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

Technical Solutions to the Problem of Contaminated Cabin Air

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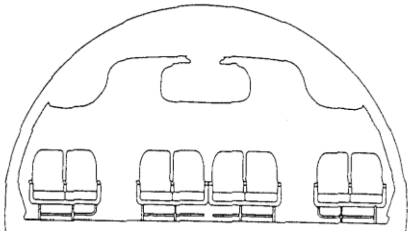

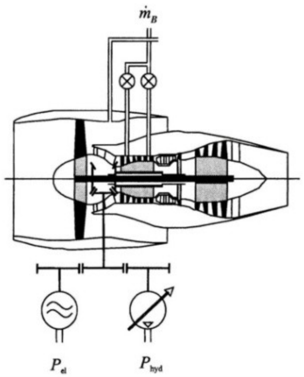

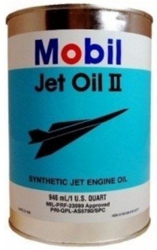

Abstract

Purpose – This presentation gives an introduction to the problem of contaminated cabin air and points out possible solutions especially by looking at carbon filters placed in the main path of the bleed air from the engine to the cabin ("total cabin air filtration") in additon to filters in the cabin air recirculation path. Maintenance issures related to the topic are also considered.

Design/methodology/approach – The literature review is complemented with own explanations, thoughts and derivations.

Findings – There is a real health and flight safety risk due to contaminated cabin air. For the infrequent flyer the risk is very low. Also aviation statistics are not dominated by cabin air related accidents. Nevertheless, a bleed air based air conditioning system can be regarded as applying a fundamentally wrong systems engineering approach. A substantial improvement of the situation can only be reached with filters added to the large fleet of existing airplanes. A full solution, however, requires airconditioning with outside air and dedicated compressors.

Research limitations/implications – The study is based primarily on references.

Practical implications – Passengers and crew are made aware of the risk of cabin air contamination based on technical facts. Given detailes of technical solutions contribute to the scientific discussion.

Social implications – Better knowledge of the problem should enable passengers and crew to maintain a firm position in the sometimes heated discussion.

Originality/value – Engineering based information with a critical view on the topic seems to be missing in public. This presentation contributes filling this gap.

Any further request may be directed to Prof. Dr.-Ing. Dieter Scholz, MSME
E-Mail see: http://www.ProfScholz.de

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Introduction

MEDICAL INVESTIGATION DAVID LEARMOUNT LONDON

Cabin air killed BA pilot, say experts

Authority on organophosphate poisoning says tissue from Richard Westgate, who died in 2012, "worst case" he has seen

Sustained exposure to organophosphates (OP) from contaminated cabin air contributed to the death of a 43-year-old British Airways pilot, a group of medical experts believe.

Their findings are likely to increase pressure on the industry to take more seriously the issue of sustained exposure to engine bleed air. Airlines and governments have dismissed suggestions that it can be a factor behind flightcrew falling ill.

The pilot, senior first officer Richard Westgate, started flying professionally in 1996 and medical details of his symptoms before death are on record.

Although no coroner's inquest has been held into his death, medical experts led by Prof Mohamed Abou-Donia of Duke University Medical School, North Carolina, the world's leading authority on organophosphate poisoning, have just published a study into two autopsies carried out on Westgate, who until his illness was a slim, fit paragliding champion.

Abou-Donia and his colleagues are also investigating the death this year of an unnamed 34-year-old BA airline steward, whose

Westgate: series of symptoms

by far." He adds: "The air transport industry constantly over- cabin, but they – and aircraft manufacturers – maintain that this is at a harmless level. Abou-Donia argues this was not so in Westgate's case, despite the fact that the pilot had never logged an actual "fume event" during his career.

WATERSHED

Frank Cannon, the lawyer acting for the families of both deceased, says the Westgate case is a watershed in this controversy: "They can try explaining one [case] away, but not another and then another." Cannon says he has "about 50" cases on his books.

■ ■ ■

(Flight International 2014)

... but ...

The Telegraph

By **Telegraph Reporters**

13 APRIL 2017 • 3:23PM

The family of a British Airways co-pilot who believed he had been poisoned by contaminated cockpit air have accused the airline industry of having its "head in the sand" over the issue.

Richard Westgate, 43, died in December 2012 after moving to the Netherlands to seek help from a specialist clinic for his symptoms which he thought were caused by "aerotoxic syndrome", which has been called "pilot's disease".

A coroner ruled Mr Westgate died accidentally at the Bastion Hotel in Bussum, Netherlands after taking an unintentional overdose of the sleeping tablet pentobarbital.

(Telegraph 2017)

A controversial issue!

Definition: Aircraft Cabin Air

Aircraft cabin air is the air in the cabin of an aircraft. The air in the cockpit is included in this definition. In pressurized cabins it is the air inside the pressure seals. Pressure control is such that cabin pressure is reduced down to a pressure equivalent to 8000 ft (referring to the ICAO Standard Atmosphere) as the aircraft climbs. In unpressurized aircraft cabins the air is at ambient pressure. Temperature control is done by heating or cooling as required. Venting ensures frequent exchange of cabin air with fresh air from outside. In addition, cabin air can be recirculated and filtered. When flying at high altitudes, cabin air is at similar low relative humidity as the air outside.

Definition: Quality

Degree to which a set of inherent characteristics fulfills requirements.

(ISO 9001)

Definition: **Contamination**

The process of making a material unclean or unsuited for its intended purpose, usually by the addition or attachment of undesirable foreign substances.

Adapted from (Wiktionary 2018)

The presence of a minor and unwanted constituent (contaminant). Related to health: A harmful intrusion of toxins or pathogens e.g. in food, water, or air.

Adapted from (Wikipedia 2018a)

Definition: **Fume Event** (Rauchereignis)

In a fume event, the cabin and/or cockpit of an aircraft is filled with fume. The fume originates from the bleed air and enters the cabin via the air conditioning system. 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.

Adapted from (Wikipedia 2018b)

Introduction

Fume Event on US Airways Flight 432 Phoenix to Maui in 2010
Video on: https://youtu.be/AZqeA32Em2s

Note:
- Smell events (without fumes) are much more frequent than fume events.
- Health effects have been reported from smell events alone (where patients never encountered a fume event) .

Definition: **Smell Event** (Geruchsereignis)
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. Note: Other reasons for smell in the cabin are possible. The term "smell event", however, is generally used as defined here.

Definition (ECA): **Smoke & Fume / Smell Event (cabin air contamination)**
An incident may cause only fume, only smell or both. The European Cockpit Association (ECA) explains: "In the context of the ICAO circular [ICAO Circular 344 'Guidelines on Education Training and Reporting Practices related to Fume Events'], fumes and odours are deemed to be synonymous, and the term 'fume(s)' includes both fumes and odours."
(ECA 2017)

Definition (IATA): **Cabin Air Quality Event (CAQE)**
"Cabin air quality events (CAQEs) [are] particularly ... the so-called fume events" (smoke, fumes / odours).
(IATA 2017)

Proposed new Definition:

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).

Headache	Drowsiness
Dizziness	Impaired vision
Nausea	Vomiting
Tingling (e.g. hands, feet, etc.)	Trembling
Numbness	Irritated eyes/throat/nose
Difficulty speaking and finding words	Memory problems
Muscle incoordination	
Breathing difficulties	Coughing

Typical symptoms following a CACE (ECA 2017)

Intention with the new definition: Detach the definition from merely human sensation. Allow also drastic health degradation to define the event. Objective measurements would certainly be best, but are usually not available.

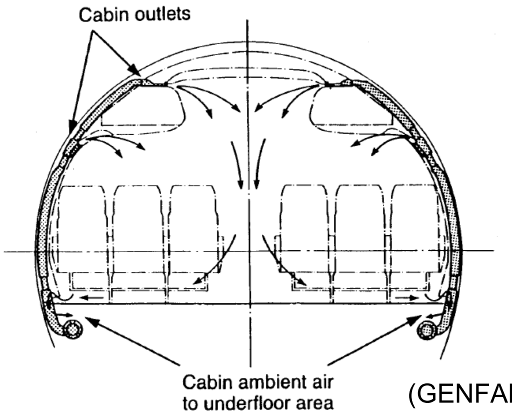
Introduction

Condensation on AirAsia flight AK6303 with A320 from Langkawi (LGK) to Kuala Lumpur (KUL). Departure in tropical rainforest climate ("PlaneHunter", http://bit.ly/2oUJYKP)

Condensation on A319 ("EGGD", http://i56.tinypic.com/2gwhoif.jpg)

Definition: Condensation Event

In a condensation event, warm and humid air in the cabin mixes with cold air from the air conditioning system. This usually happens during departure, when the cabin is still filled with air from outside and starts to mix with cold air leaving via the cabin outlets. *Note: Do not confuse this with a fume event!*



(GENFAM A320)

Civil Aviation Authority (CAA), UK, 2017:
"CABIN AIR CONTAMINATION INFORMATION SHEET FOR PATIENTS"

Where does the cabin air supply come from?

... from the engines ...

What are the causes of contamination of the cabin air supply?

The cabin air may be contaminated when an oil seal fails, allowing jet oil or hydraulic fluid to leak into the bleed air supply. This can result in an oil mist or odour in the aircraft which is sometimes described as smelling like 'sweaty socks' ...

What are the concerns regarding contamination of the cabin air ...?

... both short and long term adverse effects on health ...

Which chemicals might contaminate bleed air?

It is difficult to determine exactly what substances are present in contaminated bleed air. When jet oils and hydraulic fluid are subjected to very high temperatures, they break down to produce other compounds including potentially harmful substances such as carbon monoxide, aldehydes (that can irritate the airways) and various acidic compounds (that produce unpleasant odours). Aircraft engine oils also contain small amounts of organophosphates, ... toxic effects, particularly on the nervous system ...

Civil Aviation Authority (CAA), UK, 2017:

"CABIN AIR CONTAMINATION INFORMATION SHEET FOR PATIENTS"

What are the short term health effects?

... irritation of the eyes, nose and throat, headache, dizziness and tingling in the hands, feet and face ...

What are the long term health effects?

Symptoms that have been reported include:

- neurological symptoms such as headaches, fatigue, weakness, problems with balance, pain, numbness, memory problems
- psychological symptoms such as depression, anxiety, poor concentration
- skin problems, respiratory or gastro-intestinal symptoms are also occasionally reported

... remains an area of scientific uncertainty.

(CAA 2017)

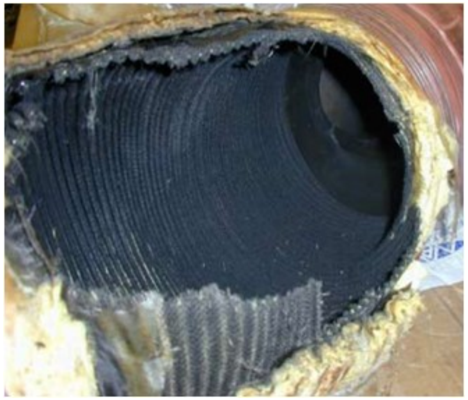
How Do We Know about Oil in the Cabin?

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

1. Oil traces in bleed duct
2. Oil traces in air conditioning ducts
3. Oil traces in recirculation filters
4. Oil traces on cabin surfaces (wall panels, seats, ...)

