

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Aircraft Cabin Air and Engine Oil

– An Engineering View

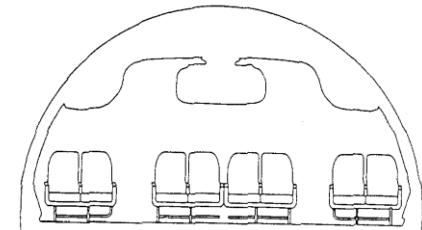
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Aircraft Cabin Air and Engine Oil – An Engineering View

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 pyrolyzed (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.

Aircraft Cabin Air and Engine Oil – An Engineering View

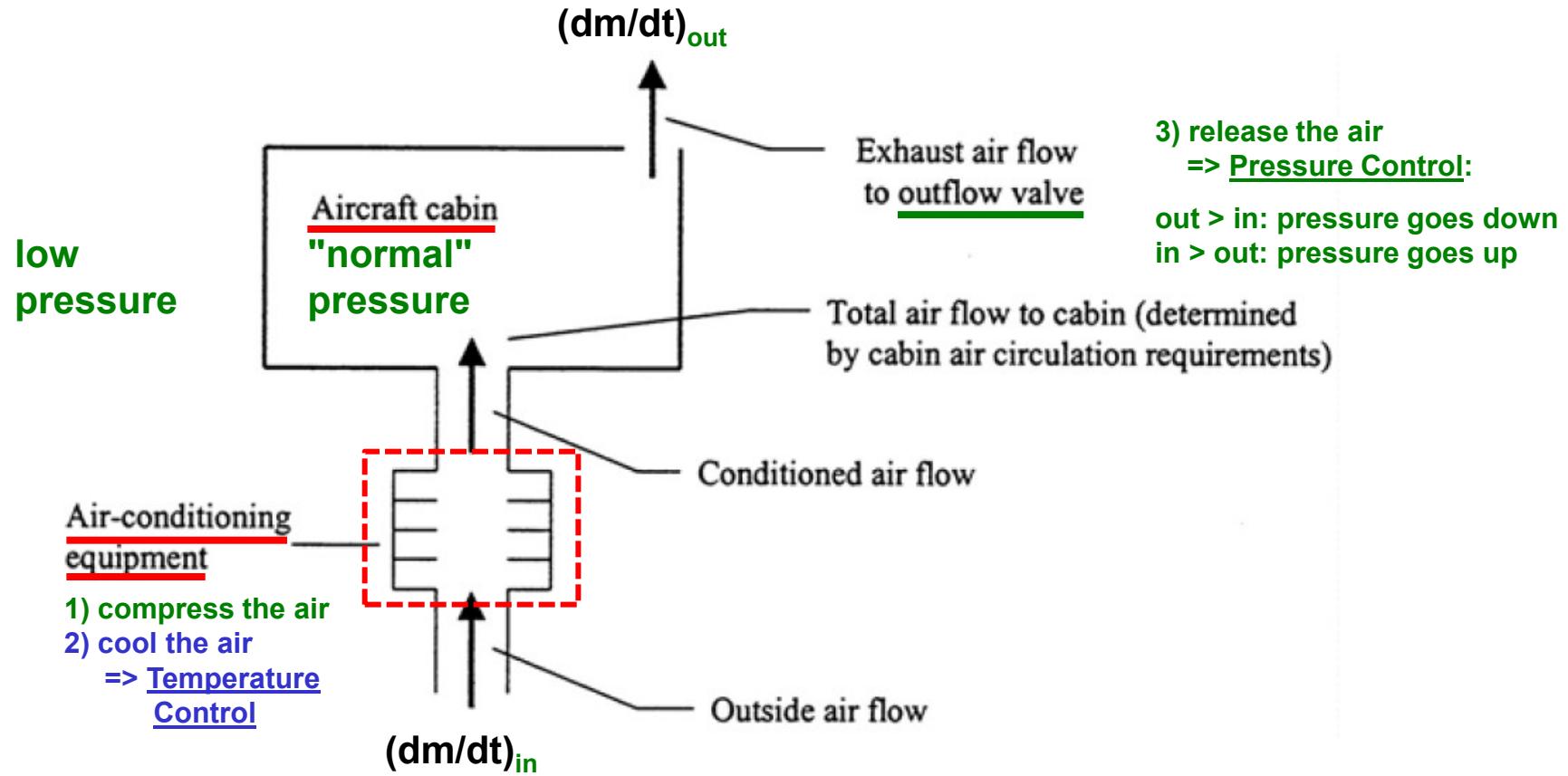
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Air Conditioning Technology

Air Conditioning Basics

Temperature Control, Pressure Control, Ventilation

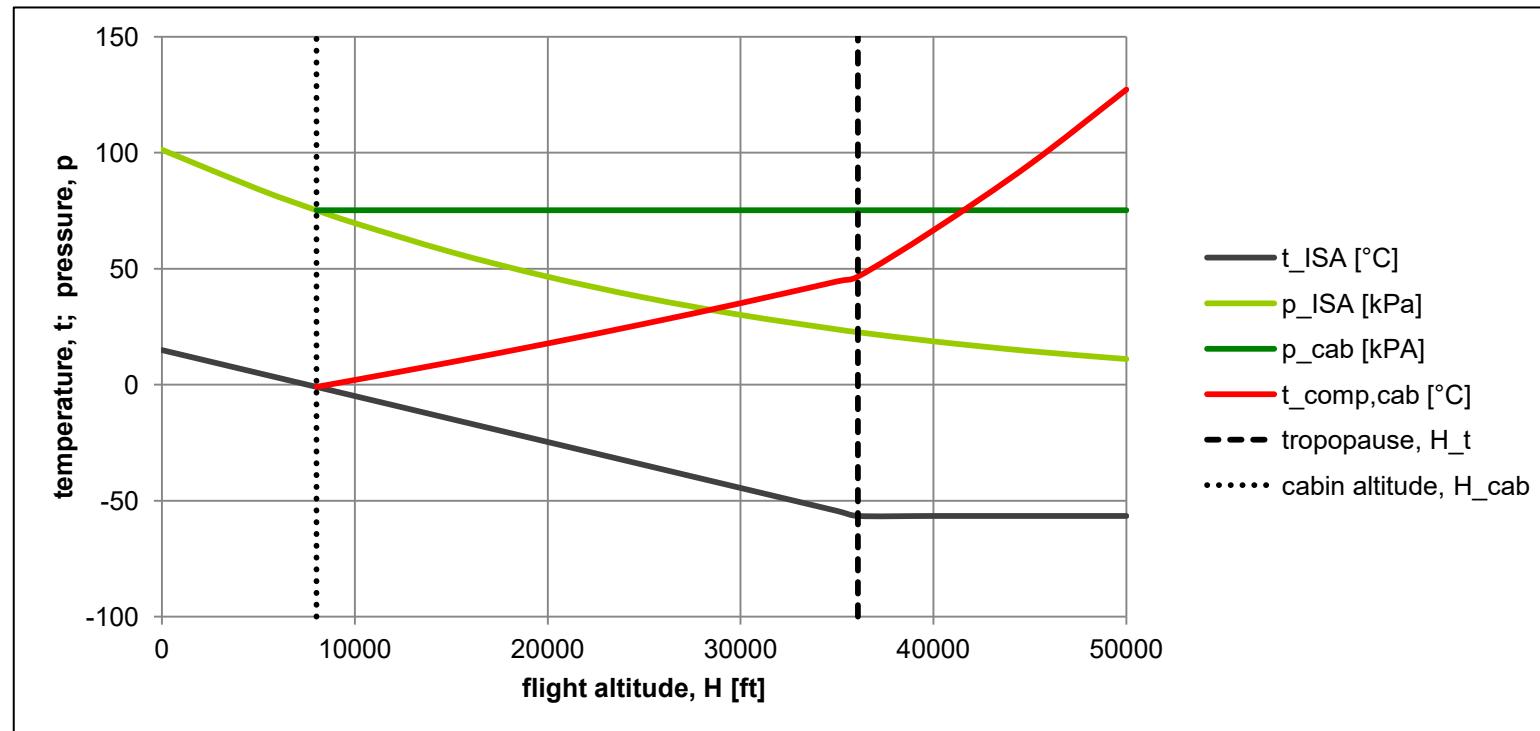


Adapted from (NRC 2002)

Air Conditioning Technology

Air Conditioning Basics

Increasing Temperature of Air due to Compression from Ambient to Cabin Pressure



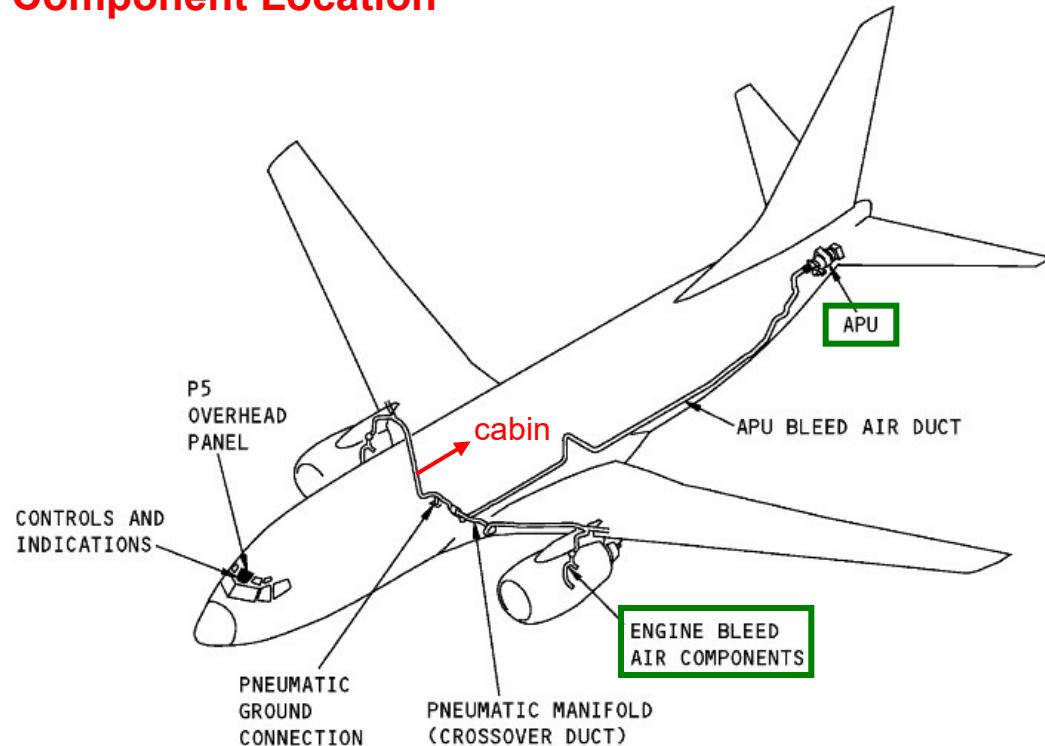
- 1) compress the air => increasing temperature of air
- 2) cool the air

Air Conditioning Technology



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

Major Component Location



PNEUMATIC - COMPONENT LOCATIONS

Adapted from (AMM B737)

Air Conditioning Technology

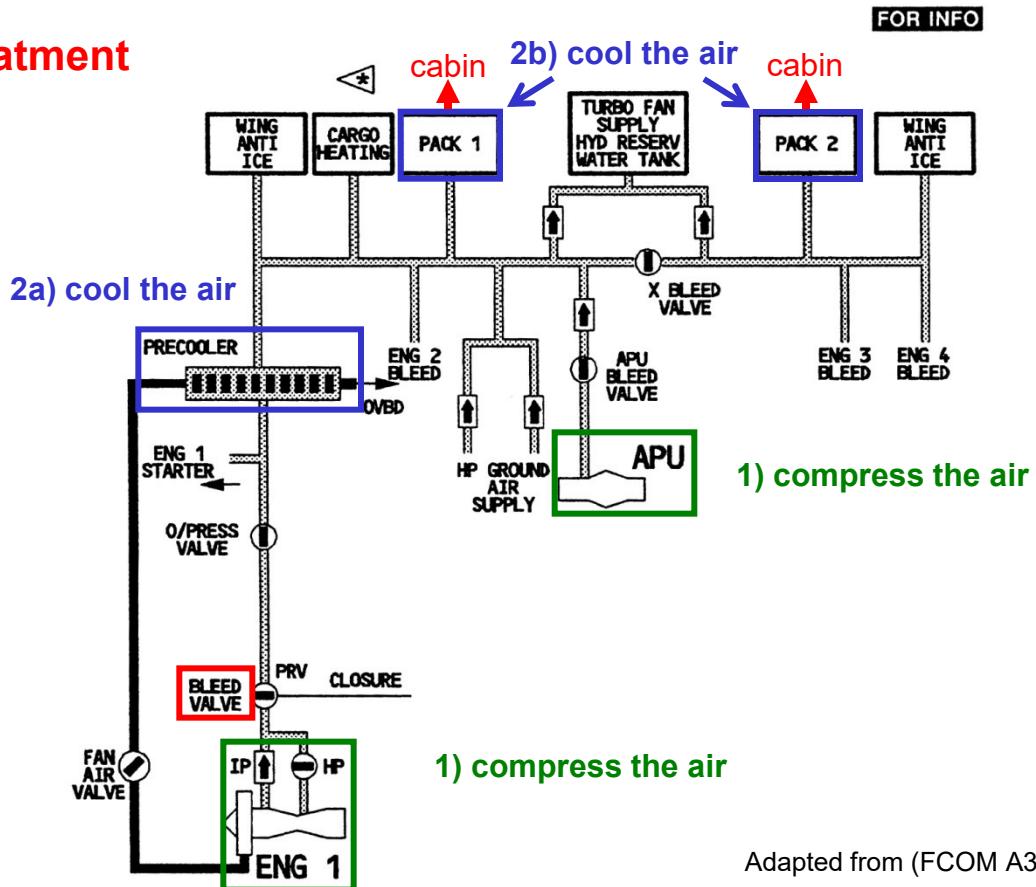
A340 FLIGHT CREW OPERATING MANUAL	PNEUMATIC DESCRIPTION	1.36.10	P 3
		REV 05	SEQ 001

"Bleed Air" Generation and Treatment

compress and cool the air

"Bleed Air"

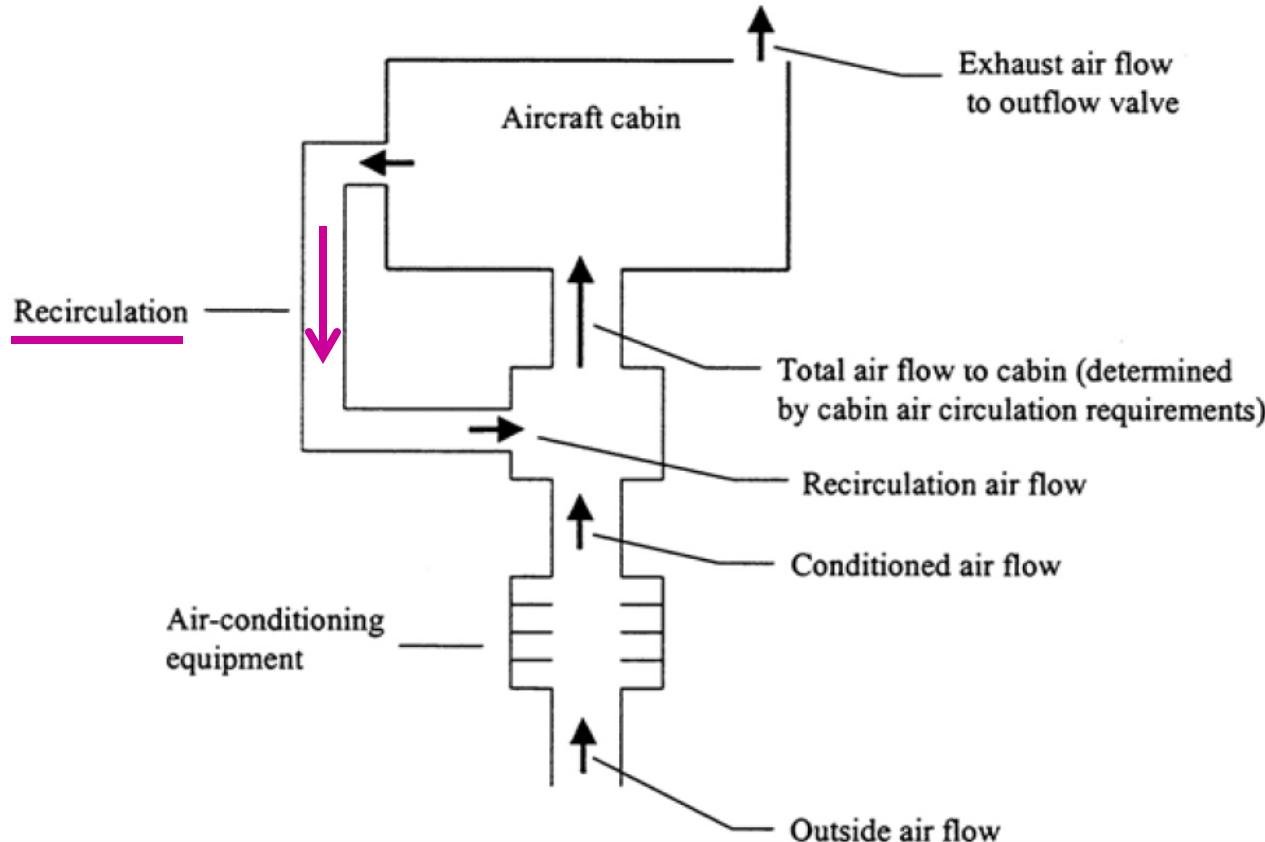
is "precious air" taken off the engine compressor – air which was initially intended to be used for the engine cycle



Adapted from (FCOM A340)

Air Conditioning Technology

Air Conditioning with Recirculation

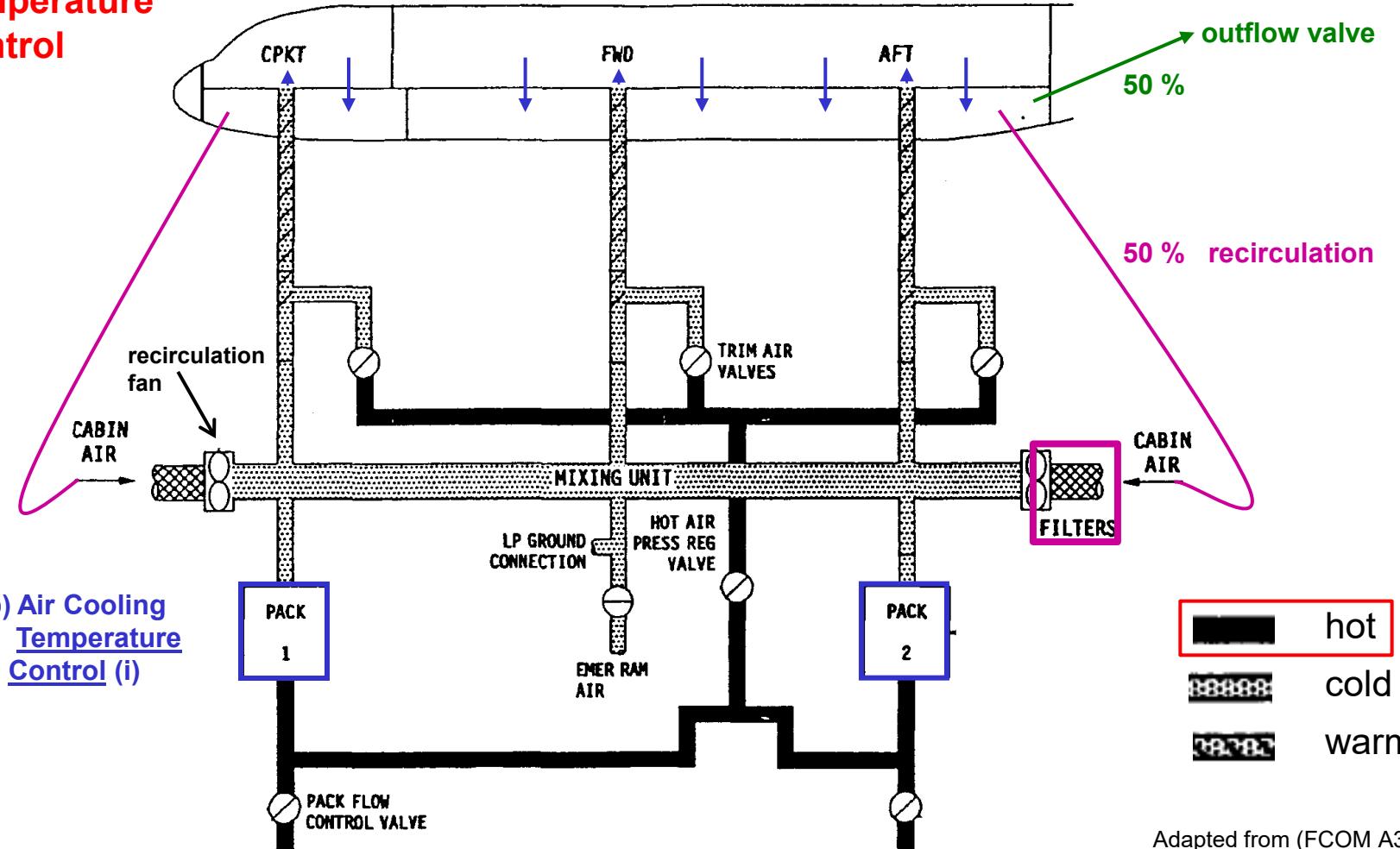


Adapted from (NRC 2002)

