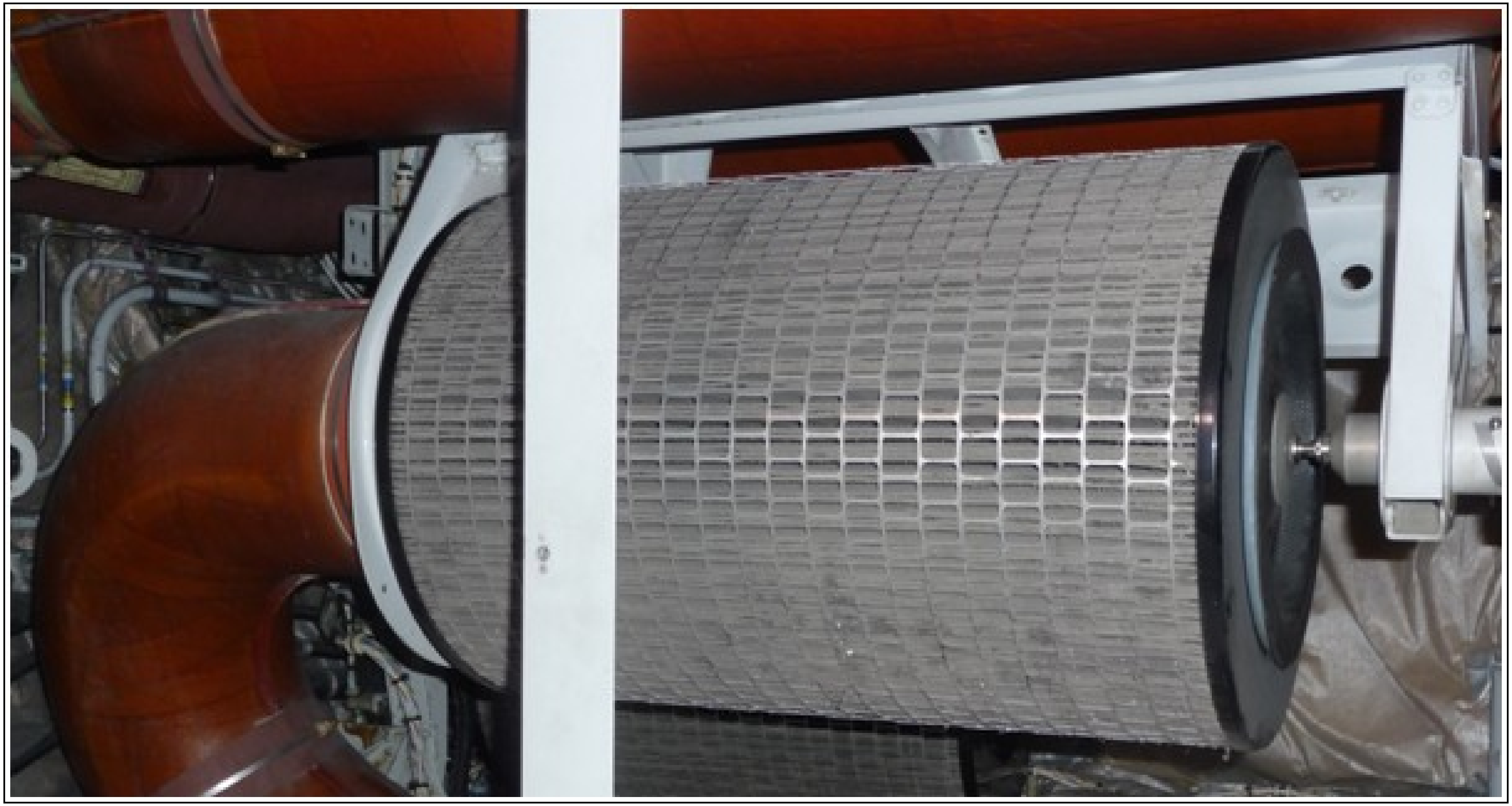
Air Distribution – Supply and Riser Ducts