Evidence collected in: Scholz 2017


1.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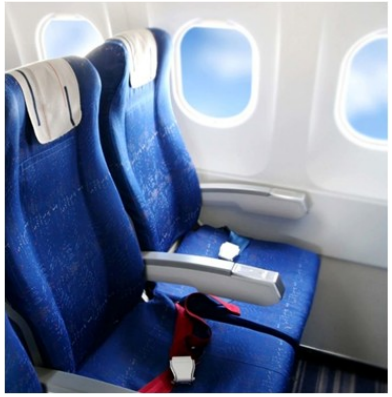
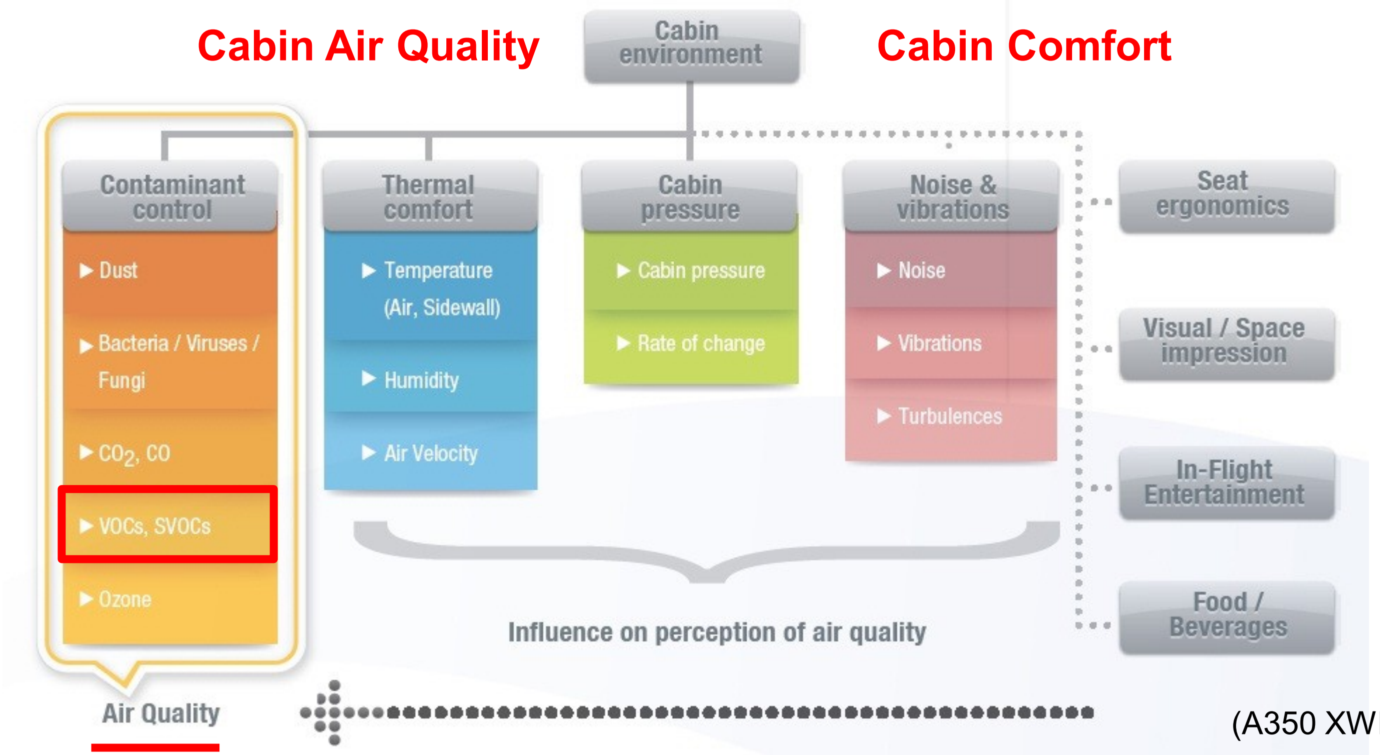
3.


4.

Cabin Comfort and Cabin Air Quality –

Health and Flight Safety Implications



(A350 XWB News 2012)

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)

Potential Concerns Related to Cabin Air Quality

• Cabin Pressure	Can effect people with cardio-respiratory diseases from lack of oxygen
• Relative Humidity	Temporary drying of skin, eyes, and mucous membranes
• Carbon Monoxide	High concentrations during air-quality incidents. Frequency is believed to be low. CS 25.831: Concentration must be lower than 50 ppm.
• Carbon Dioxide	Concentrations are generally below FAA regulatory limits. Associated with increased perceptions of poor air quality. CS 25.831: Concentration must be lower than 0.5%.
• Ozone	Elevated concentrations on aircraft without ozone converters. Airway irritation and reduced lung function. CS 25.832: Concentration < 0.25 ppm resp. 0.1 ppm.
• Pesticides	From aircraft “disinsection" with pesticides.
• **Engine Oil**	Fumes from hot engine oil may enter the cabin via the bleed air system.
• Hydraulic Fluids	Frequency of incidents is expected to be relatively low. Mild to severe health effects.
• Deicing Fluid	Hazardous substance. Skin sensitizing and irritant.
• Airborne Allergens	Exposure frequency is not known. Irritated eye and nose; sinusitis; acute increases of asthma; possible anaphylaxis.
• Nuisance Odors	Can be present on any flight.

Adapted from (NRC 2002)

Possible Sources Affecting Cabin Air Quality

- Engine or APU Ingestion of
  - De-icing fluid into inlet *(See precautions in FCOM 2.02.13 (A300-600/A310) or PRO-SUP-91-30 (A320 and A330/A340 family) or PROC/SUPP PROC/COLDWEATHERPROC (A380)*
  - Exhaust fumes from other aircraft, GPU etc
  - Pollution (eg. smoke from fires)
  - Hydraulic fluid leaks
  - Birds
  - Compressor wash procedure residues
  - Pollens
- Galley Equipment, ovens, coffee makers etc (Ref MPD tasks for galley and toilet air extraction systems)
- Damaged electrical wiring or components
- Inappropriate or excessive use of CO_2 (dry ice) by caterers or excessive quantities being transported (see EngOps-16326)
- Toilet fluid spillage, leakage and also unapproved mixing of different disinfectant fluids within the toilet.
- Leakage of the rain repellent system or rain repellent contamination within the cabin or flightdeck.
- Spillage's within cargo compartments
- Items stowed in overhead overhead bins
- APU oil leaks into the bleed system
- Engine oil leaks into the bleed system
- Contamination of the ECS

(Airbus 2017)

Health Effects: Occupational Health & Flight Safety

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

- **Long-term heath effects**:
  - to passengers
  - to crew => **occupational health** (OH) **=> CS 25.831**
    usually related to
    Time-Weighted Average (TWA)
    Permissible Exposure Limits (PEL)

- **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)

Occupational Health – Long Term Health Effects

EASA CS-25: **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)

EASA European Aviation Safety Agency

BFU

Bundesstelle für Flugunfalluntersuchung

German Federal Bureau of Aircraft Accident Investigation

Flight Safety Implications – Immediate Health Effects

There have been **several** (much debated) **critical flight instances**,
but so far (luckily) **no death** (due to flight safety implicatons) and **no hull loss**.

Compare e.g. with the issue "Degraded Manual Flying Skills" (Flight International 2017)

Fatal in-flight loss of control accidents

Year	Operator	Type	Location	Fatalaties
2016	Egyptair	Airbus A320	Mediterranean Sea off Egypt	66
	Flydubai	Boeing 737-800	Rostov-on-Don, Russia	62
2014	AirAsia Indonesia	Airbus A320	Java Sea, Indonesia	162
2013	Swiftair	Boeing MD-83	Mali	116
	Tatarstan Air	Boeing 737-500	Kazan, Russia	50
	Asiana Airlines	Boeing 777	San Franciso, USA	2
2010	Afriqiyah Airways	Airbus A330-200	Tripoli, Libya	103
	Ethiopian Airlines	Boeing 737-800	Near Beirut, Lebanon	90
2009	Yemenia	Airbus A310-200	Comoros Islands	152
	Air France	Airbus A330-300	South Atlantic	228
	Caspian Airlines	Tupolev Tu-154	Iran	168
	Colgan Air	Bombardier Q400	Buffalo, New York, USA	49
2008	Aeroflot Nord	Boeing 737-500	Perm, Russia	88
2007	Adam Air	Boeing 737-400	Java Sea, Indonesia	102
2006	Armavia	Airbus A320-200	Sochi, Russia	113
2005	West Caribbean	Boeing MD-82	Venezuela	160
2004	Flash Airlines	Boeing 737-300	Sharm el-Sheikh, Egypt	148
2000	Gulf Air	Airbus A320-200	Bahrain	143
	Crossair	Saab 340	Near Zurich, Switzerland	10
Total				**2,012**

Source: FlightGlobal

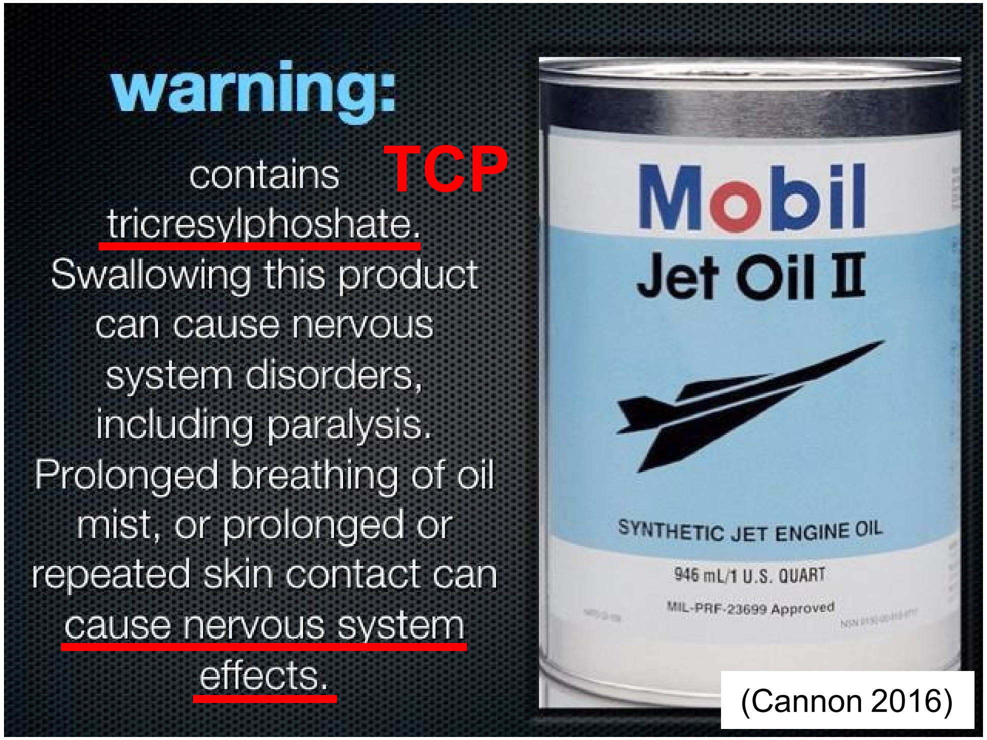
From 2000 to 2017:

- 19 fatal accidents
- 2012 fatalaties

Remark:
There are certainly several issues in aviation of more pressing nature than "cabin air quality / contamination", however, the suffering of individuals (potentially / probably) due to cabin air contamination can not be ignored (may it just be for ethical reasons), because the underlying deficits in aircraft system design are a fact (see below) and need to be solved.

Jet Engine Oil

Jet Engine Oil



(Cannon 2016)

Judging Jet Engine Oil Based on Warnings Given by Manufacturer

ExxonMobil

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 2016c)

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 2016c)

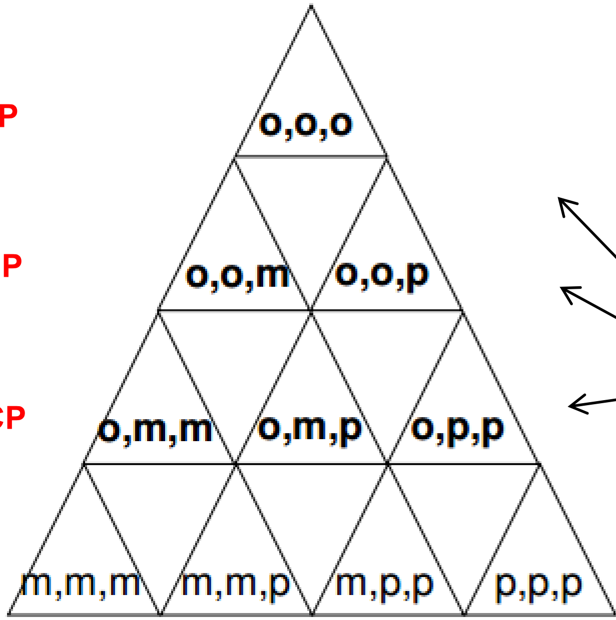
Jet Engine Oil

Tricresyl Phosphate (TCP)

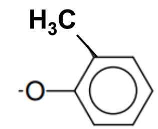
TOCP

DOCP

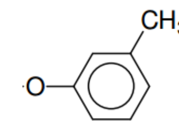
MOCP



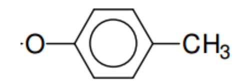
T = tri (3)
D = di (2)
M = mono (1)

o ortho-cresyl group 

OC

m meta-cresyl group 

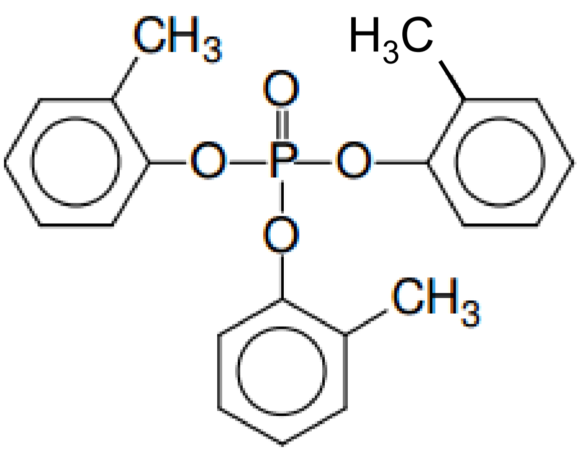
MC

p para-cresyl group 

PC

ortho-cresyl group containing molecules are highlighted in **bold**, *they are the* ***toxic*** *isomers.*

TOCP:



(Winder 2001)

Jet Engine Oil

Actual OCP Content of the TCP --- Isomerization

Ramsden 2013a:
OC content in the TCP:

TCP Class 1: 30%	(about 1930)
TCP Class 2: ?	
TCP Class 3: 3%	(about 1958, "modern TCP")
TCP Class 4: 0.3 %	(since 1992, "conventional TCP")
TCP Class 5: ≈ 0,03 %	(since 1997, "low-toxicity TCP")

TCP Class 6: 0 %	**(since 2017**, "zero-OCP TCP") Remark / Introduction: Proposal for a new class definition

Ramsden 2013 / Imbert 1997:
Another possibility is that **isomerization** of the **TCP** takes place within the engine during operation.

