Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

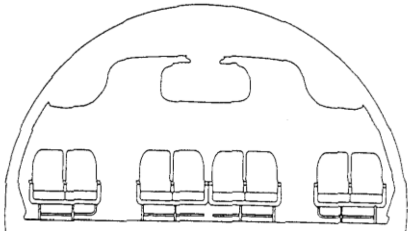
Cabin Air Contamination Events – Engineering Aspects

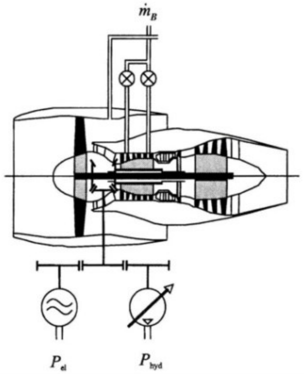
Dieter Scholz Hamburg University of Applied Sciences

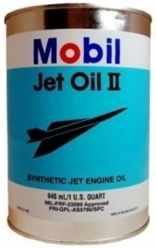
https://doi.org/10.5281/zenodo.13763432

International Aircraft Cabin Air Conference 2023

Online, 27 - 29 June 2023







Cabin Air Contamination Events – Engineering Aspects

Abstract

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, jet engine seals leak oil by design in small quantities. The oil leaking into the compressor contains toxic additives. Deicing fluid, hydraulic fluid, and fuel can find their way into the cabin on various pathways.

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. **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. 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.

In failure cases, Cabin Air Contamination Events (CACE) due to engine oil can fill the cabin densely with white smoke. **Cabin ventilation can be described** in a simplified way **with a differential equation**. Application of this equation shows that **10 minutes** of oil contamination can be sufficient to fill a cabin with smoke. If contamination stops, most of the smoke is gone within the next 10 minutes and after further 10 minutes there is hardly any smoke left in the cabin.

Fire is the biggest danger on bord. In case of smoke, when a fire can be ruled out and the smoke source cannot be isolated, diversion and **descent to 10000 ft** for direct ventilation with air from outside is required. The aircraft must be flown slower, but still range is reduced (fuel consumption is higher). This is taken care of in normal flight planning (to take care of a possible loss of cabin pressure).

Oil concentration in the cabin is decreasing with engine size (if all other parameters are assumed to be equal).

Pack burn is an attempt for decontamination of ducts and components. It releases oil fumes impressively to the outside, but cleaning is only partial.

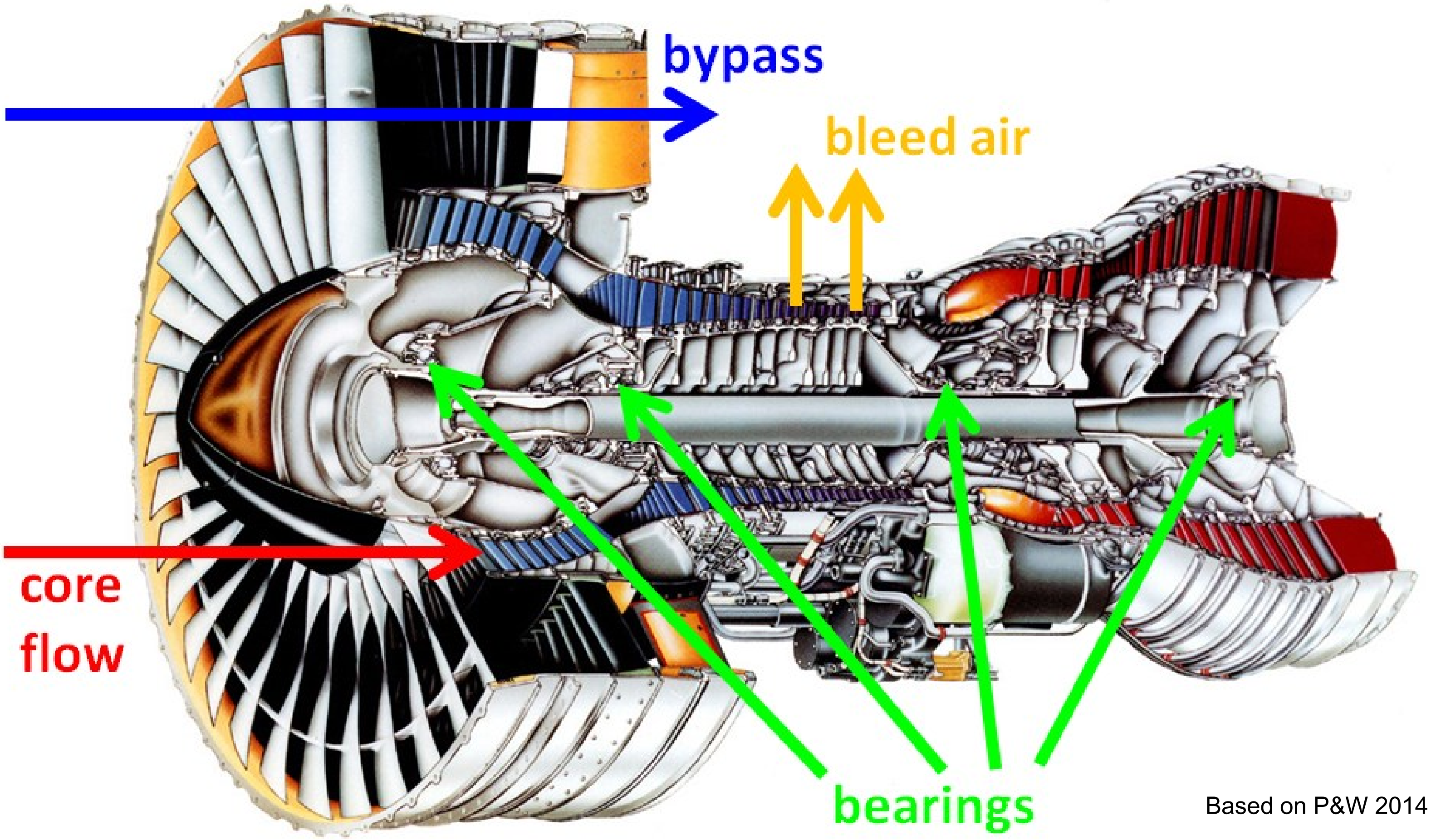
An investigation of **layover times after a CACE** shows that many aircraft are released back into service so quickly that proper maintenance is impossible. Some severe CACE have, however, left aircraft in maintenance for up to one month.