Air Conditioning Technology

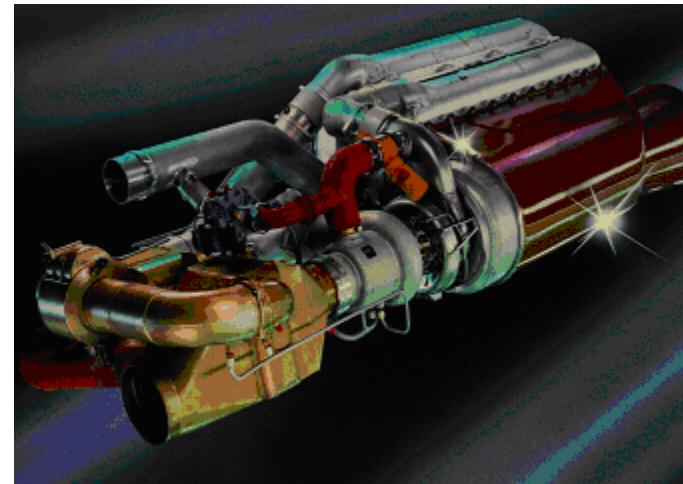
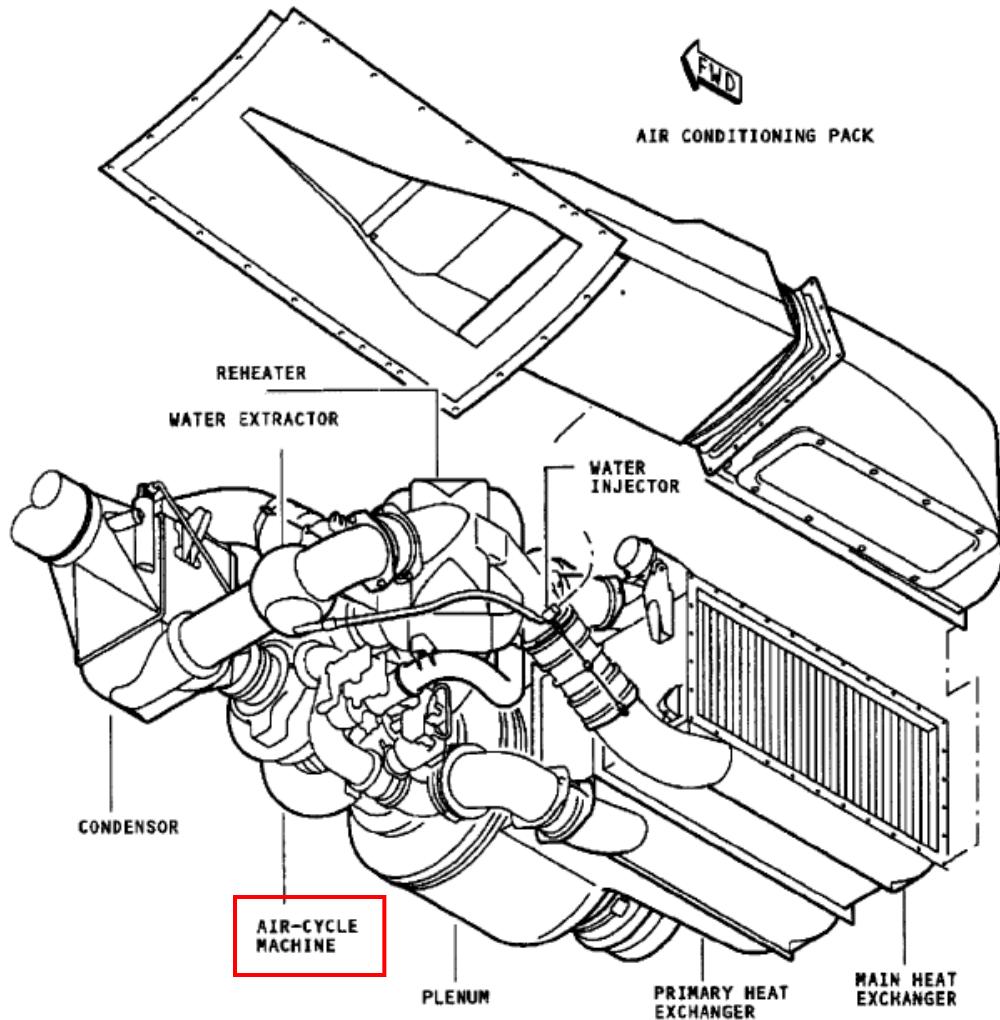
A320

Temperature Control



Adapted from (FCOM A320)

Air Conditioning Technology



Liebherr Aerospace

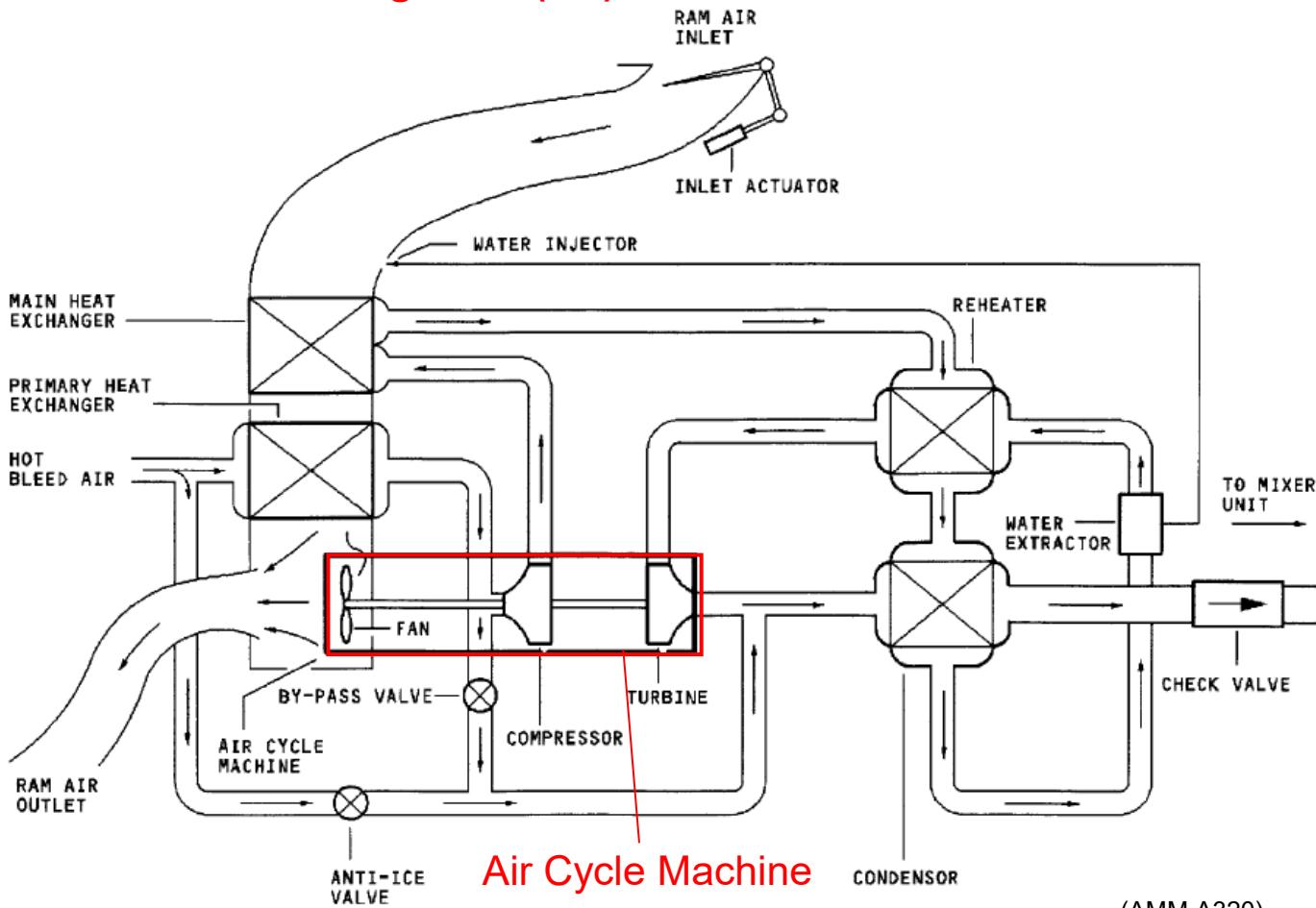
Air Conditioning Pack (1/2)

A320

(AMM A320)

Air Conditioning Technology

Air Conditioning Pack (2/2)

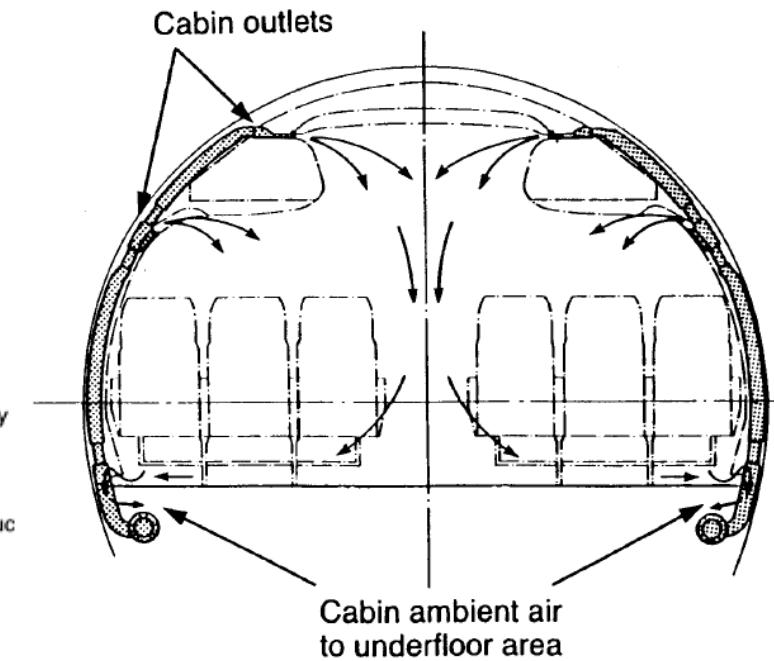
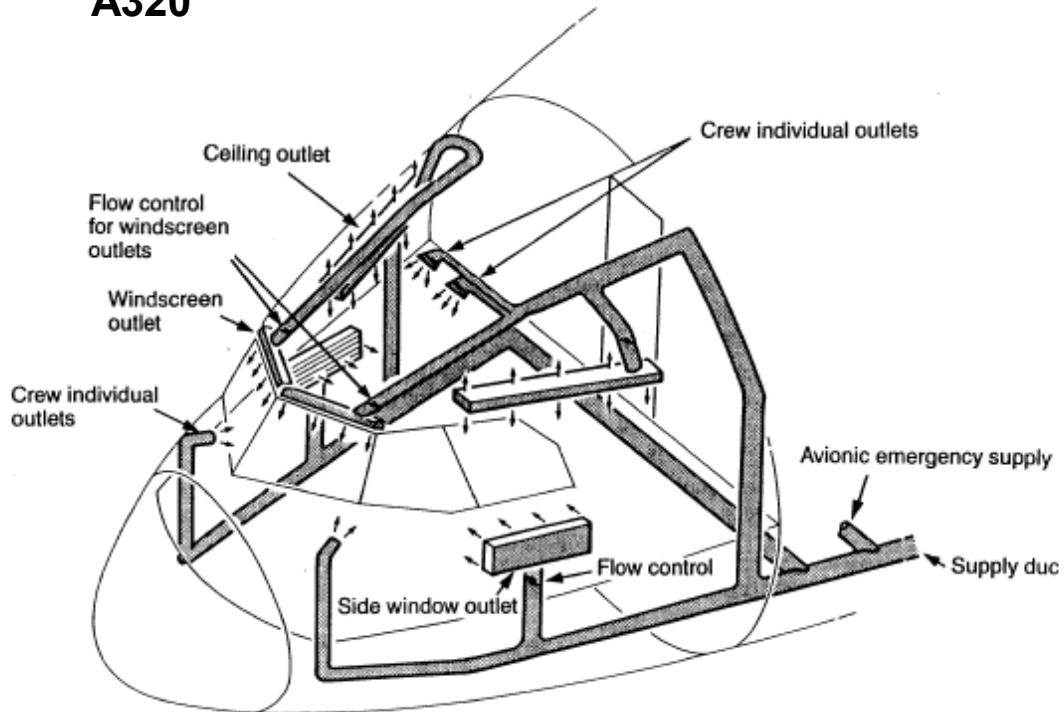


- An **Air Cycle Machine (ACM)** is a high energy rotor device.
- An ACM may need some form of lubrication (=> oil)
- Lubrication needs will be much smaller than in aircraft engines or the APU.
- Use of air bearings is possible.

Air Conditioning Technology

Cabin Air Distribution

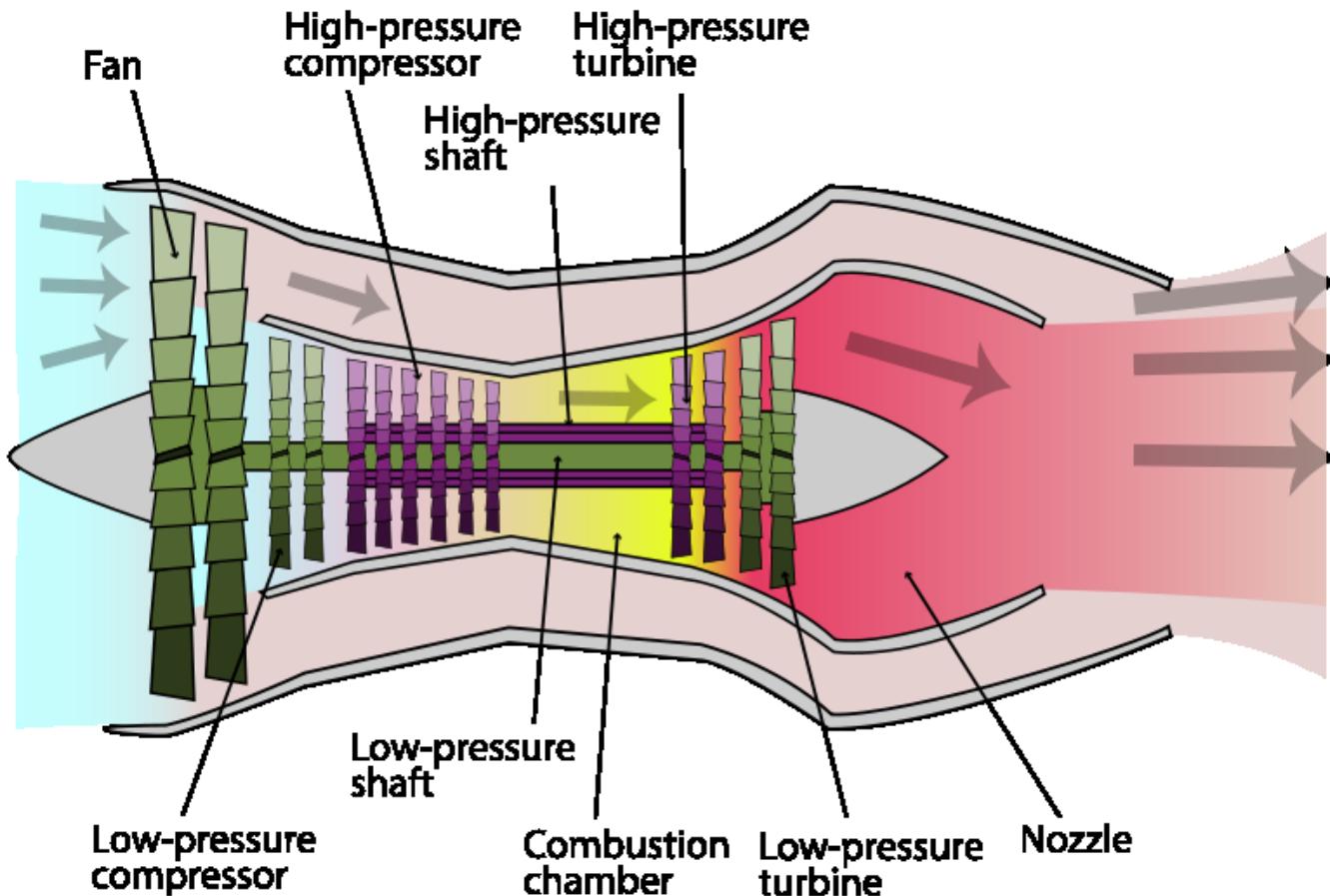
A320



(GENFAM A320)

Jet Engine

Engine Overview

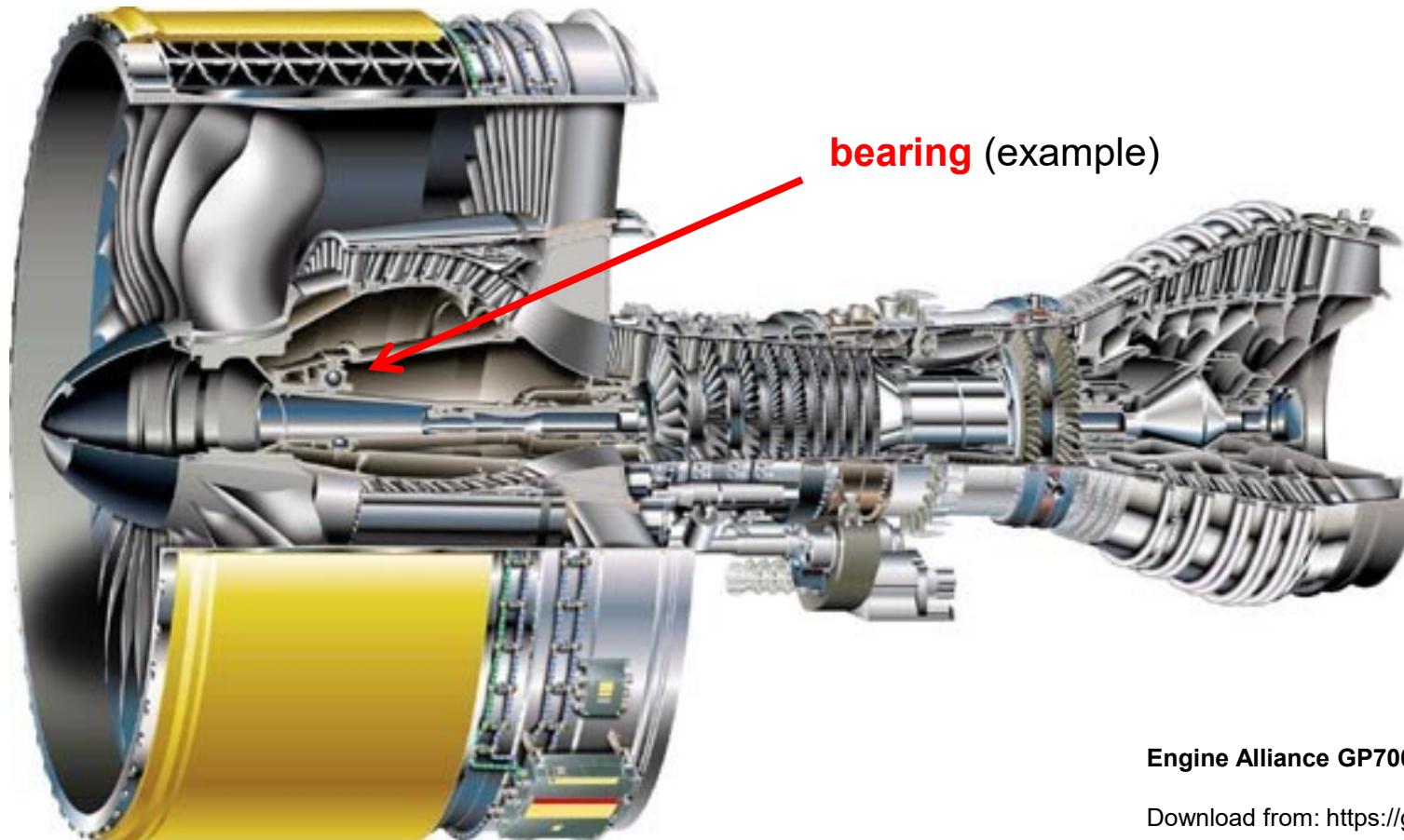


K. Aainsqatsi

https://upload.wikimedia.org/wikipedia/commons/7/77/Turbofan_operation_lbp.svg

Jet Engine

Engine Overview



Engine Alliance GP7000

Download from: <https://goo.gl/images/gYIW31>

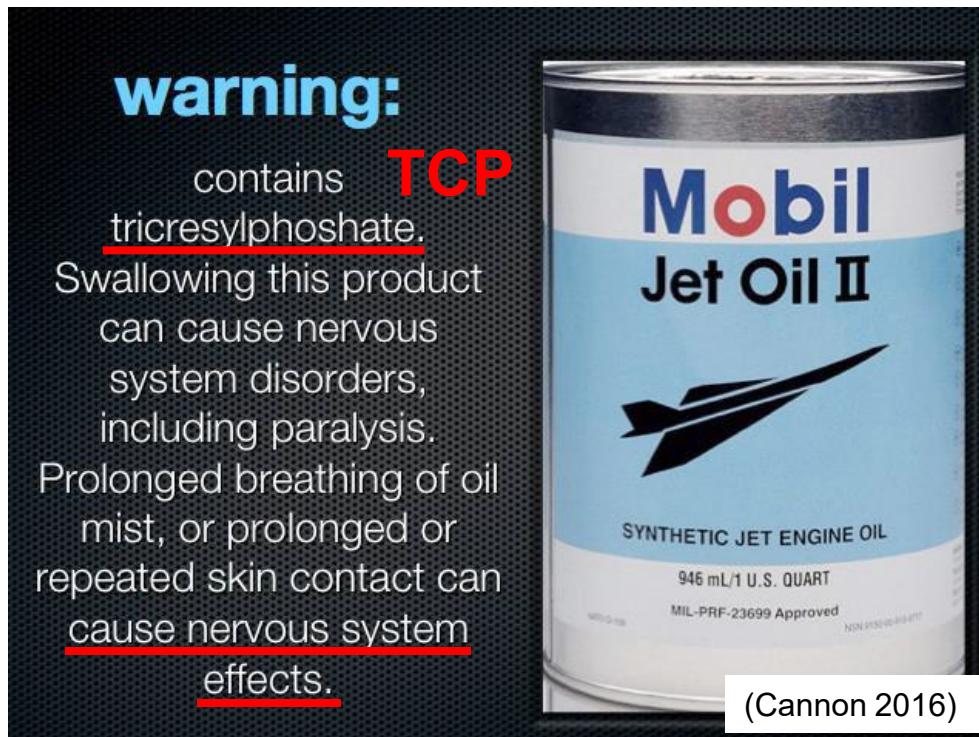
Jet Engine

Jet Engine Bearing



(Exxon 2016b)

Jet Engine



This warning was changed in 2004 (Michaelis 2012) to:

"This product is not expected to produce adverse health effects under normal conditions of use ... Product may decompose at elevated temperatures ... and give off irritating and/or harmful ... gases/vapours/fumes. Symptoms from acute exposure to these decomposition products in confined spaces [aircraft cabin] may include headache, nausea, eye, nose, and throat irritation."