Megson 2016:
... **temperatures of 400 °C**. These temperatures have the potential to alter the composition of the original oil and **create other toxic compounds**.

There is currently a large degree of **uncertainty as to what compounds are produced** and how toxic they are through **inhalation** in the vapour phase at high altitudes.

Jet Engine Oil

Actual OCP Content Measured

A comparison of fresh and used aircraft oil for the identification of toxic substances ...

(Megson 2016)	CAS #	[M+] m/z	Formula	Concentration in oil (%)					
				Fresh oil 1	Fresh oil 2	Fresh oil 3	Used oil 1	Used oil 2	Used oil 3
ooo-TCP	1330-78-5	368.118	$C_{21}H_{21}PO_4$						
oom-TCP		368.118	$C_{21}H_{21}PO_4$						
oop-TCP		368.118	$C_{21}H_{21}PO_4$						
omm-TCP		368.118	$C_{21}H_{21}PO_4$						
omp-TCP		368.118	$C_{21}H_{21}PO_4$						
mmm-TCP		368.118	$C_{21}H_{21}PO_4$	0.68	0.70	0.70	0.40	0.52	0.59
opp-TCP		368.118	$C_{21}H_{21}PO_4$						
mmp-TCP		368.118	$C_{21}H_{21}PO_4$	1.51	2.01	1.58	1.05	1.16	1.22
mpp-TCP		368.118	$C_{21}H_{21}PO_4$	1.21	1.42	1.39	0.78	0.97	0.87
ppp-TCP		368.118	$C_{21}H_{21}PO_4$	0.45	0.55	0.53	0.22	0.26	0.24
		Summation of TPC (%):		4.85	4.68	4.20	2.45	2.91	2.92

No tri-ortho cresyl phosphate **TOCP** isomers were detected.
No di-ortho cresyl phosphate **DOCP** isomers were detected.
No mono-ortho cresyl phosphate **MOCP** isomers were detected.

TCP Class 6: No OCP Content (2016)

How much Oil Gets into the Cabin?

EASA Study 2017: AVOIL (EASA 2017b)

AVOIL – Characterisation of the toxicity of aviation turbine engine oils after pyrolysis

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

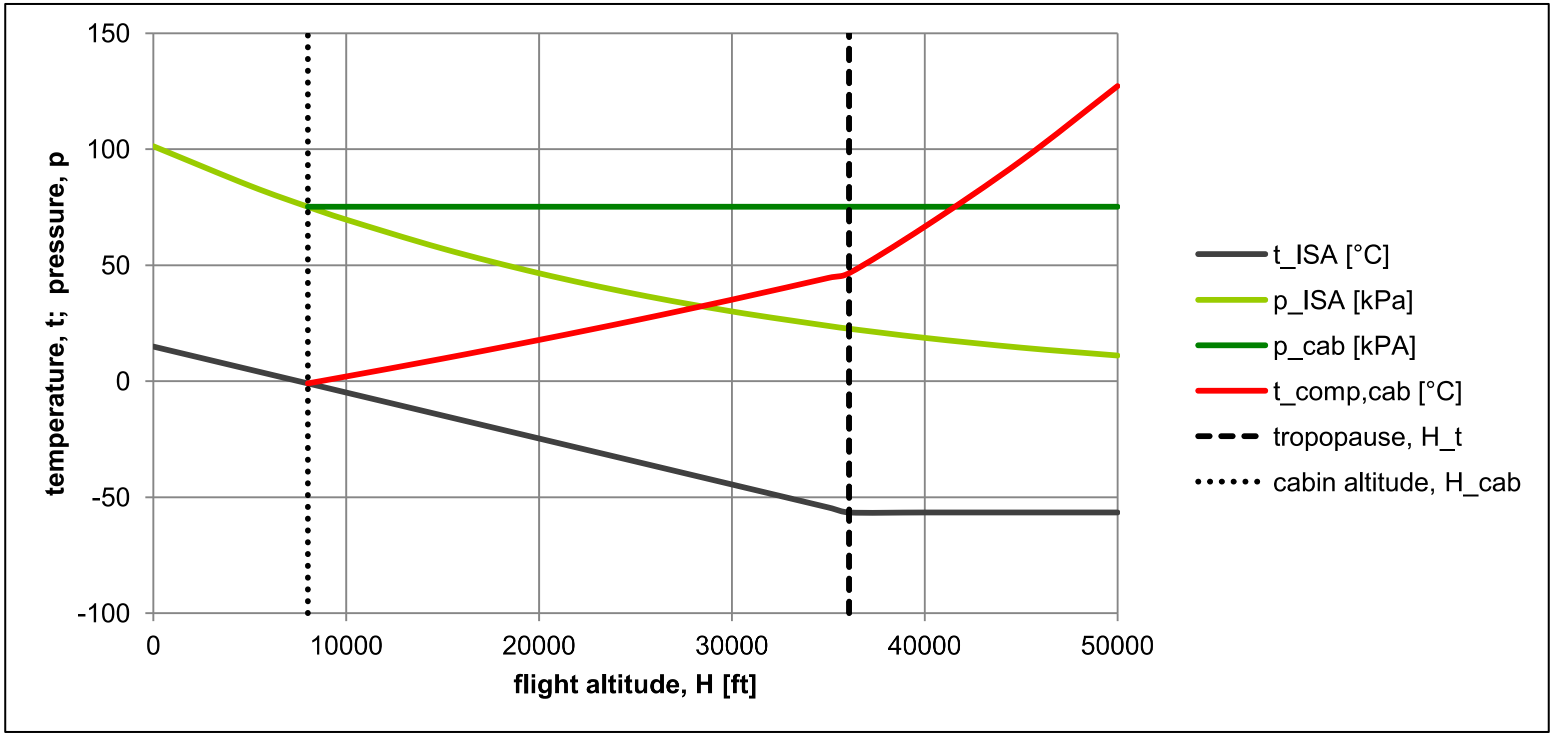
Compound #	Name	CAS	Harmonized classification	Self-classification*
1	Diethyl Phthalate	84-66-2		NC
2	1-Nonene, 4,6,8-trimethyl-	54410-98-9		
3	2-Ethylhexyl salicylate	118-60-5		Skin Irrit. 2
4	Acetophenone	98-86-2	Acute Tox. 4 Eye Irrit. 2	
5	Benzaldehyde	100-52-7	Acute Tox. 4	
6	Benzene, 1,3-bis(1,1-dimethylethyl)-	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	Decanal	112-31-2		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

Air Conditioning Technology

Air Conditioning Basics

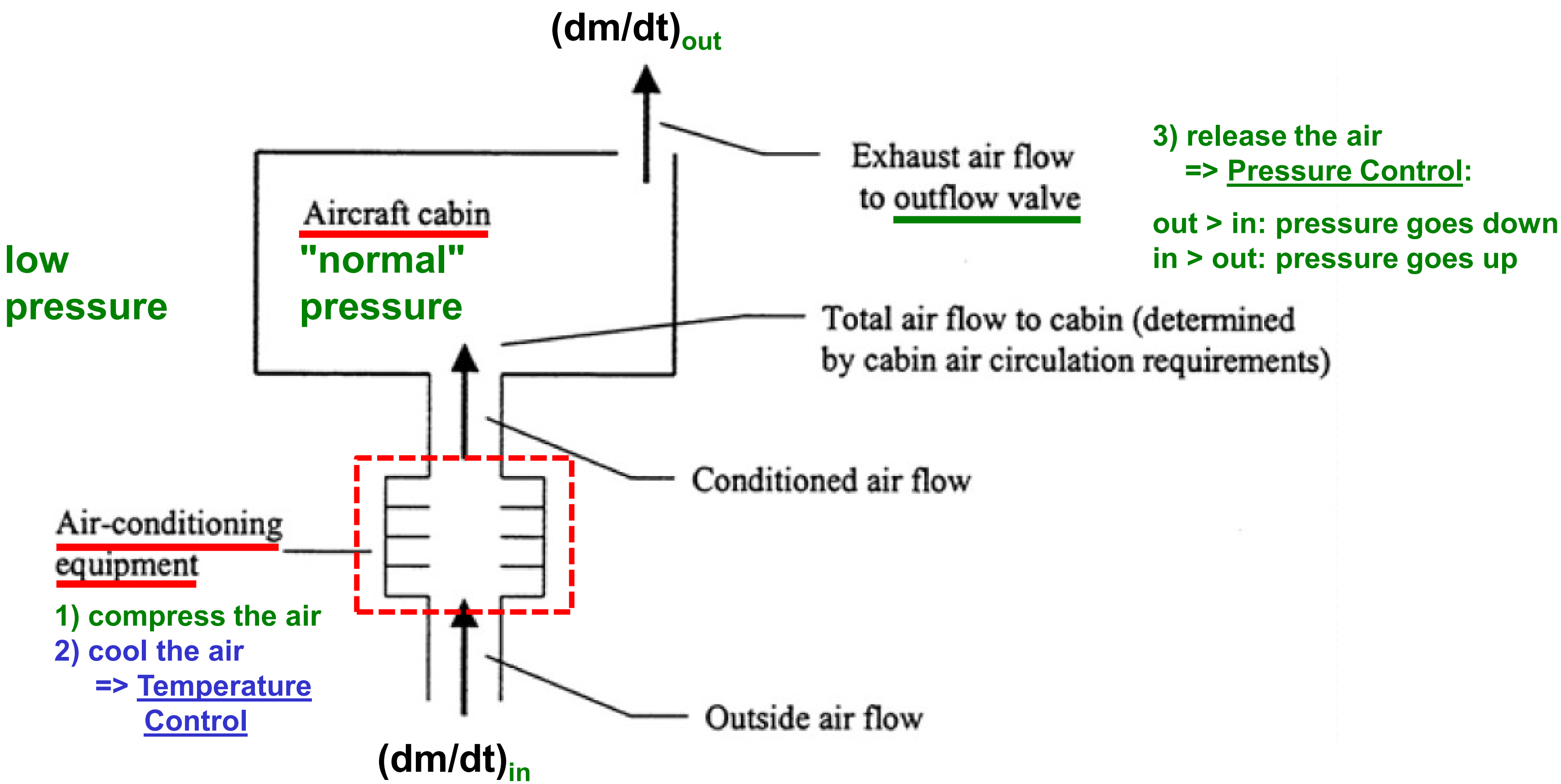
Increasing Temperature of Air due to Compression from Ambient to Cabin Pressure



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

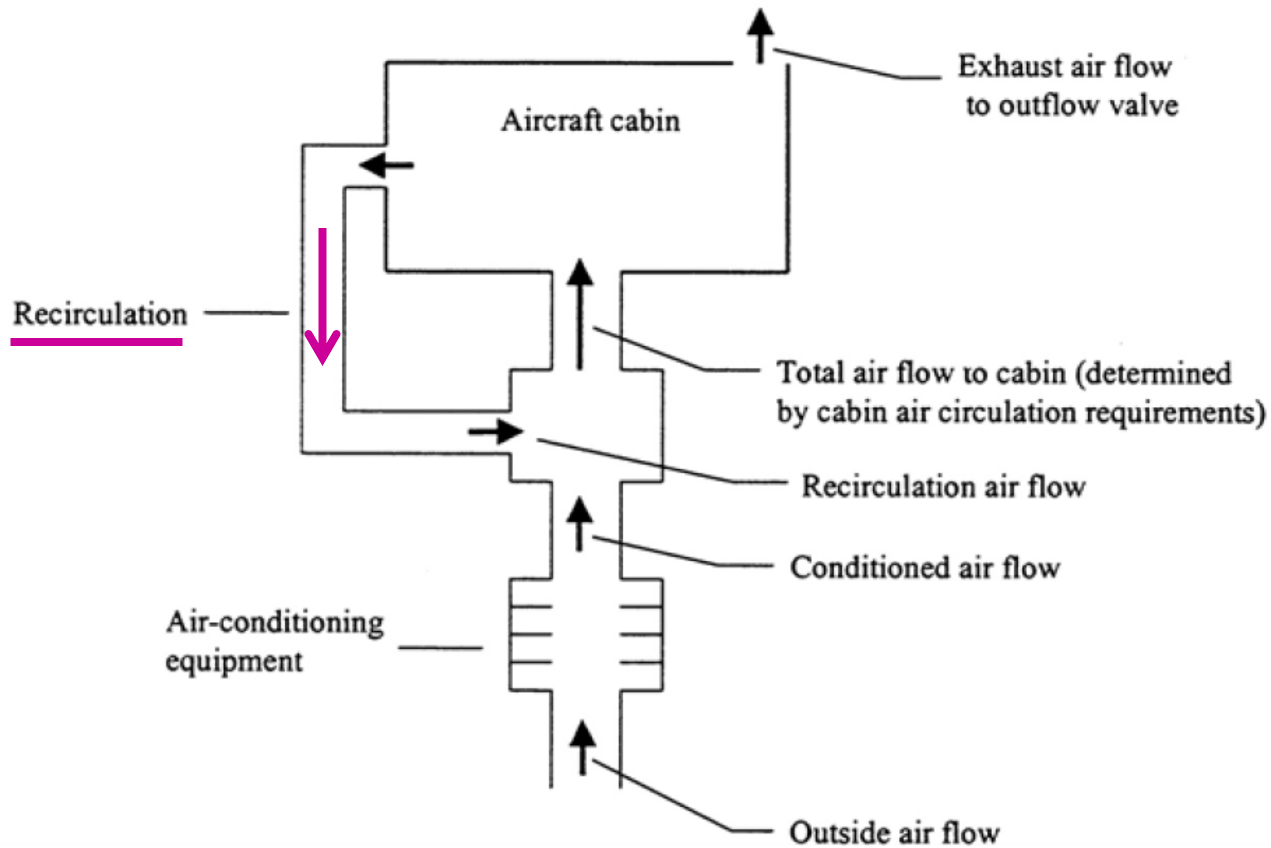
Air Conditioning Basics

Temperature Control, Pressure Control, Ventilation



Adapted from (NRC 2002)