Contents

Air from the Jet Engine into the Cabin

Air from the Jet Engine into the Cabin

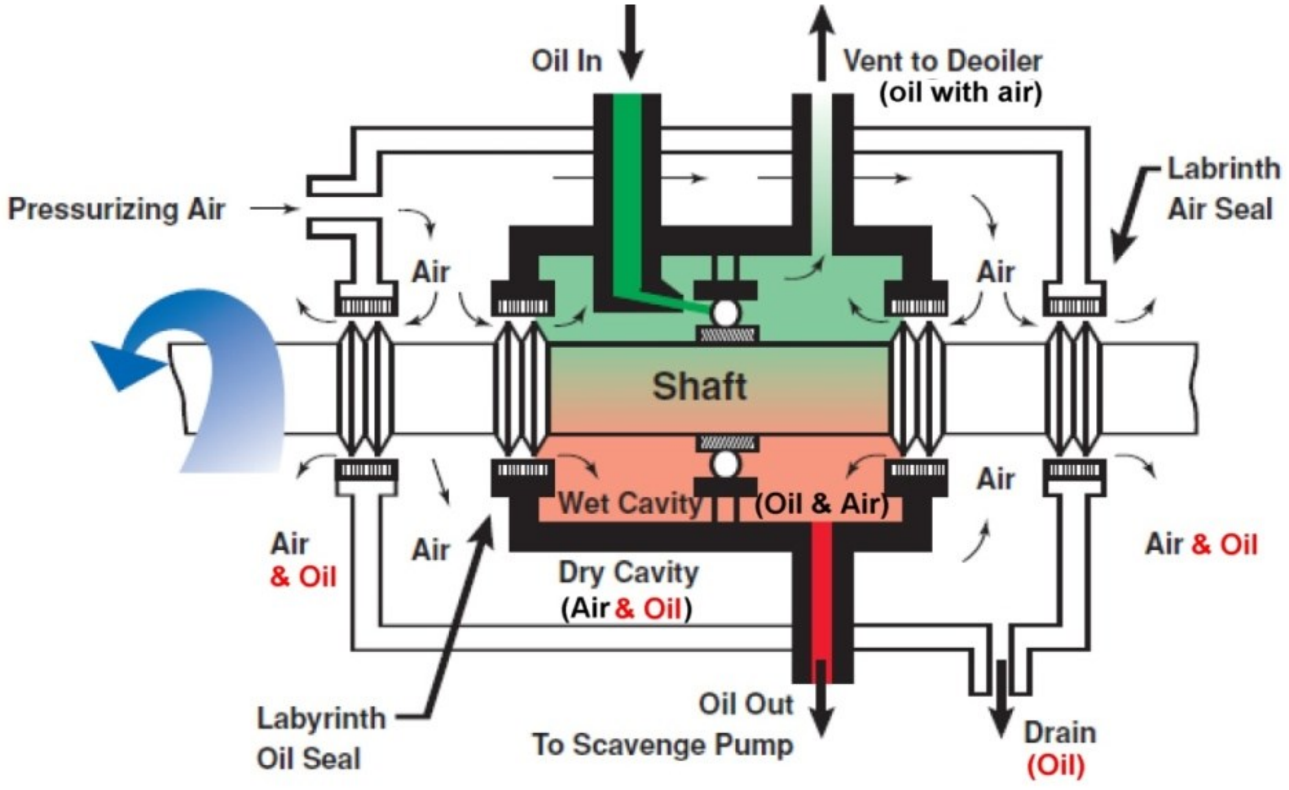
Engine Bearings and Bleed Air



Based on P&W 2014

Air from the Jet Engine into the Cabin

Lubrication and Sealing of Engine Bearings



Based on Exxon 2017

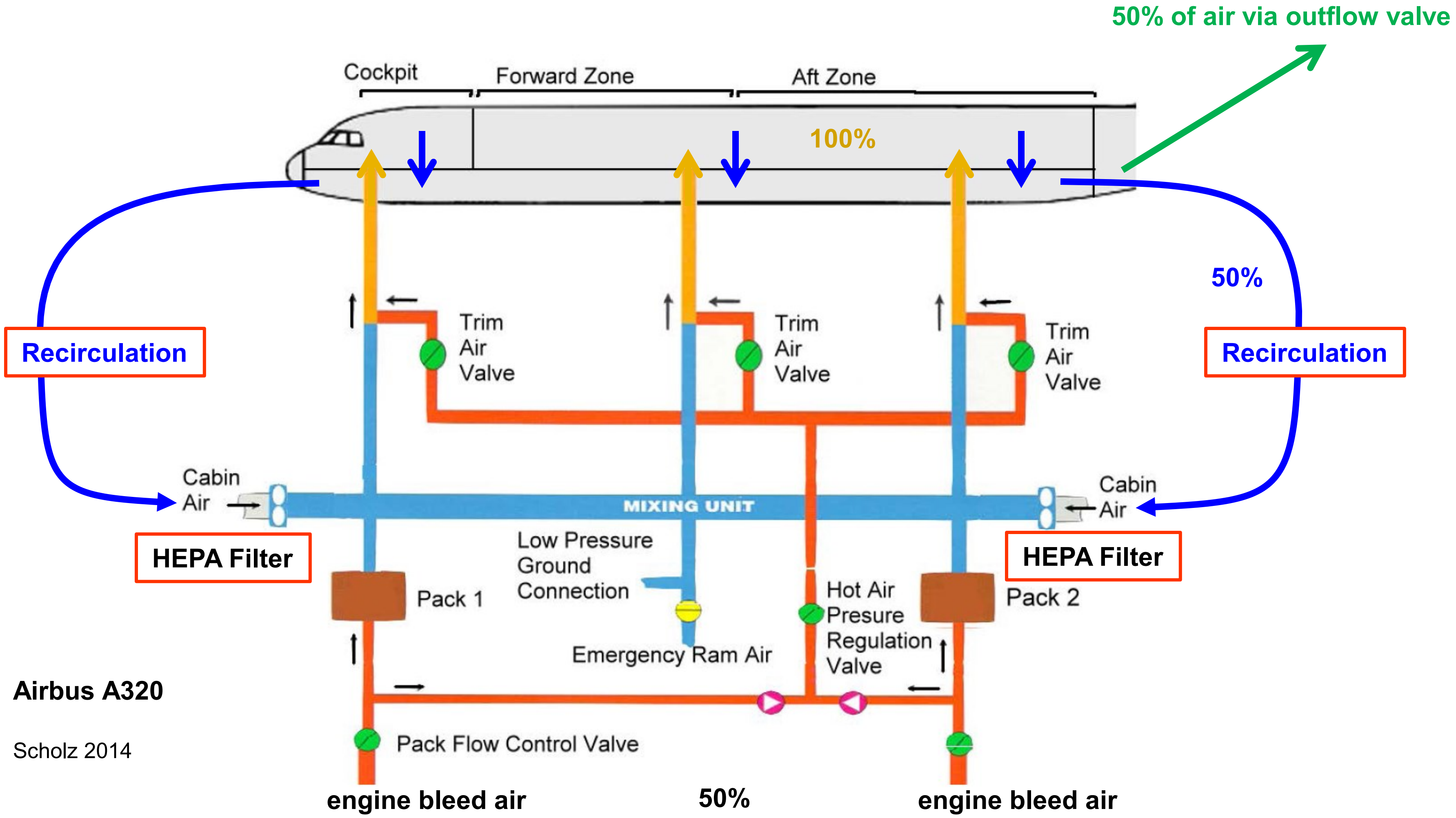
Normal operation of engine seals:

