Bearing chamber sealing and the use of aircraft bleed air

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Who am I?

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

- Ongoing concerns - jet engine oils leaking into cabin air supply
  - Reports - 1950’s onwards; wide variety – e.g: toxicity, leakage, effects
  - Frequency – Rare to frequent; under-reporting
  - Exposures – occurring (ad hoc studies)
  - Safety – compromised (impairment in flight)
  - Increasing actions being undertaken
  - Key issue – Oil leakage seen in a variety of ways
1952/53 – J57 Engine

• Bleed air
• Synthetic jet oils
“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.”

Ref: Loomis T, Krop S. MLR No. 61 - Cabin Air Contamination In RB-57A Aircraft. Maryland: Army Chemical Center, 1955.
Bureaus of air safety

Bleed air supply contamination

• Numerous reports
• 22 key recommendations and findings
• 8 bureaus of air safety
• Mid 1990s – 2016
• 8 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
International actions
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
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
Health & Science

• Exposure to a complex (heated) mixture including OPs
• Hazardous substances: EU Classification reg. 1272/2008; MSDSs/chemical databases *
• Chronic low level exposure
• Primary pattern identified - Acute on chronic exposures with diffuse effects
• UFPs (<10-150nm)/OPs & complex mixture – mechanism?

Oil leakage seen in 3 main ways

1. Rare bearing seal failure

2. Failure condition + operational factors - Oil spillage, seal wear....

3. Design factor - low level leakage of oil in normal flight
Aims & Objectives

Aim- assess gap between aircraft certification requirements for the clean air in crew and passenger compartments of transport aircraft using the bleed air system and the theoretical and practical implementation of the requirements.

Objectives – Assess (bleed air system)
1. clean air certification requirements
2. Theoretical documented understanding of bleed air contamination of cabin
3. Feasibility of implementation of clean air requirements
Methodology

2 Interview groups:
- Regulators x 2 - FAA & EASA
- Engineers x 12 – (aerospace x 10 & seal suppliers x 2) – Highly experienced

Interview questions (Q)
  - Regulators – Practical process of certification & compliance- X 7 Q
  - Engineers – Professional view how oil leaks past bearing seals – x 8 Q
Aviation regulations/standards/Guidance material - cabin air quality 1/2

- CS/FAR 25.1309... - Equipment and Systems Design – Airframe (25.1309c- warning systems)

- CS E 510 & FAR 33.75... – safety Analysis (engine & APU) → bleed air (Incapacitation < $10^{-7}$/efh; impairment < $10^{-5}$/efh)

- CS E 690... – Bleed air purity- (engines/APU)

- Failure condition effects

![Diagram showing the relationship between probability of failure condition and severity of failure condition effects. The x-axis represents probability of failure condition ranging from Remote, Extremely Remote, and Extremely Improbable, while the y-axis represents severity of failure condition effects ranging from Minor, Major, Hazardous, and Catastrophic. The graph shows that the combination of high probability and high severity results in an unacceptable condition.]
Aviation regulations/standards/guidance material - cabin air quality 2/2

- CS & FAR 25.831 a/b - ventilation
  A) Enough fresh air for duties — without undue discomfort/fatigue (10cfm+)
  B) Free of harmful hazardous concentrations of gases or vapors -(CO, CO2, O3) +++?

- AMC 21.A.3B(b) – Unsafe condition – Impairment/ discomfort – Incr frequency

- (EU) Reg 2015/1018 - Reporting: e.g: Contaminated air in cockpit or cabin which could endanger aircraft/occupants / fumes/ leaking liquid…. 
Oil/air system

• Oil system provides oil under high pressure:
  • Lubrication, cooling, sealing.....
    • e.g: main shaft bearings in bearing chambers (continuous supply & removal of oil)
• Secondary (core/bleed) air from compressor – many functions incl.
  • Cooling engine/accessory components
  • **Bearing chamber and oil cooling/sealing**
  • Control turbine tip clearances
  • **Cabin pressurisation/ventilation**
• Amount of secondary air used is highly controlled & minimized – Reduce SFC penalties- Oil and Air Seals are required to do this.
Bearing compartment sealing