(Exxon 2017)

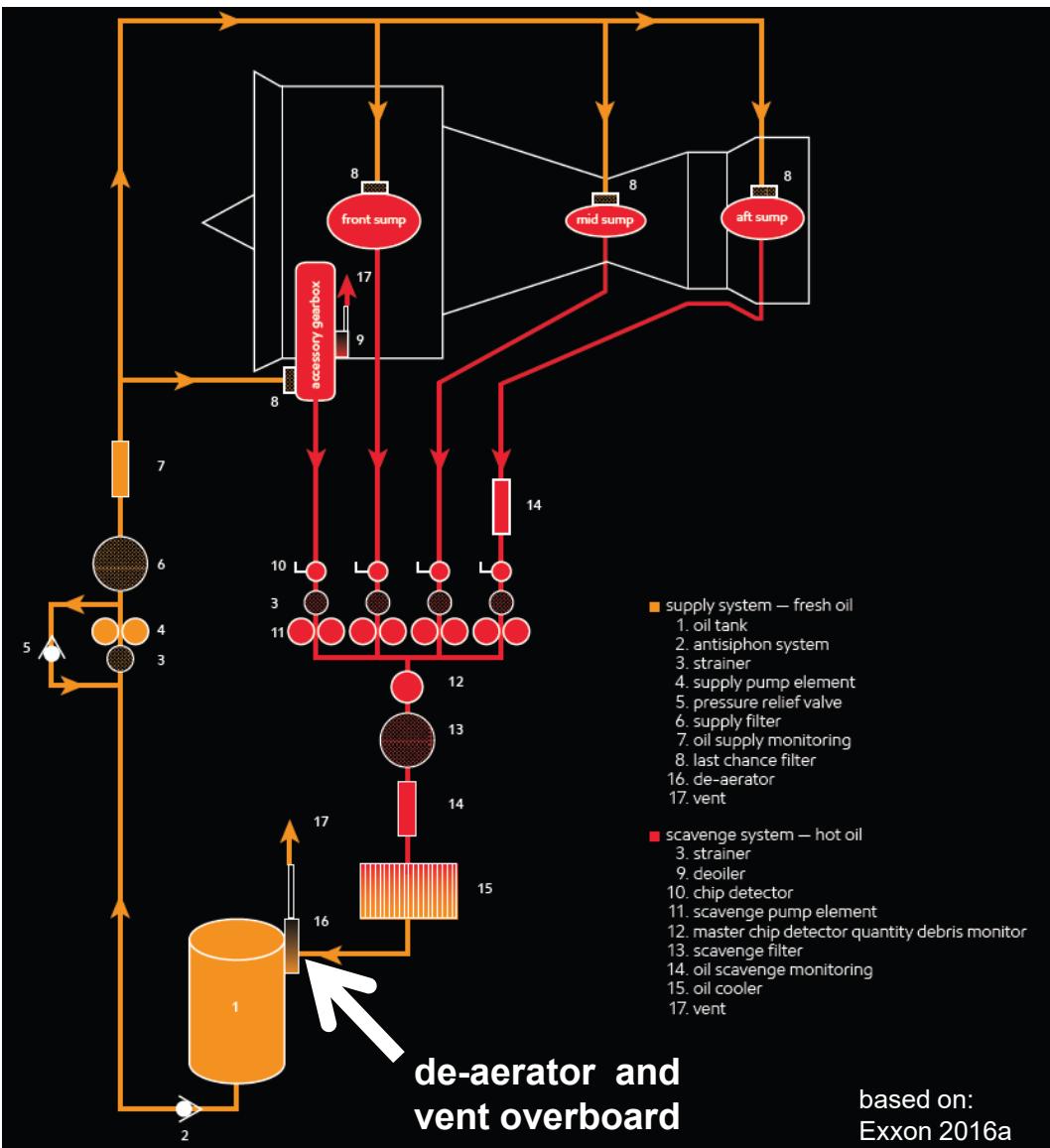
Judging Jet Engine Oil Based on Warnings Given by Manufacturer

Material Safety Data Sheet (MSDS)

FIRST AID MEASURES, INHALATION

Remove from further exposure [*in a fume event?*]... Use adequate respiratory protection [*not available for passengers!*]. If respiratory irritation, dizziness, nausea, or unconsciousness occurs, seek immediate medical assistance. If breathing has stopped, assist ventilation with a mechanical device or use mouth-to-mouth resuscitation.

(Exxon 2017)



Engine Air and Oil System

Quotes from: Exxon Mobile (2016a):
“Jet Engine Oil System – Overview”

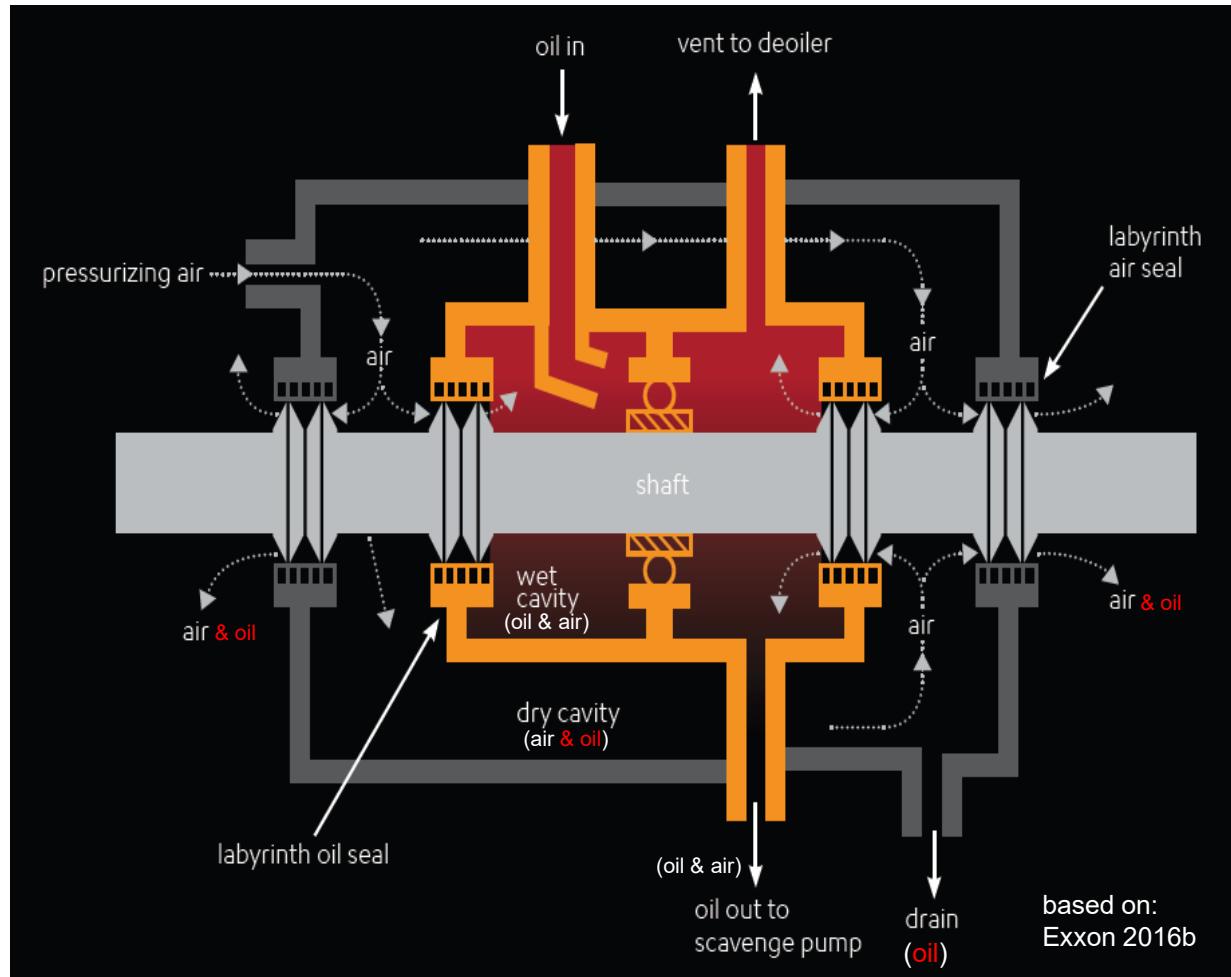
with remarks:

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

(Exxon 2016a)

Jet Engine

Engine Air and Oil System



Remarks:

- 1.) When a double wall design is used, 'air with some oil' is in the so called 'dry cavity' (some of this oil is drained).
Air with a low oil content is leaving the 'dry cavity' into the compressor (see picture).
- 2.) When double walls are used, oil leaks from the inner seal to the 'dry cavity'.
Therefore: When only a single wall design is used, air and oil leak directly into the compressor.
- 3.) Conclusion: In both cases:
Jet engine seals leak oil by design.

On this topic also:

(Michaelis 2016a) (Michaelis 2016b)

Jet Engine

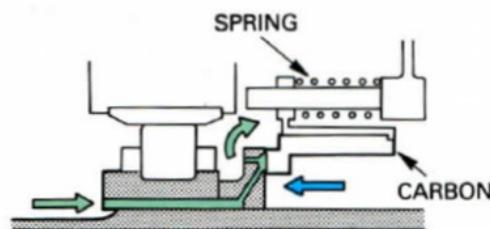
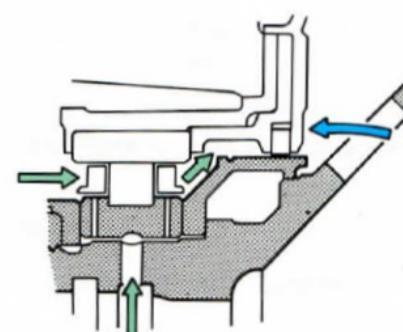
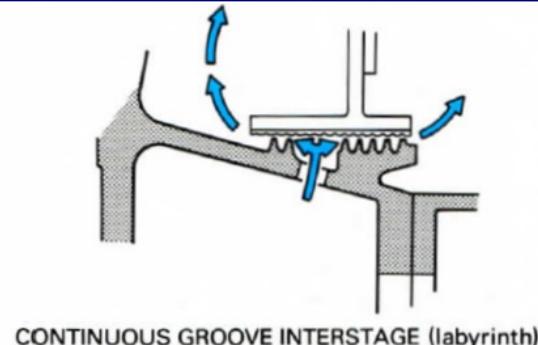
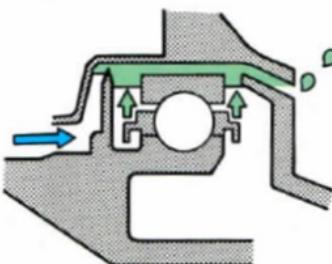
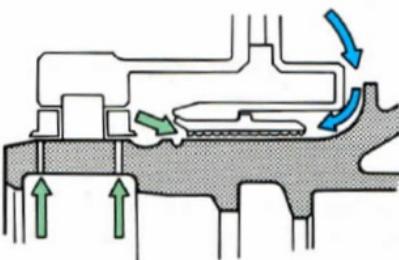
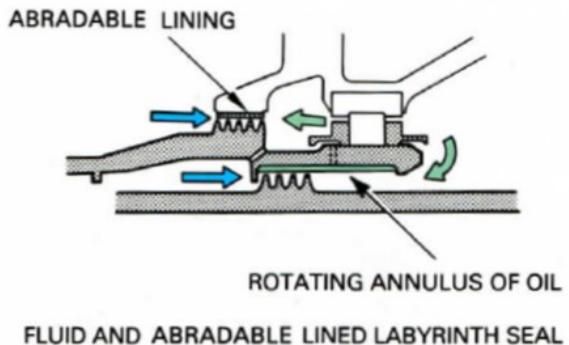
Types of Jet Engine Seals

→ air
→ oil

Seal Contact Type:

- without contact
- with contact

(Rolls Royce 2015)



Jet Engine

Types of Jet Engine Seals

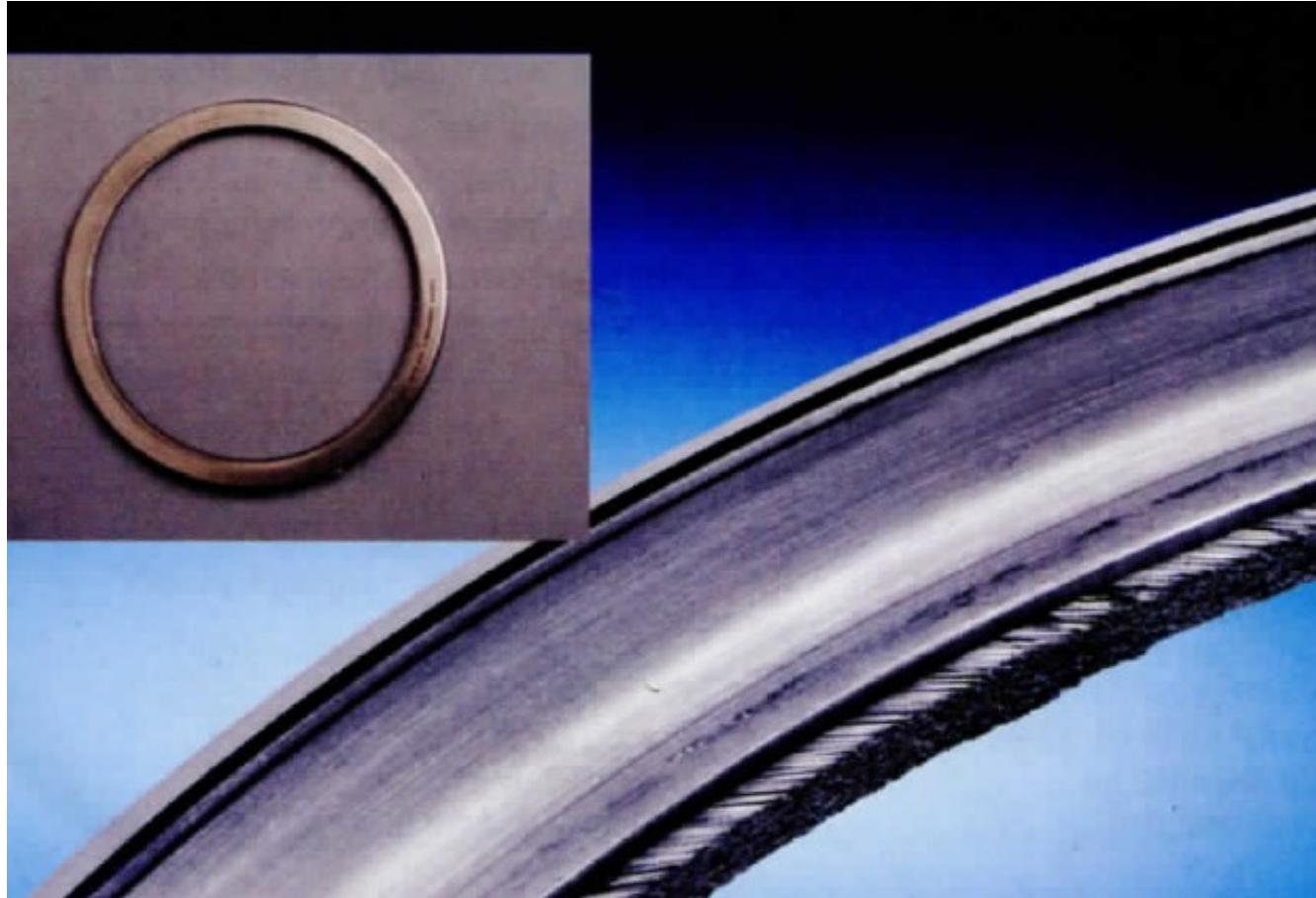
Brush Seal

with contact

e.g. on

PW1000G

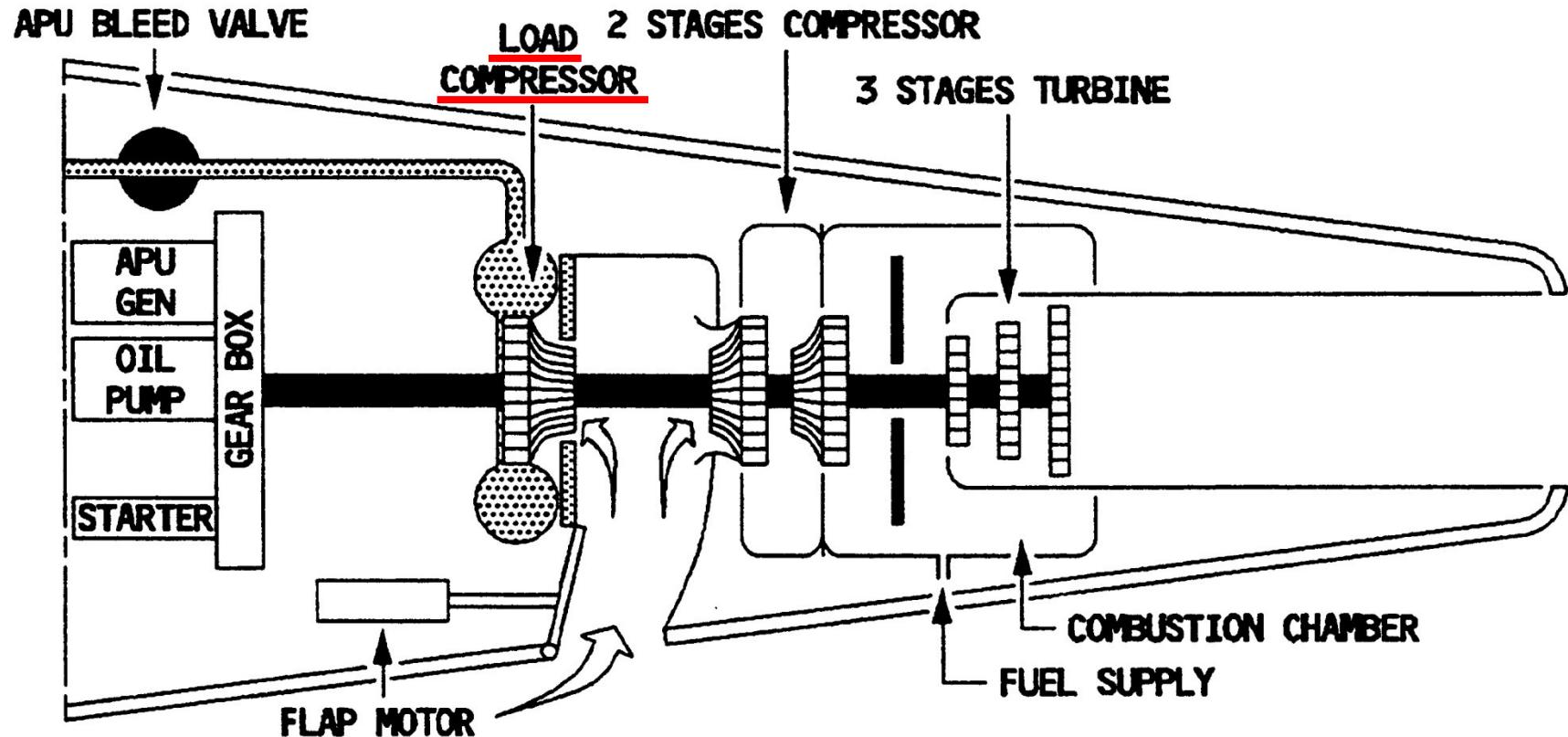
geared turbo fan



(DGLR 2014)