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!**

Air from the Jet Engine into the Cabin

Air Conditioning System



Airbus A320

Scholz 2014

Distribution of Fluids

Engine Oil

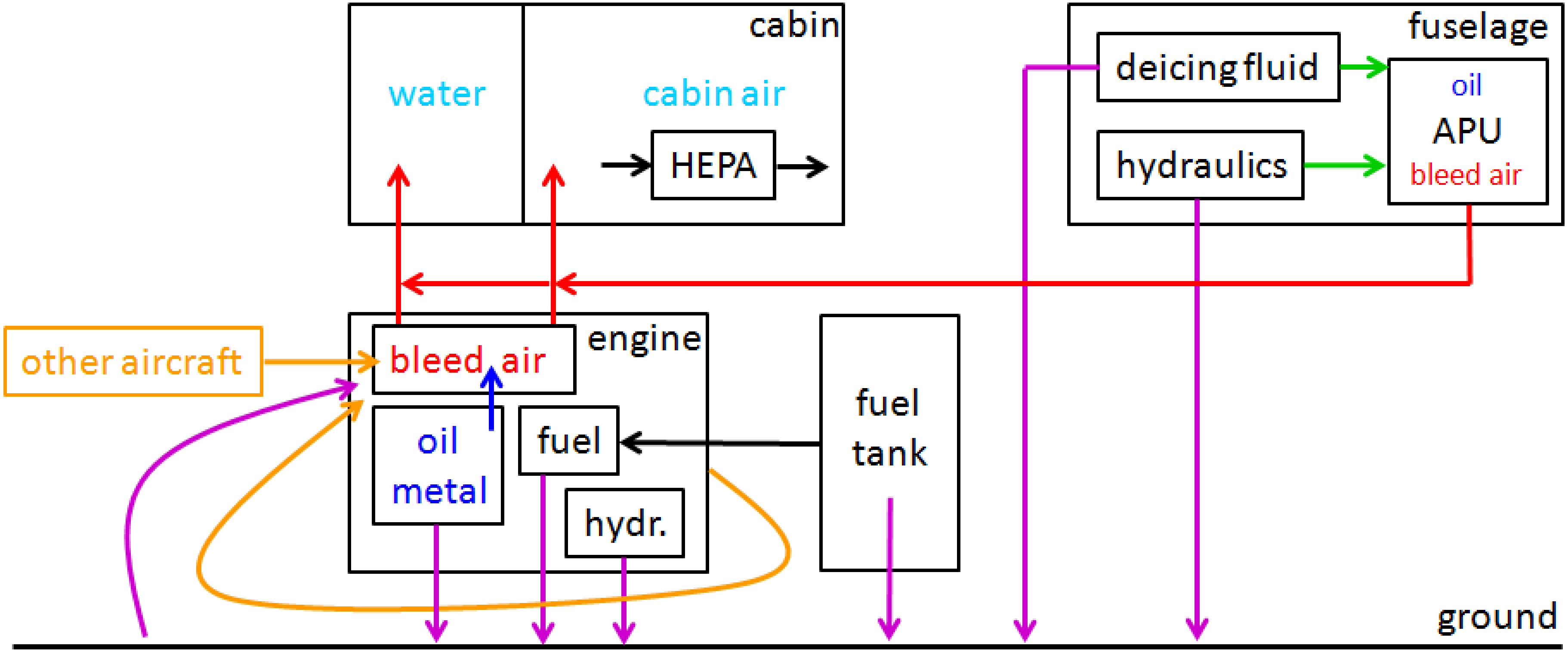
Hydraulic Fluid

Deicing Fluid

Fuel

Distribution of Fluids

Contaminants and Their Routes Into the Cabin

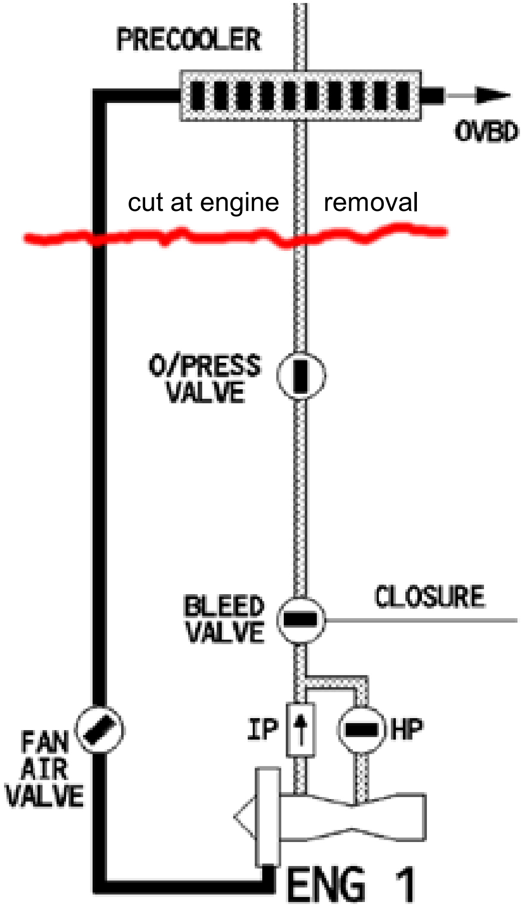


Scholz 2022

Distribution of Engine Oil

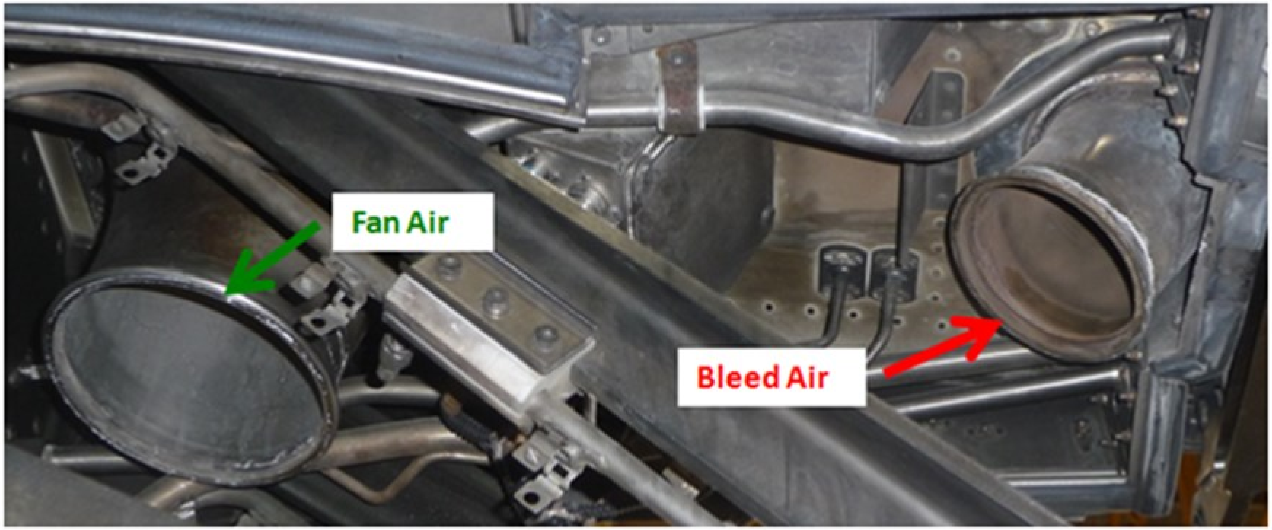
Distribution of Engine Oil

Engine Oil Colors Bleed Air Duct Brown



Airbus A320 FCOM

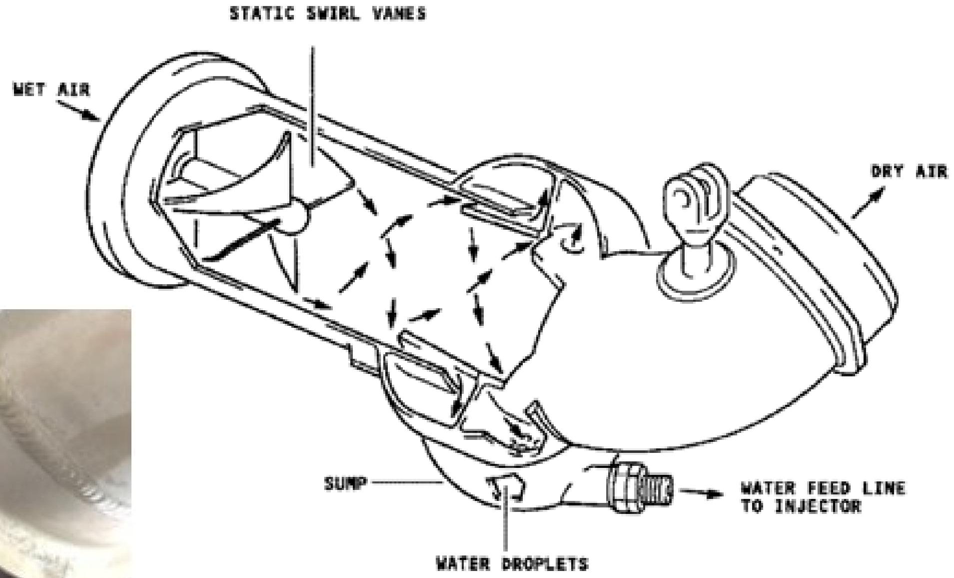
Fan air and bleed air ducts at the interface between engine and wing on an Airbus A320. The brown stain in the bleed air duct appears to be engine oil residue. In comparison, the fan air duct is clean. Air temperature in the bleed air duct about 400 °C.



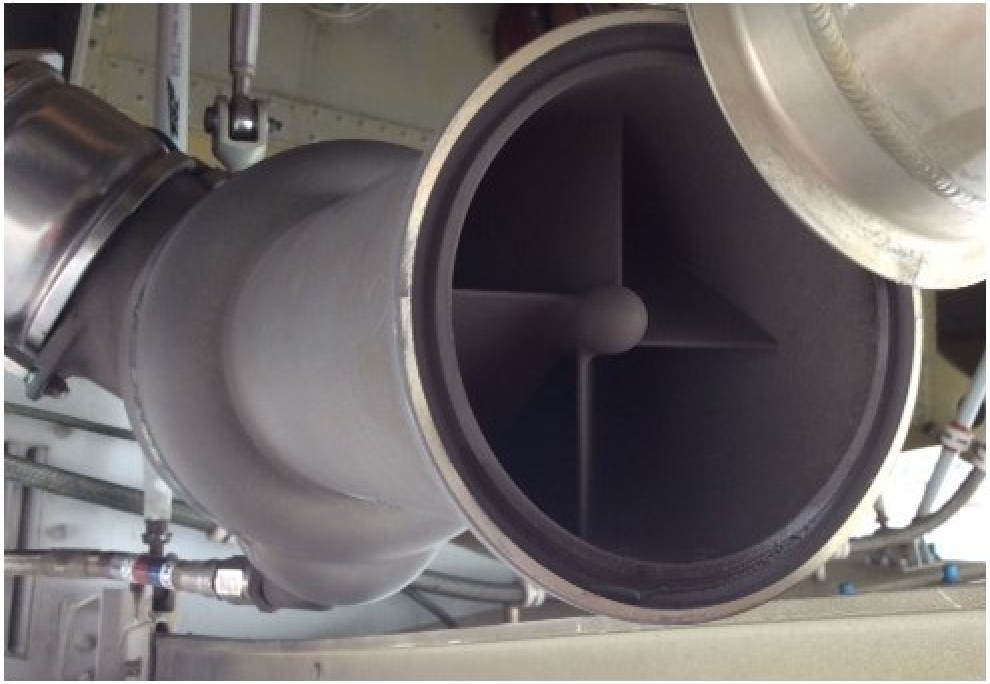
Scholz 2022

Distribution of Engine Oil

Engine Oil Residue Accumulates in Water Extractor



Airbus 1999



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

Distribution of Engine Oil

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.

Scholz 2022

Distribution of Engine Oil

Flow Limiter in Air Conditioning Ducts

Scholz 2022

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).

