The science supporting inapplicability of hazardous limits applied to the cabin air environment

SAE- AC9 meeting No. 107: Aircraft Environmental System Committee

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Global Cabin Air Quality Executive
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Who am I?

MSc: (Cranfield, 2016) - http://www.susanmichaelis.com/caq.html
Presentation outline

• Questions to answer
• History
• Hazards
• Flight safety
• Airworthiness
• Health
• Science
• Use of occupational exposure limits?
Questions to answer!

• Where to set trigger levels?
• Are health/performance limits to be used?

• SAE comment-AC9M: (4/3/18): Sensor trigger levels must be based on hazardous limits so as to identify when maintenance action to be taken:
  • 1. Engine health monitoring
    – Major oil leakage
    – On condition or hard time maintenance
  • 2. Human health
    – Hazardous limits breached
    – Scientific link: Cabin air & adverse health

  NO
HISTORY - 1947 –
Boeing 377 Stratocruiser

Carbon Monoxide Detectors and Filters
Sea level cabin at 15,000ft - Max 6.55 PSI
18 December 1953

Boeing Document D-14766-2
B-52 Decontamination Program

• Testing of a filter system
• The possible toxic effect of the contamination is still unknown.
• Smoke or haze is reported in only a few flights.
• Obvious increases in the contamination level were noted during changes in engine power conditions.
October 1955

North American Aviation

Aware of oil contamination issue for last two years – suspect compressor bearing seals main source

In-depth look at filter options.

Solutions:

The Separate Compressor As A Solution – This method of eliminating contamination is considered to be the most positive... also the heaviest, most complicated and most expensive.
Royal Aeronautical Society - 1954

- Air can be taken off compressor if:
- Intake not contaminated with exhaust gasses & harmful fluids (deicing…)
- Enough pressure at high altitude/ engines throttled back

Compressor provides ‘simple and convenient means of obtaining pressurizing air’
“At approximately 1530 hours on 15 May 1954, I was flying aircraft number 52-1436, an RB-57A, in a three (3) plane formation from Shaw Air Force Base, South Carolina. Approximately 40 minutes after take-off while flying over an overcast at 7000 feet, I experienced blurred vision, became nauseated and experienced considerable dizziness.

I recall no strange or unpleasant odors, nor did I taste anything out of the ordinary. I did feel a definite dryness of mouth and throat.

This condition lasted possibly a minute or two. As I became more aware of the situation or nearly to the passing out point I recall dropping back from the formation and opening the clear vision window and unhooking the oxygen mask. Fresh air from this open window seemed to relieve the unpleasant conditions I felt.”
27 May 1955 – Caravelle 1st Flight

1st airliner to use Bleed air for pressurisation
After preliminary examination of these possible sources, it appeared to be quite probable that the source of the headaches could be contaminants derived from the engine bleed air source for cabin pressurization. This report is limited to consideration of this aspect, and the analysis of the report quoted in the introduction of this report. The contaminant, from its odor and description by personnel affected, would appear to be an irritant gas, although it may well be accompanied by asphyxiants such as CO or CO₂. This report elaborates on this premi-
HAZARDS - Oils and fluids are hazardous

- Material safety data sheet: Boeing, ExxonMobil...
- Oil/fluid can labels
- EU regulations: EU Classification reg. 1272/2008
- Chemical databases
- 1954 patent
- Published literature: Michaelis et al (2017)....
- Industry reports: FAA (2009), Rolls Royce (2003)...