Air Conditioning with Recirculation

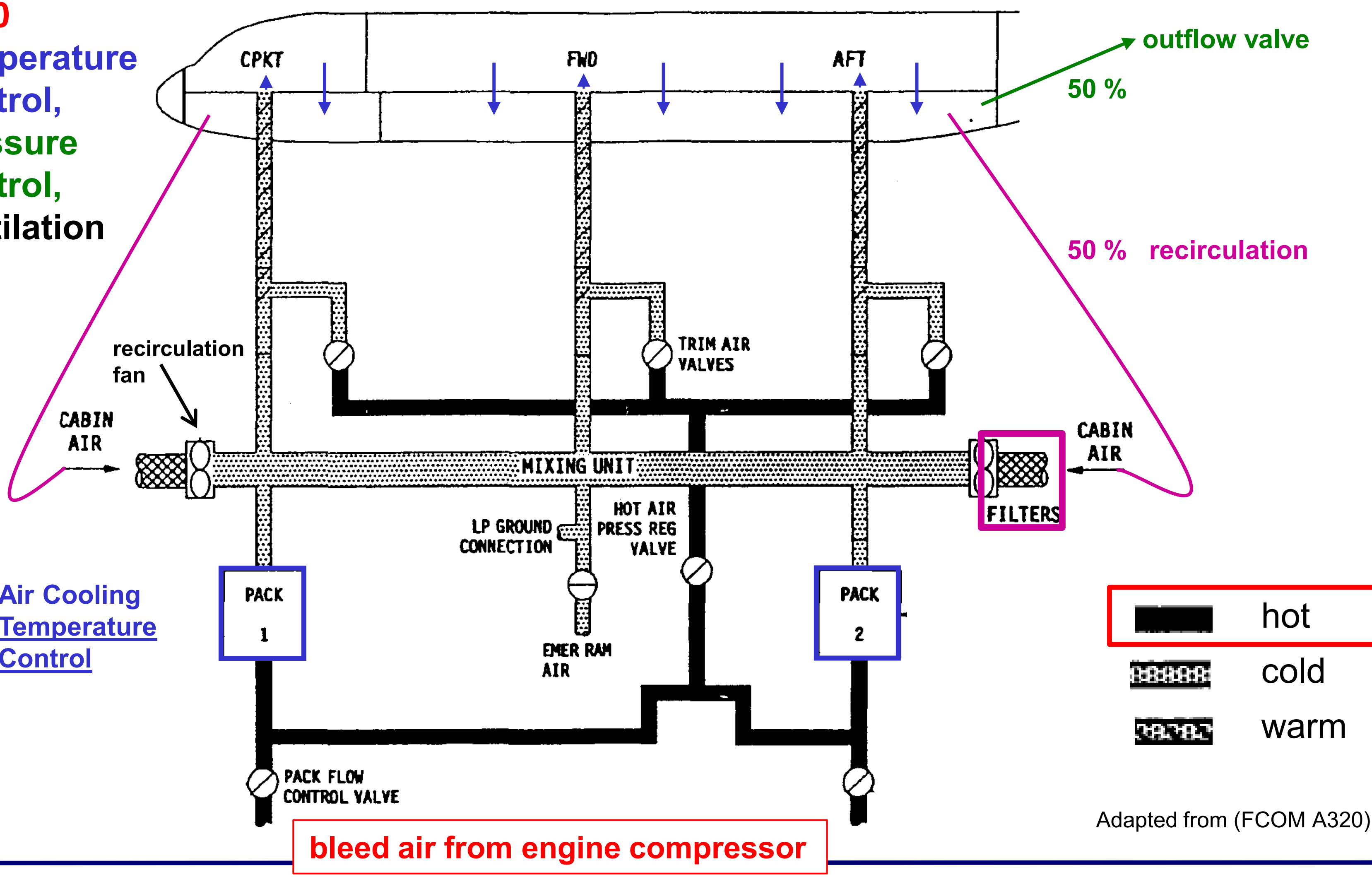


Adapted from (NRC 2002)

Air Conditioning Technology

A320

A320
Temperature Control,
Pressure Control,
Ventilation

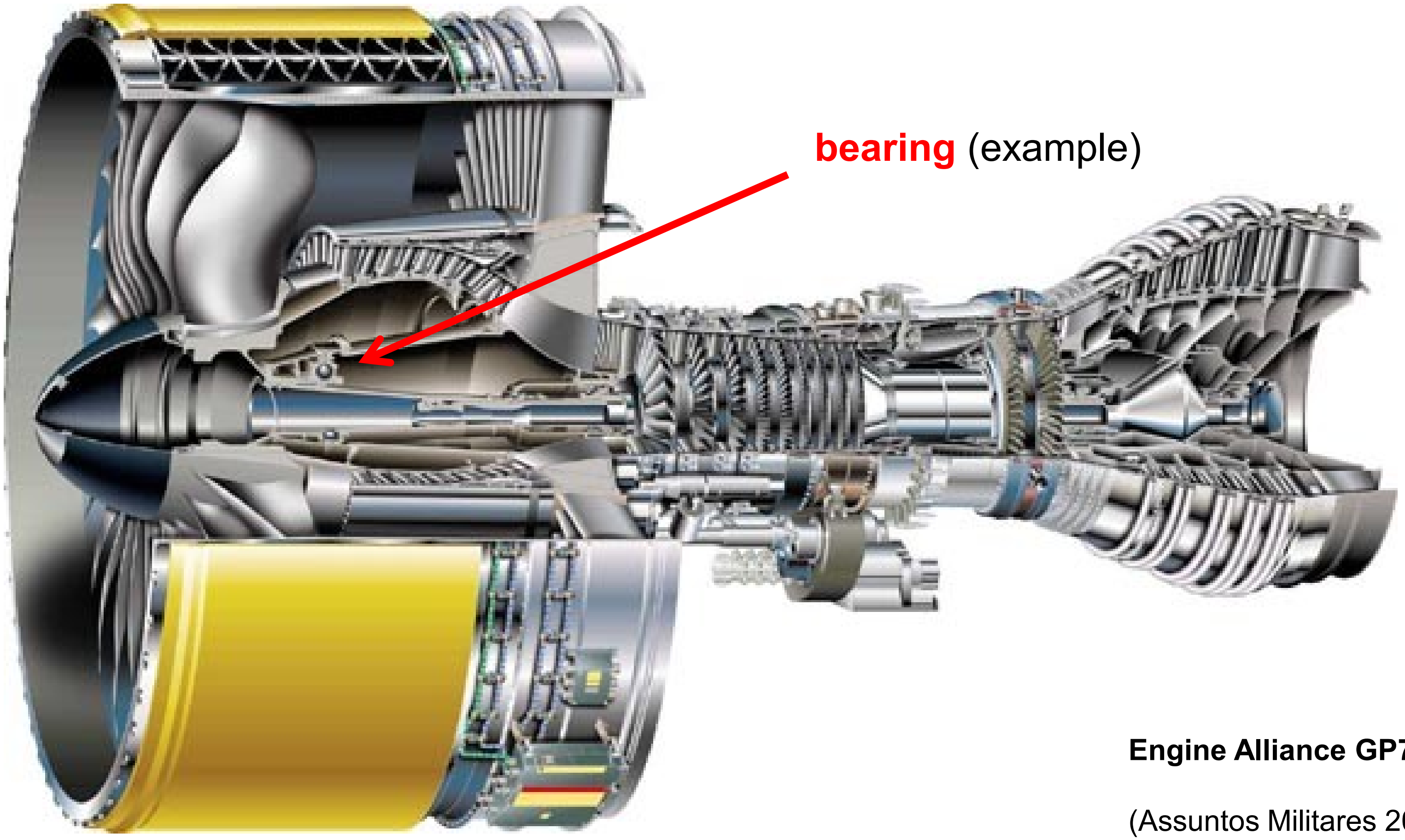


2) Air Cooling
Temperature Control

Adapted from (FCOM A320)

Jet Engine

Engine Overview

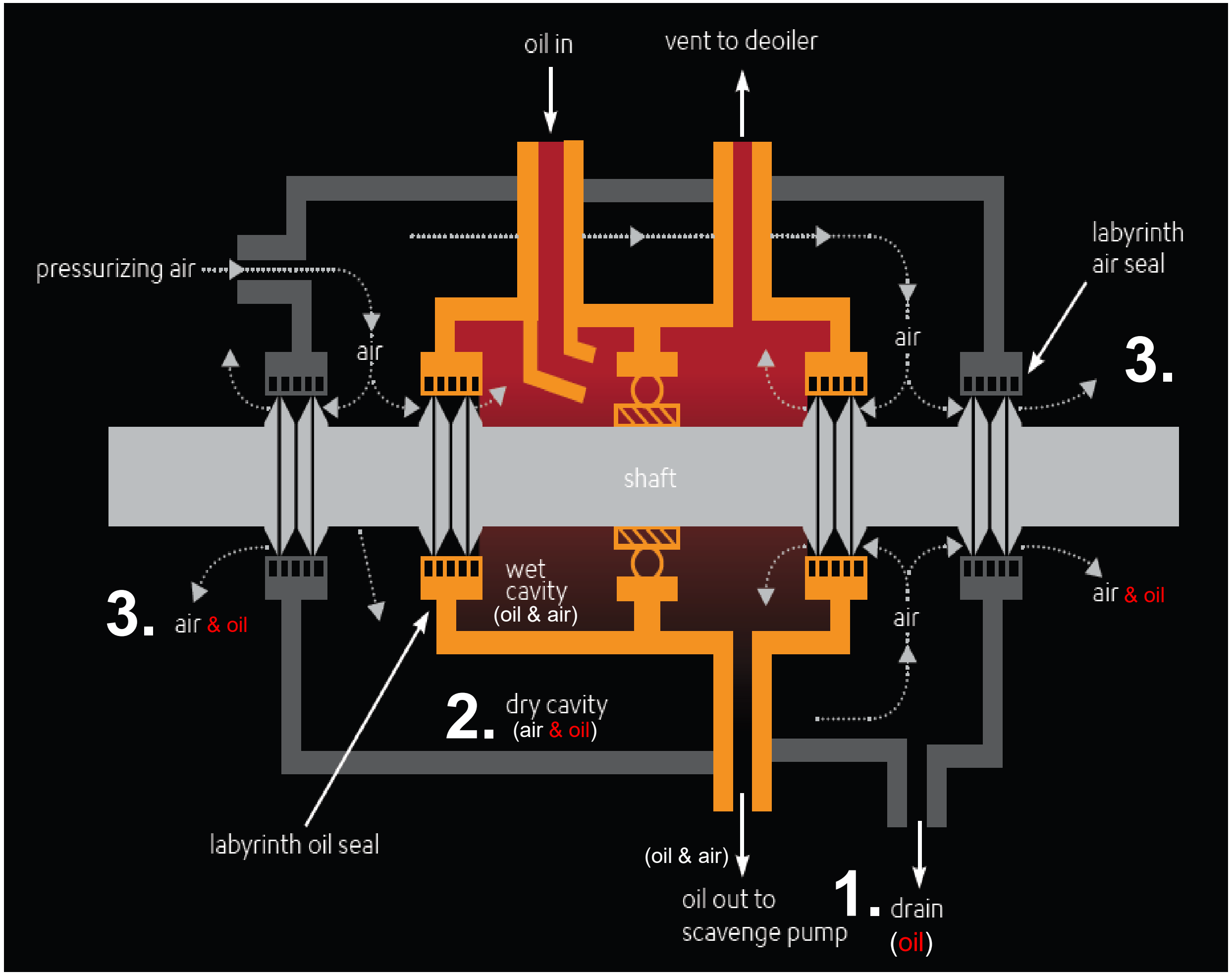


Engine Alliance GP7000

(Assuntos Militares 2013)

Jet Engine

Engine Air and Oil System



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!**

based on (Exxon 2016b)

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)

Maintenance

The Case of Engine/APU Oil Contamination

Trouble Shooting and Cleaning

Aircraft Trouble Shooting

One possibility where the source of an oil leak/odour cannot be determined would be to operate the aircraft with each bleed supply OFF (in accordance with the MMEL requirements) in turn to identify a bleed configuration that confirms the odour. If this does not identify a bleed source of the odour, then operate using a single ECS pack to try and identify an ECS pack as a source of the odour. Note that a build-up of oil contamination within an ECS pack can occur over time and eventually cause the ECS pack itself to be the source of an odour. The reporting sheet at attachment 2 can be used to track the different ECS configurations and aid this process.