Hansen 2019

Distribution of Engine Oil

Engine Oil Colors Riser Ducts Black

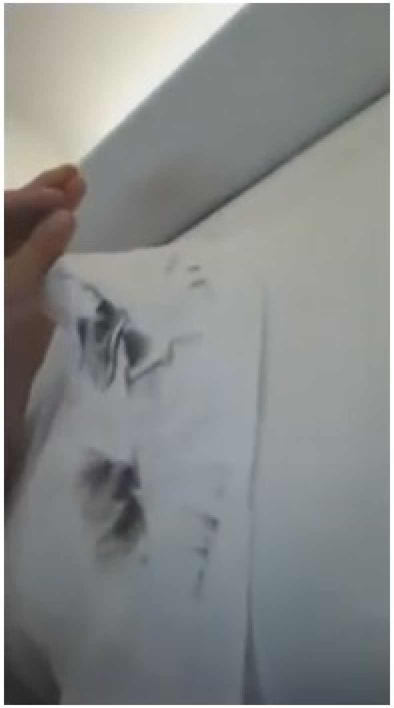
Video:
https://bit.ly/2YXcL3a

Scholz 2022

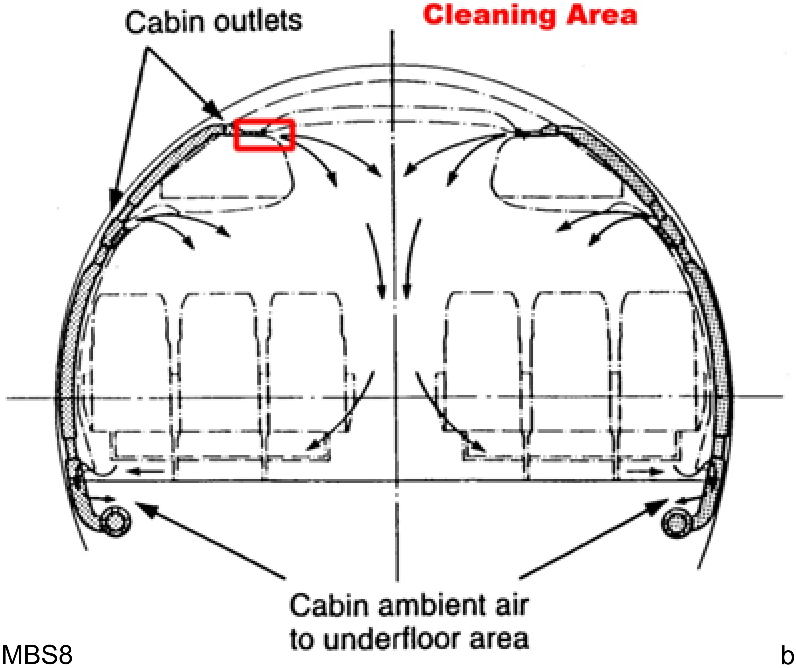
Riser ducts and lower cabin air outlet on an Airbus A320 aircraft. The red line close to the cabin floor shows, where the duct was separated and opened. It is black inside from engine oil residue.

Distribution of Engine Oil

Black Residue Settles on the Overhead Bin's Surfaces



Video:
https://youtu.be/uQfA_DiMBS8



based on Airbus 1999

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.

Right: Airbus A320 cabin cross section with the upper cabin air outlet releasing potentially contaminated air on top of the overhead bins.

Cabin Ventilation Basics

Cabin Ventilation Basics

Cabin Air Contamination Event Due to Engine Oil After Technical Fault

Top: 2010-09-17, US Airways US-432, Boeing 757-200. Bottom: 2018-12-10, Indigo flight 6E-237, Airbus A320neo.

Cabin Ventilation Basics

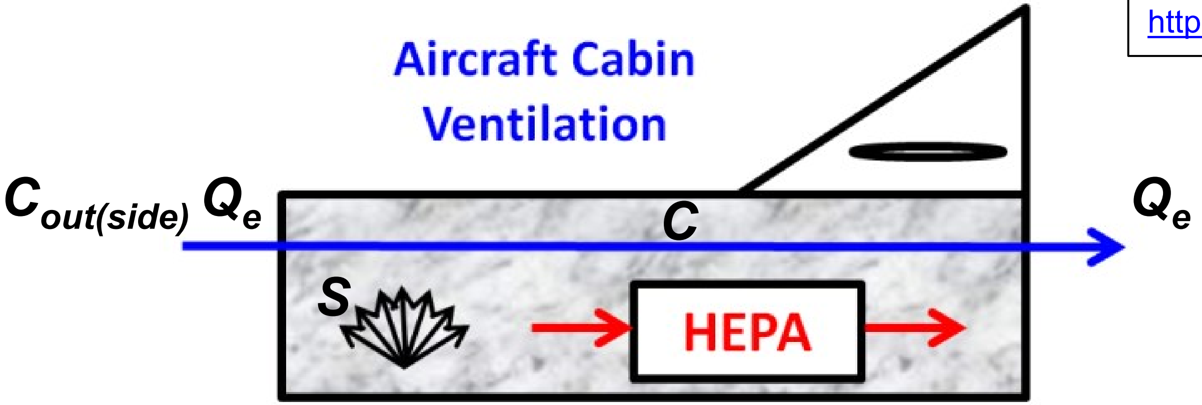
Cabin Air Contamination Event Due to Engine Oil After Technical Fault

Top:2019-08-22, Hawaiian Airlines HA47, A321neo. Bottom: 2019-08-05, British Airways BA-422, Airbus A321.

Cabin Ventilation Basics

Ventilation Equation

SCHOLZ, Dieter, 2020.
Aircraft Cabin Ventilation Theory,
Memo.
Hamburg University of Applied Sciences.
https://doi.org/10.31224/osf.io/ac6p8

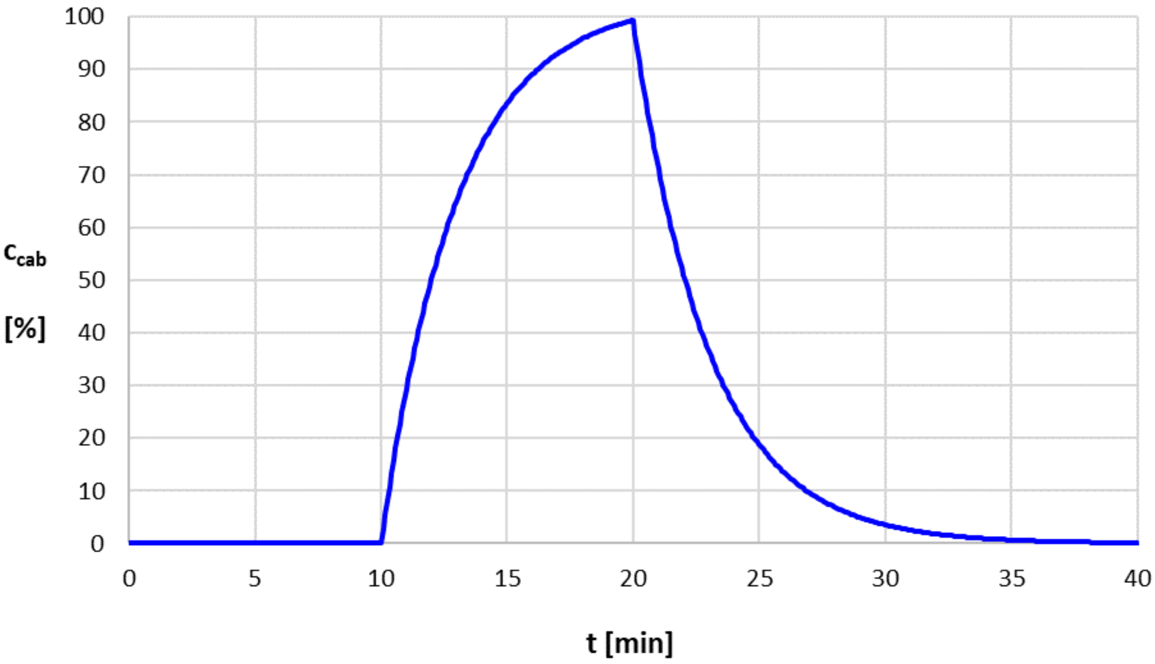


$$S + Q_e C_{out} - Q_e C = V \frac{dC}{dt}$$

S:	source strength in kg/s
Q_e:	effective air flow rate for ventilation in m³/s
C:	concentration of CO2 or any other substance in kg/m³ in the room
C_{out}:	concentration of CO2 or any other substance in kg/m³ outside of the room
V:	volume of the room

Cabin Ventilation Basics

Cabin Air Contamination – Time History



The hydrocarbon concentration in the cabin, c_{cab} is calculated from a simple box model. In this example, oil is released at constant rate for t = 10 minutes. Within another 10 minutes the cabin is mostly ventilated. After another 10 minutes there is hardly any contamination left in the cabin. Assumed are 20 air exchanges per hour, in other words one exchange every 3 minutes.