Mixing Unit, HEPA Filters, Recirculation Fan



HEPA Filter



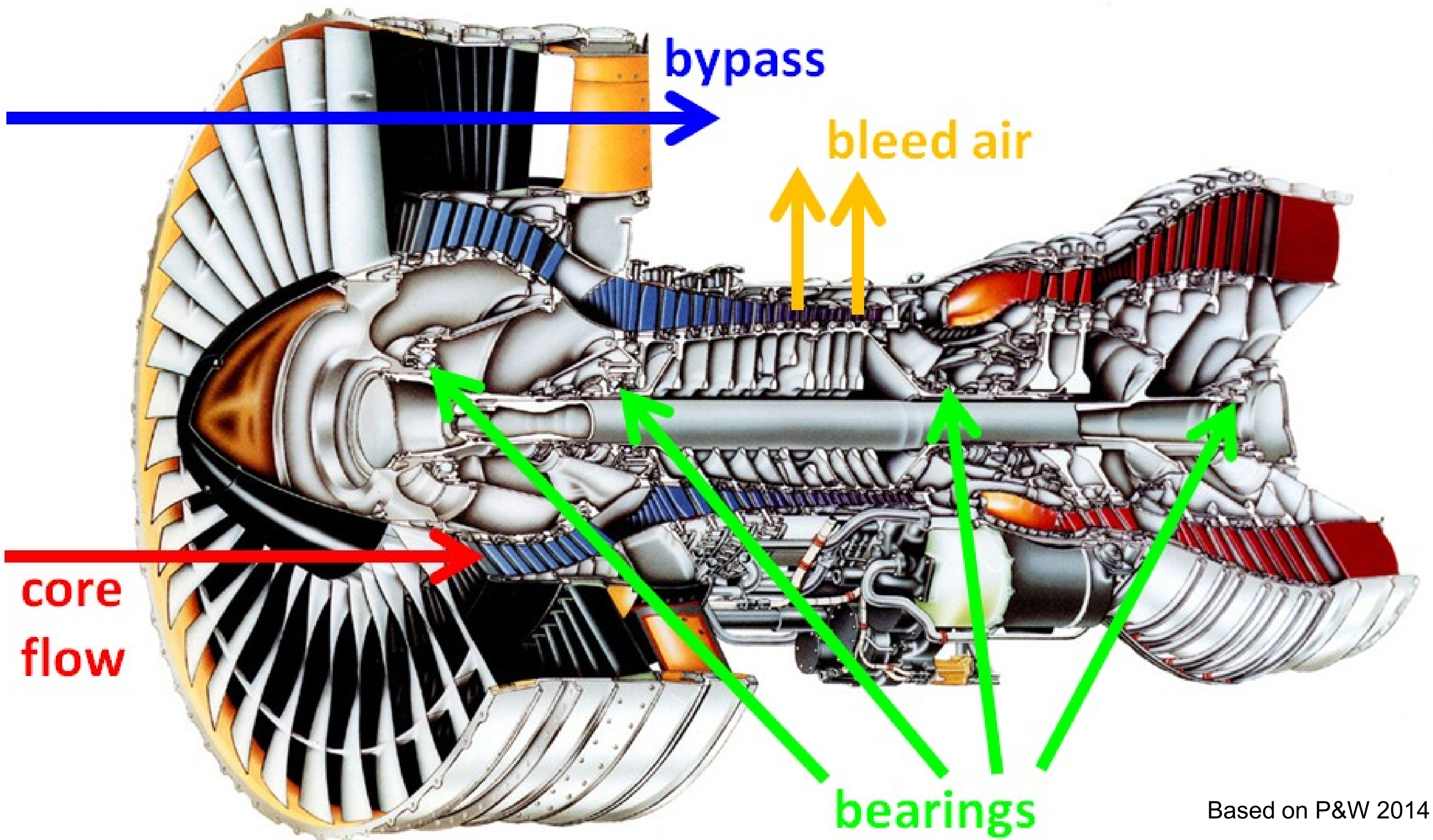
HEPA Filter

A380, Emirates

Jet Engine Technology

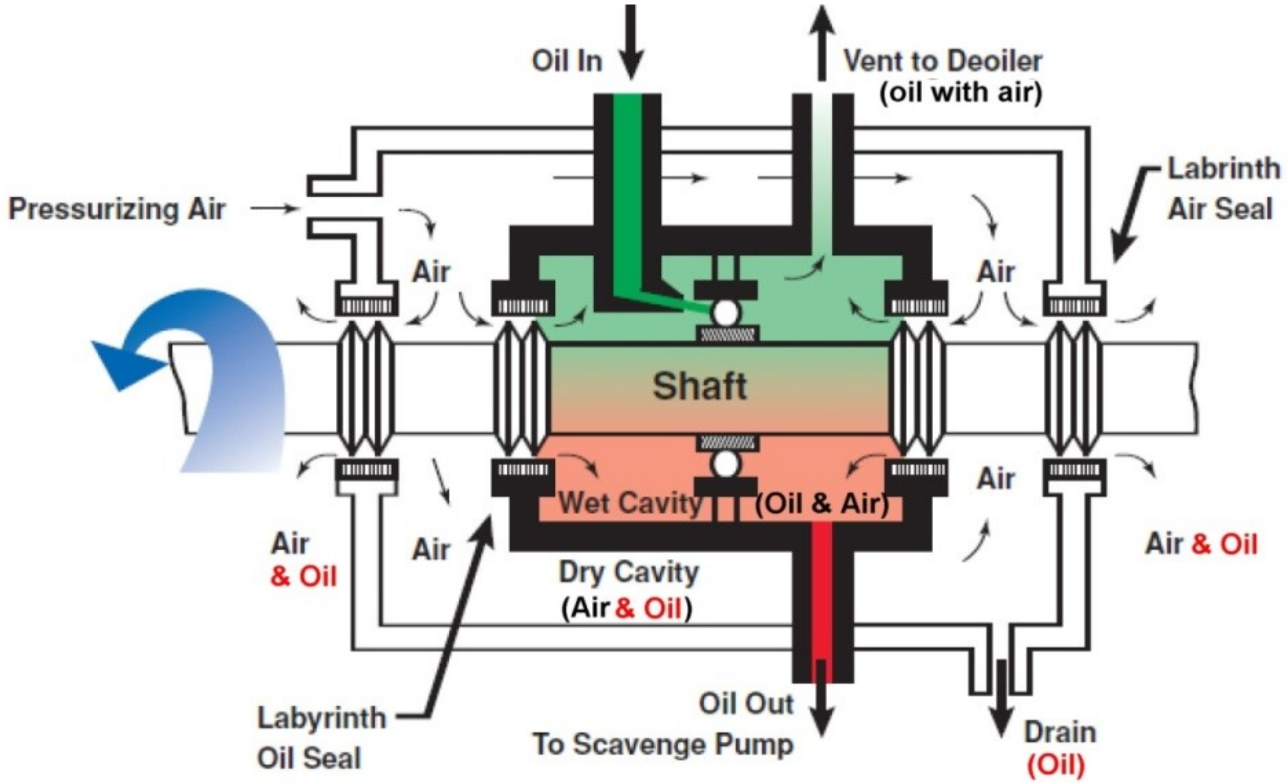
Jet Engine Technology

Engine Bearings and Bleed Air



Based on P&W 2014

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

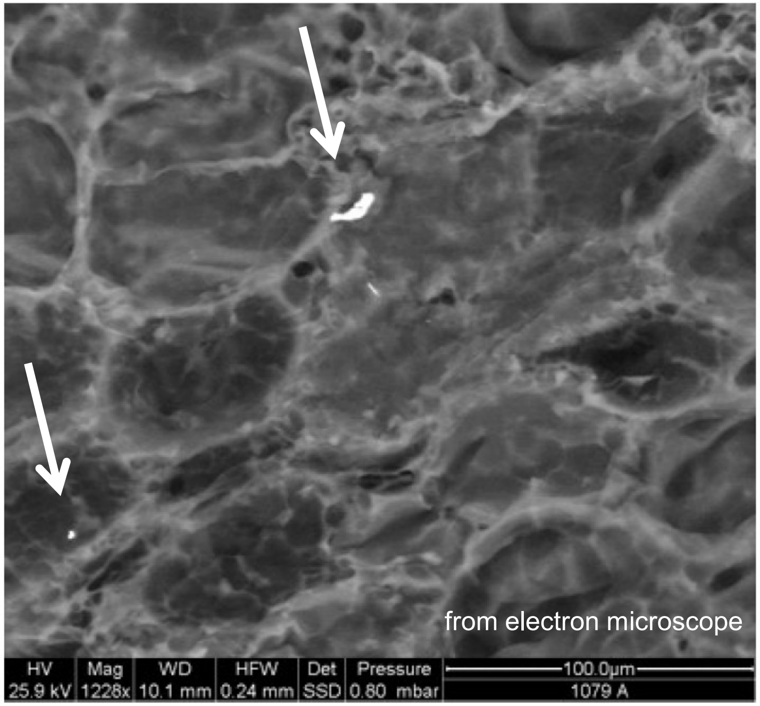
- Spectrometric Oil Analysis Program (SOAP) is an analysis of metal particles in the oil.
- SOAP can be combined with oil filter inspection and magnetic chip detector inspection which identifies larger metal particles.
- A monitor program helps to identify the condition of the engine:
- Catastropic failure 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!**

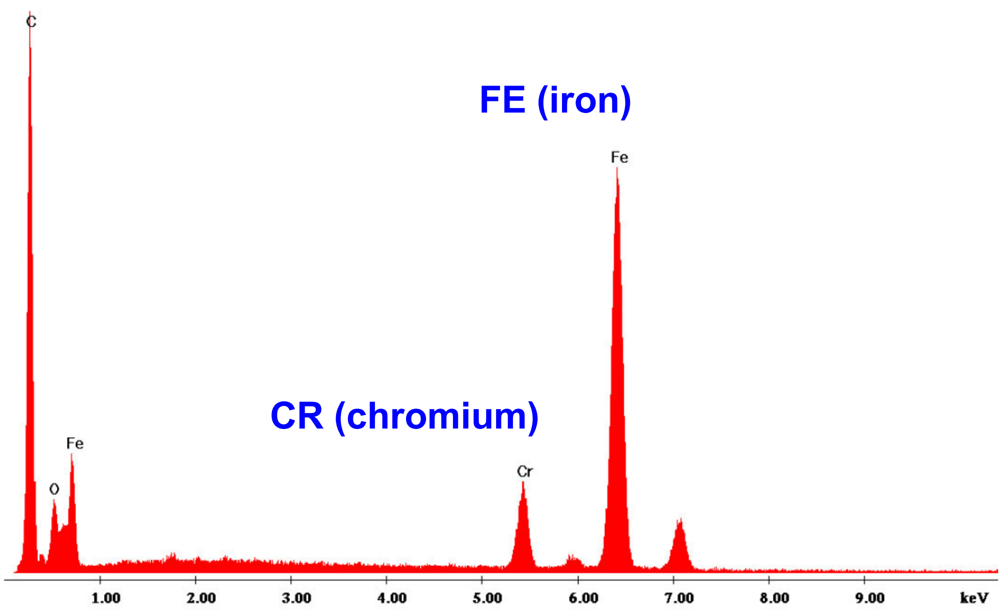
Partially based on Exxon 2016b

Jet Engine Technology & Results

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



(Gatti 2019, report written for client)