Auxiliary Power Unit (APU)

Overview

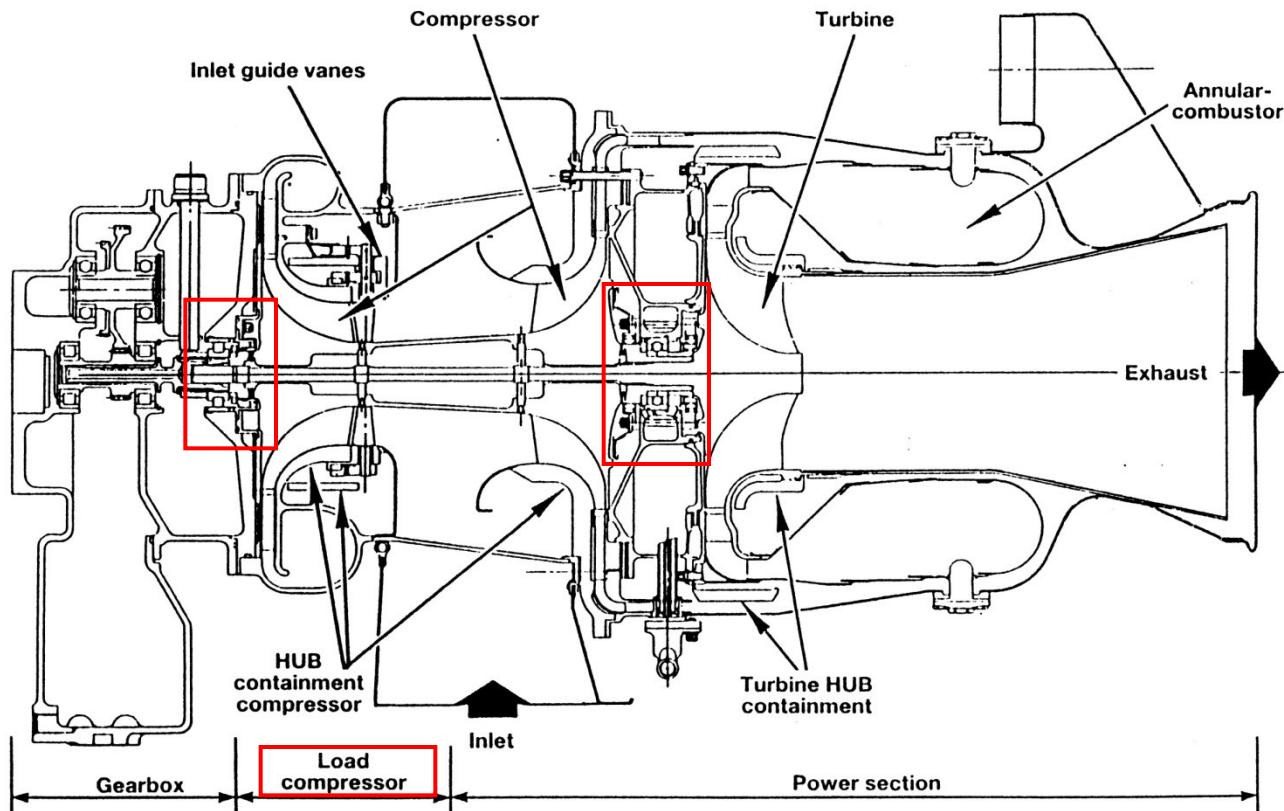


(FCOM A340)

Auxiliary Power Unit (APU)

Bearings and Load Compressor

APU GTCP36-300

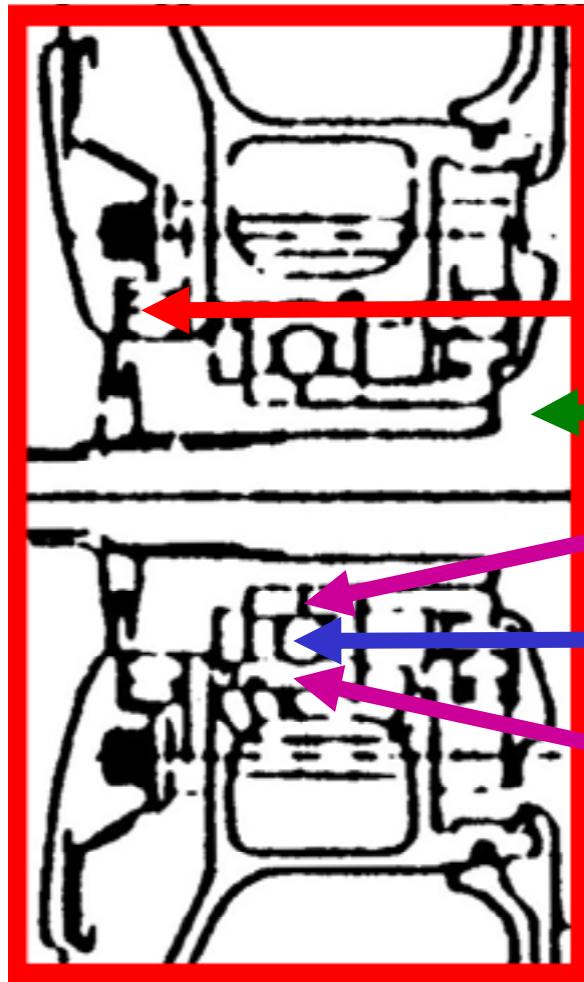


(GENFAM A320)

- An Auxiliary Power Unit (APU) is a gas turbine engine.
- An APU will need some form of lubrication (e.g. oil).
- Lubrication needs will be smaller than in aircraft engines, but the APU otherwise experiences the same problems with oil leakage as described for the engine.

Auxiliary Power Unit (APU)

Bearing Components



seal

rotating shaft

inner bearing ring

ball from ball bearing

outer bearing ring

(GENFAM A320)

Engineering Design Principles for Air Conditioning from SAE

SAE about the Design of the Air Conditioning Pack



SAE ARP 85E: Air Conditioning Systems for Subsonic Airplanes

5.2.2.d.: Bearings:

Air cycle machines typically use precision angular contact ball bearings or **air bearings**.

In either case, **the bearing system** should be self-contained, **requiring no external oil supply or external pressurizing air source**.

Engineering Design Principles for Air Conditioning from SAE

SAE about the Design of the Bleed Air System

SAE 1796: Engine Bleed Air Systems for Aircraft

(first edition 1987, A in 2007, B in 2012)



Bleed Air Quality: **Requirements** should be **imposed on the engine manufacturer** regarding the quality of the bleed air supplied to occupied compartments.

Under normal operating conditions:

The engine bleed air shall be **free of engine-generated objectionable odors, irritants, and/or toxic or incapacitating foreign materials**.

Following any type of engine ... failure, the engine bleed air shall **not contain the above substances to a harmful degree**.

... or bleed air systems should incorporate a **bleed air cleaner**.

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.**”



SAE AIR 1116: Fluid Properties

(first edition: 1992, A in 1999, B in 2013)

“**Until adequate toxicity data are available** **precautions** must be observed in handling any unfamiliar fluid.”

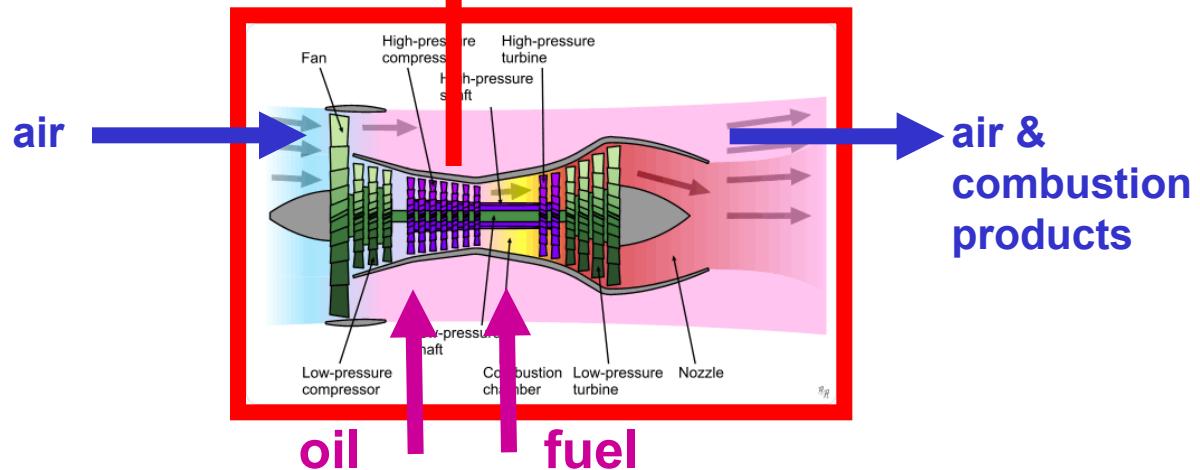
This means:

It is not the task of passengers and crew to prove that engine oils and hydraulic fluids as used today are dangerous. Just on the contrary, **industry has to prove that fluids and equipment are safe before they intend to use them**, because **standards have been agreed among engineers already long time ago, not to use bleed air on transport aircraft!**

How much Oil Gets into the Cabin?

How much Oil
Gets into the Cabin?

Think: System Boundaries



How much Oil Gets into the Cabin?

- Determine engine oil consumption per flight hour (airline maintenance records): \dot{V}_{oil}
- Estimate ratio of oil out of all seals versus the total oil out
(including that oil leaving the deaerator): x_{seal}
- Determine number of all bearings or seals: n_{bear}
- Determine number of bearings or seals upstream of first bleed port: $n_{bear,up}$
- Calculate „upstream“ bearing ratio: $x_{bear,up} = n_{bear,up} / n_{bear}$
- Consider the number of engines: n_{eng}
- Get the Bypass Ratio (BPR) of the engine: μ
- Get engine frontal area from engine inlet diameter: $S_{eng} = D_{eng}^2 \pi / 4$
- Get aircraft cruise Mach number: M_{CR}
- Get aircraft cruise altitude: h_{CR}
- Get speed of sound in cruise altitude (from ISA Table or calculated): $a(h_{CR})$
- The steady state oil concentration in the cabin is equal to the oil concentration of the inflow. Finally: **Calculation of the Oil Concentration in the Cabin:**

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

How much Oil Gets into the Cabin?

Background

Ramsden (2013b) proposed already in 2013 to take "jet engine oil consumption as a surrogate for measuring chemical contamination in aircraft cabin air".

However, he did neither show a derivation nor a final equation. He gives an estimate for the TCP concentration of 18 mg/m³. He writes: "The fact that it has been measured to be about 80000 times less ...".

This would be equal to **7,5 µg/m³** for the total oil concentration in the air.

How much Oil Gets into the Cabin?

Derivation

The mass flow through the core of the engine can be calculated from the mass flow through the engine's inlet and the engine bypass ratio μ .

$$\mu = \frac{\dot{m}_{bypass}}{\dot{m}_{core}} \quad \dot{m}_{total} = \dot{m}_{bypass} + \dot{m}_{core} \quad \frac{\dot{m}_{total}}{\dot{m}_{core}} = \frac{\dot{m}_{bypass}}{\dot{m}_{core}} + 1 = \mu + 1 \quad \dot{m}_{core} = \frac{\dot{m}_{total}}{\mu + 1} \quad (1)$$

Oil entering the compressor through the bearing seals is a fraction, x_{seal} of the total oil consumption (oil mass flow rate). Only oil from bearings upstream of the bleed ports can enter through the bleed ports. The fraction of this oil is $x_{bear,up}$ and the oil mass flow rate approaching the bleed ports in the compressor is

$$\dot{m}_{oil,comp} = \dot{m}_{oil} x_{bear,up} x_{seal} \quad (2)$$

Some air (and oil) gets tapped off through the bleed ports. The oil concentration in the bleed flow is the same as the oil concentration in the compressor, if uniform oil distribution is assumed in the compressor. Furthermore, the oil concentration in the cabin is the same as the oil concentration in bleed flow (after steady state is reached), because cabin air is conditioned bleed air (ignoring filtered recirculated cabin air at this point). The oil concentration is calculated from the oil mass flow rate and air mass flow rate together with (1). Note, air density, has to be considered, when oil concentration is presented as mass of oil (in μg) per volume of air (m^3).

$$\frac{m_{oil,cab}}{m_{cab}} = \frac{\dot{m}_{oil,cab}}{\dot{m}_{cab}} = \frac{\dot{m}_{oil,comp}}{\dot{m}_{core}} = \frac{\dot{m}_{oil,comp}}{\dot{m}_{total}} (\mu + 1) \quad \frac{m_{oil,cab}}{V_{cab} \rho_{cab}} = \frac{\dot{m}_{oil,comp}}{\dot{V}_{total} \rho_{CR}(h_{CR})} (\mu + 1)$$

$$\frac{m_{oil,cab}}{V_{cab}} = \frac{\dot{m}_{oil,comp}}{\dot{V}_{total}} \frac{\rho_{cab}(h_{cab})}{\rho_{CR}(h_{CR})} (\mu + 1) \quad (3)$$

How much Oil Gets into the Cabin?

Derivation

Air density, ρ has to be calculated from the International Standard Atmosphere (ISA) as a function of the respective altitude, h . Cabin altitude, h_{cab} has to be less than 8000 ft (EASA CS-25).

Often $h_{cab} = 8000$ ft in cruise and as such $\rho_{cab} = 0.963 \text{ kg/m}^3$. Cruise altitude h_{CR} may be set to 11 km (tropopause) for passenger jets, if no other value is given and as such $\rho_{CR} = 0.364 \text{ kg/m}^3$.

The total flow into all engines of the aircraft is calculated from engine inlet area S_{eng} , number of engines n_{eng} and cruise speed V_{CR} .

$$\dot{V}_{total} = S_{eng} n_{eng} V_{CR} \quad (4)$$

Cruise speed is a function of cruise Mach number, M_{CR} and speed of sound, $a(h_{CR})$, which is a function of cruise altitude, h_{CR} .

$$V_{CR} = M_{CR} a(h_{CR}) \quad \text{with} \quad a = 295 \text{ m/s} \quad \text{for} \quad h_{CR} \geq 11 \text{ km} \quad (5)$$

Equations 3 with Equations 2 and 4 (making use of 5) yields

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

$$a(h_{CR}) = a_0 \sqrt{\frac{T}{T_0}} \quad T = T_0 - L h_{CR} \quad \text{with} \quad T > 216,65 \text{ K} \quad L = 1.9812 \cdot 10^{-3} \text{ K/ft}, T_0 = 288.15 \text{ K}, a_0 = 340.29 \text{ m/s}$$

How much Oil Gets into the Cabin?

Example Calculation

$$\dot{V}_{oil} = 0.6 \text{ L/h} \quad \text{both engines, } n_{eng} = 2$$

$$S_{oil} = 1.0035 \text{ kg/L}$$

$$\dot{m}_{oil} = 0.1673 \text{ g/s}$$

$x_{seal} = 1\% \text{ (conservative estimate!)}$

$$n_{bear} = 5 \quad CFM - 56$$

$$h_{bear, up} = 3$$

$$x_{bear, up} = 0.6$$

$$\mu = 5.7$$

$$h_{CR} = 11 \text{ Km} \quad a_{CR} = 295 \text{ m/s}$$

$$M_{CR} = 0.76 \quad A320$$

$$D_{eng} = 1.73 \text{ m} \quad S_{eng} = \frac{\pi}{4} D_{eng}^2$$

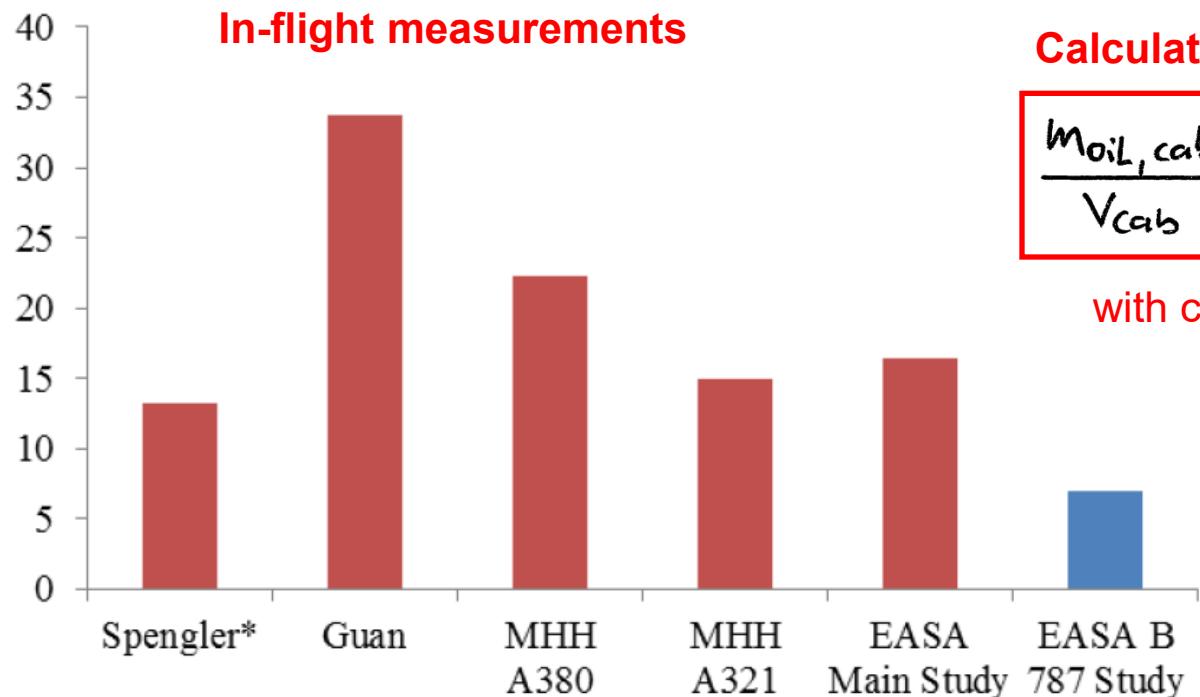
$$\frac{m_{oil, cab}}{V_{cab}} = \frac{\dot{m}_{oil} x_{bear, up} x_{seal}}{S_{eng} n_{eng} M_{CR} a(h_{CR})} \cdot \frac{\rho_{cab}}{\rho_{CR}} (\mu + 1)$$

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

How much Oil Gets into the Cabin?

Example Calculation Compared with Measurements

$\mu\text{g}/\text{m}^3$ Σ aromatic hydrocarbons (median)



Calculated:

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

with conservative estimate:

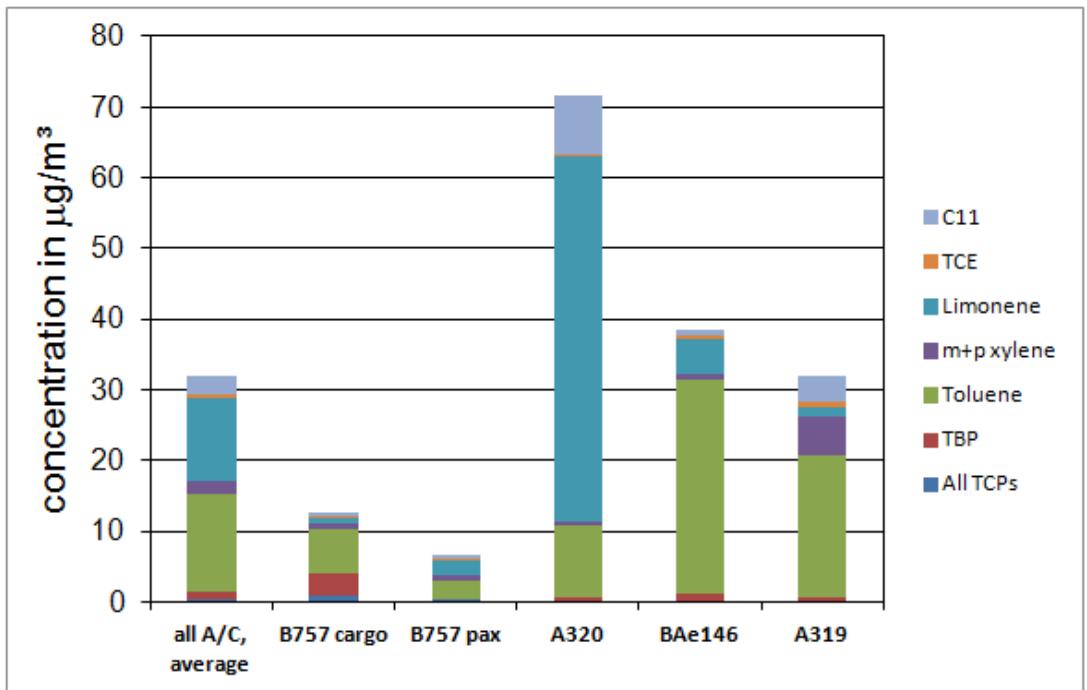
$$x_{seal} = 1\%$$

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

(EASA 2017a)

How much Oil Gets into the Cabin?