STICHTERNATH, Lukas, 2021.
Pilot Measures against Cabin Air Contamination.
Bachelor Thesis.
Hamburg University of Applied Sciences.
https://doi.org/10.15488/11531

Descending to 10000 ft

STICHTERNATH, Lukas, 2021. *Pilot Measures against Cabin Air Contamination*. Bachelor Thesis. Hamburg University of Applied Sciences. https://doi.org/10.15488/11531

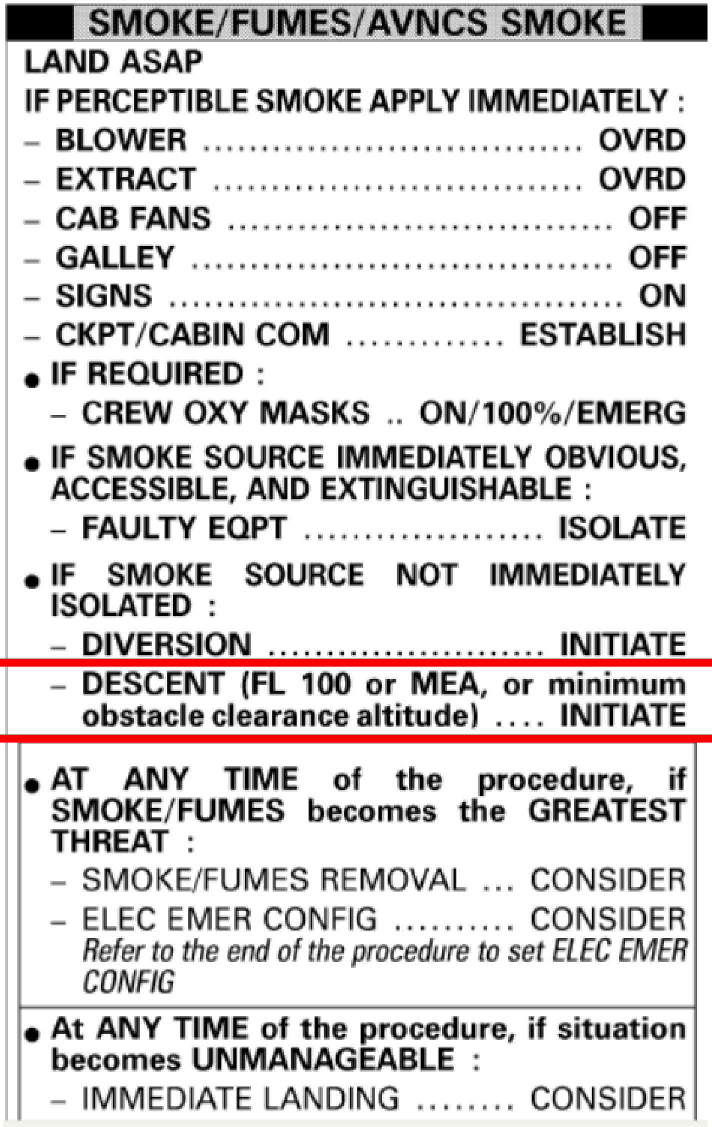
Also in this Project:

Sensor-Based Trouble Shooting

Descending to 10000 ft

Evaluation of Check Lists

Standard actions (example A320):
Must be applied **in all cases of smoke.**



SMOKE/FUMES/AVNCS SMOKE

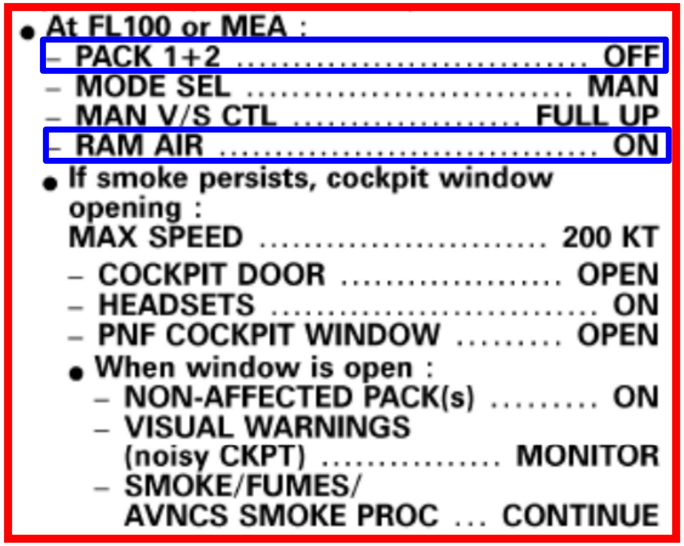
LAND ASAP

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



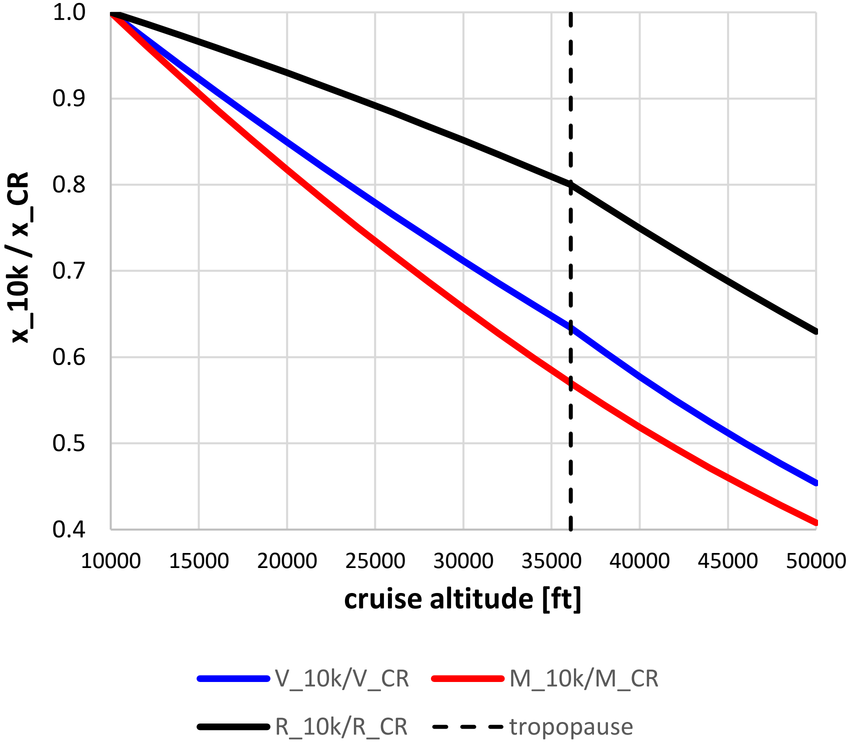
- At FL100 or MEA :
  - PACK 1+2 .... OFF
  - MODE SEL .... MAN
  - MAN V/S CTL .... FULL UP
  - RAM AIR .... ON
  - If smoke persists, cockpit window opening :

    MAX SPEED .... 200 KT
    - COCKPIT DOOR .... OPEN
    - HEADSETS .... ON
    - PNF COCKPIT WINDOW .... OPEN
    - When window is open :
      - NON-AFFECTED PACK(s) .... ON
      - VISUAL WARNINGS (noisy CKPT) .... MONITOR
      - SMOKE/FUMES/ AVNCS SMOKE PROC ... CONTINUE

https://www.smartcockpit.com

Descending to 10000 ft

Necessary to Reduce Mach Number and Speed, but Range is Reduced



The diagram gives approximate ratios, x_10k/x_CR of speed (x=V), Mach number (x=M), and range (x=R) after descending to 10000 ft (10 kft) – marked "10k". The dashed line shows the tropopause at 11000 m (36089 ft) in mid-latitudes. Optimum cruise flight typically takes place around this altitude. If a CACE happens e.g. in 36000 ft and the aircraft descends from this altitude down to 10000 ft, Mach number needs to be reduced to 57% (speed to 64%), range is only about 80% compared to its original value.