(Airbus 2017)

Aircraft Duct Cleaning

in order to simulate both heating and cooling conditions. This involves pack operation for approximately 15 minutes with cabin temperatures selected full cold and 15 minutes with temperatures selected full hot.

(Airbus 2013)

Maintenance

Special situation at an engine start of a new aircraft coming from Final Assembly Line at Airbus, Germany (Balk 2018)

Cleaning

Pack Cleaning

The simplest method of removing the contamination is again using high temperature airflow (from the APU) although additional maintenance maybe necessary in the event of heavy contamination within the pack. In order to facilitate the pack decontamination whilst preventing further downstream contamination it is necessary to remove the pack outlet duct and blank the downstream ducting . This allows the contaminated air to exit the aircraft via the pack bay and facilitates inspection of the pack condenser to determine the extent of pack contamination. During initial inspection the presence of thick oily deposits inside the condenser (visible following outlet duct removal) would indicate heavy contamination within the pack and therefore necessitate off aircraft maintenance for certain components.

(Airbus 2013)

Cleaning

Aircraft 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) fume/smell event
are most probably not cleaned as instructed by Airbus,
because ducts can not be removed
from behind the panels in this short time.

Engineering Design Principles

from SAE

SAE ARP 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** of 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.”

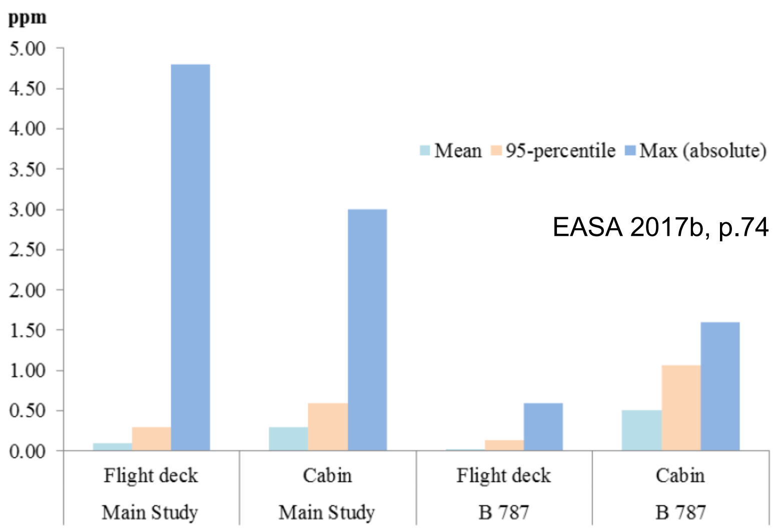
This means:
It is not the task of passengers and crew to prove that engine oils and hydraulic fluids as used today are dangerous. Just on the contrary, **industry has to prove that fluids and equipment are safe before they intend to use them**, because standards have been agreed among engineers already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

Solution:
Sensors and Filters

Solution: Sensors and Filters

Get Informed => Personal CO Detector. Get Protected in the Cabin => Breathing Mask

Normal CO Situation



- The **Carbon Monoxide** (CO) level in normal operation is much lower than the **limit of 50 ppm** (specified in CS 25.831). Failure cases did not occur during these measurements.
- We know much **CO is present in the cabin during a Fume Event. The elevated CO concentration indicates the severity of the event. Therefore, crew should carry their personal CO detector, be informed and make decisions accordingly!**
- If smoke is present, checklists tell pilots to put on their oxygen mask. In such a case, cabin **crew should consider wearing a personal breathing mask protecting against nerve gas.**

Failure Case: Fume Event

US Airways Flight 432 Phoenix to Maui (2010)

Get CO Detector and Breathing Mask

Cabin crew protection !

Solution: Sensors and Filters

KKmoon CO Meter: Test on Ground and Measurements on Aircraft

Test in car exhaust gas => up to 77 ppm CO (Video: https://youtu.be/iwqcgPdht-w)

Cabin limit:
50 ppm

Measurements on aircraft:

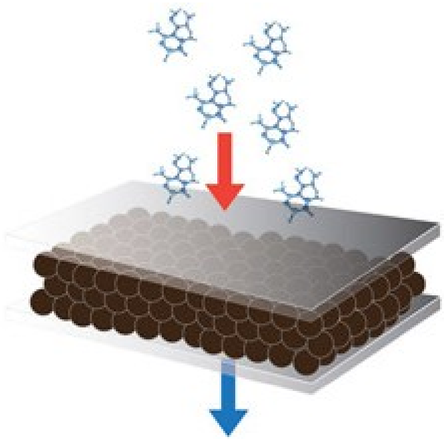
- Generally: 0 ppm
- One measurement: 5 ppm
  (measured at cabin outlet on A320, during take-off, HAM, RWY 33)

Solution: Sensors and Filters

Filters to Remove TCP and VOC

Pall has **several treetment** solutions for cabin air on offer:
- Carbon Filter
- Photo Catalytic Oxidization (with UV light)
- Catalytic Converters (oxidization). Location is possible:
  - upstream of the pack,
  - downstream of pack,
  - at recirculation filter
    (reduced efficiency compared to a filter in line with the pack – see next page)

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. Carbon adsorbents have some effectiveness with ozone but not with carbon monoxide (CO). Removal of these compounds from the cabin air is by adsorption on to carbon based filters. (Pall 2011)


Schematic of carbon Filter (Pall 2011)

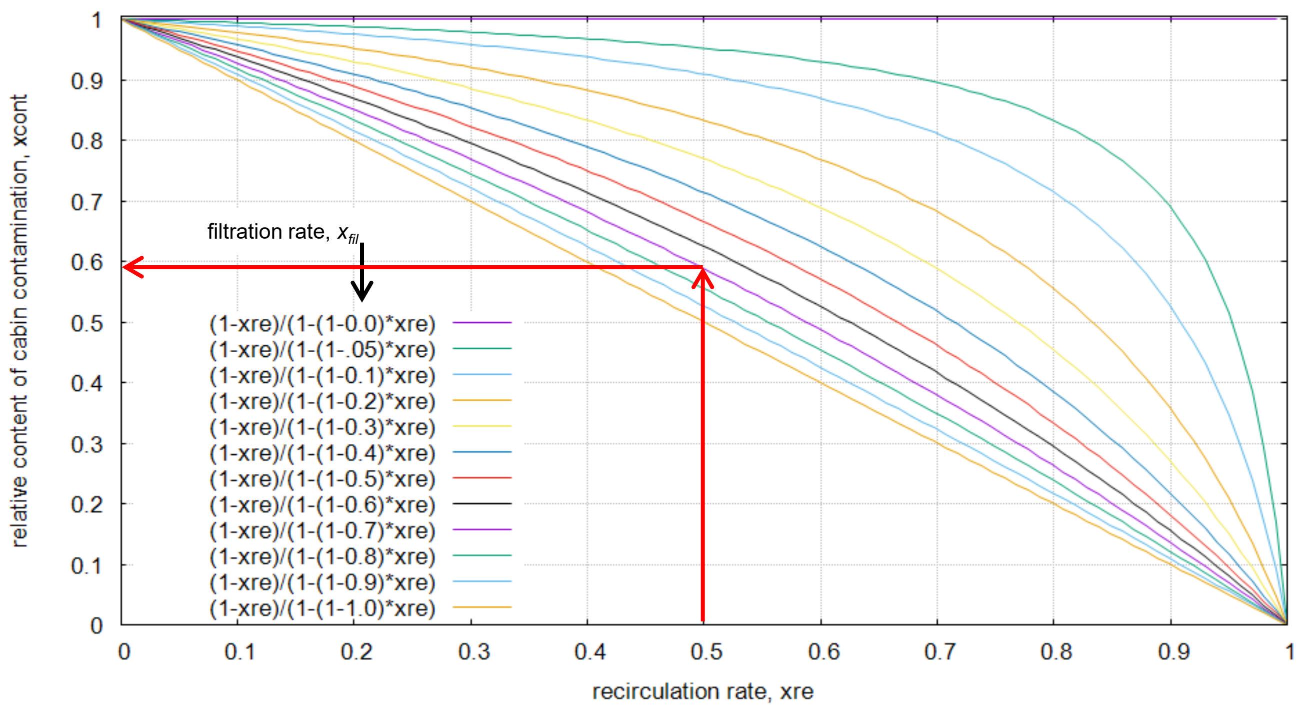
Application of carbon filters:
- 33 HEPA-Carbon filters have been added (so far) to A321 aircraft at Lufthansa Group. (Lufthansa 2017)
- EasyJet started in 2016 to retrofit their fleet of A320 family aircraft with Pall Aerospace PUREair Advanced Cabin Air Filters (A-CAF) combining HEPA filters and carbon filters to remove Volatile Organic Compounds (VOC) from aircraft cabin air. (Pall 2016)
- Pall carbon filters are installed on the B757 cargo fleet of DHL.
  Carbon filters are installed in place of the air ducts leading to
  the cockpit. EASA issued an STC for the installation. (EASA 2010)

Solution: Sensors and Filters

But: How Efficient are Filters in the Recirculation Path?

Example calculation:

- The Pall carbon adsorbent is effective at adsorbing volatile organic compounds with a removal efficiency of 65% ... 73% when challenged with TCPs in the gaseous phase. (Pall 2011)
- The A320 has a recirculation rate of 50%.
- With a filtration rate, x_{fil} = 0,7 and a recirculation rate, x_{re} = 0,5 the filter reduces the incoming concentration to 58,9%.



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

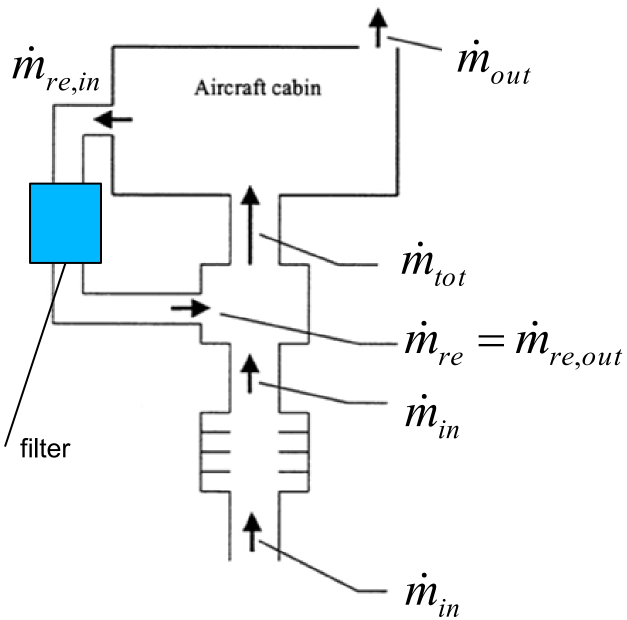
for $x_{fil} = 1$:

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

Solution: Sensors and Filters

Derivation:

Efficiency of Filters in the Recirculation Path



Adapted from (NRC 2002)

$$\dot m_{out} = \dot m_{in}$$

$$\dot m_{tot} = \dot m_{in} + \dot m_{re}$$

Def.: $\frac{\dot m_{re}}{\dot m_{tot}} = x_{re}$

$$\dot m_{re} = x_{re} \cdot \dot m_{tot}$$

$$\dot m_{tot} = \frac{\dot m_{re}}{x_{re}} \qquad (1)$$

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

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

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

$$\dot m_{tot} = \frac{\dot m_{in}}{1 - x_{re}} \qquad (2)$$

$$\dot m_{tot,cont} = \dot m_{in,cont} + \dot m_{re,out,cont} \qquad (3)$$

cont: contaminated

Def.: $\frac{\dot m_{in,cont}}{\dot m_{in}} = x_{cont,in}$

$$\frac{\dot m_{out,cont}}{\dot m_{out}} = \frac{\dot m_{tot,cont}}{\dot m_{tot}}$$

$$x_{cont,cab} = \frac{\dot m_{re,in}}{\dot m_{re}}$$

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

with (3)

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

Solution: Sensors and Filters

Derivation:

Efficiency of Filters in the Recirculation Path

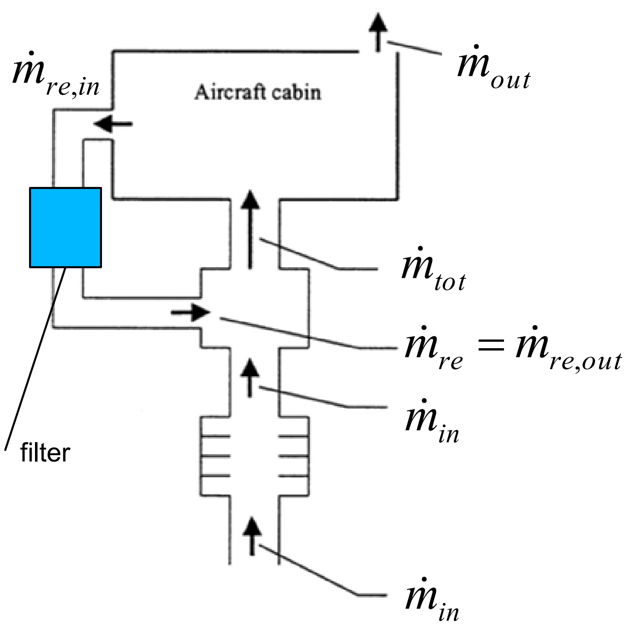
$$x_{cont,cab} = x_{cont,in}(1-x_{re}) + (1-x_{fil}) \cdot x_{re} \cdot x_{cont,cab}$$

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

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

for $x_{fil} = 1$:

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



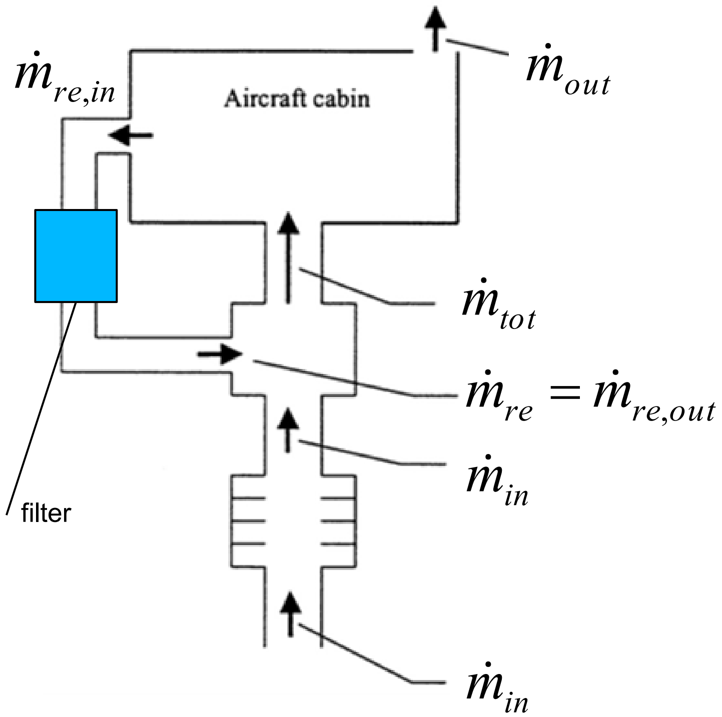
Adapted from (NRC 2002)

Solution: Sensors and Filters

Filter in the Recirculation Path

Example :

- The Pall carbon adsorbent is effective at adsorbing volatile organic compounds with a removal efficiency of 65% ... 73% when challenged with TCPs in the gaseous phase. (Pall 2011)
- The A320 has a recirculation rate of 50%.
- With a **filtration rate, x_{fil} = 0.7** and a **recirculation rate, x_{re} = 0.5** the filter **reduces the incoming concentration down to 58,9%**.



Adapted from (NRC 2002)

[redacted]

easyJet

EasyJet to filter toxic air in cabins

Andrew Gilligan
September 17 2017, 12:01am,
The Sunday Times
https://www.thetimes.co.uk/article/easyjet-to-filter-toxic-air-in-cabins-6qzrf6sjx

The budget carrier is the first to take action over links to an illness long denied by airlines.

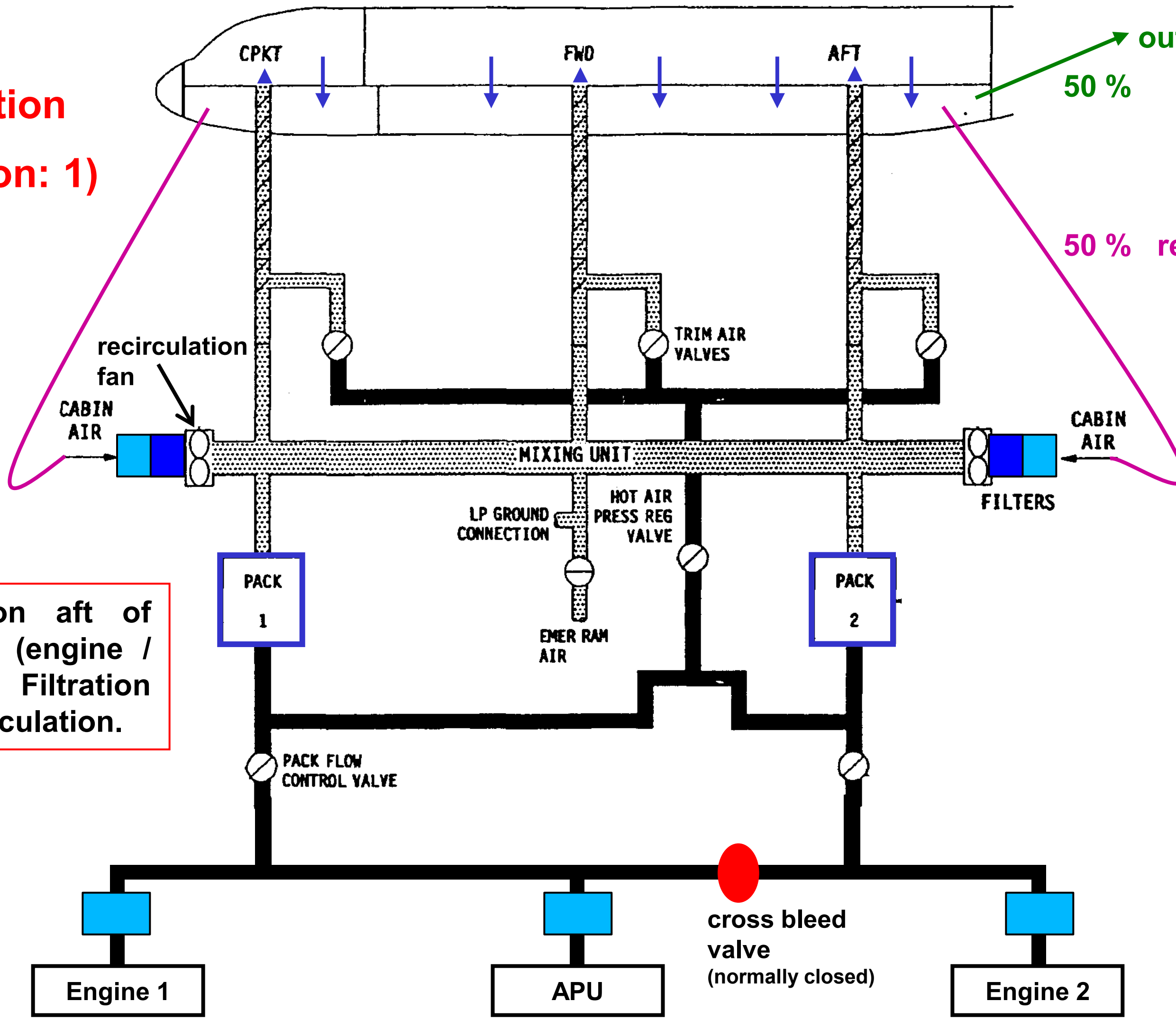
EasyJet said 'health concerns' led it to design a new air filtration system for testing on aircraft next year.

"Total Air Filtration"

Video
https://youtu.be/1-uzihfve_4
and full article
http://bit.ly/2x1uUzv
also on
http://CabinAir.ProfScholz.de

Solution: Sensors and Filters

Full Filtration (Option: 1)



Filtration aft of source (engine / APU). Filtration in recirculation.

$$\frac{x_{cont,cab}}{x_{cont,in}} = (1 - x_{fil})\, f_{recirc} \approx 0.3 \cdot 0.6 = 0.18$$

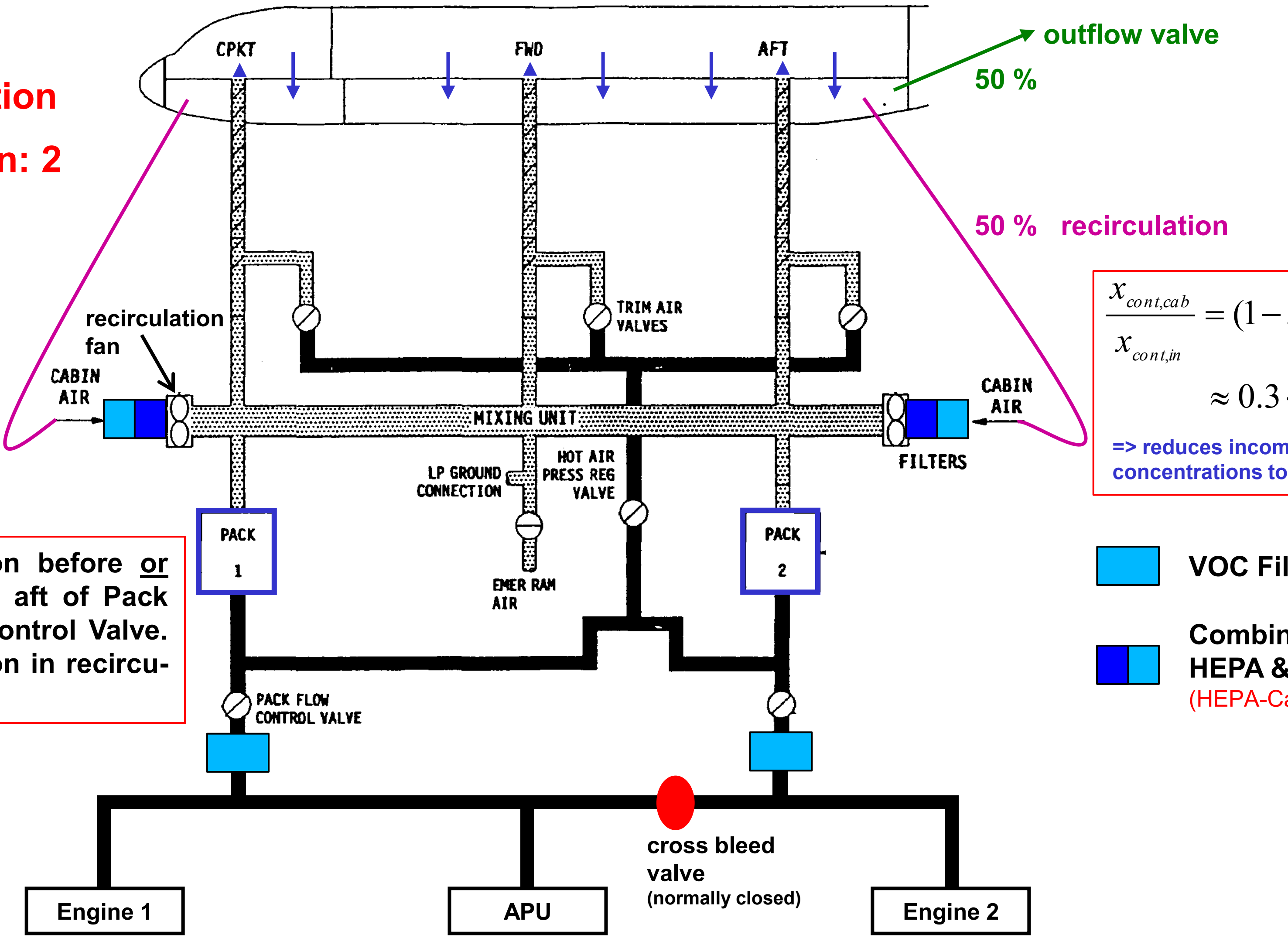
=> reduces incoming pollutant concentrations to ≈ 18%

VOC Filter

Combined HEPA & VOC Filter
(HEPA-Carbon Filter)