Example Calculation Compared with Measurements (Cranfield)



Calculated:

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

with conservative estimate:

$$x_{seal} = 1\%$$

(Cranfield 2011)

Sum of the concentration of measured VOCs.

Note: Also other VOCs could be present, but are not given in the study.

Therefore: Sum of VOC concentration could be higher than shown.

How much Oil Gets into the Cabin?

Health Effects? => EASA Study 2017: AVOIL

AVOIL – Characterisation of the toxicity of aviation turbine engine oils after pyrolysis (EASA 2017a)

"a ... list of 127 compounds [VOC] was ... identified ... ". The **hazard profile** is given in Appendix 6:

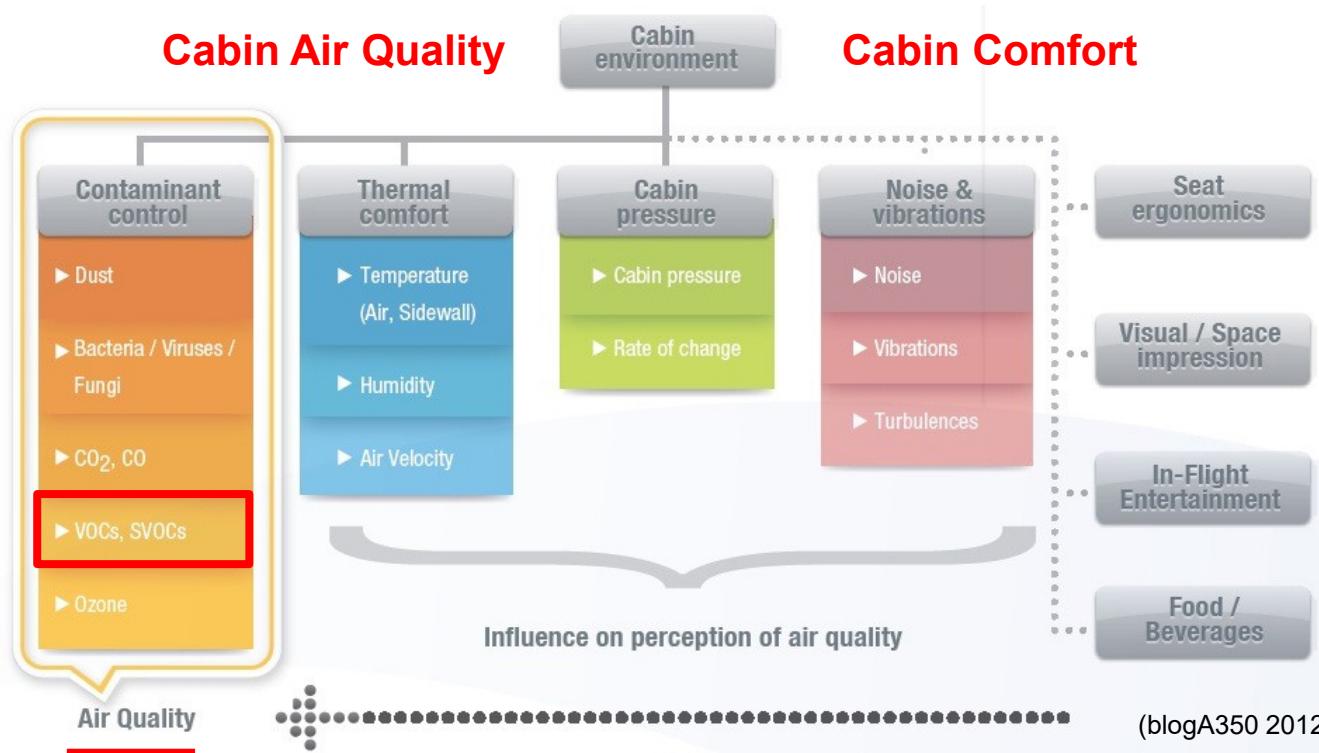
Compound #	Name	CAS	Harmonized classification	Self-classification*
1	Diethyl Phthalate	84-66-2		NC
2	1-Nonene, 4,6,8-trimethyl-	54410-98-9		
3	2-Ethylhexyl salicylate	118-60-5		Skin Irrit. 2
4	Acetophenone	98-86-2	Acute Tox. 4 Eye Irrit. 2	
5	Benzaldehyde	100-52-7	Acute Tox. 4	
6	Benzene, 1,3-bis(1,1-dimethylethyl)-	1014-60-4	NR	NR
7	Heptane, 4-methyl-	589-53-7	Asp. Tox. 1 Skin Irrit. 2 STOT SE 3	
8	Nonanal	124-19-6		NC
9	2,4-Dimethyl-1-heptene	19549-87-2		Asp. Tox. 1
10	-----	140-24-0		Eye Irrit. 2
124	Isopropyl myristate	110-27-0		NC
125	Tetradecanoic acid	544-63-8		NC
126	1-Pentene, 4-methyl-	691-37-2		Asp. Tox. 1 Or Skin Irrit. 2 Eye Irrit. 2 STOT SE 3
127	2-Cyclopenten-1-one	930-30-3		NC

* according to the largest number of notifiers

NC = not classified for human health effects

NR = not registered under REACH

Cabin Comfort and Cabin Air Quality



VOC: Volatile Organic Compounds are (organic chemicals – i.e. including carbon) contained in many products and can be released from these products into the surrounding air. Regulations limit VOCs.

SVOC: Semi-Volatile Organic Compound

(Eurofins 2017)

Cabin Comfort and Cabin Air Quality

Potential sources ... of air contamination	Potential impact
Engine start during push back	<u>Exhaust gases</u> (e.g., CO, CO ₂ , NO _x , fuel, particles)
Bleed air switch off during engine start	Short time increase of CO ₂
Cabin cleaning in general	VOC, e.g. alcohols, flavors (terpenes), aldehydes
Interior cleaning	Residual of tetrachloroethene
No ozone converters installed	Ozone, particularly in cruise
De-icing fluids	1,2-Propanediol (major constituent) and various additives (e.g., dyes, thickener, antioxidants)
Aircraft traffic at the airport	Exhaust gases (e.g., CO, CO ₂ , NO _x , fuel, particles)
Car traffic at the airport	Exhaust gases (e.g., CO, CO ₂ , NO _x , gasoline, particles)
Passengers	Emission of CO ₂ , various VOCs, offensive smell
Restrooms	Smell, VOC from cleaning products
Furnishings	VOC/SVOC, particulate organic matter (POM), flame retardants e.g. organophosphates
Maintenance	Various VOCs, lubricants
Lubricants	Oil base stock, organophosphates, POM
Hydraulic fluids	e.g. Tributyl phosphate (TBP), triphenyl phosphate (TPP)
Engine oils	Tricresyl phosphate (TCP), trixylyl phosphate (TXP), Amines
In case of thermal degradation	<u>VOCs</u> , organic acids, aldehydes, CO, CO ₂ , potential unknown products

only
considered
here is:

(EASA 2017b)

Health and Flight Safety Implications – Certification Requirements

Health Effects: Occupational Health & Flight Safety

Health effects may be experienced soon after exposure or, possibly, years later:

- **Long-term health effects:**
 - to passengers
 - to crew => **occupational health (OH)**
usually related to
Time-Weighted Average (TWA)
Permissible Exposure Limits (PEL)

=> CS 25.831
- **Immediate health effects:**
 - to passengers
 - to cabin crew
 - to cockpit crew => **flight safety implications** can lead to:
injury or death of
 - passenger
 - crew

=> CS 25.1309

(Eurofins 2017, EASA CS-25)

Health and Flight Safety Implications – Certification Requirements

Long Term Health Effects – Occupational Health

EASA 2017: CS 25.831 Ventilation

- (a) Each passenger and crew compartment must be ventilated ... to enable crewmembers to perform their duties without undue discomfort or fatigue.
- (b) Crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapours. In meeting this requirement, the following apply: (1) Carbon monoxide concentrations in excess of one part in 20000 parts of air [50 ppm] are considered hazardous. For test purposes, any acceptable carbon monoxide detection method may be used. (2) Carbon dioxide concentration ...

"**EASA** is of the opinion ... only applicable for ... CO and CO2"

*Remark: EASA's interpretation of certification rules: The **cabin is allowed to be contaminated with other substances!***

"The **BFU** is of the opinion that 'harmful concentration' should be interpreted ... to mean that **health impairments** (including long-term) through contaminated cabin air should be **eliminated**."

"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)



Bundesstelle für Flugunfalluntersuchung
German Federal Bureau of
Aircraft Accident Investigation

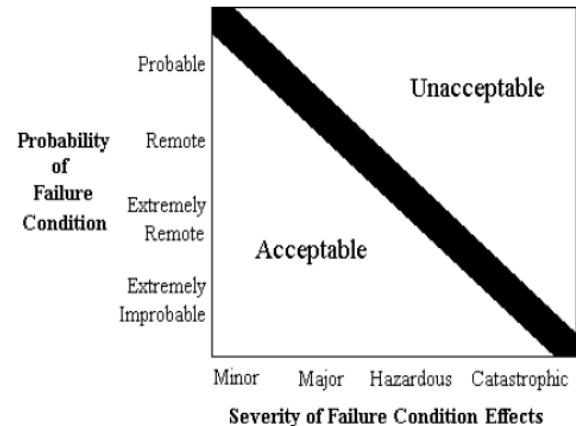
Health and Flight Safety Implications – Certification Requirements

Immediate Health Effects – Flight Safety Implications

EASA 2017: CS-25.1309(b)

The aeroplane systems and associated components, considered separately and in relation to other systems, must be designed so that

- (1) Any catastrophic failure condition
 - (i) is extremely improbable; and
 - (ii) does not result from a single failure; and
- (2) Any hazardous failure condition is extremely remote; and
- (3) Any major failure condition is remote.



EASA 2017: CS-25.1309 / AMC: System Design and Analysis

The following definitions apply to the system design and analysis requirements of CS 25.1309

Error: An omission or incorrect action by a crewmember or maintenance personnel, or a mistake in requirements, design, or implementation.

Failure: An occurrence, which affects the operation of a component, part, or element such that it can no longer function as intended, (this includes both loss of function and malfunction). Note: Errors may cause Failures, but are not considered to be Failures.

It was assumed, arbitrarily, that there are about one hundred potential Failure Conditions in an aeroplane [one in each of an assumed number of 100 systems], which could be Catastrophic.

The CS-25 airworthiness standards are based on ... the fail-safe design concept ... The fail-safe design concept uses the following design principles:

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

Health and Flight Safety Implications – Certification Requirements

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

CS-25:

The aeroplane systems and associated components, must be designed so that

- (1) Any catastrophic failure condition
- (2) (ii) does not result from a single failure

Attention: A single seal failure has the potential to cause a catastrophic failure due to pilot incapacitation. This is in contradiction to CS-25.

CS-25:

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

The failure probability of a system is calculated based on the Mean Time Between Failure (MTBF) of its components. The components are normally functional, but may fail randomly. 100% reliability of components does not exist. This is much in contrast to the situation of bleed air taken from the engine which is systematically contaminated (to some extend) with engine oil. This is not a failure (for which a probability could be calculated), but a design error (violating existing SAE design conventions).

CS-25:

The fail-safe design concept uses the following design principles:

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

But with bleed air from jet engines:

- (i) *Design integrity is not given!*
- (v) *Failure Warning in case of cabin air contamination is not provided!*

Furthermore:

- (xi) *Known deficiencies are not allowed. The system has to be error-tolerant to yet UNKNOWN design errors that have to be envisaged because it is a known fact in life that errors do occur (and as such they are foreseeable). The system's error-tolerance is compromised, if it has to cope with already known design errors that are not rectified out of negligence relying on the systems error-tolerance.*

Health and Flight Safety Implications – Certification Requirements

Flight Safety Implications?

EASA 2017: CS-25.1309(b) / AMC

"In regard to the demonstration of compliance in accordance with CS-25.1309, EASA classifies the **impairment** of the capability to act (without incapacitation) as "**Major**" [$< 10^{-5}$]. This means, however, that **these events**, with a certain frequency of occurrence, **are accepted**. The **social acceptance** of this value **cannot be assessed** ..."

(BFU 2014)

Remarks:

1. **EASA's classification is wrong.** "**impairment**" is "**Hazardous**" ($< 10^{-7}$) and demands less frequent occurrence by a factor of 100.
2. **CS-25.1309 is meant for failure cases of statistical nature and not as an excuse for known and deliberate negligence in design!**

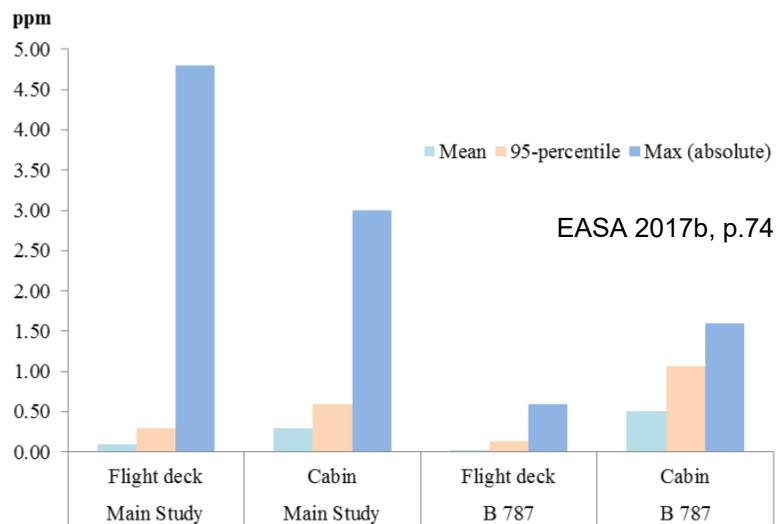
Effect on Aeroplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on Occupants excluding Flight Crew	Inconvenience	Physical discomfort	Physical distress, possibly including injuries	Serious or fatal injury to a small number of passengers or cabin crew	Multiple fatalities
Effect on Flight Crew	No effect on flight crew	Slight increase in workload	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatalities or incapacitation
Allowable Qualitative Probability	No Probability Requirement	<---Probable--->	<----Remote---->	Extremely <-----> Remote	Extremely Improbable
Allowable Quantitative Probability: Average Probability per Flight Hour on the Order of:	No Probability Requirement	<-----> $<10^{-3}$ Note 1	<-----> $<10^{-5}$	<-----> $<10^{-7}$	<-----> $<10^{-9}$
Classification of Failure Conditions	No Safety Effect	<----Minor---->	<----Major---->	<--Hazardous-->	Catastrophic

Note 1: A numerical probability range is provided here as a reference. The applicant is not required to perform a quantitative analysis, nor substantiate by such an analysis, that this numerical criteria has been met for Minor Failure Conditions. Current transport category aeroplane products are regarded as meeting this standard simply by using current commonly-accepted industry practice.

Hints for Pilots

CO in Passenger Aircraft Cabins => Pilot's Personal CO Detector

Normal CO Situation



The **Carbon Monoxide** (CO) level in normal operation is much lower than the limit of 50 ppm (specified in CS 23.831 and CS 25.831). Failure cases did not occur during these measurements.

CO: 1 mg/m³ = 0.87 ppm (at 25°C) (EASA 2017b, p. 73)



Failure Case: Fume Event



US Airways Flight 432 Phoenix to Maui (2010)
(<https://youtu.be/AZqeA32Em2s>)

EASA 2017a (p. 75 - 77):

"Until the oil has reached 180°C hardly any emission of CO arises. However, it appears that following the increase of temperature of the oil from 180°C to 375°C, CO emissions are formed due to incomplete combustion of the oil." "[At 375°C] the CO concentration is increasing severe[ly]." "It is not meant that results of our work can be up-scaled, neither be related to typical aircraft ... [nor] engines."

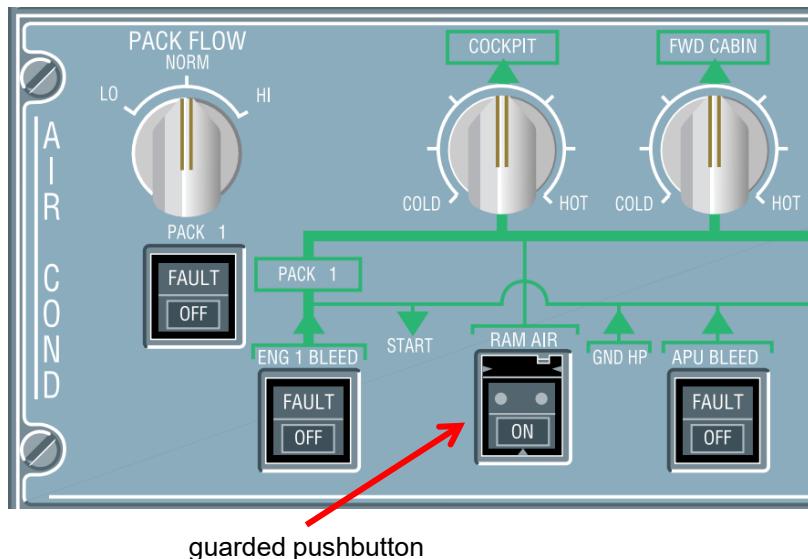
Air in the compressor reaches more than 500°C. So, we know much **CO is present in the cabin during a Fume Event. The elevated CO concentration indicates the severity of the event. Therefore, pilots should carry their personal CO detector and make decisions accordingly!**

Hints for Pilots

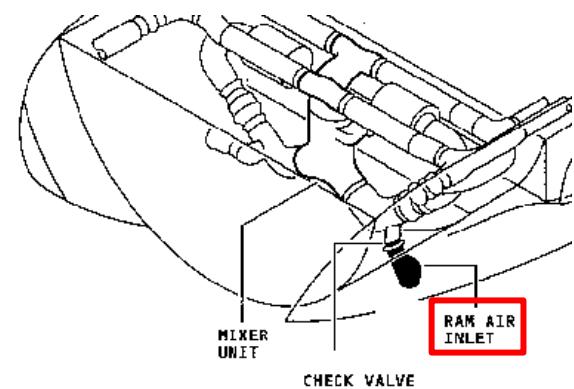
Direct Venting of the Cabin in 10000 ft

Direct venting (independently of bleed air) is possible for most passenger aircraft. On the **Airbus A320**, an emergency ram-air inlet can be opened. These conditions have to be met:

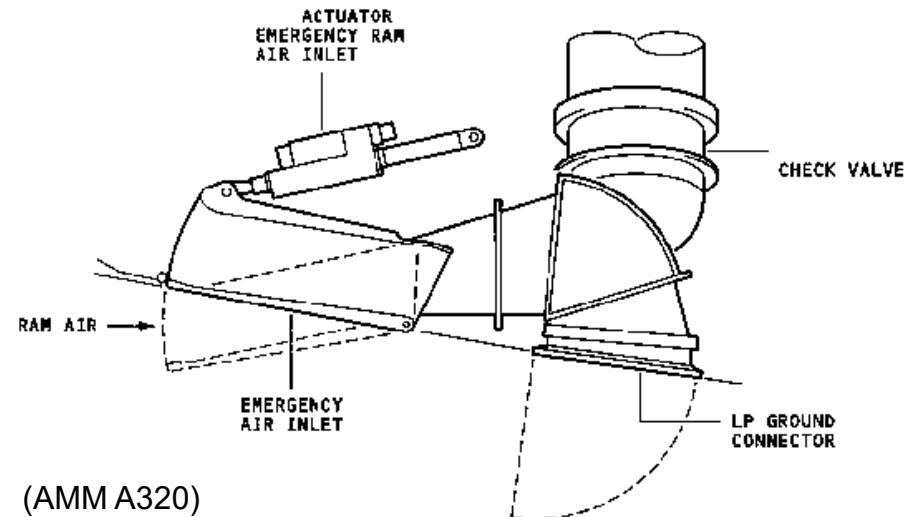
- the altitude of the aircraft is less than 10000 ft,
- the difference between the pressure in the fuselage and the external pressure is less than 70 hPa.