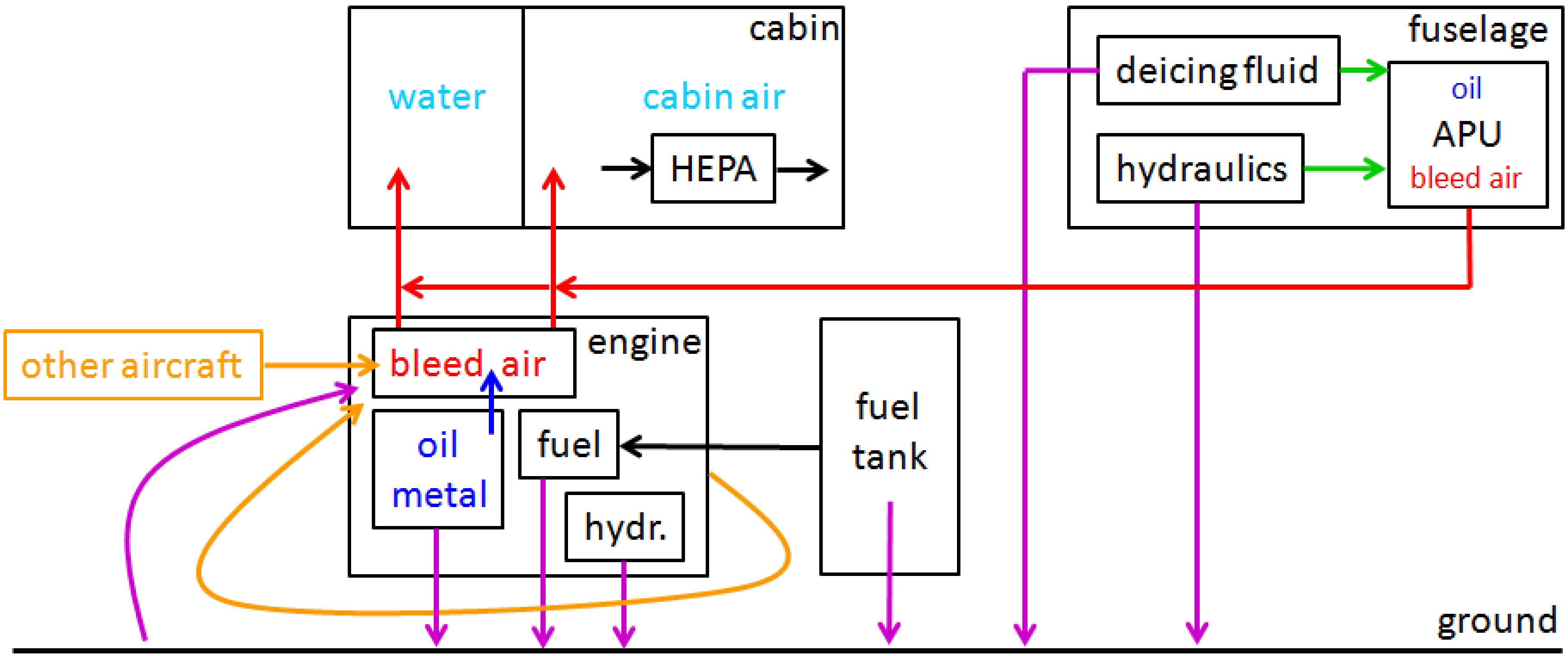


Analysis 8 of Table I. High-magnification image (1228x) and EDS spectrum of 10-micron and 1-micron brighter-looking particles composed of Carbon, Iron, Chromium and Oxygen: a stainless-steel composition. EDS: Energy-Dispersive X-ray Spectroscopy.

Distribution of Engine Oil with Metal Nanoparticles

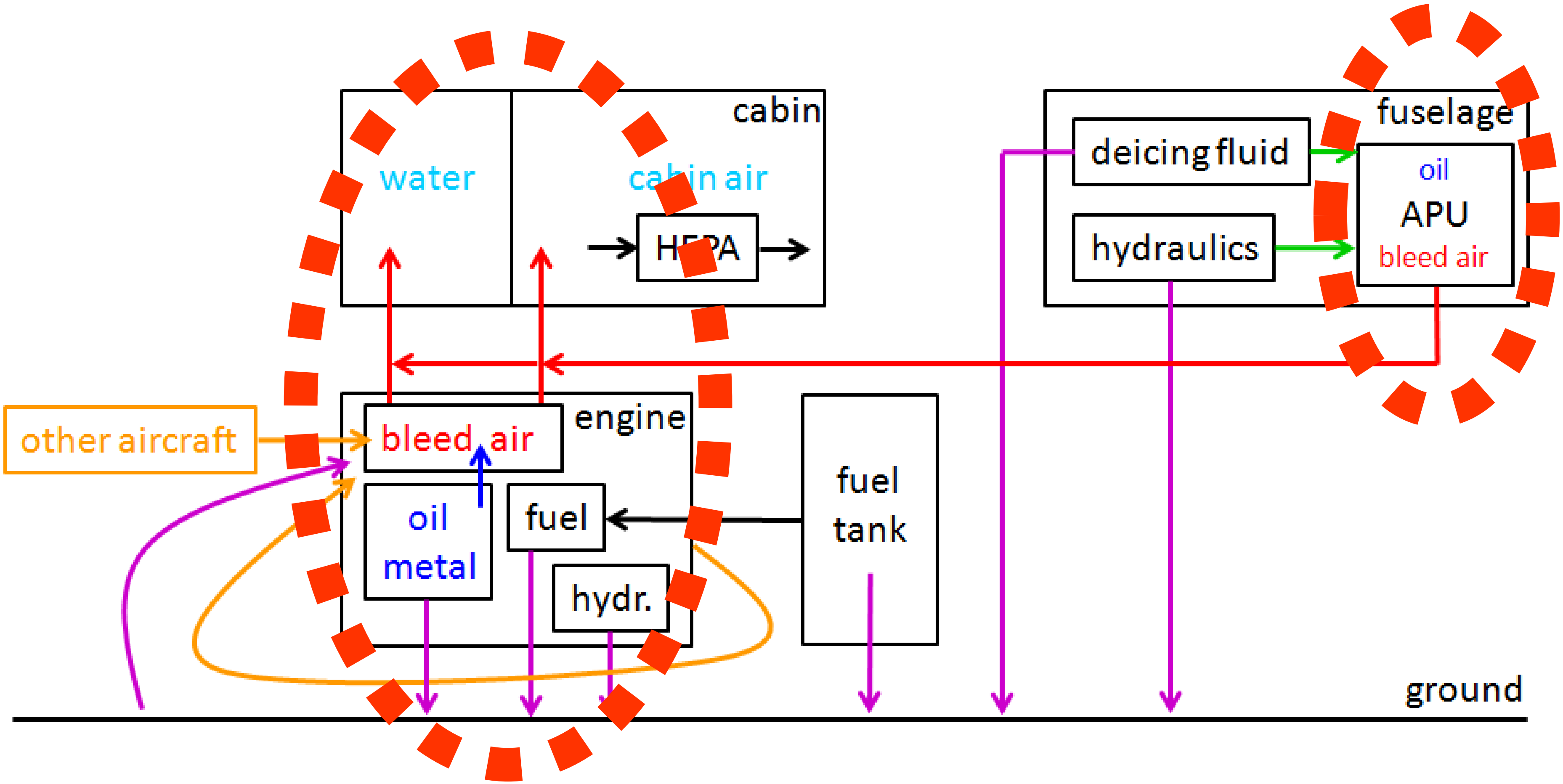
Distribution of Engine Oil with Metal Nanoparticles

Contaminants and Their Routes Into the Cabin



Distribution of Engine Oil with Metal Nanoparticles

The Route of Engine Oil Into the Cabin



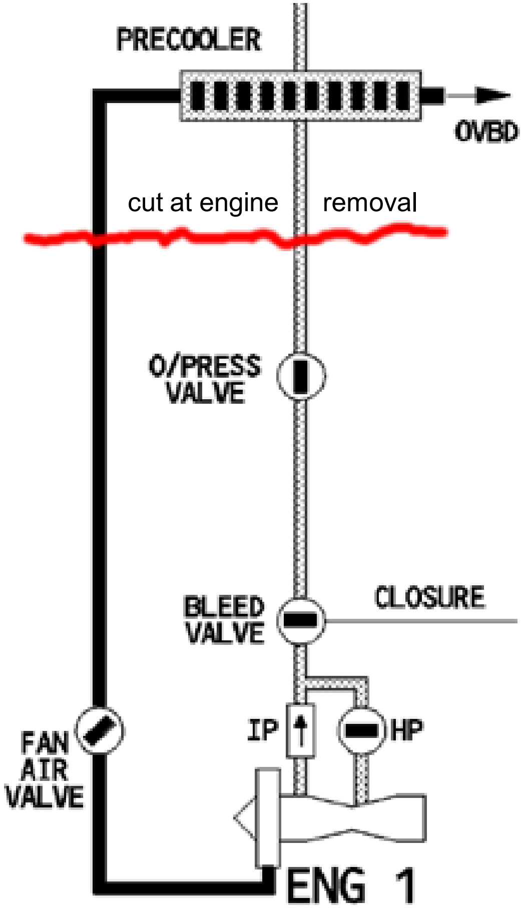
Engine Oil in the Potable Water

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.