Heated complex mixture - Cannot define toxicity
(Howard et al. 2018)--- FAA 2009
Substances – Oils & Hydraulic fluids

- Synthetic ester base stock ~95%
- Antiwear additive - Triaryl phosphate (OP) ~3%
  - TCP - includes orthos isomers/TOCP... & TXP...
- Amine antioxidant – (1%)
- Proprietary substances
- Wide variety of pyrolysis substances
- Endocrine disruptors (TCP; TBP; TPP)

Hydraulic and deicing fluids – can leak into air supply

Routinely identified in CAQ monitoring studies
: eg: EASA (2017)
Key findings on exposures

- Complex mixture
- Low levels – Below exposure limits
- TCP/TBP & other OPs routinely found
- EASA: Oil bleed air leakage
  - Primary oil contamination - sealing failure/overfill
  - Secondary oil contamination – Oil deposits in bleed air/air con system – more frequent smell events
  - Permanent low level oil leakage – below detection limits – chronic seal failure

Ram Air Cabin Pressurizing System- Patent Boeing 1954

- One difficulty with utilizing the air compressor of a turbojet engine, for example, as the source of pressurized air for the airplane pressure cabin is the danger of air contamination. Lubricant decomposition products of a noxious and even toxic nature can be produced in the operation of these engines which, in the absence of sufficient precaution, may be carried into the pressure cabin with air delivered by the compressor. Suitable decontamination filters entirely adequate to meet this situation have not been forthcoming.

EU/UN Hazard Classifications (CLP /REACH)

**Oil, hydraulic, deicing fluids:**

**HAZARDS**

<table>
<thead>
<tr>
<th>Harmful if swallowed/dermal:</th>
<th>Eye/skin irritant &amp; ? Respiratory irritant</th>
</tr>
</thead>
<tbody>
<tr>
<td>May (suspected) cause damage fertility or harm the unborn child</td>
<td>Skin sensitizer</td>
</tr>
<tr>
<td>Single exposure &amp; repeated target organ toxicity - nervous system</td>
<td>Very toxic by inhalation</td>
</tr>
<tr>
<td>May cause genetic defects</td>
<td>May cause allergy/asthma or breathing difficulties if inhaled</td>
</tr>
<tr>
<td>May (Suspected) of causing cancer</td>
<td>May cause drowsiness or dizziness</td>
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</tbody>
</table>

**TXP – Substance of Very High Concern (SVHC) – REACH**

✈ **May cause harm to the unborn/Impair fertility**
Hazardous substances

Michaelis et al (2017)

- Oils, hydraulic & deicing fluid hazards identified
- EU Classification (CLP)
- Hazards databases- HSDB, ICSC, NIOSH....
Oil warnings

MSDS - Boeing 2007

• MJO II: Signs & symptoms of exposure: Irritation of eyes, skin, nose, throat & lungs. Neurotoxicity may be characterized by dizziness, headache, confusion & “intoxication”.

Oil can label

Do not breathe mist of vapor from heated material
MIL SPEC & SAE

• MIL –E- 5007 D (1973)
  – Oil leakage within engines not to cause contamination of bleed air or deposits (s. 3.7.7.3.2- internal oil leakage)
  – Bleed air contamination levels- listed (s. 3.1.2.11.3)
• SAE (1957)
  – Air delivered to cabin should be free from oil vapors……
  – Warning provided for CO
• Major user (1957)
  – Fresh air supply must be entirely uncontaminated
• BCAR
  – Entry of toxic gases must be prevented


(Absence of oil fumes… soon forgotten)
Conflicting views

✈ 1954: Unknown mixture / Hazardous / toxic - Boeing

✈ 2006: “Who knows what the byproducts are in hot synthetic turbine oil.” - Boeing

✈ 2013: ”Decomposition reactions of engine oils & hydraulic fluids are largely unknown.”

   BUT

   – Levels are too low to be harmful
International actions
Flight Safety

- Under reporting is occurring (FAA, EASA, Michaelis etc…)
- Flight safety issue widely recognized
    - Fumes- negative impact on safety issue
    - Slow degradation of performance/not recognized
  - IFALPA/ECA (2013/2017)
  - ADs- CAA, FAA, CASA…
  - FAA - SAFO (2018) - enhance flight crew procedures that mitigate the risk to passengers and crew in the event of odors, smoke and/or fumes.
  - SAE (2005)
  - Others: Michaelis (2010), Harisson (2009); FAA (2009)
Bureaus of air safety

