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ABSTRACT

The use of jet-fuel, de-icing fluids, lubricants, hydraulics, engine oil and other fluids, are associated with single repeated/accidental or chronic exposure(s) to ground staff, flight-deck and cabin crew and passengers. These fluids can become airborne in vapor or aerosol phases, and are known to contain neurotoxicants, carcinogens, irritants and other toxic ingredients. Exposures (single or repeated) to these toxic materials are not rare events and some typical failures/working conditions include mechanical failures, seal leaks, and operational procedures, such as take off while fumes detected, pack burn outs.

A method for calculation of exposure dose is proposed. The additional impact of exposure to toxicants in conditions of lowered pressure (and reduced oxygen level), other potentiation factors are still largely unknown, but are not presumed to be beneficial.

These occupational and public exposures can impact on a range of issues, including: air safety; public liability; ground and air crew safety; control requirements on the supply/ handling/use/disposal of these products; and national and international regulations.

A number of toxicity studies report a consistent range of symptoms in exposed individuals (Rayman, 1983; Van Netten, 1998). Because flight safety can be compromised, due to significant symptoms such as disorientation, blurred vision, impaired memory, altered coordination and so on, attempts have been made to address these problems worldwide. These include changes in engine design, drainage, containment, retrofitting of engine filters, modified maintenance and operation and procedures and the like. Some of these changes were developed in past decades or are being currently worked-out while new technologies are being developed that enable significant reduction in concentrations of toxic airborne chemicals.

However, while the problem persists, exposure of staff and the public to levels of toxicants that may affect safety and health continues.

ENVIRONMENTAL CONTROL SYSTEMS

AIRCRAFT GENERATED CONTAMINANTS – Outside air is heated and compressed in engines (or APU during some ground and in flight operations). During flight, cabin air is partly recycled (filtered) in most passenger aircraft types. The ratio bleed to recycled air typically averages 50%. New aircraft designs plan on a higher recirculation ratio (60-70%). Recirculated air is likely to be poorer in air quality than fresh air.

Contamination by aircraft fluids can be due to :

- Smoke from engine fires and leaks of partially combusted or pyrolysed materials
- Accidental condition: seal failure
- Maintenance: wear and aging
- Operation: ground operations at gate or on tarmac as airport surrounding, de-icing procedures, pack burnout procedures, recirculation
- Design: seals, fluids accumulating at the APU inlet, rear engines ingesting hydraulic leaks from « distant » origin (for example, the wheel well), thrust reverser hydraulic lines
- Residual contamination from lack of cleaning (PACKs and Airducts) after contamination events

Aircraft fluids are typically emitted into the cabin through engines or APU. Most frequent contamination events are due to engine/APU oil seal failures, hydraulic line failures, failure of ECS filters.

Due to pressure (hydraulics) and pressure/rotating parts (engine), most of the oil and hydraulics are aerosolized that is they are in liquid or solid rather than vapour form. Engine wall temperatures are high (up to 500°C), higher than the smoke point of these two fluid types (between 200°C and 300°C), (Van Netten, 1998), and can cause thermal decomposition, producing airbone contaminants such as CO and phosphated by-products which may have toxicities greater than the original phosphated additives.

Other factors influencing concentration ranges are :

- Air flow rate, recirculation ratio
- Equipment failure
- Maintenance
- Flight phases (take off / landing, ground operation versus flight cruise)
- Passenger load (Perry, 1995)
- Presence of catalytic converters
- Abnormal conditions

Examples of some available statistics include leak events, complaint aircraft with reported symptoms:

- 2 to 5 in cabin smoke events per month in the USA. Either self reported or as on media due to passenger admission in emergency rooms / emergency landing
- Leak rates (measured from engine « top-up » volumes) as high as 7 liters per day are commonly reported on some aircraft types
- A minimum estimate of 300 incidental flights and over 40,000 crew and passengers significantly exposed annually (Balouet, 1998)

In-cabin generated airborne chemicals – Possible sources of in cabin generated contaminants include :

- Aircraft compounds: offgasing due to paints, coatings, carpets and seats, walls
- Service compounds: cleaning fluids, food and beverage services, and insecticides
- Passenger generated components
- Human metabolites as due to passenger respiration and perspiration (Perry J.L., 1995)

EXAMPLES OF CHEMICALS USED IN AIRCRAFT

Lubricating oil – MSDS specifies the content:

- 3 % tricresyl phosphate (TCP)
- 2 % β-naphthalenamine

β–naphthalenamine is a bladder carcinogen part of IARC Category 1 list, and banned in most applications and most countries.

Tricresyl phosphate is one of the most toxic organophosphates, especially its ortho isomer. Amongst other uses of this organophosphate are chemical weapons, pesticides, as an antiwear and / or flame retardant additive (IPCS, 1990). Other phosphate compounds present either singly or in combination, cannot be considered to have no toxicity. Indeed the toxicity of phosphate ester containing materials used in aviation has been known for many years (Carpenter et al, 1959).