Solution: Sensors and Filters

Full Filtration Option: 2



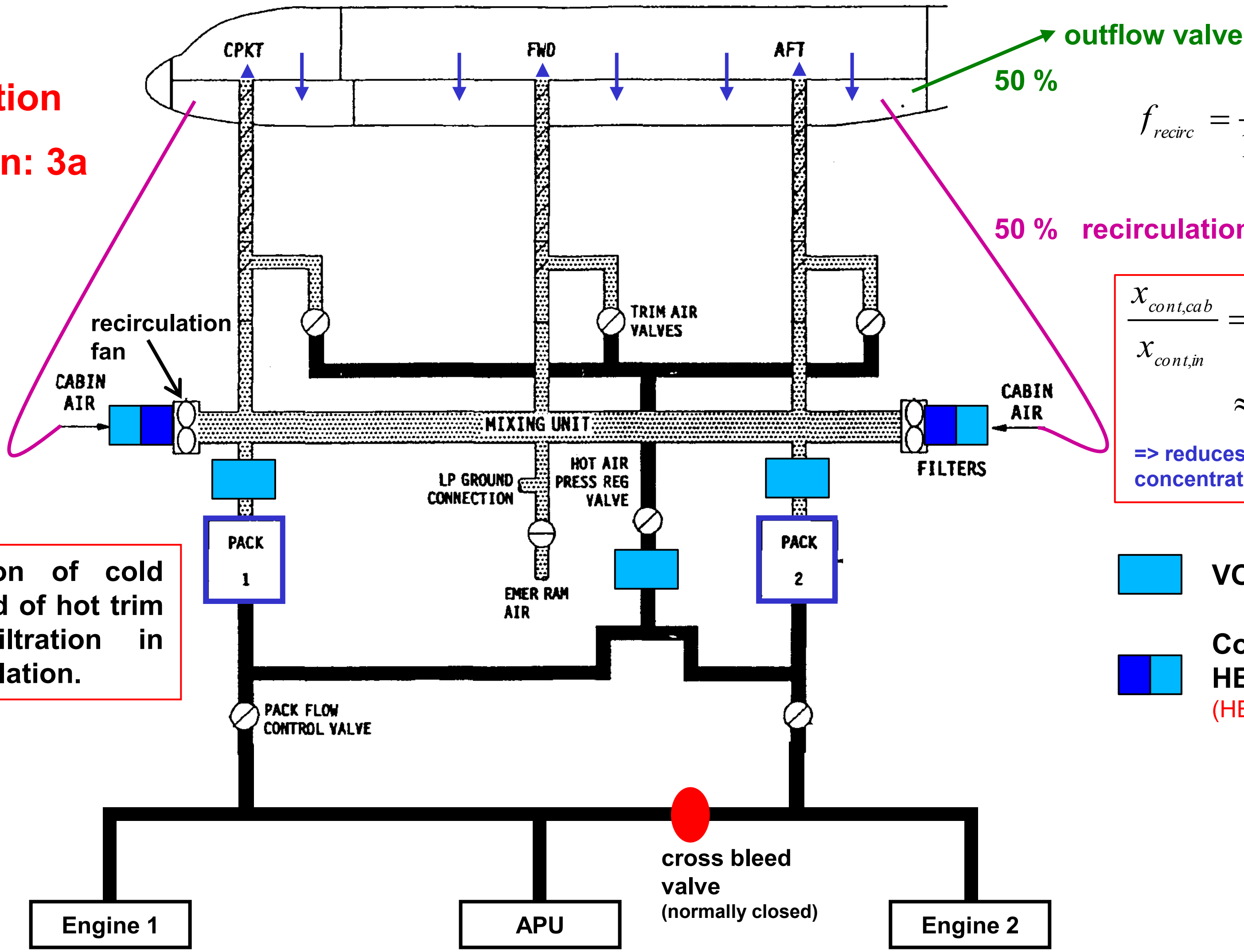
$$\frac{x_{cont,cab}}{x_{cont,in}} = (1 - x_{fil})\, f_{recirc} \approx 0.3 \cdot 0.6 = 0.18$$

=> reduces incoming pollutant concentrations to ≈ 18%

Filtration before or directly aft of Pack Flow Control Valve. Filtration in recirculation.

Solution: Sensors and Filters

Full Filtration Option: 3a



$$f_{recirc} = \frac{1 - x_{re}}{1 - (1 - x_{fil})\, x_{re}}$$

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

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

=> reduces incoming pollutant concentrations to ≈ 18%

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

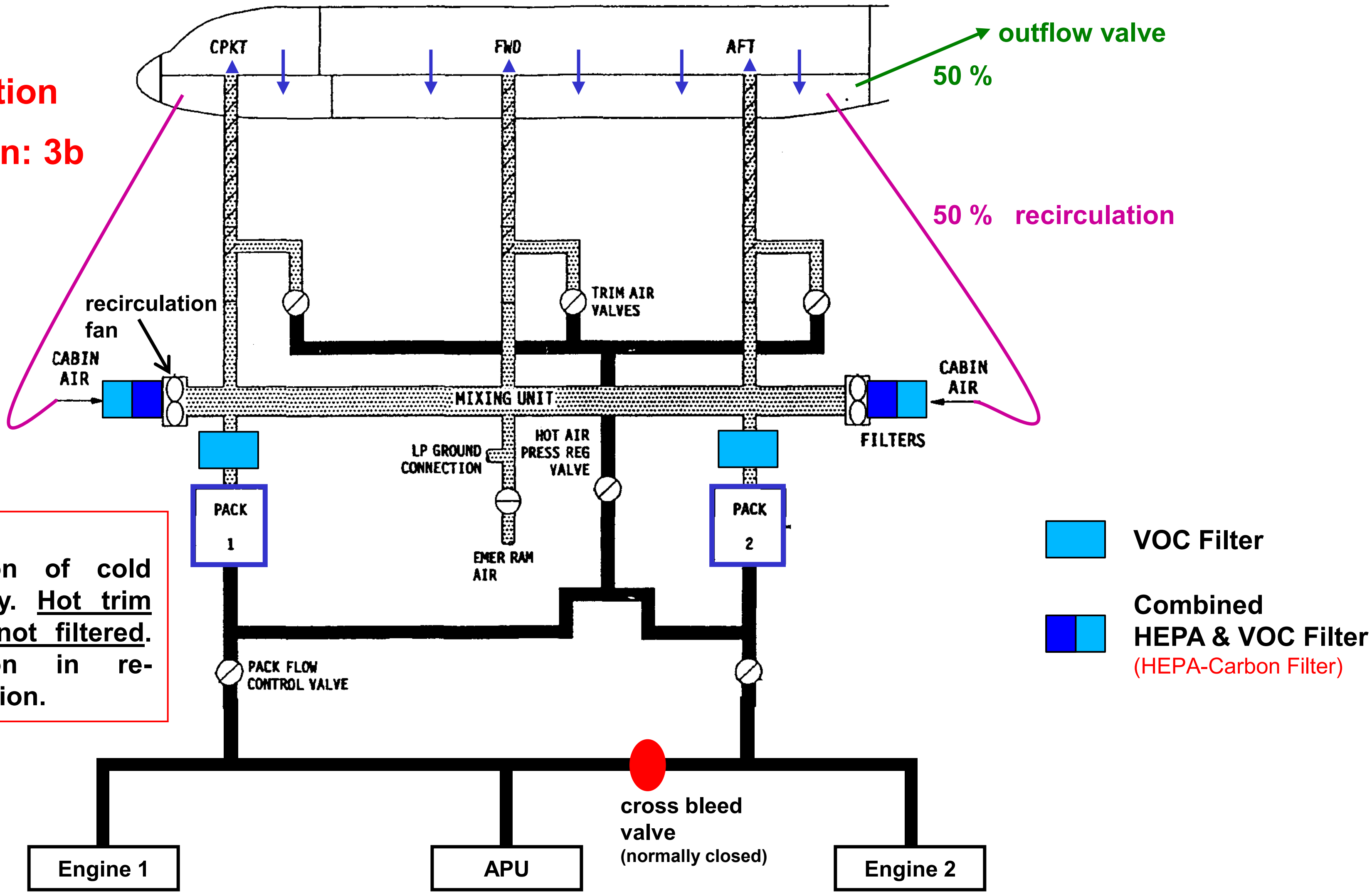
VOC Filter

Combined HEPA & VOC Filter (HEPA-Carbon Filter)

Solution: Sensors and Filters

Full * Filtration

Option: 3b



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

Solution: Sensors and Filters

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 ≈ 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:

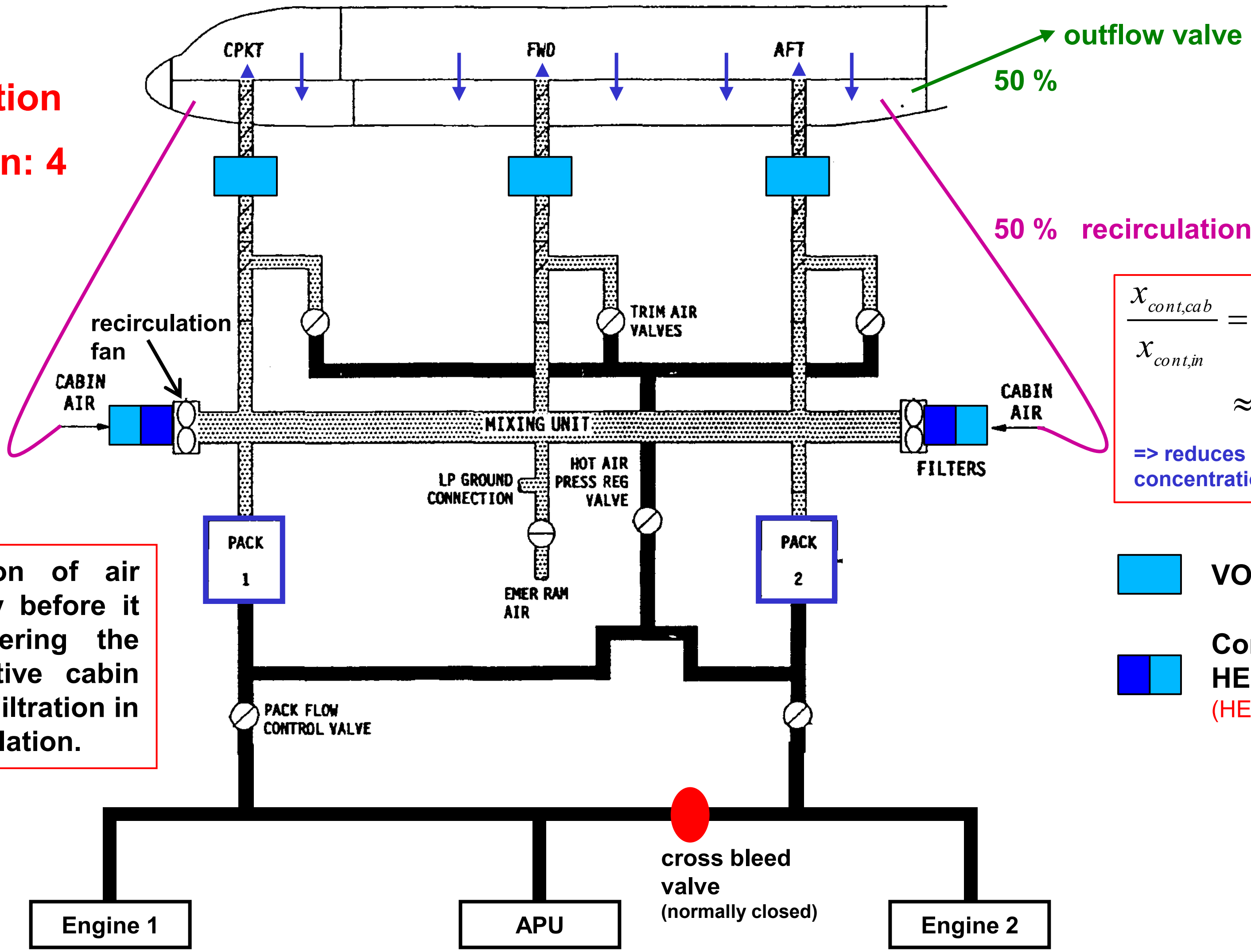
Cockpit zone:

$$\frac{x_{cont,cockpit}}{x_{cont,in}} = \frac{\dot{m}_{trim}}{\dot{m}_{tot}} + \frac{x_{cont,cab}}{x_{cont,in}}\left(1 - \frac{\dot{m}_{trim}}{\dot{m}_{tot}}\right) \approx 0.058 + 0.18(1 - 0.058) = 0.23$$

=> reduces incoming pollutant concentrations to only ≈ 23%

Solution: Sensors and Filters

Full Filtration Option: 4



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

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

=> reduces incoming pollutant concentrations to ≈ 18%

Filtration of air directly before it is entering the respective cabin zone. Filtration in recirculation.