Component location



Emergency ram air inlet



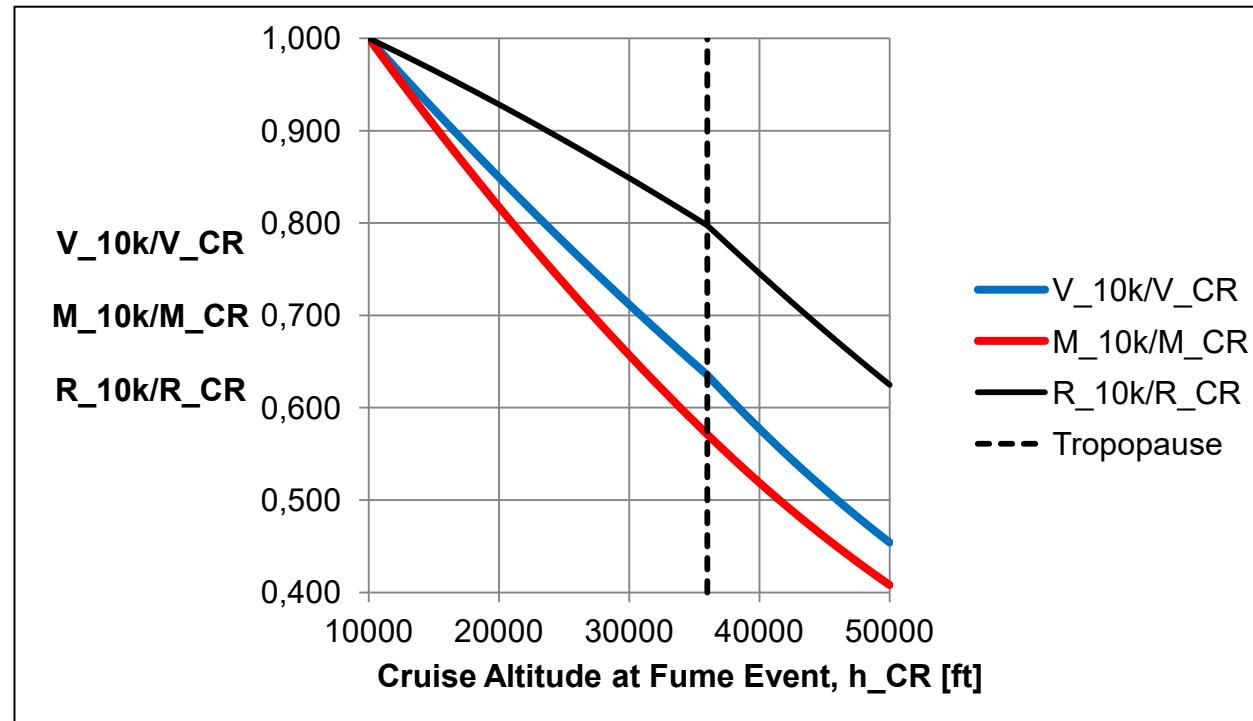
(AMM A320)

Hints for Pilots

Direct Venting of the Cabin in 10000 ft

The cruise Mach number has to be reduced considerably otherwise very high fuel burn will result

- The aircraft is designed for a certain cruise lift coefficient that should be kept constant.
- If the altitude is reduced, the aircraft flies in air with higher density. This has to be compensated
 - by lower **cruise speed in 10000 ft, V_{10k}** (given as True Air Speed, TAS) compared to original cruise speed at cruise altitude, V_{CR} or
 - by lower **Mach number in 10000 ft, M_{10k}** compared to original Mach number at altitude, M_{CR} .
- Although speed /Mach number are correctly reduced, **range in 10000 ft, R_{10k}** is still less than original range at cruise altitude, R_{CR} .
- Calculated is a conservative estimate of range reduction, because drag reduction due to Mach number reduction has not been considered.



Technical Solutions

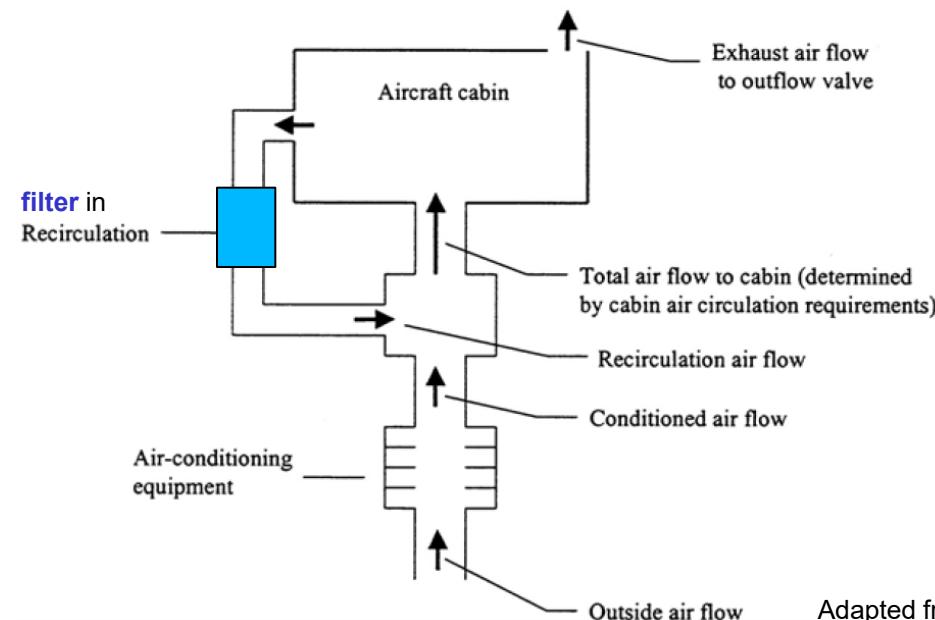
Filter in the Recirculation Path

Pall offers Odour/VOC Removal Filters

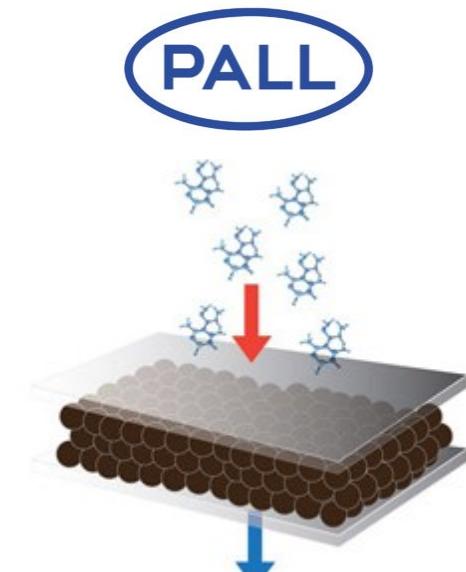
- "The carbon adsorbent is effective at adsorbing volatile organic compounds (VOC). Test results have shown a removal efficiency of 65% ... 73% when challenged with TCPs in the gaseous phase." (Pall 2011)

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 recirculation path of the cabin air.



Adapted from (NRC 2002)



Schematic of carbon filter
(Pall 2011)



(Lufthansa 2017)

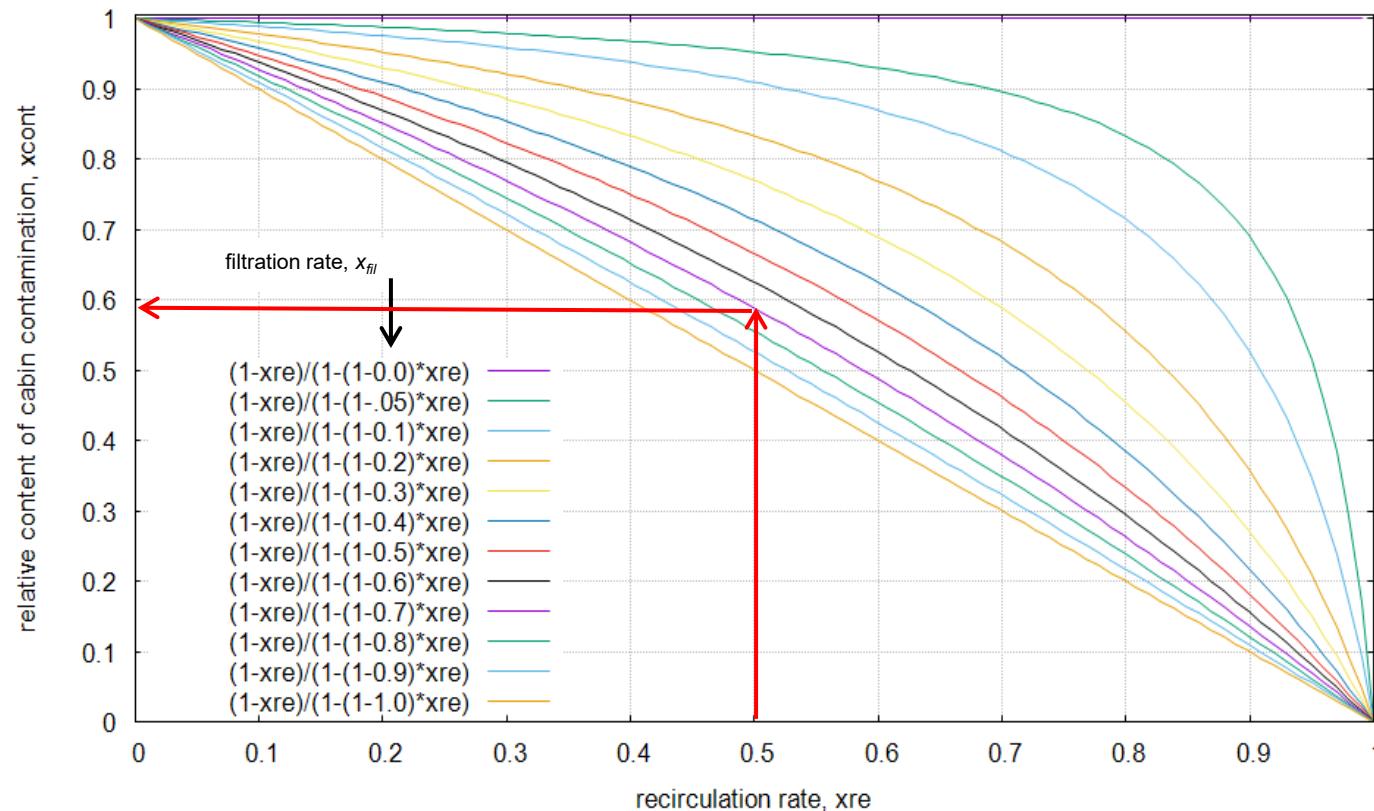
Technical Solutions

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%** or around $\approx 60\%$.

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

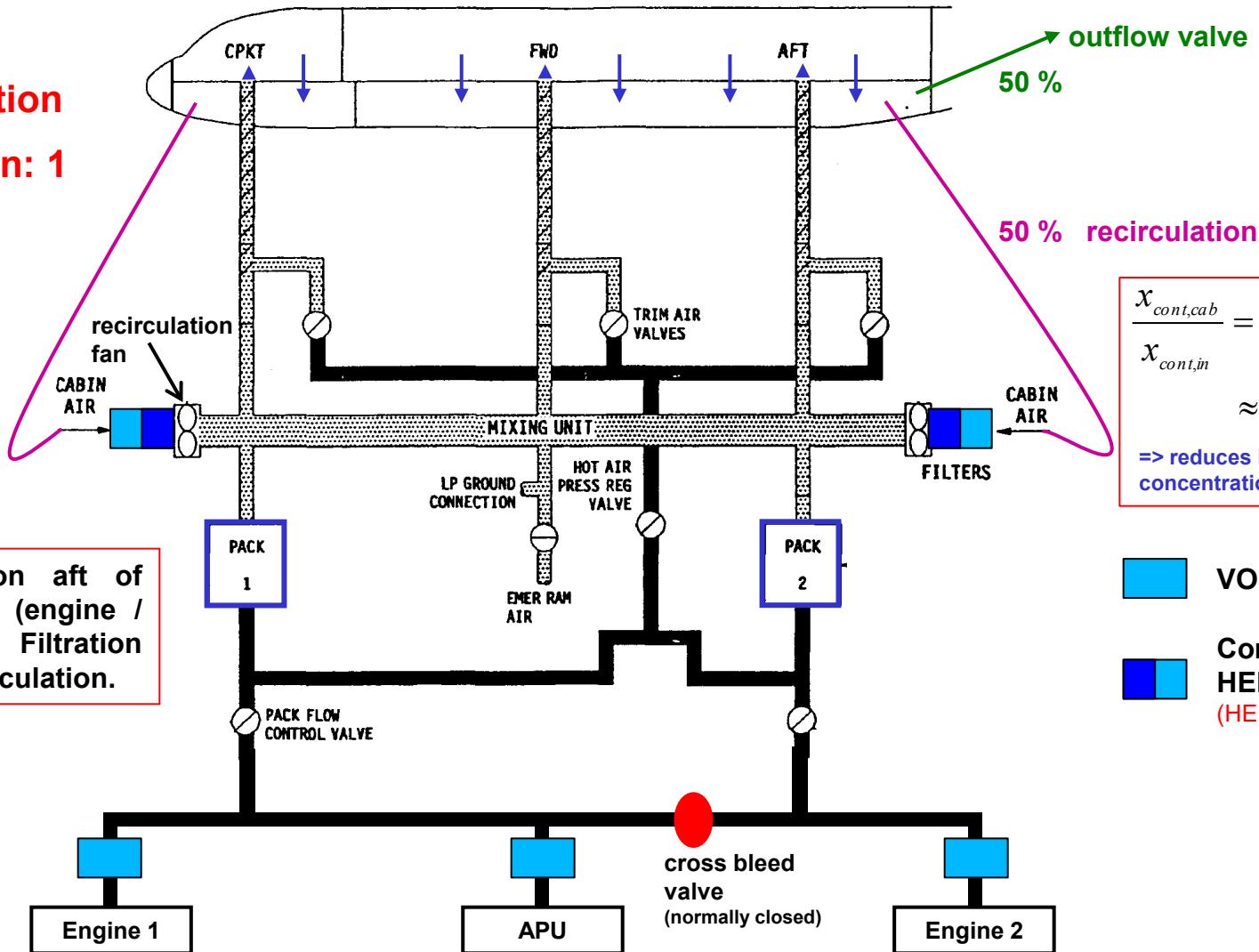


for $x_{fil} = 1$:

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

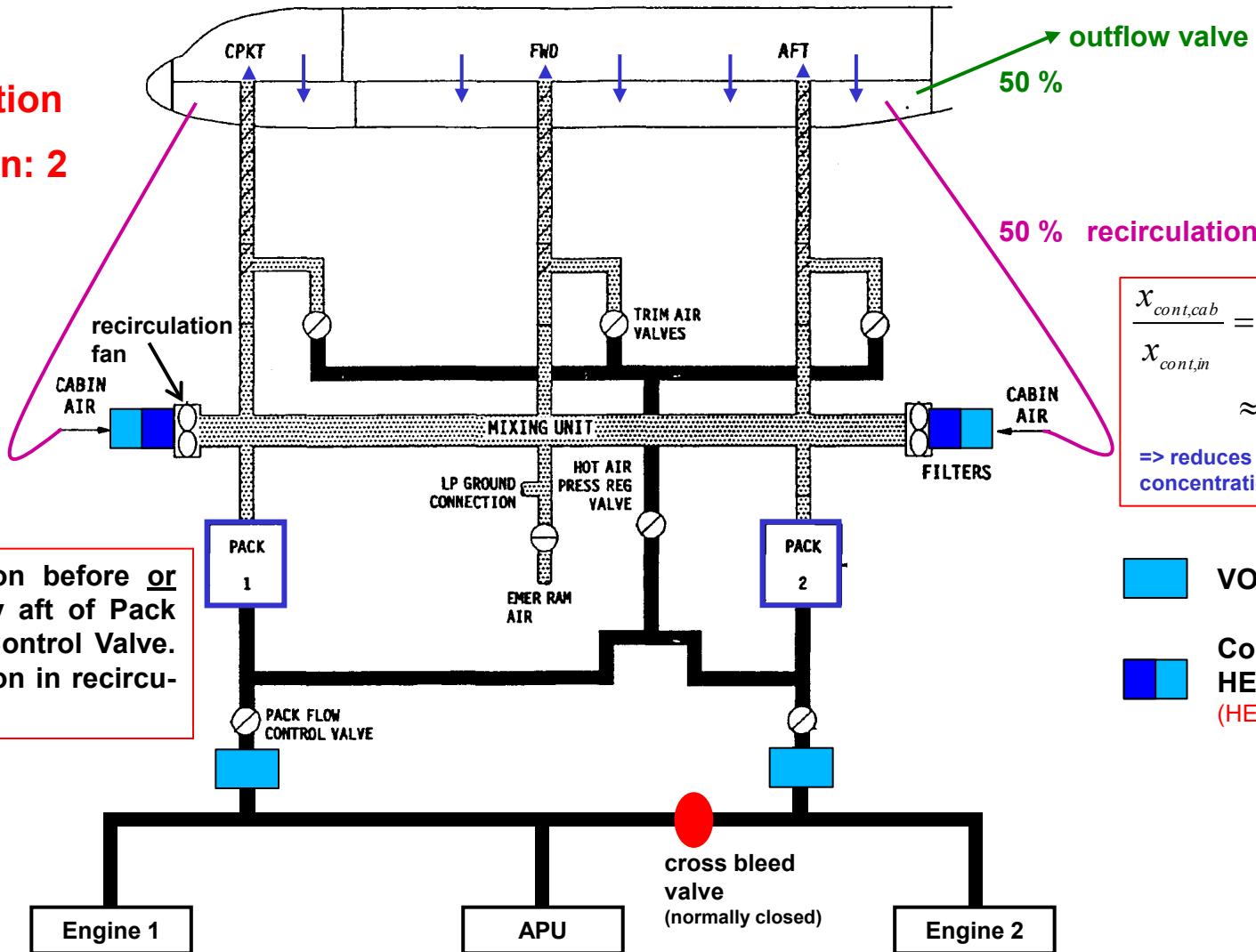
Technical Solutions

Full
Filtration
Option: 1



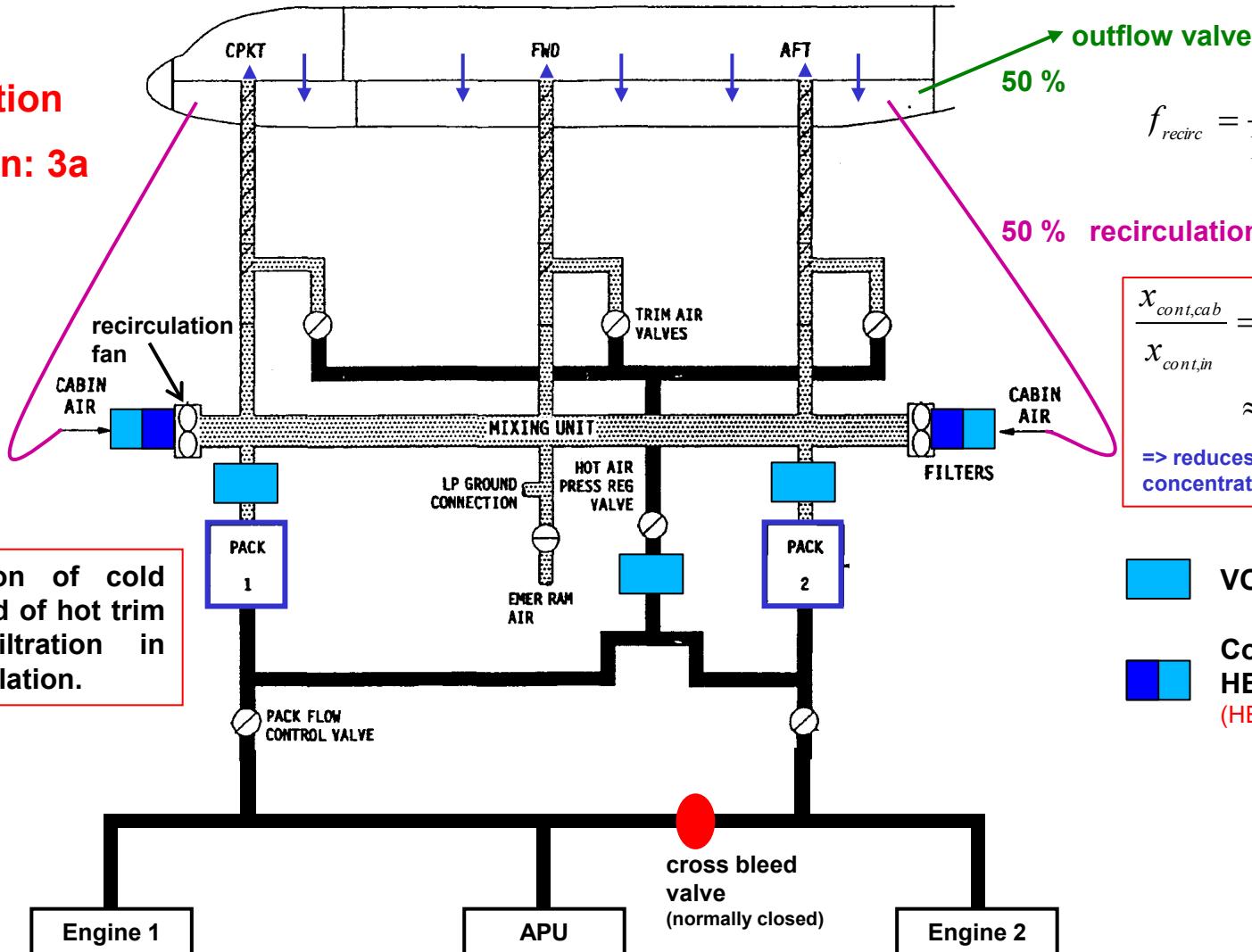
Technical Solutions

**Full
Filtration
Option: 2**



Technical Solutions

**Full
Filtration
Option: 3a**

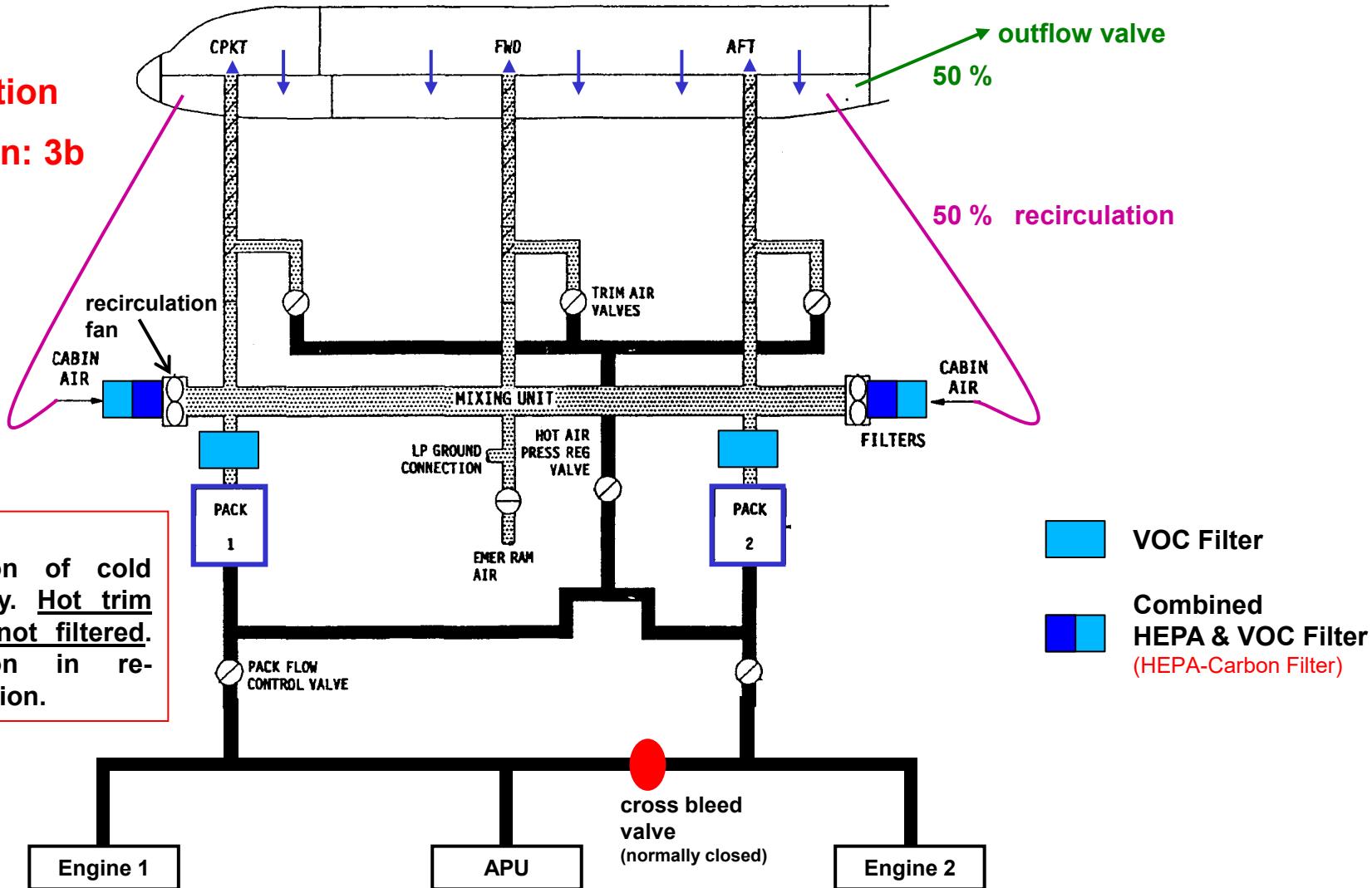


Technical Solutions

Full *

Filtration

Option: 3b



Technical Solutions

Full *

Filtration

Option: 3b

*

**Filtration of cold air only.
Hot trim air is not filtered.
Filtration in recirculation.**

Cabin FWD and AFT zone:

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

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

=> reduces incoming pollutant concentrations to $\approx 18\%$

On the occasion of the same selected temperature in all three zones, trim air is mostly used in the cockpit. It is used also in the forward zone (FWD), if the cabin layout has a business class. Air from the packs is controlled to such a (low) temperature to just meet the cooling needs of the "hottest" zone, which is usually the aft zone (AFT) because it has most passengers per cabin area.

We assume:

- ⇒ FWD and AFT zone have no trim air.
- ⇒ Demanded and achieved cabin temperature in all zones is 21 °C.
- ⇒ Cooling needs are met with a temperature in the mixing unit of 10 °C.
- ⇒ Bleed air (aft of the precooler) is at 200 °C.
- ⇒ Mass flow into the cockpit is much smaller than into the cabin.
- ⇒ Trim air mass flow is much smaller than mass flow from the mixing unit into the cabin.

This leads to:

- ⇒ Flow rate into the cockpit consists of 5.8% trim air and 94.2% air from the mixing unit.
- ⇒ Relative concentration of pollutants:

Cockpit zone:

See Appendix for details.

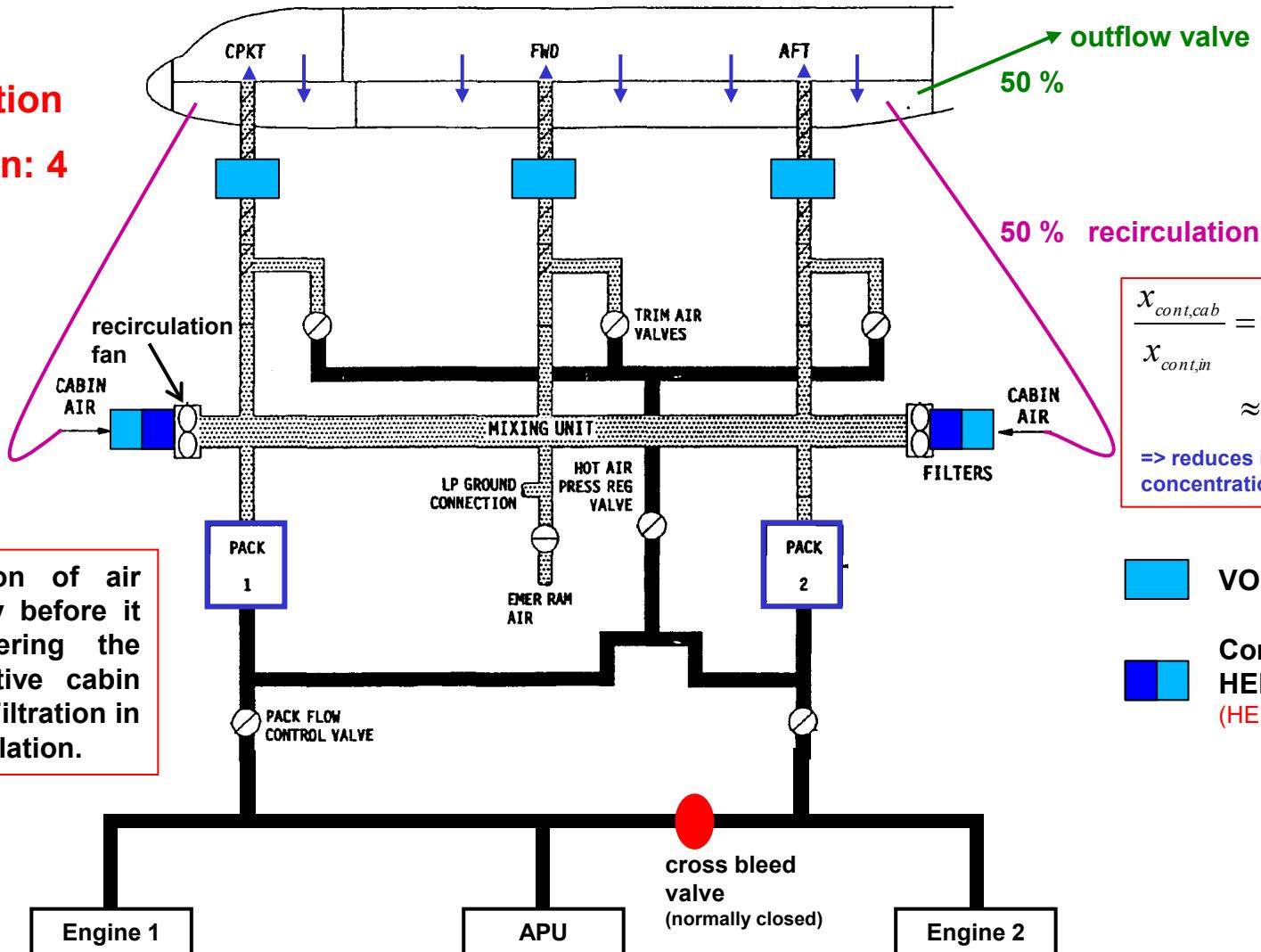
$$\frac{x_{cont,cockpit}}{x_{cont,in}} = \frac{\dot{m}_{trim}}{\dot{m}_{tot}} + \frac{x_{cont,cab}}{x_{cont,in}} \left(1 - \frac{\dot{m}_{trim}}{\dot{m}_{tot}} \right)$$

$$= 0.058 + 0.18(1 - 0.058) = 0.23$$

=> reduces incoming pollutant concentrations to only $\approx 23\%$

Technical Solutions

Full
Filtration
Option: 4

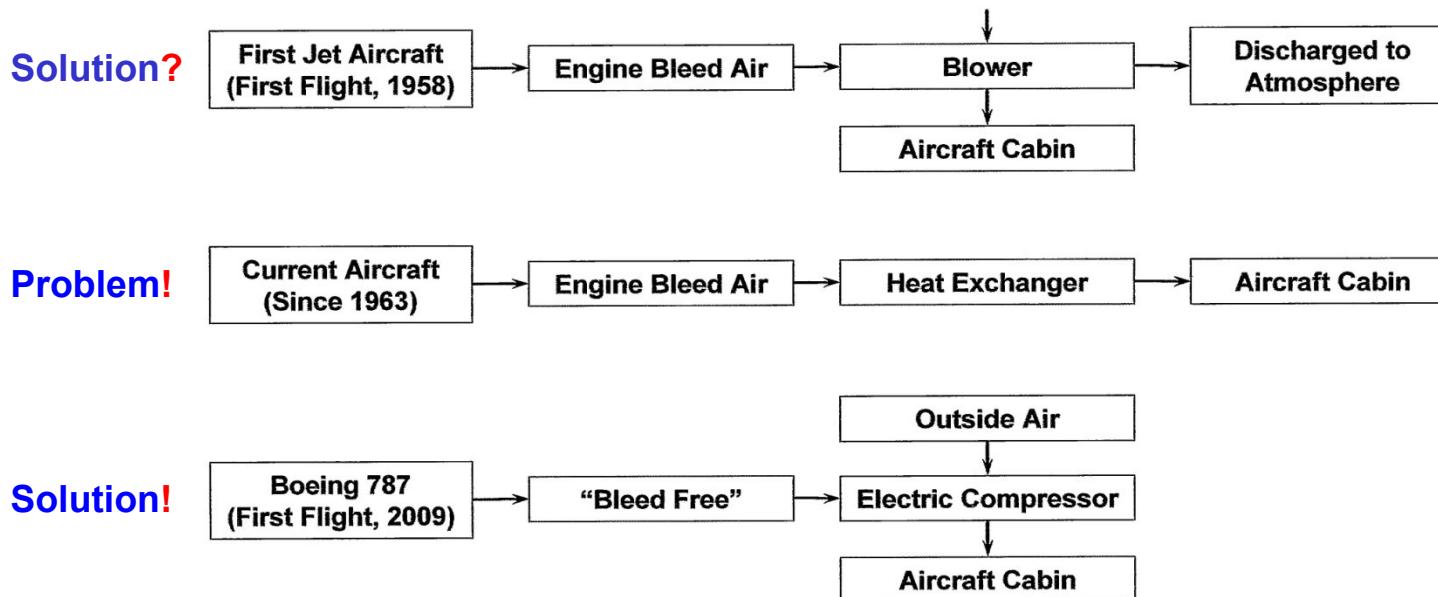


Technical Solutions

Cabin Pressurization Principles and Solutions

Overview

- **First Jet Aircraft** used a "blower" or "**turbocompressor**" (TC). The TC is the coupling of a turbine with a compressor. Bleed air from the engine compressor drives the TC turbine. The TCs compressor compresses outside air to meet the pressurization requirements of the cabin. The hot compressed air needs to be cooled. This can be done with a "vapor cycle system" (as known from the refrigerator).
- **Current Aircraft** make **use of bleed air directly**. It is compressed so much that it contains enough energy to also drive the pack that cool the bleed air down to temperatures considerably less than 0°C.
- The **Boeing 787** uses electrical power to drive an electric motor to drive a compressor. The **energy is extracted from the engine by means of shaft power driving a generator**. No bleed air is used. The engine is "Bleed Free".



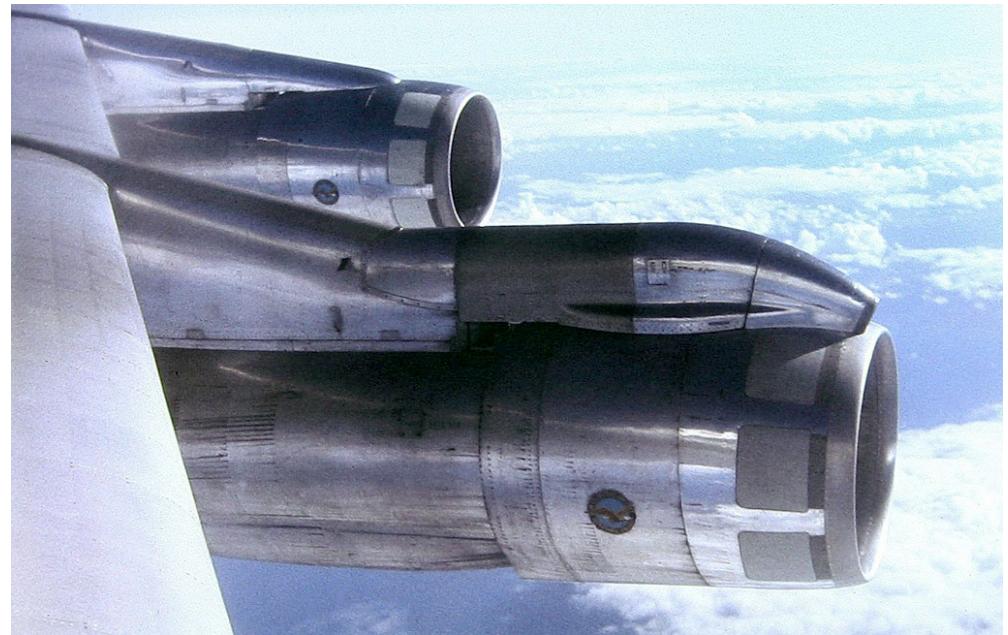
(Michaelis 2010)

Technical Solutions

Aircraft with Turbocompressors

Solution B707?

- The B707 engines are Pratt and Whitney JT3C's. Unlike modern passenger jet engines, they are not equipped to provide air for cabin pressurization. So for cabin air purposes, you need one of the key 707 spotting features - the turbocompressors. **The turbocompressor is basically a little engine-driven turbine that sits right above the engine's fan casing, just ahead of the pylon.** For obvious reasons, Boeing put a nice little fairing over the turbocompressor (TC) and faired it into the pylon. But it leaves an obvious "hump" on top of the engine just in front of the pylon. A TC hump doesn't necessarily mean there's a TC in there. Some B707 have 4 TC humps, others have only 2 TC's. The other two are empty humps. Engines 2 and 3 have the humps, 1 and 4 don't. AA's B707 have only 2 TCs and only 2 humps. (Hingtgen 2004)
- Inlets to TCs usually appear only on the number 2, 3, and 4 engines and generally not on the number 1 engine.
- The reason for only three turbocompressors is that only 3 were required for adequate pressurization and redundancy.
- The smaller non-intercontinental - non ocean crossing 707 sister, the 720, had only two turbocompressors. They are found on #2 and #3 engines only. Less redundancy needed for mostly overland flight with closer diversion airports.
- A volume of air was bled off the engine to turn the turbocompressor supplying the aircraft's pressurization needs. **The engine bleed air was then dumped overboard once it powered the turbocompressor's turbine.** There is a small opening on the side of the upper nacelle just behind the turbocompressor. That is the turbine exhaust.
- There were also concerns about engine oil contaminating the air conditioning system if the air was bled directly off the engine.
- Engine bleed air can be used to supplement a TC** should it shutdown or be subject to a MEL, or in addition if extra airflow is required. (Discussion 2001)



B707-320C with Pratt & Whitney JT3D engines. Martin J. Galloway
(https://upload.wikimedia.org/wikipedia/commons/c/c1/Boeing_707_engineviewedit.jpg)

Technical Solutions

Aircraft with Turbocompressors

Solution DC-8?

- Bleed air was used to power a turbocompressor, which compressed the ram air to the proper pressure. That air was cooled by a Freon vapor compression-cycle air conditioner for temperature control before being distributed to the cabin. The arrangement was **heavy, expensive**, and inefficient because of the **inefficiencies of the turbocompressor** (E. Marzolf, retired, Douglas Aircraft Co.) (NRC 2002)
- Even more important was the **high amount of maintenance** that the systems required (R. Kinsel, retired, AlliedSignal) (NRC 2002)
- The inlets on the front of the DC8 are for the 4 turbocompressors [TC's] used to pressurize the cabin. The top and bottom inlets feed the turbo compressors. [The middle inlet] feeds heat exchangers to cool the compressed air from the TC's. The bleed air from the engines which is used to spin the turbo compressors exhausts overboard from the vent located on the side of the fuselage [only a little] aft [and a little higher]. (Jetpilot 2001)
- "The TC's on the DC8 were extremely noisy in the cockpit, and had a tendency to have uncontained [rotor] failures which scared the shit out of you as the pieces had a tendency to rip into the cockpit on occasion. To find the condition of a TC on the preflight one only had to **look at the TC exhaust duct and find how much oil from the bearing case had leaked past the seal and run all over the fuselage**. I never saw a TC that didn't leak. They also made strange noises notifying you of their impending doom." "TC's spool up to about 13000 RPM in about 2 seconds." (Jetpilot 2001)



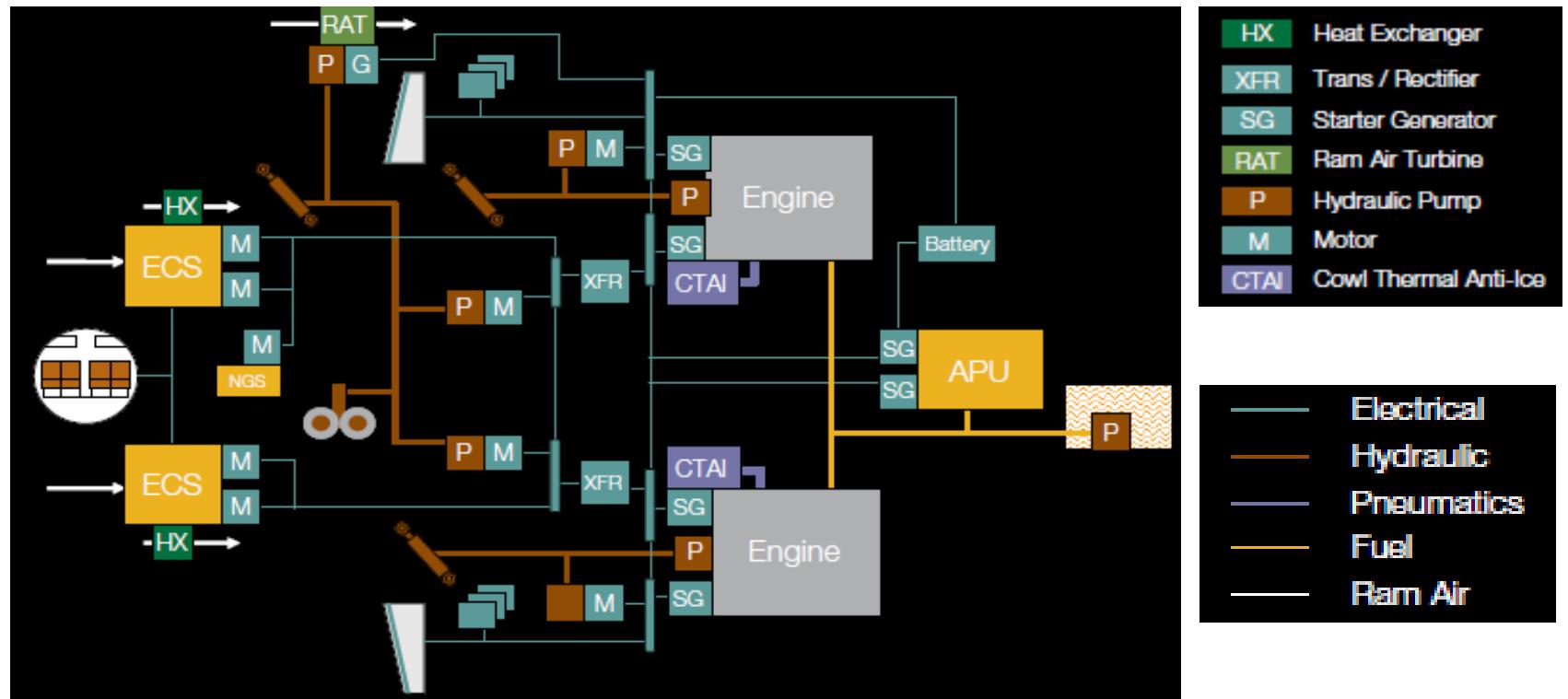
DC-8 (<http://image.airlineratings.com/articles/DC-8 DWDCropfb.jpg>)

Technical Solutions

Electrical (Bleed Free) Cabin Air Supply

Solution B787!