Bleed air supply contamination
• Numerous reports
• 26 key recommendations and findings
• 9 bureaus of air safety
• Mid 1990s – 2016
• 9 countries, 2 continents

Refer: Loraine T. Air Accident Investigation Findings and Recommendations. Presentation at International Aircraft Cabin Air Conference, Imperial College London. 19-20 September, 2017:
https://www.aircraftcabinair.com/films
AIB Key Findings

• Many including:
  • Subtle impairment occurring/lack of awareness
  • Pilots not using O2/emergency/abnormal checklist (focus on fire/smoke)
  • Maintenance difficulty in identifying source
  • Lack of reporting detection systems
  • Not generally safety issue/OHS issue
  • Fumes not new/numerous aircraft types
  • Regulations focus on design/ignore effect on people
  • Filters not designed to filter oil fumes
During the descent, both crew members began to feel disorientated and found that they had to concentrate hard to carry out their normal duties. At this point the commander began to feel ‘confused’.

The flight crew expressed concern that neither had detected the slow degradation in their performance as this only became fully apparent after they had donned oxygen masks and began to recover.

Cause: Oil leak from engine entering air supply
Key recommendations -

• 2001: ✊ Suspicion of unhealthful cabin air – Pilots to use of oxygen masks selected to 100% oxygen

• 2007/2009: 🇬🇧 Detection system for smoke/oil mist

• 2014: 🇩🇪 EASA demonstrate certification & compliance (airframe/engine/APU) that CAQ does not lead to permanent health effects
Flight safety - Impairment

- BAe 146 study*: Immediate/ST effects = 44%
- 15 incidents study*:
  - Impairment = 93% (73% involved pilots)
  - 33% - full or partial incapacitation of 2 pilots
  - 87% positive oil identification

Other – Crew impairment rates
- CAA MORs: 2006-2011 - 30%
- BFU – 27%
- Michaelis (PhD, 2010) – 32%

http://www.euro.who.int/__data/assets/pdf_file/0019/341533/5_OriginalResearch_AerotoxicSyndrom_ENG.pdf
Reporting requirements - EU

• REGULATION (EU) No 376/2014 – Reporting:
• Commission Implementing Reg (EU) 2015/1018

✈ 4(3) Contaminated air in the cockpit or in the passenger compartment which has or could have endangered the aircraft, its occupants or any other person.

Serious under-reporting continues
Airworthiness

• Oil leakage seen in 3 main ways:
  ✈ Rare bearing seal failure
  ✈ Failure condition + operational factors- Oil spillage, seal wear....
  ✈ Design factor- low level leakage of oil in normal flight

Therefore…

MSc completed in 2016 (Cranfield University, UK)

✦ How oil leaks out of bearing compartment
Oil seals

Oil bearing compartment

Oil seals

• Labyrinth: Clearance (200-400nm)
• Mechanical/face seals: lubricated face (250-1000nm)
  ✔ rely on pressurised air
  ✔ Responsive to thermal/mechanical changes in structures & pressure changes

✔ All dynamic seals designed to leak - in normal operation
✔ Path to enter cabin air supply ✔
Factors affecting seal leak rates

• Seal leakage concepts

Hydro Mechanical
- Hydrostatic pressure distribution
- Hydrodynamic / pressure distributions
- Hydraulic balance / separation
- Pressure distortion

Hydro-mechanical
- Total gap profile
- Frictional heat
- Fluid / Gas viscosity
- Fluid / Gas Film
- Thermal distortion
- Gap temp.
- Heat transfer
- Sealing gap characteristics
- Components
- Seal / housing component characteristics

Other
Common assumptions – Oil leakage

1. Higher pressure in gas path than inside bearing chamber – Keeps oil in bearing chamber
2. Seals only leak when failure occurs
3. Reverse pressures to be avoided – prevents leakage

However

A) Oil may flow with & against positive pressure gradient with both types of seals
B) Positive pressure gradient difficult to attain at near ambient pressures (used in sealing bearing chambers)
C) Reverse pressures over seals- Allow oil to flow in opp direction – Both seal types
   • Labyrinths- clearance
   • Mechanical face seal- face opens up