VOC Filter

Combined HEPA & VOC Filter (HEPA-Carbon Filter)

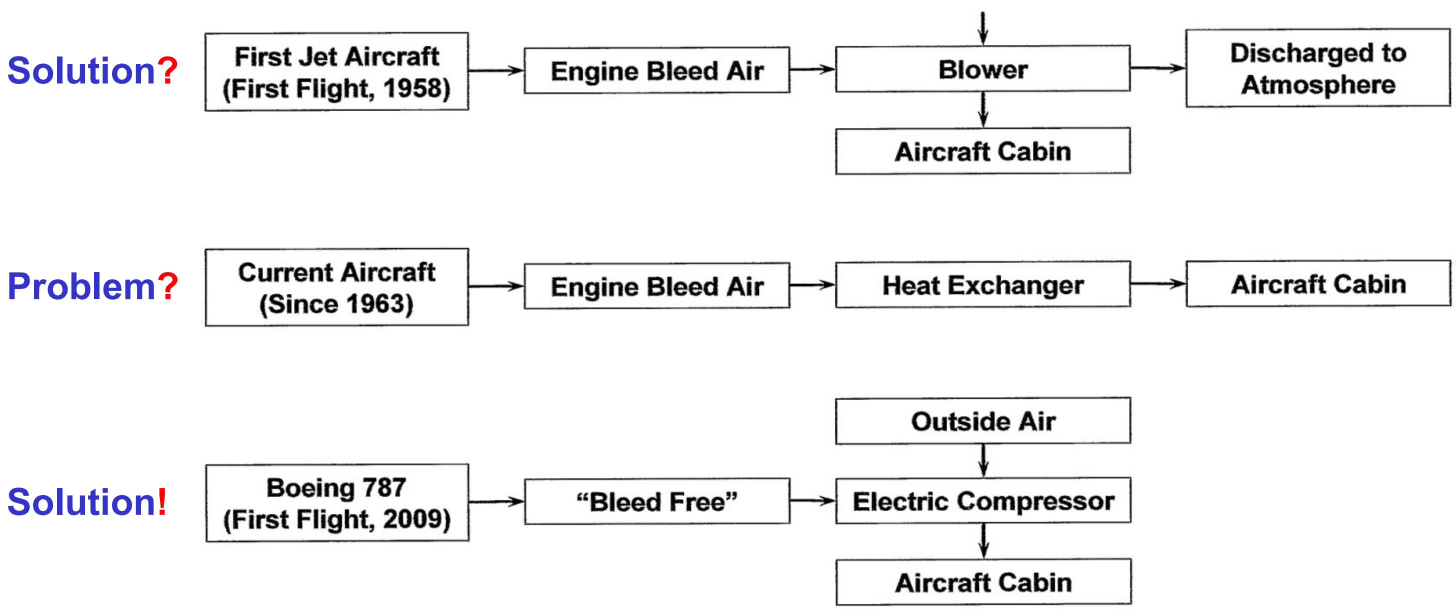
Solution:
ECS Principles

Solution: ECS Principles

Cabin Pressurization Principles and Solutions – Overview

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".



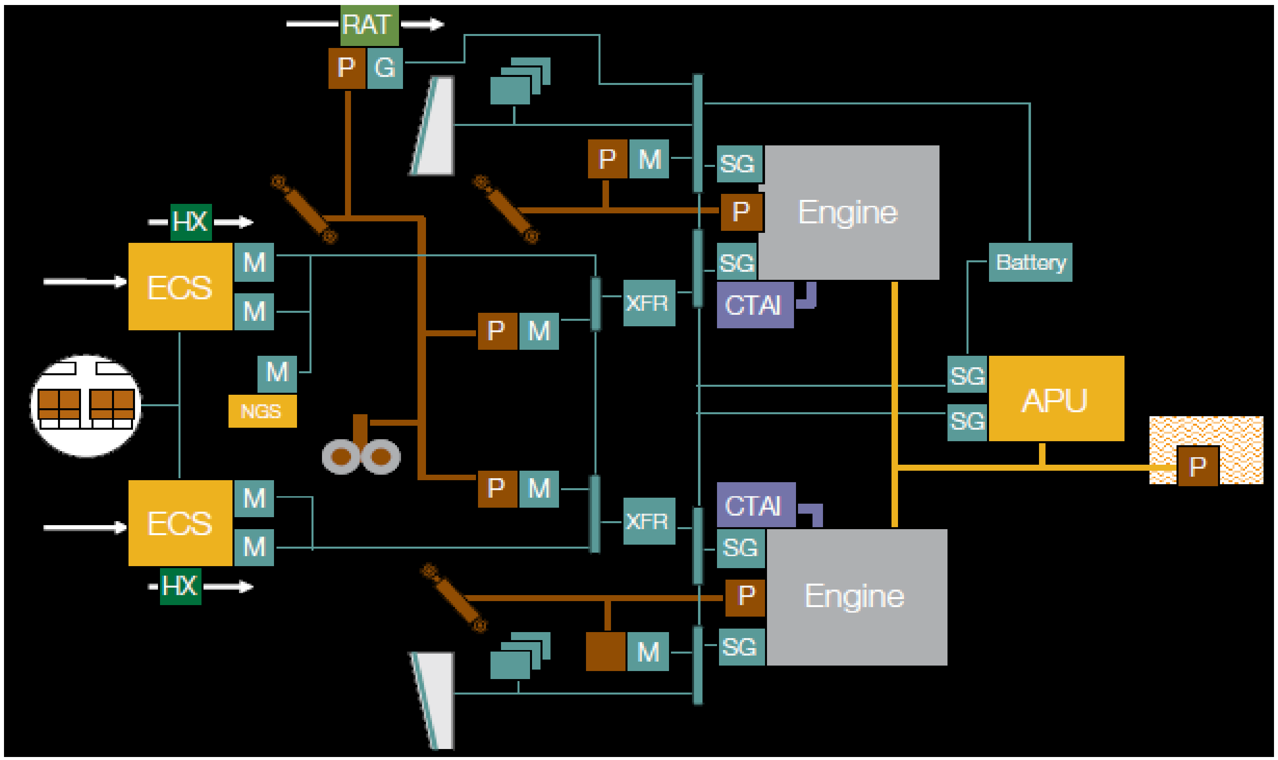
(Michaelis 2010)

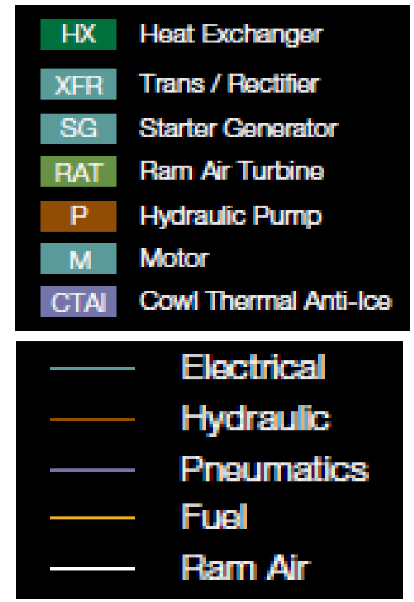
Solution: ECS Principles

Electrical (Bleed Free) Cabin Air Supply

Solution B787!

(Boeing 2007)



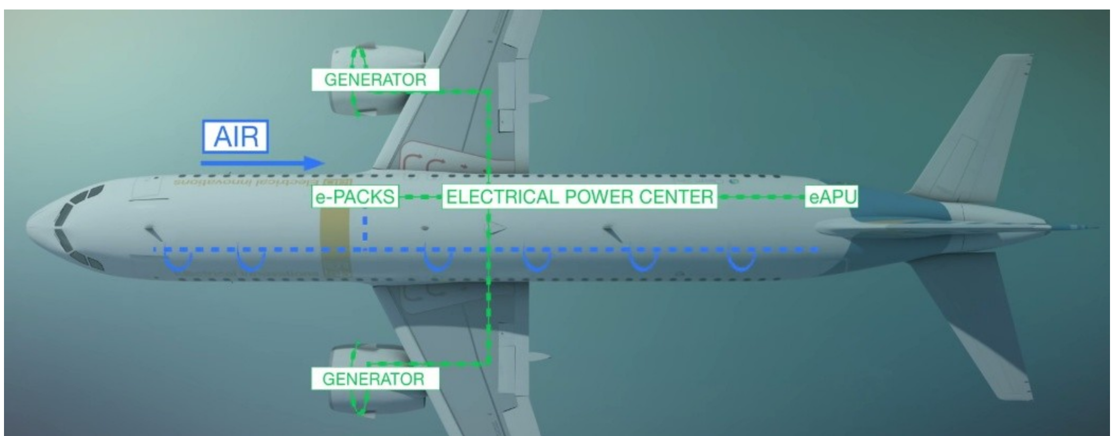


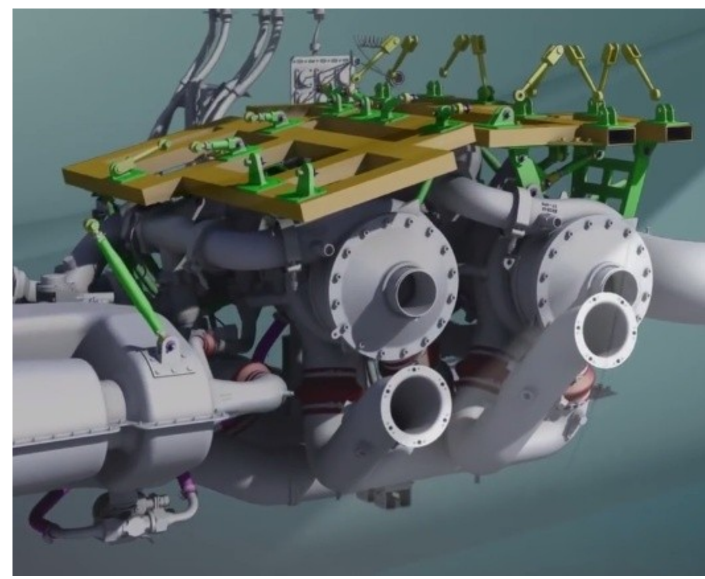
The "Pack" of the B787's Environmental Control System (ECS) is powered by electric motors (M) to compress ambient air up to cabin pressure and to push the air through the heat exchangers (HX) for cooling. The power for the electric motors is produced by generators (SG) connected to the aircraft's engine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

Solution: ECS Principles

More Electric A320?

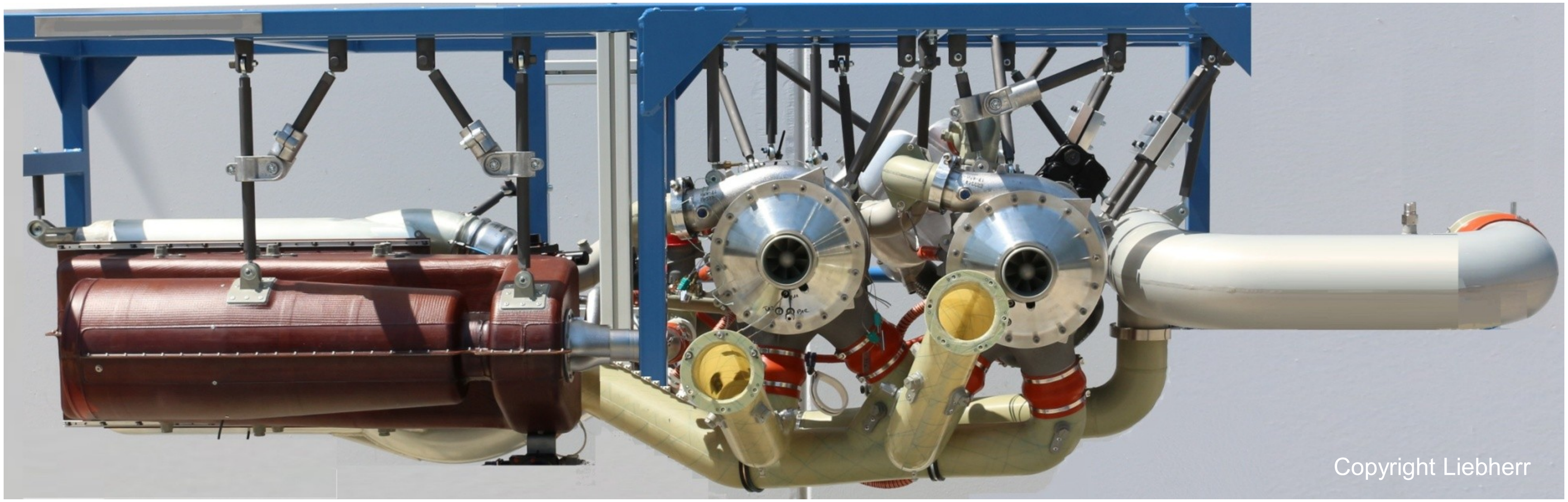
Electrical innovations
flightlab





Solution: ECS Principles

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)

Summary

- There is sufficient evidence for a **problem** of contaminated cabin air:
  engines leak oil by design,
  oil can be traced on its way from the engine into the cabin, ...
  CAA, Airbus, ... document the problem,
  Lufthansa, EasyJet, ... take action

- **Short term partial technical solution: Carbon filter:**
  a) in the duct to the cabin and
  b) attached to the recirculation filter
  suitable for **retrofit**

- **Long term full technical solution: Bleed-free architecture with direct air intake and dedicated compressor**
  suitable only for **newly designed aircraft**

Contact

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http://www.ProfScholz.de

http://CabinAir.ProfScholz.de

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See also:

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