Oil Seal Functions - Bearing Compartments
• Prevent oil leakage out (fires/fumes in cabin/ loss of aerodynamic perf’)
• Prevent moisture & dirt in
• Control of air leakage in → Improve performance
• Reduce oil consumption
• Operate under positive & reverse pressures

Pressurised air from the compressor is used to prevent oil leaking through bearing seals & to cool/ventilate bearing sumps

Philosophy: Use pressurised air to maintain bearing compartment at a lower pressure than surroundings → Inward flow /prevent outward leak

1950s: High awareness of oil contamination of the bleed air but desire to reduce costs of extra compressor – Bleed air accepted as similar quality to outside air
2 main types of seals used: Labyrinth & mechanical
Oil Bearing chamber

ExxonMovil (2016)- Jet Engine Oil System -Part One And Two, ExxonMobil Aviation Tech Topics.
Factors affecting seals

• How seals operate

  • All dynamic seals are designed to leak
  • How much they leak depends on many factors / hydrodynamic effects
    • Style of seal & balance ratio or tooth pattern
    • Lubricating regime
    • Operating conditions (speed / temperatures / pressures)
    • Component condition / wear life / distortion

\[ M_{rel} = \frac{V_{rel}}{\gamma R T_s} \]
\[ m = \frac{\pi h^3 \rho (P_1 - P_2)}{6 \mu \ln \left( \frac{R_1}{R_2} \right)} \]

Simplified leakage formulae
Factors affecting seals

- Labyrinth seal

The Jet Engine, Rolls Royce 2005
Factors affecting seals

- **Labyrinth seal**

  - Non contacting clearance type seal
  - Operates with tight clearances (200-400nm)
  - Controls leakage of air or liquid over restrictions reduces pressure over seal
  - Fluid can flow in either direction depending on pressure/momentum/design

- Performance deteriorates with time, wear, changes in operating conditions
- ‘Rubs’ can have immediate detrimental impact on leakage as clearances increase
- Various benefits- low cost/simple

The Jet Engine, Rolls Royce
Factors affecting seals

• Mechanical face (carbon) seal
Factors affecting seals

• Mechanical face (carbon) seal

Hydrodynamic effects

Increases In Speed Viscosity Waviness Roughness = Increased Gap

• Micro seal face separation typically 10 to 40 micro-inches (0.25 – 1.0 µm), so low leakage
• Pressure and temperature distortion can impact the parallelism of the seal faces and reduce or increase leakage
• Surface roughness 1 to 10 micro-inches RA (0.025 to 0.25 micrometres CLA can influence fluid film condition

• Performance less likely to deteriorates with time, wear, or changes in operating conditions as designs can often compensate during wear life
• Materials can usually recover from intermittent contact, but not continuous dry running
• More complex and expensive

Fluid Sealing 2018
Manchester, 7th - 8th March 2018
Factors affecting seals

- Seal leakage concepts

Hydro Mechanical

- Hydrostatic pressure distribution
- Hydrodynamic / pressure distributions

Thermal

- Frictional heat
- Fluid / Gas viscosity
- Gap temp.

Fluid / Gas Film

- Sealing gap characteristics

Components

- Seal / housing component characteristics

Other

Hydro Mechanical

- Hydraulic balance / separation
- Pressure distortion
- Thermal distortion
- Heat transfer

Thermal

- Total gap profile

Hydrostatic pressure distribution

- Pressure distortion

Hydro-dynamic / pressure distributions

- Thermal distortion

Fluid / Gas Film

- Fluid / Gas viscosity

Sealing gap characteristics

Components

- Seal / housing component characteristics

Other
Common assumptions – Oil leakage 1/2

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
Common assumptions – Oil leakage 2/2

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’
Engineers research 1/3

1. Oil leakage – Internal & external engine leakage /Into core & bleed air

2. Leakage past seals:
   • Seals design:
     • not absolute design- seals leak
     • Pressure differentials
     • Thermal & axial radial (mechanical) changes in engine structures
     • Leakage affected by engine speed & power
     • Design parameters don’t account for all conditions
   • Seal wear/ installation/ maintenance.....