All dynamic seals will leak, with seals designed to limit leakage/ ‘emission rather than leakage’
MSc research

• Interviews with:
  – experienced engineers & seals experts
  – FAA & EASA airframe & engine certification

• Key findings:
  – Seals not absolute design/will leak in normal ops & with varying operational factors
  – Low level emissions not given due consideration
  – No set process to show compliance
  – Focus on incapacitation

Key conclusions

Regulations
Clean air standards & AMC exist - not being met - open to interpretation

Design
Low level oil leakage over the bearing seals into the bleed air: Expected normal condition - various phases of flight

Certification req’s not being met (despite appearance they are)
  ✈ Oil leakage past seals associated with impaired/ degraded performance occurs more frequently than ‘major’ effects (remote/improbable) <10^{-5} / efh...
  ✈ Oil leakage (impairment) - Guidance material
    • Probable or above >= 10^{-5} / efh...
Conclusions
Frequency/Mechanism of oil leakage –
S Michaelis MSc (Cranfield University, 2016)

- Fugitive emissions of oil occur as a function of normal flight: Changing sealing pressures/balances/mechanical and thermal engine structures
  - Below permissible oil consumption rate
  - Frequency estimates are incorrect (Shehadi, 2015…) as focus on official reporting databases, not design
- Cannot assess using engineering failure estimates as will not take into account the low-dose leakage of oils in normal flight: Ignores engineering judgment/experience
- Lower-level leakage is regarded by industry as normal “permissible consumption rate” and regarded as a non failure/safe condition
Michaelis et al (2017)

**BAe 146 pilots study**
- 70% + response rate (274 pilots)
- Work environment confirmed to leak oil by manufacturer- BAe Syst.
- Most reported lower level normal fume events/ not failures
- 63% report symptoms consistent with exposure to oils/fluids
- 13% - chronic ill health/ retired with ill health....

**15 Incidents review**
- 80% - fumes only
- 100% - transient engine ops
- 80% - climb or descent
- 93% - impairment –incapacitation
- 33% - full/partial incapac’ of 2 pilots
- 53% - LT adverse effects
- 47% - 10-23 symptoms
- 87% - positive oil findings (93%)
- 66% - fumes reported before/ after
- ST & LT medical findings/diagnoses

- Consistent pattern
- Cause & effect identified linking environment to adverse effects
  - Occupational disease: Aerotoxic Syndrome
- Supported by literature (not just OPIDN/TOCP)
HEALTH

Aircraft air supplies contaminated by engine oil and other aircraft fluids are reasonably linked to acute and chronic symptoms and findings/diagnoses creating a cause and effect outcome.

New occupational disease?

http://www.euro.who.int/__data/assets/pdf_file/0019/341533/5_OriginalResearch_AerotoxicSyndrom_ENG.pdf
Science

• Chronic low level exposures + acute events: (Howard - 2018)
  – More susceptible
  – Diffuse pattern
  – Ultrafine particles/OPs/complex mixture

• Repeat low level exposure to OPs – greater damage than only cholinesterase mechanisms (Terry - 2012)

• Chronic pre exposure to OPs increases susceptibility (Axelrad - 2003)

• UFPs generated with heated oil under all normal conditions – (Jones – 2017) (“piggyback effect”- Howard 2018)
The purpose of this review is to discuss several non-cholinesterase targets of OPs that might affect such fundamental processes and includes cytoskeletal and motor proteins involved in axonal transport, neurotrophins and their receptors, and mitochondria (especially their morphology and movement in axons).