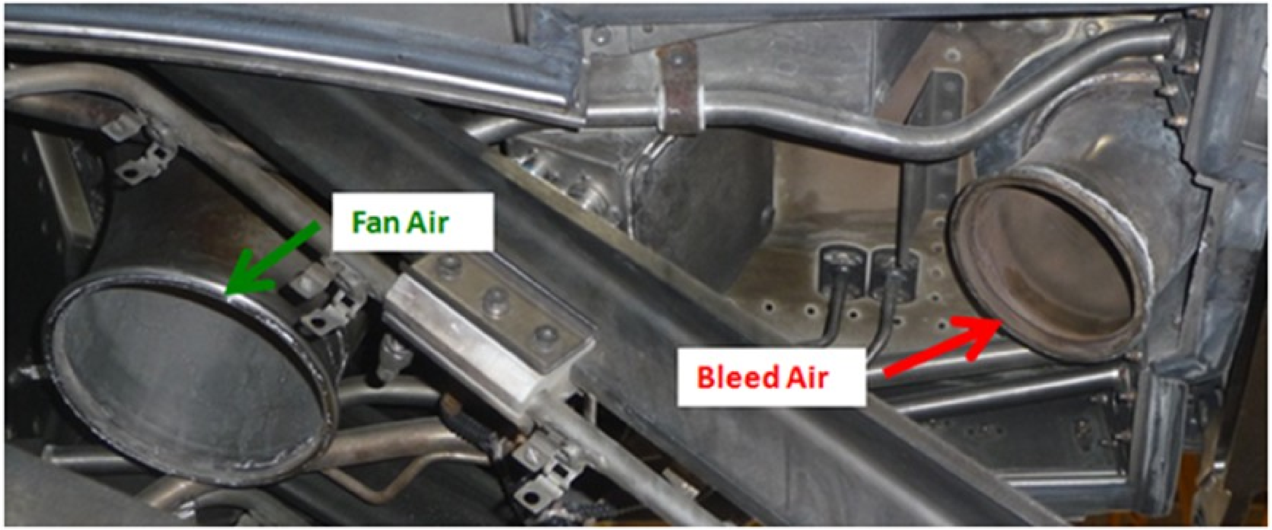
Distribution of Engine Oil with Metal Nanoparticles

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.



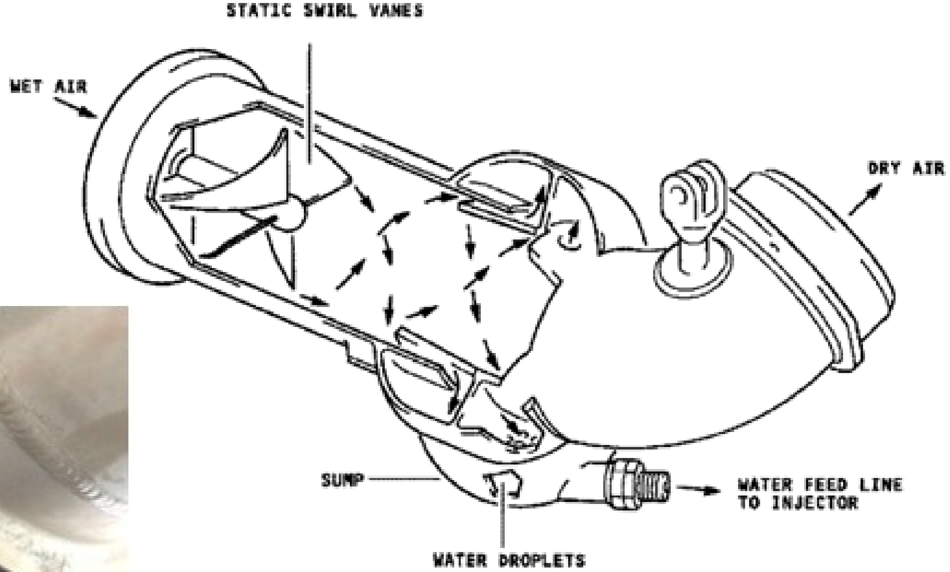
Distribution of Engine Oil with Metal Nanoparticles

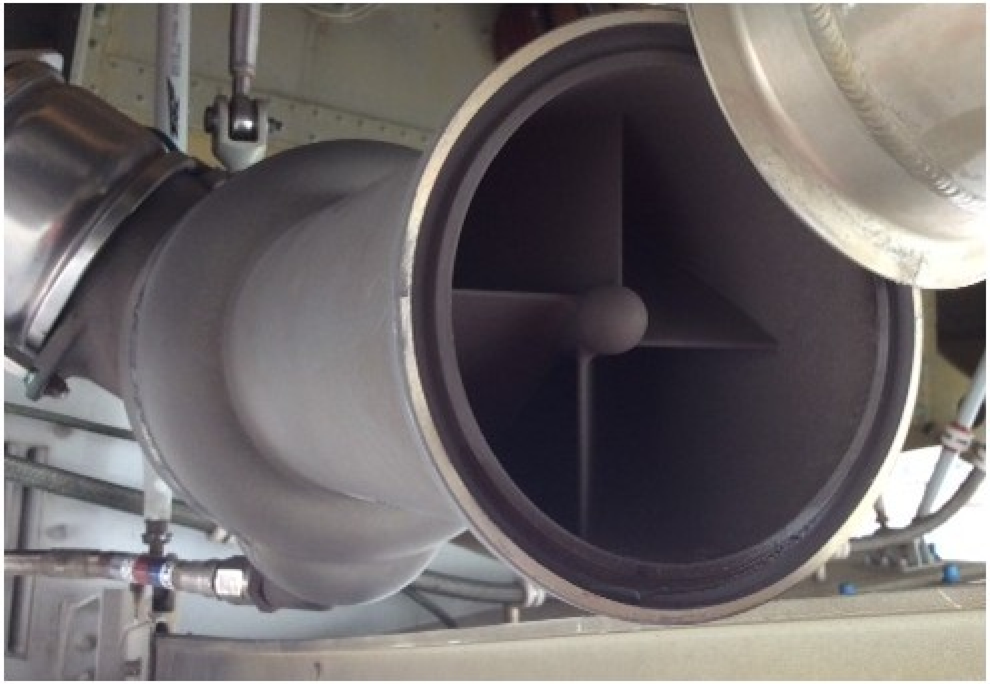
Engine Oil Colors Bleed Air Duct Black

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.