It is good to know that this **higher fuel burn <u>is</u> taken care of in <u>normal</u> flight planning**. Normal flight planning does not take a CACE into account but does consider a descent to 10000 ft in case of loss of cabin pressure. The relevant guidelines for fuel planning for a flight can be found in Section 4.3.6 of ICAO (2010a) Annex 6. Specifically, Section 4.3.6.3 f) 1) says:

> *allow the aeroplane to descend as necessary and proceed to an alternate aerodrome in the event of engine failure or loss of pressurization, whichever requires the greater amount of fuel based on the assumption that such a failure occurs at the most critical point along the route*

Oil – Path & Consumption

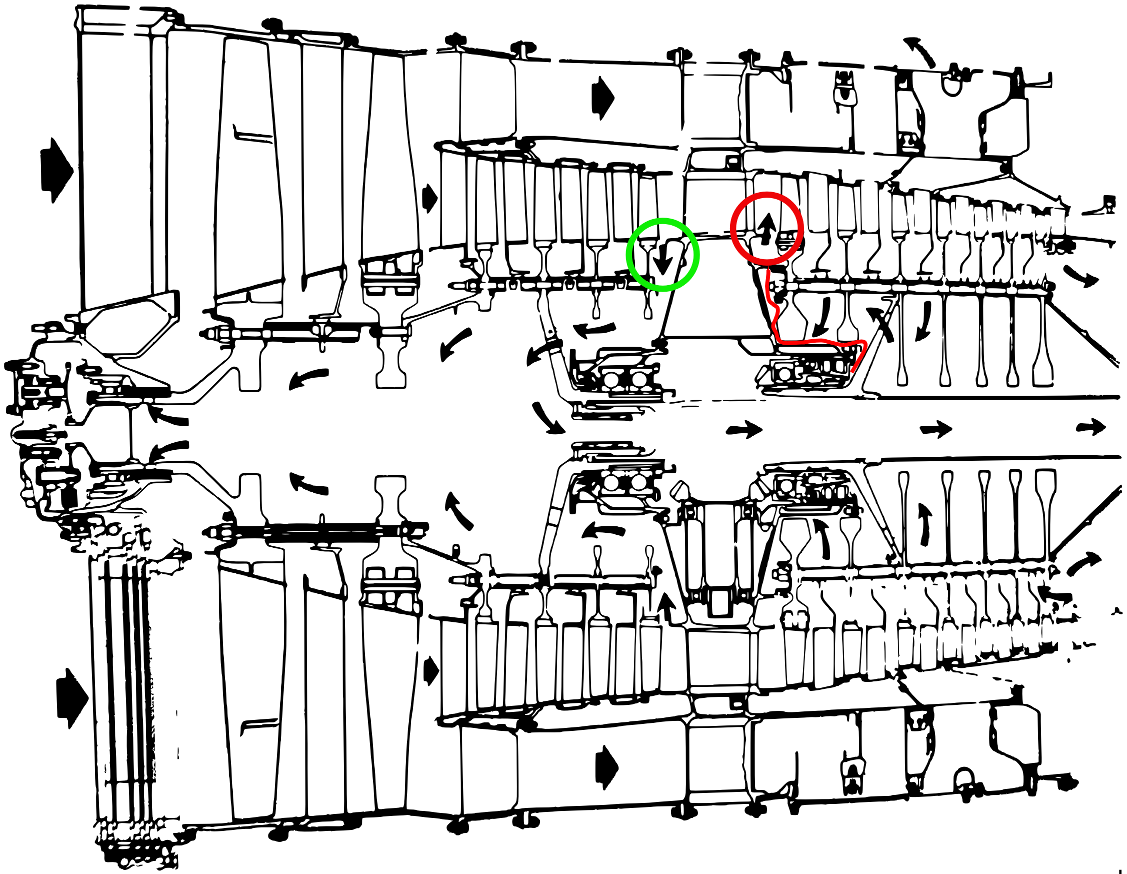
Oil Paths through Compressor

Oil Consumption

Hydrocarbon Concentration

TIETKE, Dennis, 2020. *Oil Leakage Paths within Compressors of Jet Engines and Oil Concentration in Aircraft Cabin Air*. Project. Hamburg University of Applied Sciences. https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2020-03-25.017

Oil Paths through Compressor

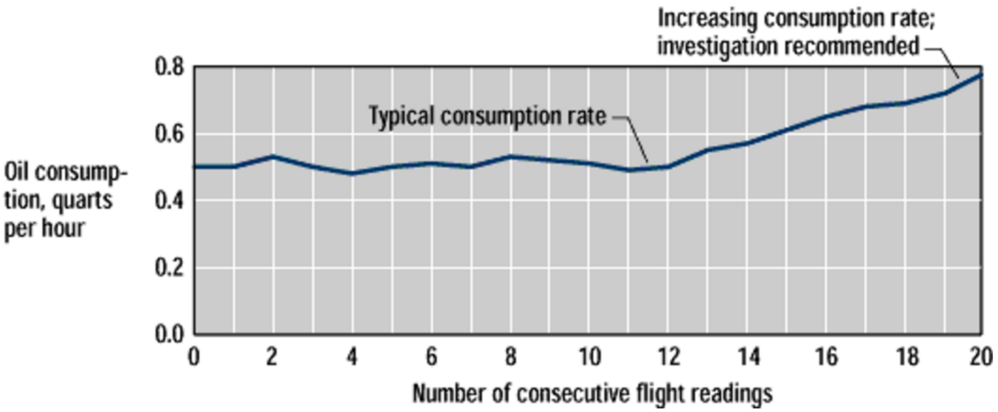


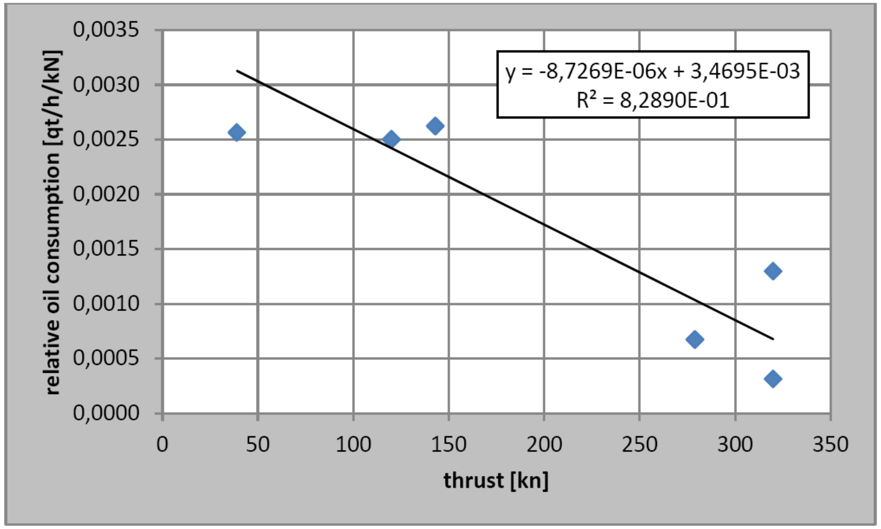
A possible path of air polluted with oil starts from the sump (indicated in red). The air returns to the main gas path in the compressor near the first stage of the high-pressure compressor.

adapted from Treager (1995)

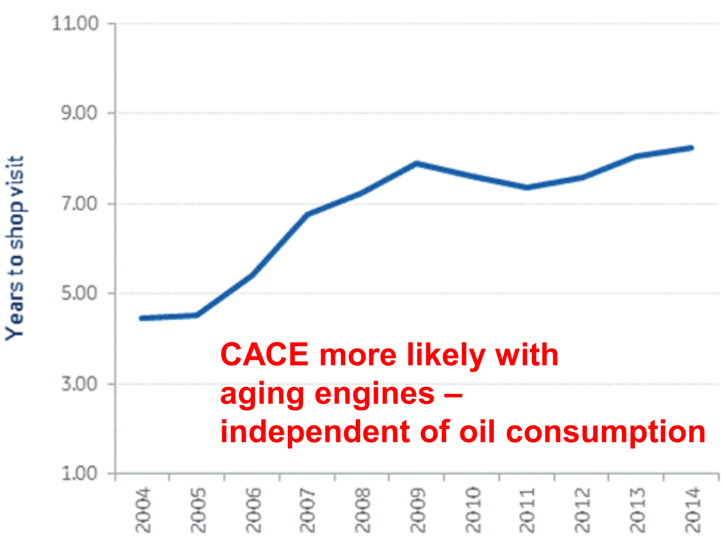
Oil – Path & Consumption

Oil Consumption – No Indicator for CACE





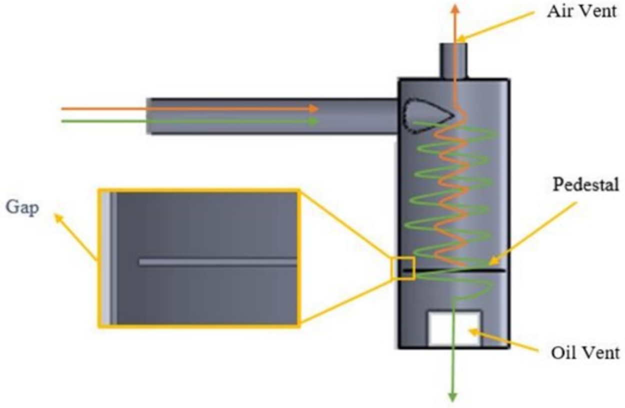
CFM56-7B time to first shop visit (years)



CACE more likely with aging engines – independent of oil consumption

Source: FDM TOW data, CFM56-7B

(AviationWeek 2016)



Oil consumption due to de-aerator design!