117 References cited (41 in vivo, 12 in vitro, 15 in silico)
there is now substantial evidence that this \textit{canonical (cholinesterase-based) mechanism cannot alone account for the wide variety of adverse consequences of OP exposure that have been described, especially those associated with repeated exposures to levels that produce no overt signs of acute toxicity}. These include covalent binding of OPs to tyrosine and lysine residues, which suggests that numerous proteins can be modified by OPs. In addition, the mechanisms of oxidative stress and neuroinflammation and the known OP targets of motor proteins, neuronal cytoskeleton, axonal transport, neurotrophins and mitochondria. This type of exposure has been associated with prolonged impairments in attention, memory, and other domains of cognition, as well as chronic illnesses where these symptoms are manifested (e.g., Gulf War Illness, Alzheimer's disease). \textit{precisely the spectrum of symptoms reported for air crew by Michaelis, Burdon & Howard (2017)}

\begin{itemize}
\item Their latest work on chlorpyrifos finds effects at 0.1 nanomolar concentration.. Gao et al. 2017
\end{itemize}
Inapplicability of exposure limits 1/6

- ‘The results show that the cabin/cockpit air quality is similar or better than what is observed in normal indoor environments (offices, schools, kinder gardens or dwellings). No occupational exposure limits and guidelines were exceeded.’ (EASA 2017)

- ‘No evidence for target pollutants occurring in the cabin air at levels exceeding available health and safety standards and guidelines.’ (Cranfield, IEH, 2011)

- ARE THEY CORRECT??

Cranfield University, IEH, 2011
DO NOT APPLY TO:
- Passengers / all workers
- Above 5000ft / minimal ambient O2 partial pressure of 132 torr or less – (Adverse physiological effects)
- Complex mixtures e.g. thermal decomposition products, gasoline, diesel exhaust...
- TCP
- Most substances do not have a set exposure standard
- Not fine lines between safe & dangerous
- Not indicator of toxicity/ adverse effects
- Recognized by HOL, Mobil, Henschler, WHO, RAAF, ACGIH, AsMA...
FIGURE F-1. Plot of oxygen partial pressure ($p_{O_2}$) (expressed in torr and kPa) with increasing altitude (expressed in feet and meters), showing the recommended oxygen partial pressure of 132 torr.
Industry awareness that TLVs/OELs do not apply to cabin environment - examples - 4/6

- **No Exposure standard for oil mixture** – ExxonMobil- 2013; House of Lords-2005

- **TOCP exposure standard does not apply to TCP exposure** – Mobil-1988,1999, Henschler-1958

  "Because of considerable variation among individuals in sensitivity to TOCP, it is not possible to establish a safe level of exposure ... Both the pure ortho isomer and isomeric mixtures containing TOCP are, therefore, considered major hazards to human health." WHO, 1990

- **OSHA & other global standards not applicable to aircraft cabin air as Industrial standards.** Aerospace med Assoc -2002; Ernsting-1988 (RAF ret);
Industry awareness that TLVs/OELs do not apply to cabin environment- examples -5/6

- Not applicable to the public in non occupational settings – Nagda 2000; AIHA-1998; ASTM-2011; Cranfield-2011; EH40/2005; ASHRAE- 2013; European Commission-2013....

“Except for industrial workplaces and certain specialized environments, such as spacecraft, indoor air quality standards do not exist for most indoor or confined environments, including aircraft cabins.” –ASHRAE 2013

“Occupational and public exposure limits apply only to exposures to a single chemical at a time. They do not reflect the actual situation in aircraft cabins, where contaminants may be present in a blend, and the possible effects of altitude on toxicity mechanisms. Also, exposure standards or limit values do not exist for all chemical species, or the various possible isomers.” – SAE 2005

Similar FAA-2009; Airbus-2005
• “the conditions in cabin air may differ from the standard conditions on which exposure limits are normally based, for example the air pressure, humidity and longer working hours. These aspects need further consideration. In addition, also possible effects relating to mixture toxicology need further investigation.”

EASA-CAQ study 2017
What to do?

• Cannot assess toxicology /hazard levels of complex mixture/ chronic exposure at present
• Identify onset of oil seal malfunction –use practical trigger levels/ not harmful limits
• Exposure to mixture is harmful over time
• Take steps to prevent exposure now.
THANK YOU to all here

FURTHER INFORMATION AVAILABLE:

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