Distribution of Engine Oil with Metal Nanoparticles

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

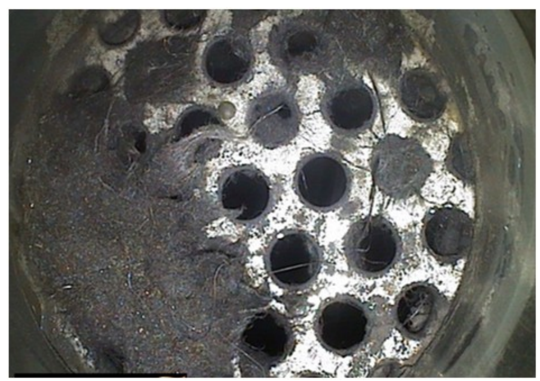
Engine Oil Colors Cabin Air Duct Black

Left: A 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

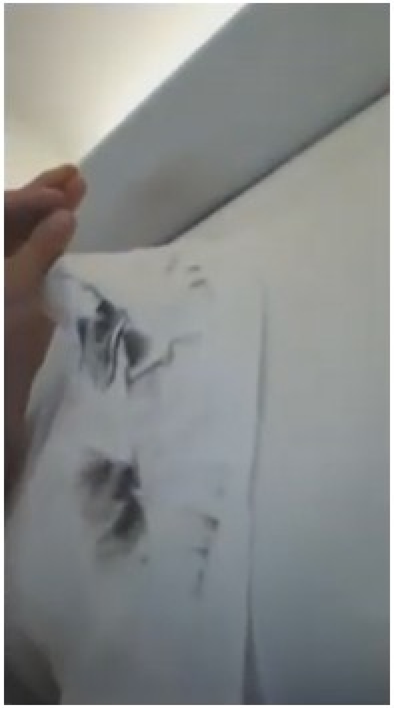
Engine Oil Colors Riser Ducts Black

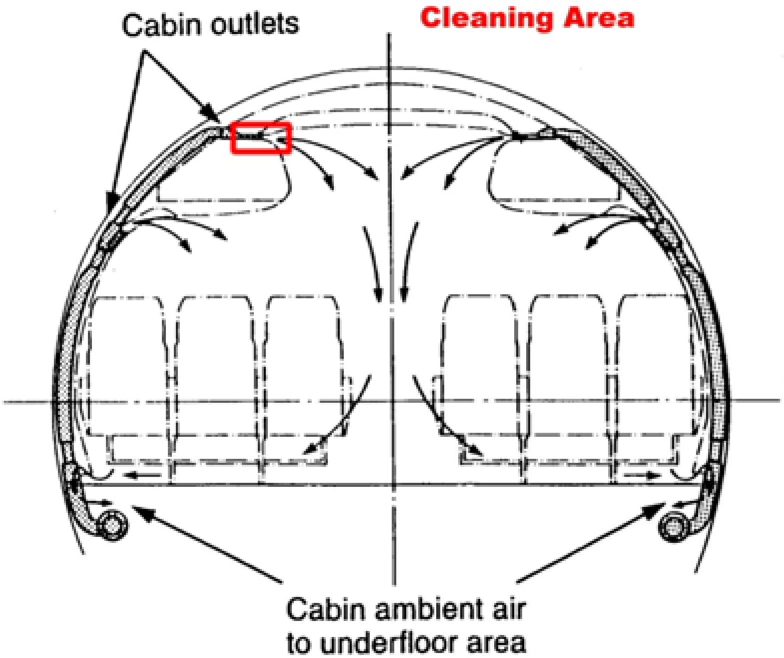
Video: https://bit.ly/2YXcL3a

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



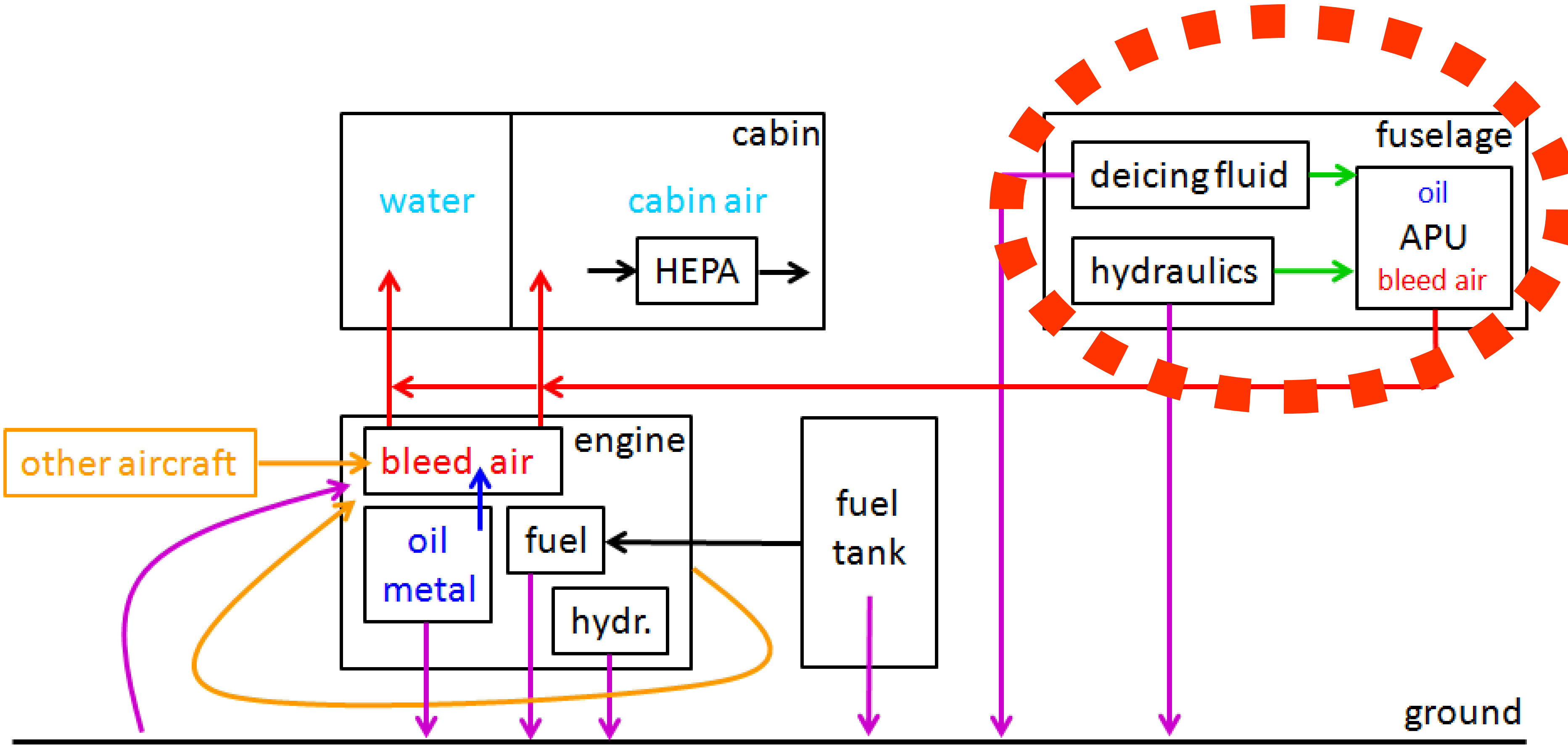


Left: Cleaning on top of the overhead bins of an Airbus A320 brings to light dirt that is clearly more than dust. The black residue known from the ducts settles also on the bin surface. Picture source: **Video**: https://youtu.be/uQfA_DiMBS8
Right: Airbus A320 cabin cross section with the upper cabin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

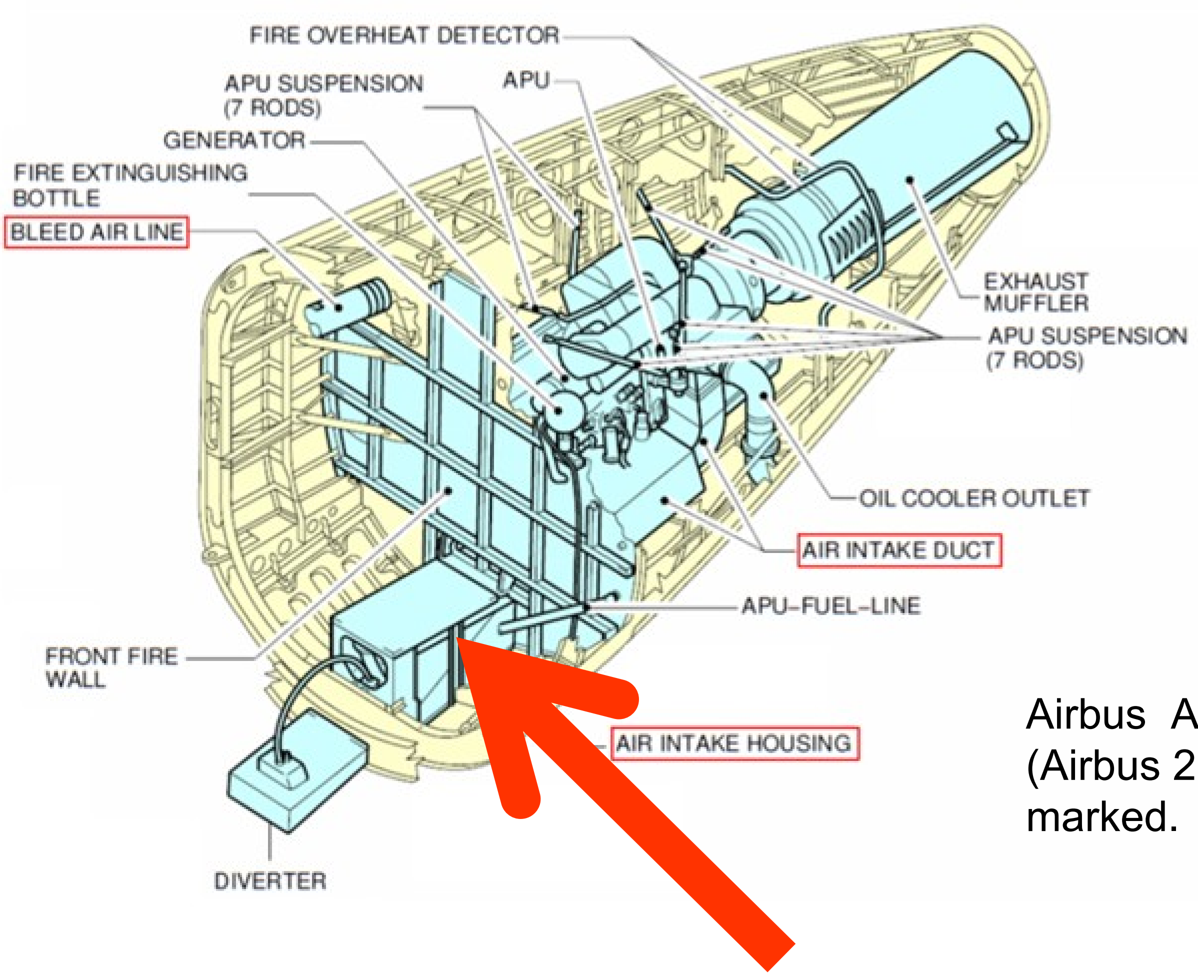
Distribution of Hydraulic and Deicing Fluid