3. Phase of flight affects leakage: Changes in engine performance (pressure differentials/ mechanical structure changes); low power settings....
4. Mechanical and labyrinth seals both leak for varying reasons:
   • Leakage is inevitable- design
   • Labyrinth- rely more on pressure diff
   • Mechanical (carbon) – Lubrication between surfaces = leakage
   • over seal faces/ More subject to wear & temperature critical
   • Leakage occurs both with & against the pressure drop- both

5. Oil leakage & regulatory compliance:
   • No published limits for oil contamination
   • No action required if leakage under permissible oil consumption
6. Oil leakage:
   • Oil leaving intended areas- Vapor/drip.... (emissions ignored)
   • Above permissible oil consumption limits

7. Reporting oil leakage:
   • Under-reporting is occurring
   • Oil ‘topping off’ is a normal procedure

8. Mitigating oil leaks to be given higher priority – solutions exist
Regulators research 1/2

1. Engine/APU certification process
   • No specific process to follow/ Must demonstrate compliance

2. Bleed air quality compliance: CS –E 510/FAR 33.75 (safety analysis)
   • Hazardous engine effects (Toxic products [e.g.: oil] in ‘cabin’ bleed air) incapacitation of crew/pax - extremely remote <= 10^{-7} -10^{-9}/efh
   • Bleed air purity testing: CS E 690/ CS APU 320
   • No specific guidance given

3. Substances reviewed & limits – toxins in bleed air?
   • None specified/ concentration sufficient to incapacitate- FAA
   • SAE ARP 4418A – EASA (recommended practice)
Regulators research 2/2

4. Airframe certification process: CS/FAR 25.831

• Air does not need to be pristine- FAA
• Enough fresh air to avoid discomfort/fatigue
• Levels provided for CO, CO$_2$, O$_3$ only
• Recent certification/sources of data (FAA): NRC, ASHRAE, AECMA-STAN (cancelled), NIOSH,CDC, Harvard public health etc....
Discussion: oil contamination of the bleed air supply

1. Regulations/standards & guidance material related to CAQ - exist

2. Theoretical understanding:
   - General - aviation industry – Rare seal leakage/within limits
   - Specialist aero/seals experts – Commonly used bearing compartment seals allow lower-level oil leakage over seals in normal flight

3. Feasibility of implementation of standards with bleed air system
   - Low-level oil leakage over seals are part of normal system function using pressurised oil bearing seals.
There is a gap between certification requirements for provision of clean air in aircraft crew and passenger Compartments using the bleed air system.
Conclusions 3/5

Design
1. Low level oil leakage over the bearing seals into the bleed air:
   • Expected normal condition - various phases of flight
2. Certification req’s not being met (despite appearance they are)
   • Literature/ aero & seal experts research
   • Oil leakage past seals associated with impaired/ degraded performance occurs more frequently than ‘major’ effects (remote/improbable) <10^{-5}-10^{-9} / efh…
   • Oil leakage (impairment) - Guidance material
     • Probable or above >= 10^{-5} / efh…
     • Unsafe condition
Conclusions 5/6

Compliance:
• Inadequately undertaken at certification
• No detection systems to monitor air in flight
• Requirements not specific enough to ensure occupants will remain free of adverse effects

Preventative control measures:
• Low-level oil emissions not taken into account
• Designs based on steady-state conditions
• No detections or filtration systems
• Rigorous controls lacking
Conclusions 6/6

Retrospectively:

• Previous certification requirements not specific enough to prevent oil leakage into air supply

Expertise & communication:

• Highly specialist area & inadequate communication between parties to ensure compliance & airworthiness
Recommendations 1/2

- Review standards, guidance material
- Preventative measures: Normal & abnormal operations
- Oil leakage not to be linked exclusively to rare failure conditions/maintenance irregularities
- Frequency – Explained by design factor
- Retrospective certification for bleed air quality
- Future aircraft- bleed free designs
- Far greater priority priority to regulatory compliance including low-level emissions in flight
- Warning systems introduced

&
• Seal designers brought into design process far earlier & part of the process
• More advanced seal/engine designs
Fail dangerous!
Seals have consequences
Synthetic Lubricant Oil
Qualified to SAE AS5780-HPC
HPC Class (High Performance Capable)
MIL-PRF-23699G-HTS
NATO CODE: O-156/O-154
NSN: 9150-01-439-0756

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Fluid Sealing 2018
Manchester, 7th - 8th March 2018
THANK YOU to all here & EU sealing Assoc

FURTHER INFORMATION AVAILABLE:

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