Boeing 2007

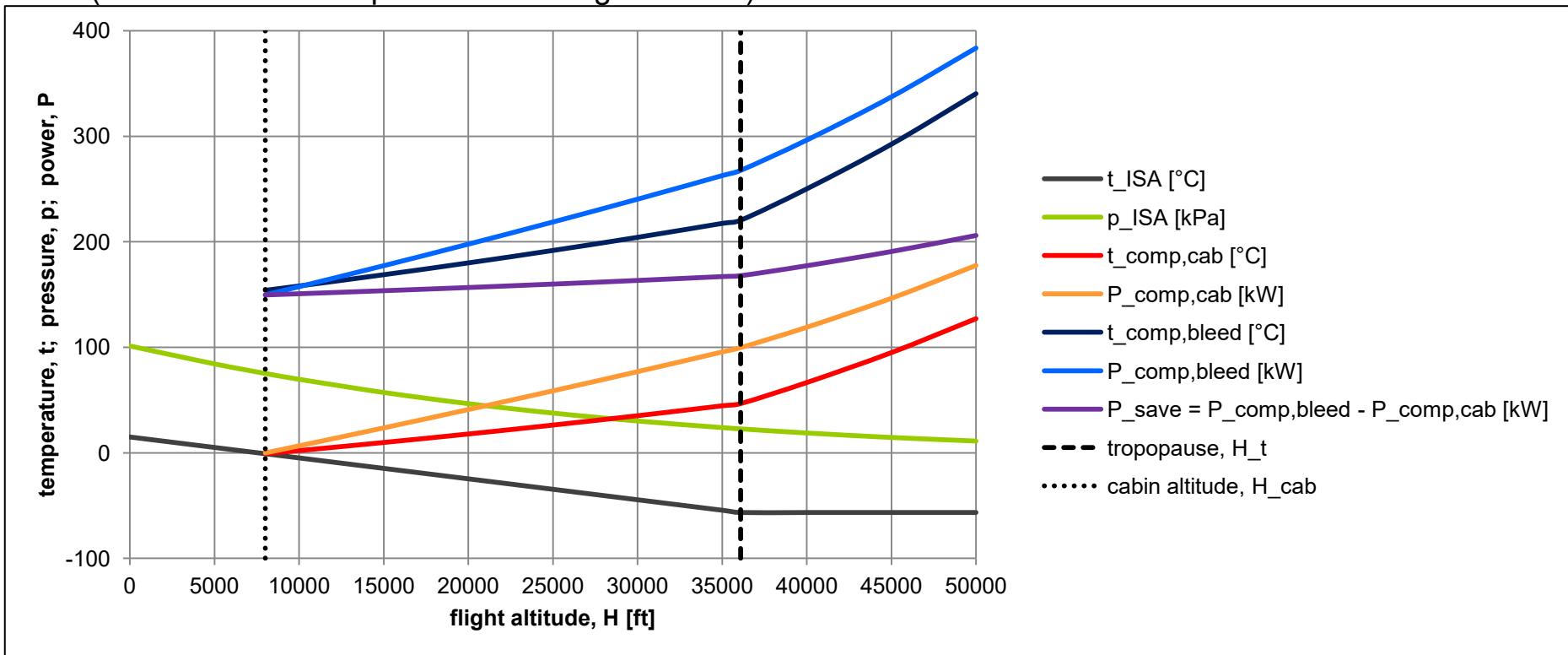


The "Pack" of the B787's Environmental Control System (ECS) is powered by electric motors (M) to compress ambient air up to cabin pressure and to push the air through the heat exchangers (HX) for cooling. The power for the electric motors is produced by generators (SG) connected to the aircraft's engine and APU. After compression and cooling the air is delivered to the cabin.

Technical Solutions

Electrical (Bleed Free) Cabin Air Supply

Power Savings from Compression* (A320): ≈ 150 kW
(almost as much as power from two generators)

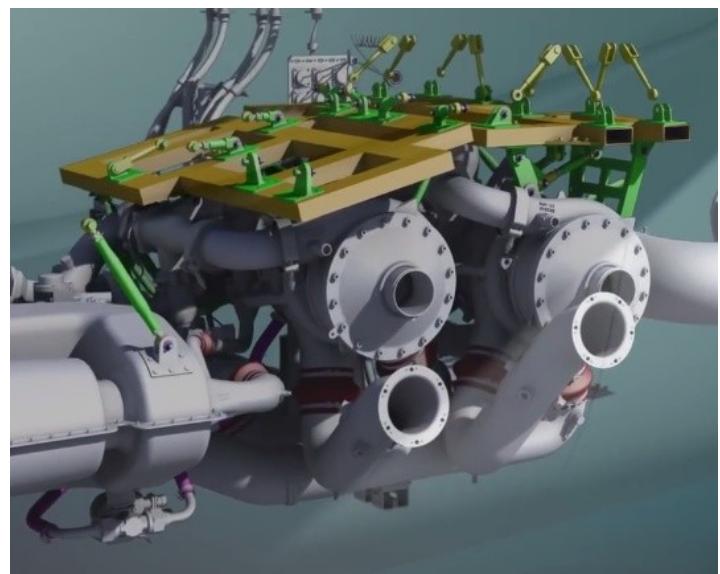
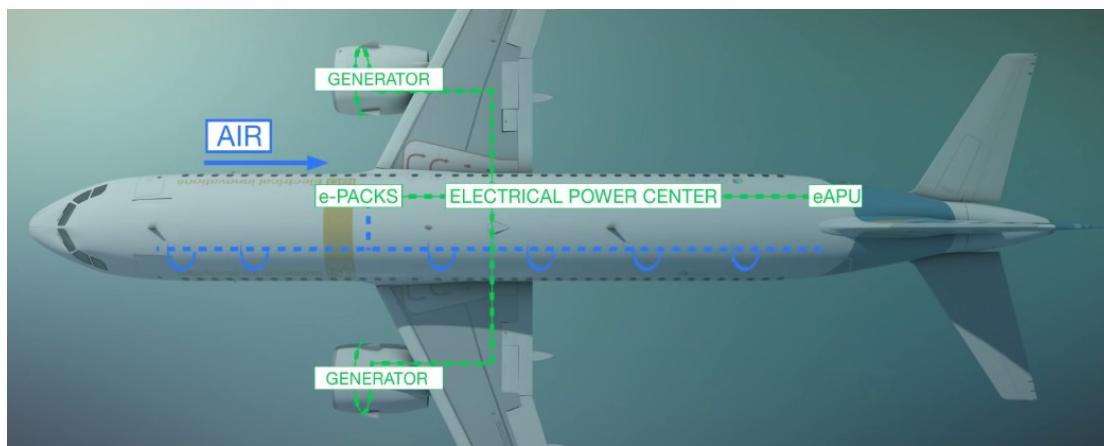


* Power savings for an electrical architecture estimated from the difference between: a) compressing to typical bleed pressure of 44 psi = 3034 hPa and b) compressing to cabin pressure at 8000 ft: 753 hPa. The bleed pressure of 44 psi is the pressure behind the bleed valve. The necessary pressure in the compressor is even higher. Electrical cabin air supply needs additional electrical power for the packs (here not considered!) that is extracted as shaft power from the engines with a high ($\approx 70\%$) efficiency. Further parameters: Air exchange rate: 1 m³/s. Compressor efficiency: 0.86 .

Technical Solutions

More Electric A320?

Electrical innovations flightlab



Technical Solutions

More Electric A320 with Electrical (Bleed Free) Cabin Air Supply?



The Electrical Environmental Control System (E-ECS) was developed by Liebherr-Aerospace Toulouse SAS, Toulouse (France), Liebherr's center for air management systems. The E-ECS is equipped with a new type of motorized turbo compressor (50 kW) which enables to use directly external air (bleed less) for air conditioning. The power electronics ensure the speed control of the motorized turbo compressor and offer synergy capabilities with other electrical loads to optimize the overall electrical power consumption on board the aircraft. The interaction between air intake and the turbo-compressors and the performance of the system in all operating conditions was tested in a flight test campaign with Airbus A320-Prototyp MSN001 from June 3 to June 24, 2016. E-ECS will also contribute to fuel burn reduction.

Liebherr 2016

Aircraft Cabin Air and Engine Oil – An Engineering View

Contact

info@ProfScholz.de

<http://www.ProfScholz.de>

Aircraft Cabin Air and Engine Oil – An Engineering View

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Contents of Appendix

- Derivation: Direct Venting of the Cabin in 10000 ft
- Derivation: Efficiency of Filters in the Recirculation Path
- Derivation: Full Filtration Option: 1b – Relative Amount of Trim Air in Cockpit
- Derivation: Full Filtration Option: 1b – Relative Pollutant Concentration in Cockpit

Hints for Pilots

Derivation: Direct Venting of the Cabin in 10000 ft

Derivation of Equations (see considerations on previous page)

- cruise speed in 10000 ft, V_{10k} (TAS)
- Mach number in 10000 ft, M_{10k}
- range in 10000 ft, R_{10k}

$$L = mg = \frac{1}{2} \rho V^2 \cdot C_L \cdot S_w = \text{const}$$

$$\rho_{CR} \cdot V_{CR}^2 = \rho_{10k} \cdot V_{10k}^2$$

$$V_{10k} = \sqrt{\frac{\rho_{CR}}{\rho_{10k}}} \cdot V_{CR}$$

$$M_{10k} \cdot a_{10k} = \sqrt{\frac{\rho_{CR}}{\rho_{10k}}} \cdot M_{CR} \cdot a_0 \cdot \sqrt{\frac{T_{CR}}{T_0}}$$

$$M_{10k} = \sqrt{\frac{\rho_{CR}}{\rho_{10k}}} \cdot \frac{a_0}{a_{10k}} \cdot \sqrt{\frac{T_{CR}}{T_0}} \cdot M_{CR}$$

$$\rho_{10k} = 0,90464 \text{ kg/m}^3$$

$$T_0 = 288,15 \text{ K}$$

$$a_{10k} = 328,39 \text{ m/s}$$

$$a_0 = 340,29 \text{ m/s}$$

Plot:

$$\frac{V_{10k}}{V_{CR}} = \sqrt{\frac{\rho_{CR}}{\rho_{10k}}}$$

$$\frac{M_{10k}}{M_{CR}} = \sqrt{\frac{\rho_{CR}}{\rho_{10k}}} \cdot \frac{a_0}{a_{10k}} \cdot \sqrt{\frac{T_{CR}}{T_0}}$$

Calculating the reduced range:

$$R = \frac{E \cdot V}{C \cdot g} \cdot \ln \frac{m_1}{m_2} \quad c = c_a V + c_b$$

$$\frac{R_{10k}}{R_{CR}} = \frac{V_{10k}}{V_{CR}} \cdot \frac{C_{CR}}{C_{10k}} = \frac{V_{10k}}{V_{CR}} \cdot \frac{c_a \cdot V_{CR} + c_b (h_{CR})}{c_a \cdot V_{10k} + c_b (h_{10k})}$$

$$= \frac{V_{10k}}{V_{CR}} \cdot \frac{c_a \cdot M_{CR} \cdot a_{CR} + c_b (h_{CR})}{c_a \cdot M_{10k} \cdot a_{10k} + c_b (h_{10k})}$$

$$a_{CR} = a_0 \cdot \sqrt{\frac{T_{CR}}{T_0}}$$

$$M_{10k} = \frac{M_{CR}}{M_{10k}} \cdot M_{CR}$$

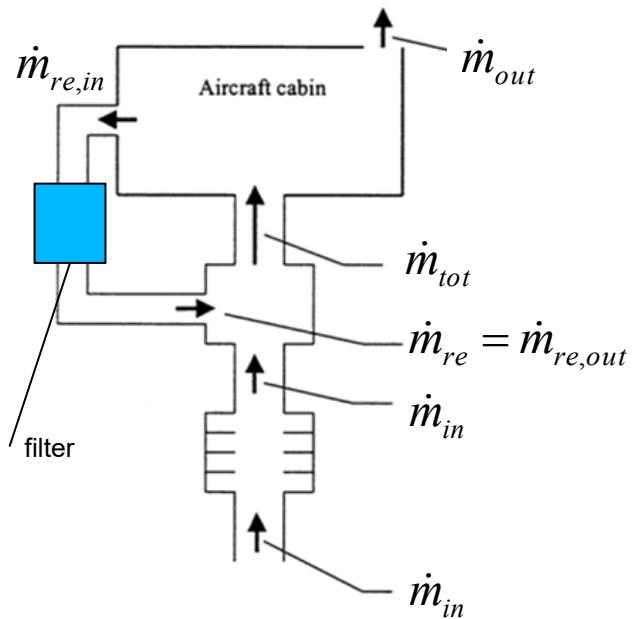
$$c_a = 3,38 \cdot 10^{-8} \text{ kg/(Nm)}$$

$$c_b = 1,04 \cdot 10^{-5} \sqrt{\frac{T_0}{T(h)}} \text{ kg/(Ns)}$$

Technical Solutions

Derivation:

Efficiency of Filters in the Recirculation Path (1/2)



Adapted from (NRC 2002)

$$\dot{m}_{out} = \dot{m}_{in}$$

$$\dot{m}_{tot} = \dot{m}_{in} + \dot{m}_{re}$$

$$\dot{m}_{tot} = \dot{m}_{in} + x_{re} \cdot \dot{m}_{tot}$$

$$1 = \frac{\dot{m}_{in}}{\dot{m}_{tot}} + x_{re}$$

$$\frac{\dot{m}_{in}}{\dot{m}_{tot}} = 1 - x_{re}$$

$$\dot{m}_{tot} = \frac{\dot{m}_{in}}{1 - x_{re}} \quad (2)$$

$$\dot{m}_{tot,cont} = \dot{m}_{in,cont} + \dot{m}_{re,out,cont}$$

cont: contaminated

$$(3)$$

$$\text{Def.: } \frac{\dot{m}_{in,cont}}{\dot{m}_{in}} = x_{cont,in}$$

$$\frac{\dot{m}_{out,cont}}{\dot{m}_{out}} = \frac{\dot{m}_{tot,cont}}{\dot{m}_{tot}}$$

$$\dot{m}_{re,out,cont} = (1 - x_{fil}) \dot{m}_{re,in,cont}$$

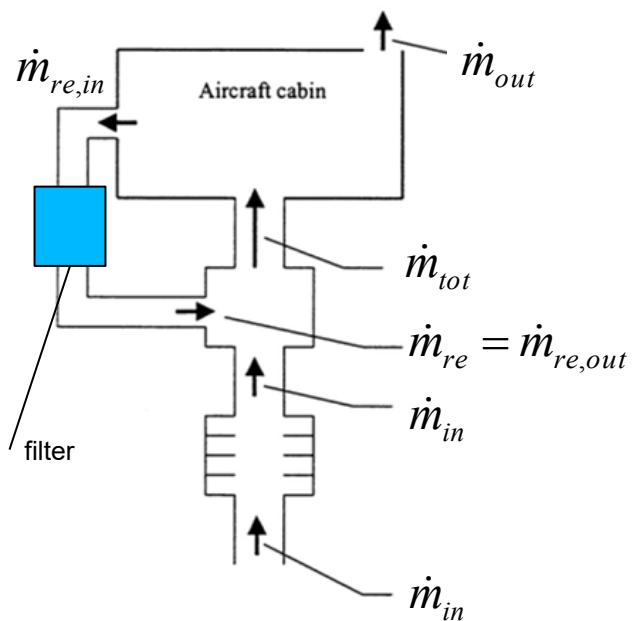
with (3)

$$\frac{\dot{m}_{tot,cont}}{\dot{m}_{tot}} = \frac{\dot{m}_{in,cont}}{\dot{m}_{tot}} + (1 - x_{fil}) \frac{\dot{m}_{re,in,cont}}{\dot{m}_{tot}}$$

Technical Solutions

Derivation:

Efficiency of Filters in the Recirculation Path (2/2)



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

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

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

for $x_{fil} = 1$:

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

Adapted from (NRC 2002)

Technical Solutions

Full Filtration Option: 3b – Derivation: Relative Amount of Trim Air in Cockpit

$$m_{\text{mix}} \cdot t_{\text{mix}} + m_{\text{trim}} \cdot t_{\text{trim}} = m_{\text{tot}} \cdot t_{\text{zone}}$$

$$m_{\text{tot}} = m_{\text{mix}} + m_{\text{trim}}$$

$$m_{\text{mix}} = m_{\text{tot}} - m_{\text{trim}} \quad \frac{m_{\text{mix}}}{m_{\text{tot}}} = 1 - \frac{m_{\text{trim}}}{m_{\text{tot}}}$$

$$m_{\text{tot}} \cdot t_{\text{mix}} - m_{\text{trim}} \cdot t_{\text{mix}} + m_{\text{trim}} \cdot t_{\text{trim}} = m_{\text{tot}} \cdot t_{\text{zone}}$$

$$m_{\text{tot}} \cdot t_{\text{mix}} + m_{\text{trim}} (t_{\text{trim}} - t_{\text{mix}}) = m_{\text{tot}} \cdot t_{\text{zone}}$$

$$m_{\text{trim}} (t_{\text{trim}} - t_{\text{mix}}) = m_{\text{tot}} (t_{\text{zone}} - t_{\text{mix}})$$

$$\frac{m_{\text{trim}}}{m_{\text{tot}}} = \frac{t_{\text{zone}} - t_{\text{mix}}}{t_{\text{trim}} - t_{\text{mix}}}$$

$$= \frac{21^\circ\text{C} - 10^\circ\text{C}}{200^\circ\text{C} - 10^\circ\text{C}} = 0,058$$

Trim air accounts for about 5.8% of total flow into the cockpit under given temperature conditions.

Technical Solutions

Full Filtration Option: 3b – Derivation: Relative Pollutant Concentration in Cockpit

$$\frac{m_{\text{mix}}}{m_{\text{tot}}} = 1 - \frac{m_{\text{trim}}}{m_{\text{tot}}} = 0,942$$

Assume:

$$m_{\text{cockpit}} \ll m_{\text{cab}} \quad m_{\text{cab}} = m_{\text{FWG}} + m_{\text{AFT}}$$

$$x_{\text{mix}} = x_{\text{cab}}$$

$$\text{for } \frac{m_{\text{trim}}}{m_{\text{tot}}} \ll 1$$

Cockpit zone: Modified concentration of pollutants due to trim air

$$x_{\text{in}} \cdot m_{\text{trim}} + x_{\text{mix}} m_{\text{mix}} = x_{\text{zone}} \cdot m_{\text{tot}}$$

$$\cancel{x_{\text{in}}} \cdot \frac{m_{\text{trim}}}{m_{\text{tot}}} + \frac{x_{\text{cab}}}{x_{\text{in}}} \cdot \frac{m_{\text{mix}}}{m_{\text{tot}}} = \frac{x_{\text{zone}}}{x_{\text{in}}}$$

$$0.058 + 0.18 \cdot 0.942 = \underline{\underline{0.23}}$$

Relative concentration of pollutants goes up from 18% to 23%.