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 2019a

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

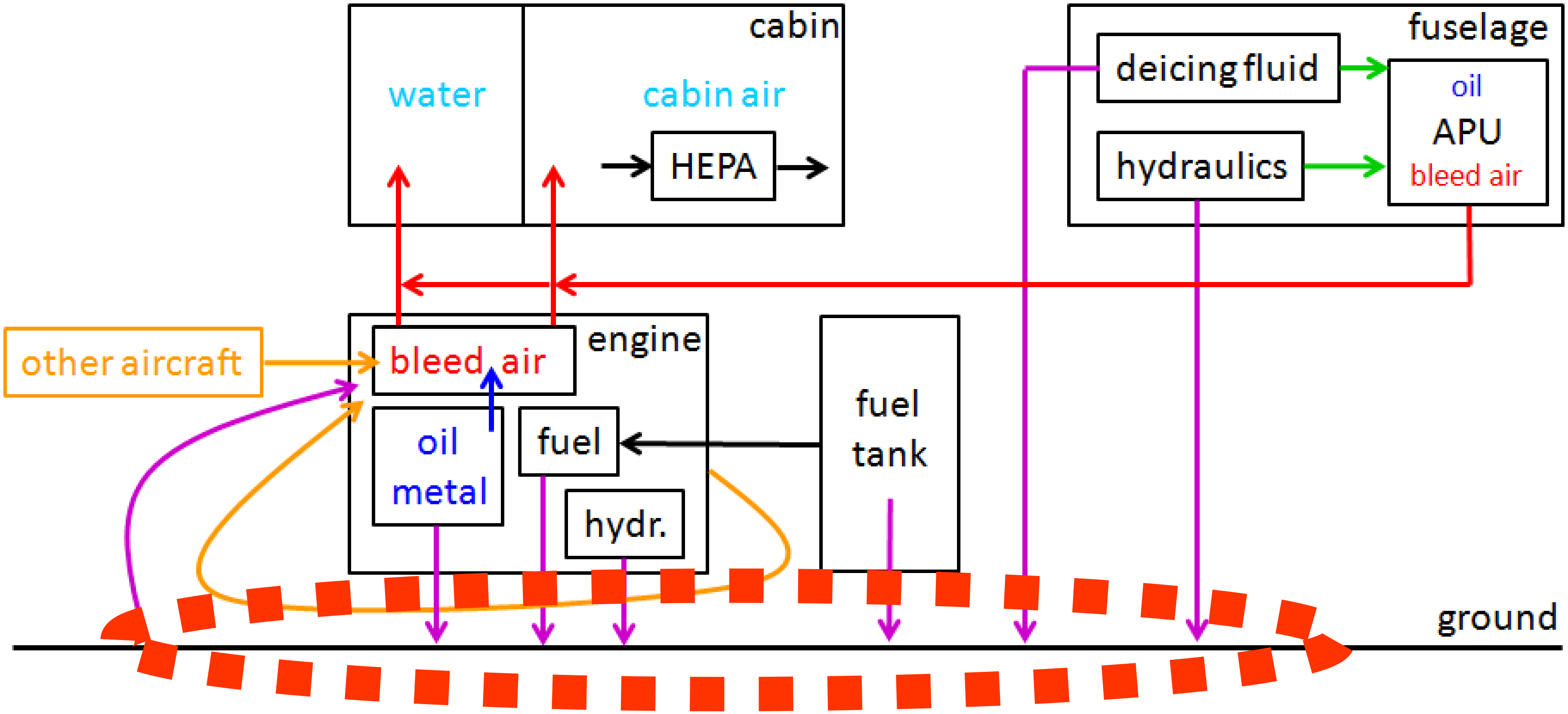
Vera-Barcelo 2013

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)

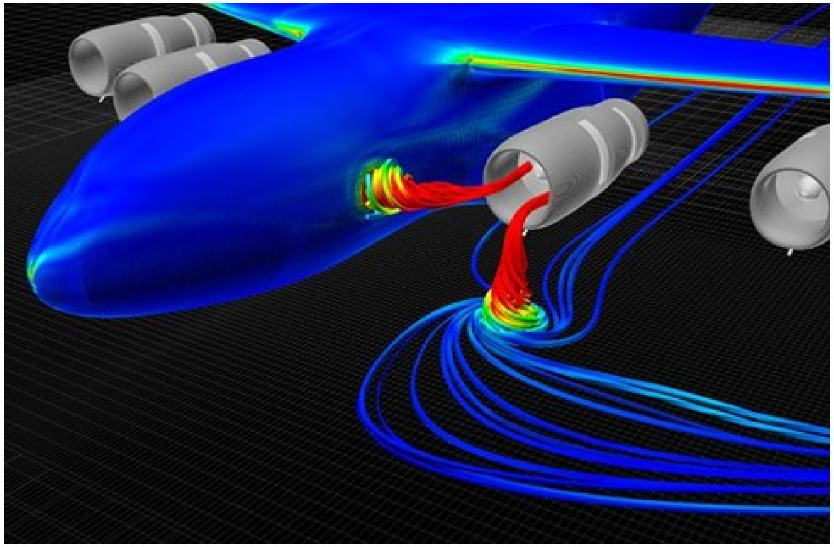
■ ■ ■

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

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).

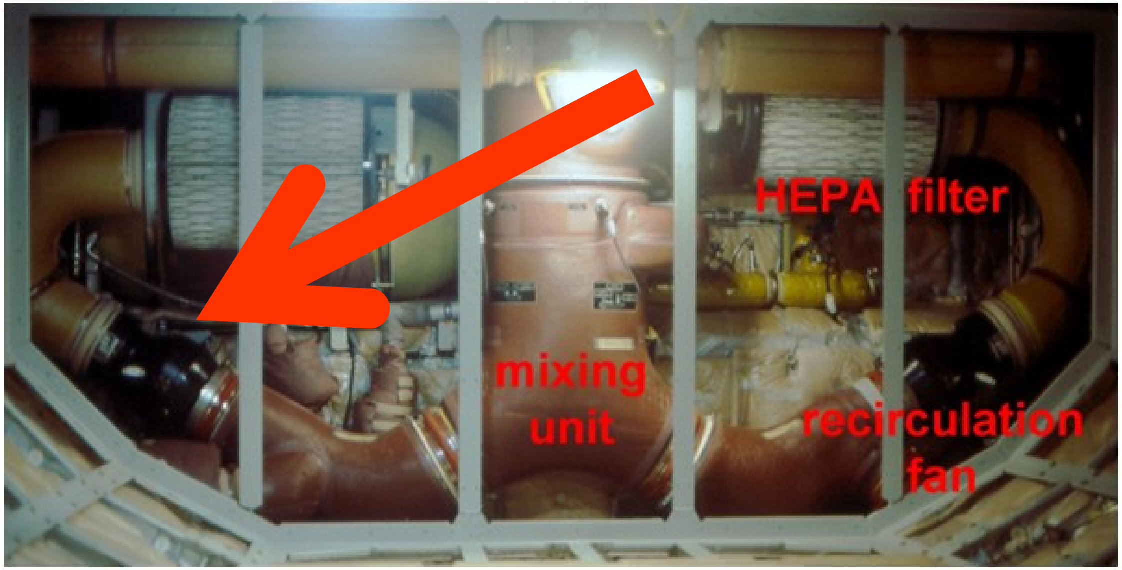


Simulation of two intake vortices, one of them as a ground vortex. The rotation of the vortex is visible (https://perma.cc/VH99-87XS).