Oil – Path & Consumption

From Oil Consumption to Hydrocarbon Concentration in the Cabin? Yes, possible

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

Engine with **increasing size**

Parameter	CF34	V2500	CFM56	PW4000	GE90
$\dot{V}_{oil}$	$0{,}2\ qts/h$ [a]	$0{,}28\ qts/h$ [a]	$0{,}3\ qts/h$ [b]	$0{,}5\ qts/h$ [a]	$0{,}34\ l/h$ [c]
$\dot{m}_{oil}$	$0{,}1115\ g/s$	$0{,}1516\ g/s$	$0{,}1673\ g/s$	$0{,}5241\ g/s$	$0{,}1895\ g/s$
$x_{bear,up}$	3/5 [d]	3/5 [e]	3/5 [b]	3/5 [f]	4/6 [g]
x_{seal}	0,01 [h]				
S_{eng}	$1{,}42\ m^2$ [i]	$2{,}06\ m^2$ [j]	$2{,}35\ m^2$ [b]	$4{,}48\ m^2$ [f]	$8{,}3\ m^2$ [k]
n_{eng}	2 [l]	2 [l]	2 [l]	4 [l]	2 [l]
M_{CR}	0,78 [l]	0,78 [l]	0,76 [l]	0,85 [l]	0,84 [l]
$a(h_{CR})$	$295\ m/s$ [h]				
ρ_{cab}	$0{,}963\ kg/m^3$ [h]				
ρ_{CR}	$0{,}364\ kg/m^3$ [h]				
μ	5,4 [i]	4,5 [j]	5,7 [b]	4,8 [f]	9 [k]
$\frac{m_{oil,cab}}{V_{cab}}$	$17{,}3\ \frac{\mu g}{m^3}$	$14{,}4\ \frac{\mu g}{m^3}$	$16{,}9\ \frac{\mu g}{m^3}$	$10{,}7\ \frac{\mu g}{m^3}$	$8\ \frac{\mu g}{m^3}$

[a] (Scholz 2018), [b] (LTT 1999), [c] (Transportation Safety Board of Canada 2012), [d] (SmartCockpit 2020), [e] (MTU Maintenance 2020), [f] (Sumner 1997), [g] (Aviation 2016), [h] (Scholz 2017), [i] (GE Aviation 2010), [j] (IAE 2016), [k] (MTU Aero 2020), [l] These parameters may vary due to engine/aircraft configuration.

On the ASSUMPTION that 1% of consumed oil leaves through the seals:

Oil concentration in the cabin decreasing with engine size

Pack Burn

Pack Burn – Only Partial Decontamination of Ducts and Components

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 to the environment. The picture is a screenshot from the **video** https://youtu.be/d7ZfIFYcYV8

Investigation of Layover Time (2019)

Connecting
Aviation Herald
and
Flightradar24

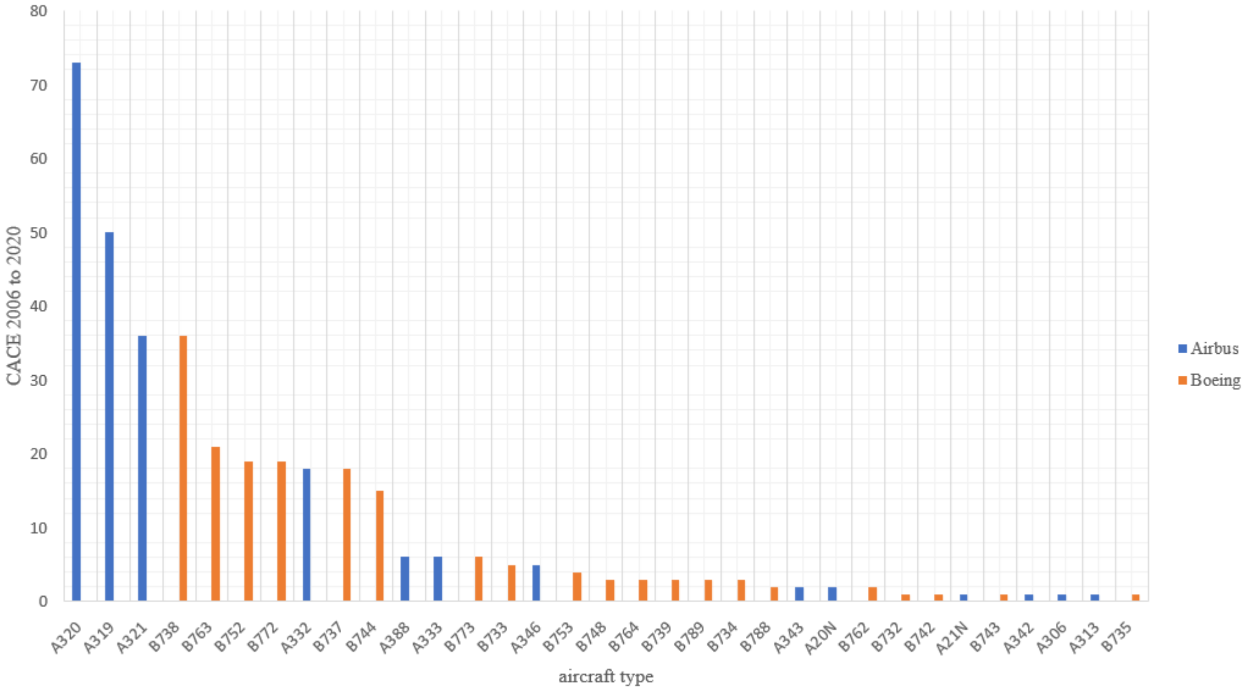
AYAN, Taner, 2020. *Analyse der Liegezeiten von Passagierflugzeugen nach Fume Events mittels Flugverfolgung*. Project. Hamburg University of Applied Sciences. https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2020-01-15.016

Investigation of Layover Time (2019)

Number of CACE from Aviation Herald: Aircraft Types

Search for "fumes" in Aviation Herald' database with subsequent manual filtering of the results and matching with Flightradar24.

Number of CACE from 2006 to 2020: 425. Per year: 28 (*only a very small sample of the global total*)
Airbus: 202 (47.5%), Boeing: 166 (39.1%), Embraer: 18 (4.2%), Bombardier: 10 (2.4%), others: 29 (6.8%).

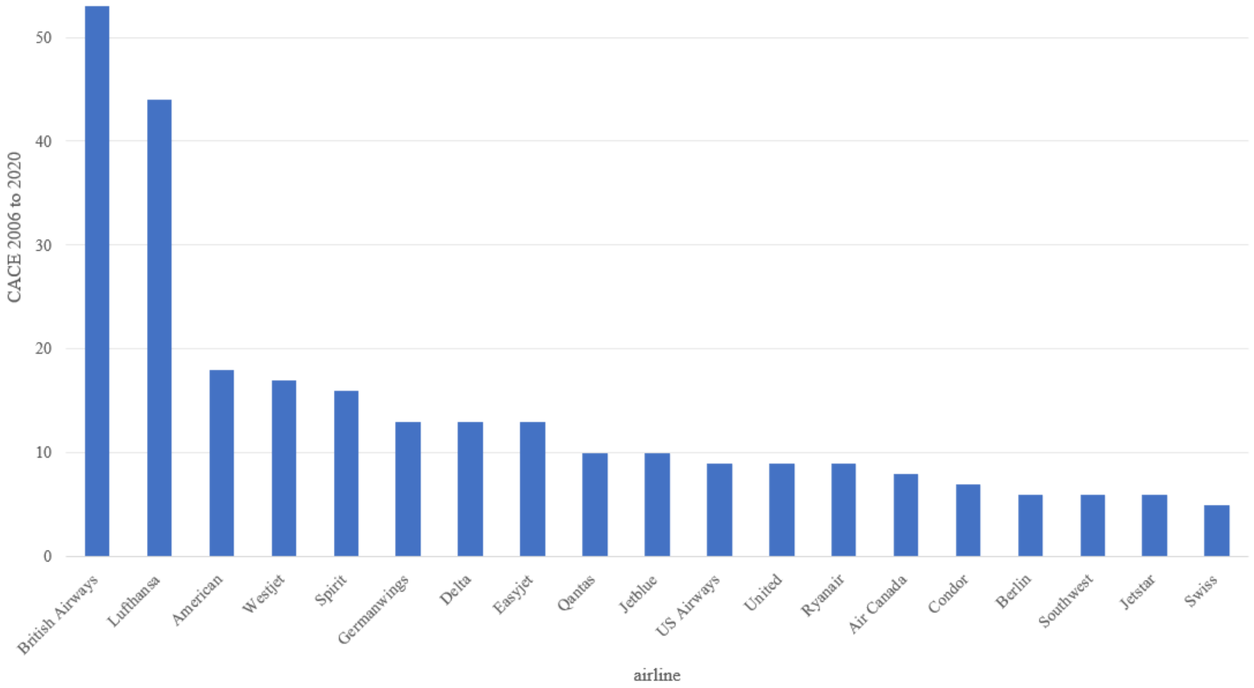


Investigation of Layover Time (2019)

Number of CACE from Aviation Herald

Search for "fumes" in Aviation Herald' database with subsequent manual filtering of the results and matching with Flightradar24.