More Contamination

More Contamination

Contaminated Recirculation Fan



The face of the recirculation fan of an Airbus A320 is covered by an oily back soft substance that can be scraped off with a screw driver. Picture source: **Video**: https://bit.ly/2YXcL3a

Contaminated Cargo Compartment Heating

The ambient air inlet in the cargo compartment of the Airbus A320 for cargo compartment heating and ventilation. The inlet is full of moist dust.

Filtration Systems

Filtration Systems

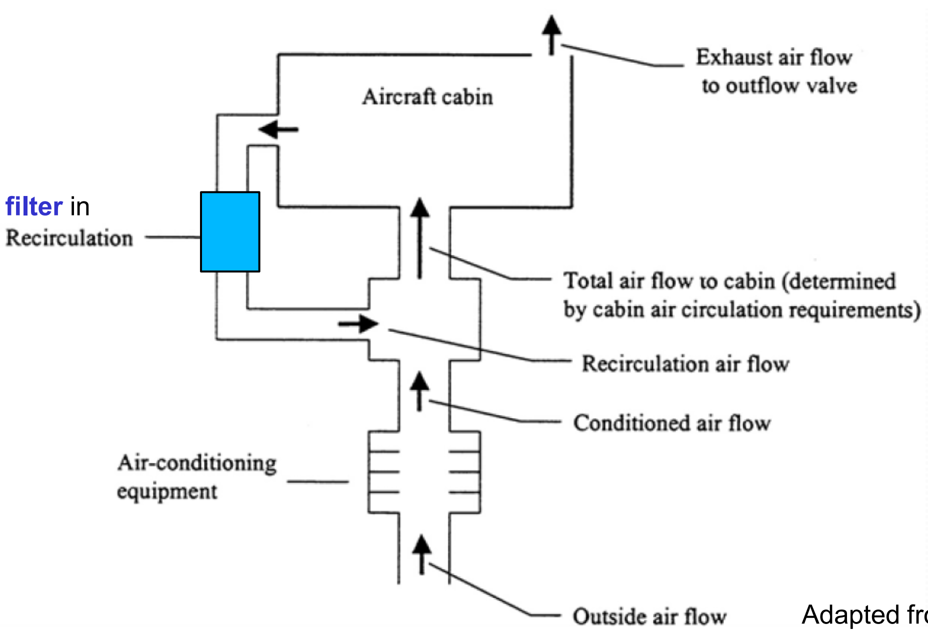
Filter in the Recirculation Path

Pall offers Odour/VOC Removal Filters

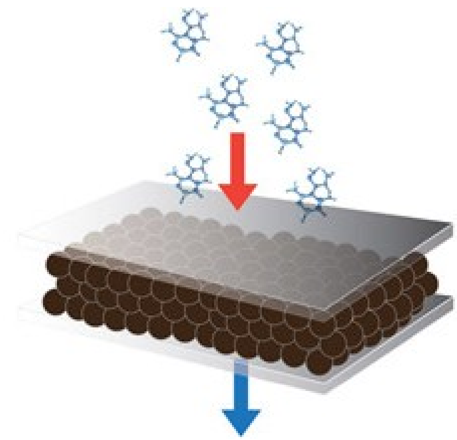
- "The carbon adsorbent is effective at adsorbing volatile organic compounds (VOC). Test results have shown a removal efficiency of 65% ... 73% when challenged with TCPs in the gaseous phase." (Pall 2011)

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)



Schematic of carbon filter
(Pall 2011)

(Lufthansa 2017)

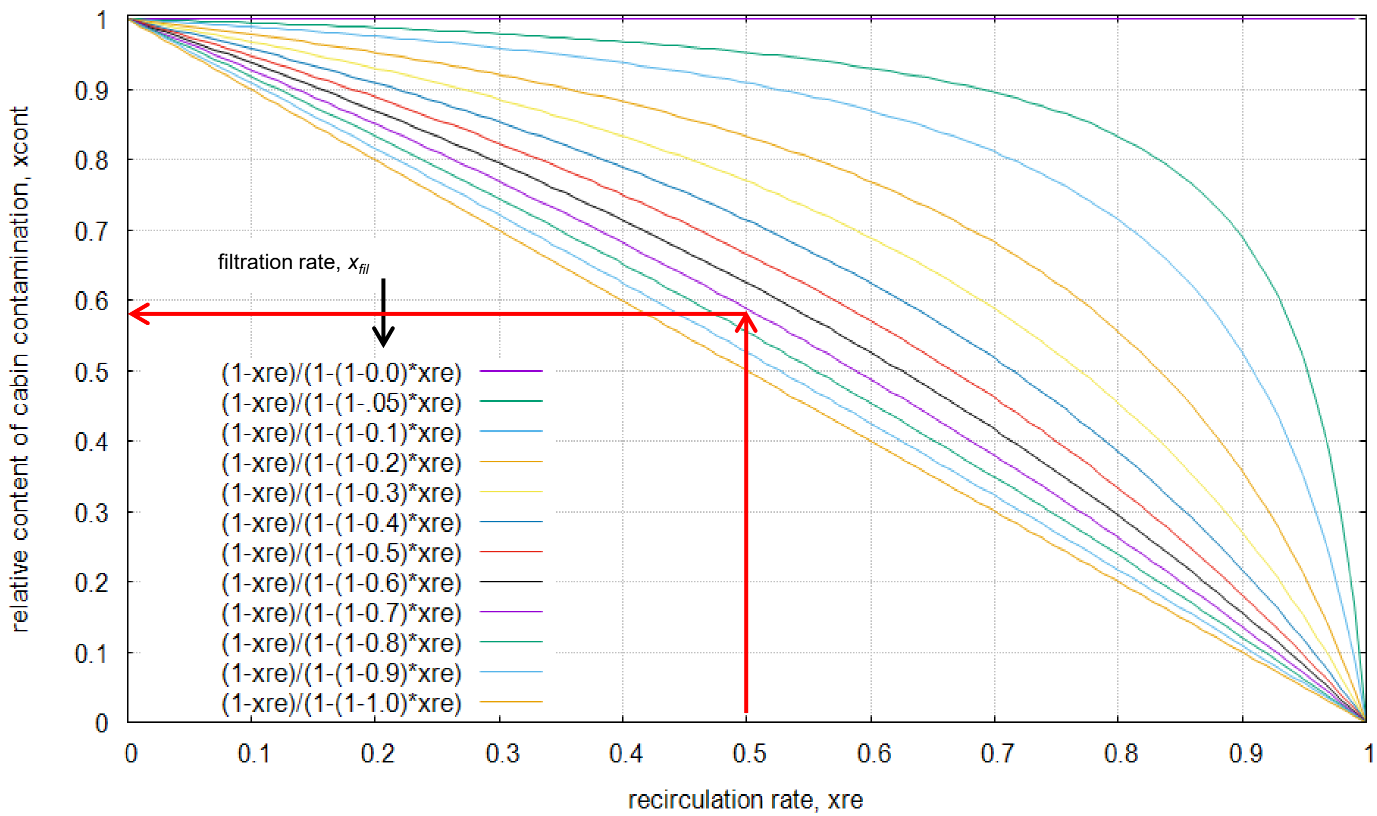
Filtration Systems

Efficiency of Filter in the Recirculation Path

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

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%.**



for $x_{fil} = 1$:

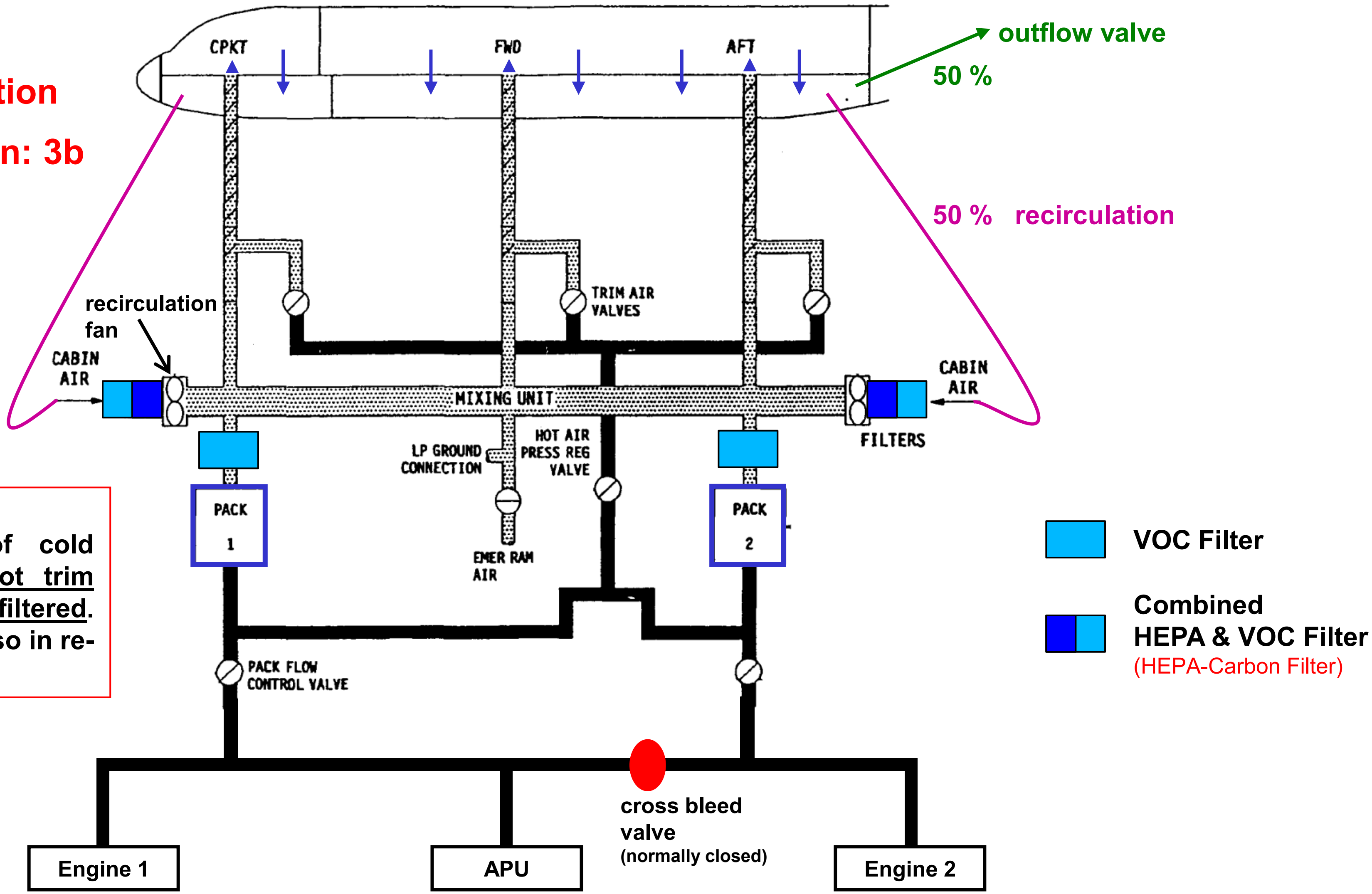
$$\frac{x_{cont,cab}}{x_{cont,in}} = 1 - x_{re}$$

Filtration Systems

Full *

Filtration

Option: 3b



*
Filtration of cold air only. Hot trim air is not filtered. Filtration also in re-circulation.

Maintenance

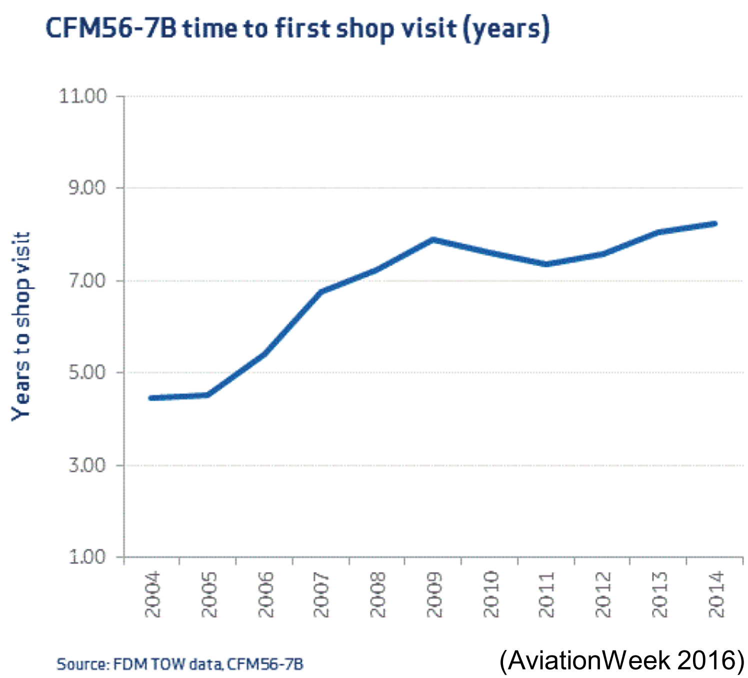
Engines Longer on Wing

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

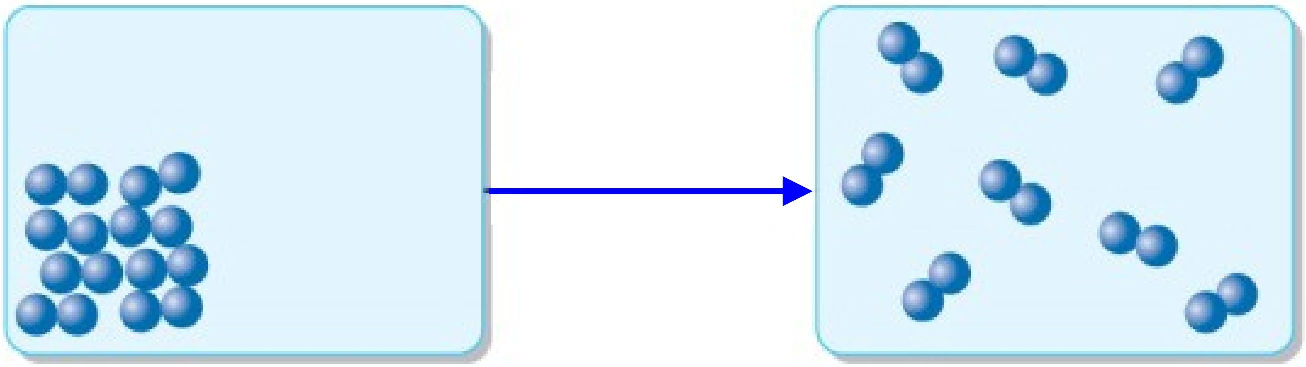
are not cleaned as instructed by Airbus, because

- ***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.***

Entropy – Distribution by Law of Nature

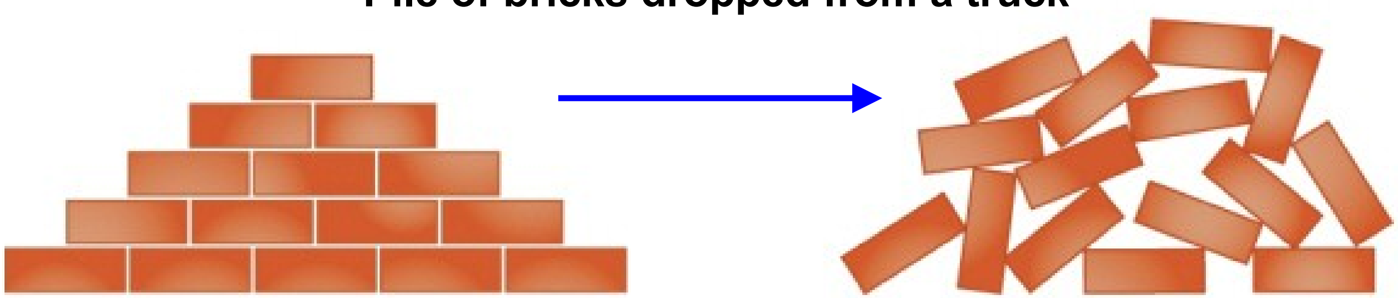
Contaminants Spread Everywhere

Gas spreads to fill space over time



Entropy (Disorder) Always Increases!

Pile of bricks dropped from a truck



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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