Number of CACE from 2006 to 2020: 425.
111 airlines with at least 1 CACE, 19 airlines with 5 CACE or more. British Airways: 53 (12.5%), Lufthansa: 44 (10.4%), American: 18 (4.2%), ...



Investigation of Layover Time (2019)

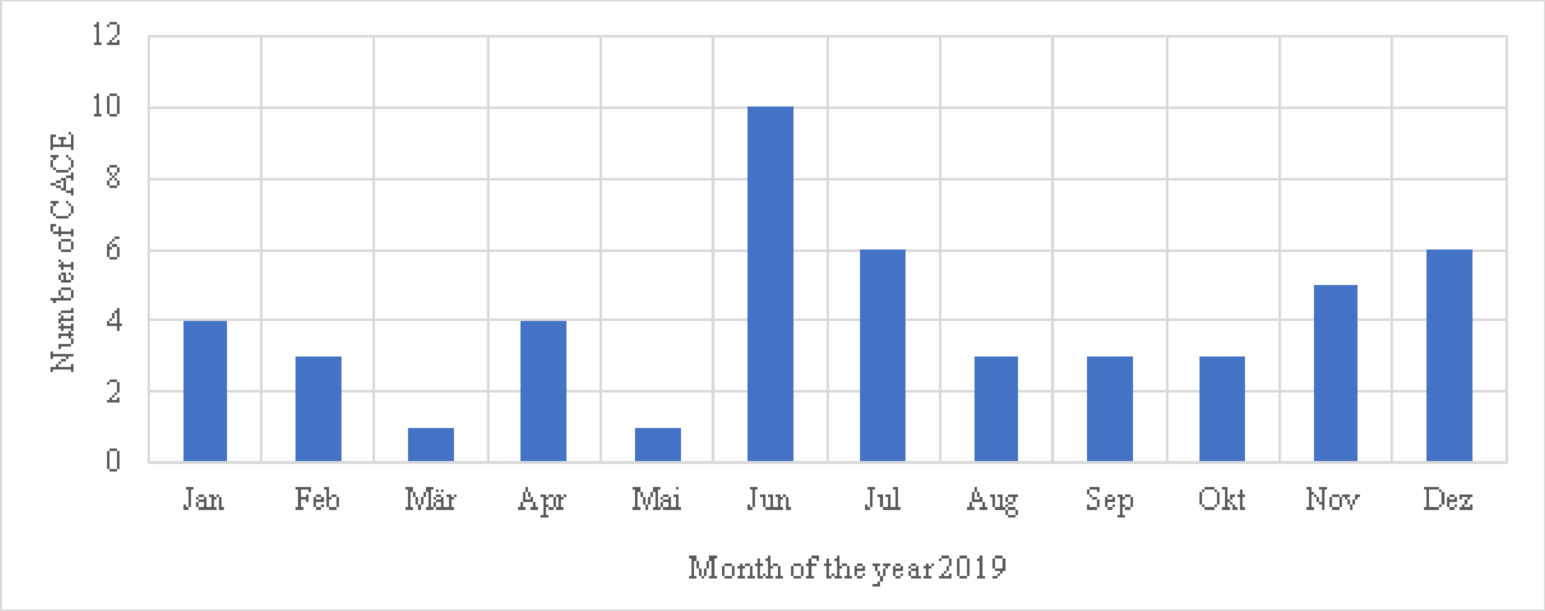
Number of CACE from Aviation Herald

Search for "fumes" in Aviation Herald' database with subsequent manual filtering of the results and matching with Flightradar24.

Number of CACE from 2006 to 2020: 425. Per year: 28 (only a very small sample of the global total)
A320-Family: 162, B737: 67 (ratio 2.42:1). Fleet ratio: 7879 : 7097 or (1.11 : 1). **A320-Family dominates CACE**

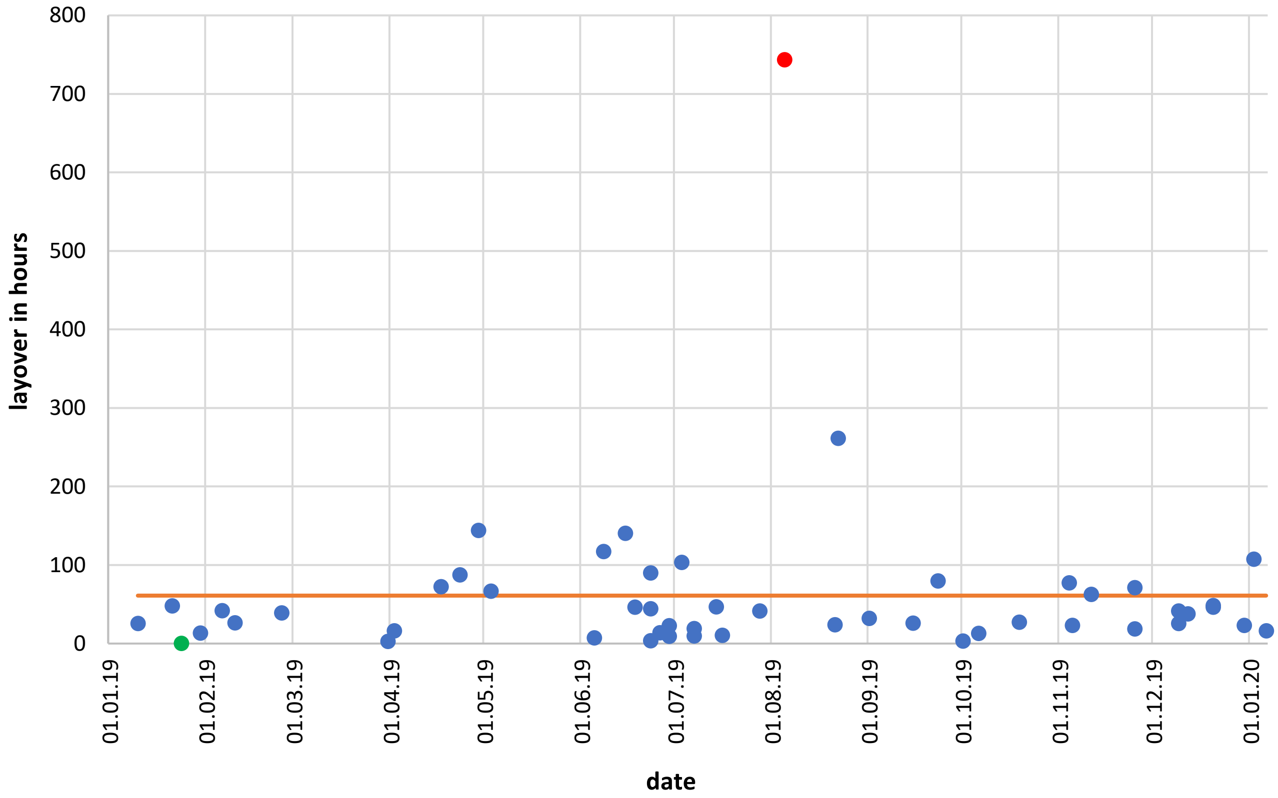
111 airlines, 19 airlines with 5 CACE or more. British Airways: 53, Lufthansa: 44, American: 18, ...

Number of CACE from Jan. to Dec. 2019 Covered also on Flightradar24: 49. Safety landings in 28 cases.



Investigation of Layover Time (2019)

Number of CACE from Aviation Herald Covered also on Flightradar24 in 2019



Layover from "no time" via 11 days up to 31 days. Average layover: 61 hours.

Cabin Air Contamination Events – Engineering Aspects

Contact:
info@ProfScholz.de

http://www.ProfScholz.de
http://CabinAir.ProfScholz.de

Quote this document:

SCHOLZ, Dieter, 2023. Cabin Air Contamination Events – Engineering Aspects. International Aircraft Cabin Air Conference 2023, Online, 27-29 June 2023.
Available from: https://doi.org/10.5281/zenodo.13763432
Download from: http://CabinAir.ProfScholz.de

See also:

SCHOLZ, Dieter, 2021. Cabin Air Contamination Events – An Engineering Update. International Aircraft Cabin Air Conference 2021, Online, 15-18 March 2021.
Available from: https://doi.org/10.5281/zenodo.4743773
Download from: http://CabinAir.ProfScholz.de

SCHOLZ, Dieter, 2018. Technical Solutions to the Problem of Contaminated Cabin Air. German Aerospace Congress, Friedrichshafen, Germany, 04.-06.09.2018. Presentation No. 0270.
Available from: https://doi.org/10.5281/zenodo.4072745
Download from: http://CabinAir.ProfScholz.de

References:
See: SCHOLZ, Dieter, 2021 and consult the List of References in the projects.