Label indicates:

- Warning: Swallowing this product can cause nervous system disorders including paralysis. Prolonged or repeated breathing of oil mist or prolonged or repeated skin contact can cause nervous system effects
- Precaution: Never swallow. Wash hands after handling and before eating. Never use in or around food. Avoid prolonged or repeated overexposure to skin or lungs

Hydraulic fluids – Typical ingredients / additives include organophosphates (tricresyl phosphate -TCP-, tributyl phosphate -TBP-, triphenyl phosphate -TPP-) and are ranging from 5 to 80% in concentration according to MSDS.

Note: Some inconsistencies between labels, MSDS, have been reported. In most cases, some of the toxic ingredients or neurotoxics effects are not disclosed.

Table 1. Some in cabin contaminants

CAS #	COMPONENT	Measurement
71-43-2	benzene	46 µg/m3
107-02-8	acrolein	6,7ppb (max), 4,0ppb (avg)
91-59-8	beta-naphtalenamine	not measured
1330-78-5	Tricresyl phosphate	not measured

TOXICITY ISSUES

Amongst identified compounds are carcinogens (for example, benzene, β-naphthalenamine), neurotoxicants (such as organophosphates, volatile organic chemicals –VOCs-, glycols), or irritants (acrolein, formaldehyde).

Neurotoxic symptoms have been known for almost 20 years (Rayman & McNaughton, 1983 ; Tashkin et al, 1980) and are real concern to aviation, as flight safety and health are implicated. Most worrisome symptoms to flight safety include : blurred vision, disorientation, blurred speech, altered memory, lack of coordination, respiratory distress, « grey outs », loss of conciousness (Balouet & Winder, 1999).

Based on US EPA’s (1998) guidelines for neurotoxicity testing, in-aircraft acute exposure toxicity events have been documented (Balouet,1998 ; Balouet & Winder, 1999), while correlation of symptoms to leak/repair/top up events is being collected (Chris Witkowsky, AFA, ASHRAE’s SPC 161, 1999 ; ITF H&S, Amsterdam, 1999).

Organophosphates, present in both lubricating oils and hydraulics, are a possible cause for such neurotoxicity, while other VOC contaminants are identified neurotoxics or OP potentiation factors (for example n-hexane). Organophosphate Induced Delayed Neuropathy (OPIDN) is a condition associated to such OP exposures (IPCS, 1990 ; Cherniak, 1988)

ALTITUDE INCREASED TOXICITY – Cabin pressure is controlled to remain below 8000 feet. Toxicity testing at cabin altitude has been conduced for CO, HCN and some other thermal decomposition by-products. These simulated high altitude studies reveal an increased toxicity measured by alterations in LC_{50}, alert and stun times, from 30-60% depending on compound and altitude/ hypobaric conditions (Kerguelen, 1993).

These changes have critical implications for air safety and health, and need to be considered in operation of existing practices and regulations.

Table 2. CO toxicity / mice. LC_{50} (20 minutes inhalational exposure), alert and stun times (for the respective LC_{50}) versus ambient pressure (Kerguelen, 1993).

Altitude (m)	Pressure (hPa)	LC_{50} (ppm)	LC_{50} (mg/m^{-3})	Alert time (min)	Stun time (min)
0	1000	5708	6537	5.1	11.4
1500	850	5295	5124	5.9	10.7
3000	700	4369	3502	6.9	13.8

MONITORING ISSUES

Certain cabin air quality factors have been investigated over the past 20 years. These include CO, CO_2, O_3, NO_2, relative humidity, pressure and O_2 partial pressure.

Data has been obtained on hundreds of flight segments which confirms the statistical consistency. It would seem that efforts should now turn to the evaluation of other airborne chemicals :

- No measurements exist for aircraft under significant leak events
- Most monitoring and analysis technology used in monitoring studies is not suitable for measurement of semi-volatile and non volatile components
- Some complaint flights (crew symptoms reported during that flight) have been monitored, but the data remain confidential
- The number of compounds measured appears limited due to selective sampling or monitoring methods, or no correlation to leak rates provided (best documented by relative engine oil top-up volumes)

To date, most monitoring studies concentrate on obtaining data for VOCs. However, measurements are only collected on up to 30 VOCs in some « exhaustive studies » as the most abundant contaminants. Semi VOCs and non volatile organic compounds are rarely studied (example of TCP : vapor pressure at 10^{-4} mm Hg) in flight measurements have not been published. Rough GC/MS data remains confidential, although such data might enable establishing an improved / more exhaustive list of compounds and concentration ranges.

The problem of sample collection methods for airbone contaminants for mists and aerosols has not been properly addressed in most studies. For this reason, the aerosolised fraction of airborne chemicals remains almost completely unknown.

Aviation practices are responsible for some further monitoring limits :

- Electronic devices are not allowed to be switched on during take off and landing (interference risks to avionics)
- In-flight testing is at cost due to space and weight, preparation of in flight sampling and monitoring
- Some materials and equipment (such as dangerous gases used in analytical equipment) are proscribed in aircraft
- Take off and landing are short flight phases although reported for the highest number of complaints. Measurement protocols should allow appropriate sampling volumes per time unit, monitor both gas and aerosol phases, coupled to sufficiently low detection/ blank values
- A tarmac simulated leak event, with controlled engine power/idle, leak rates, fluid ingestion and appropriate sampling and measurements methods should also be considered, as long as relevant factors, such as altitude, cabin ventilation and passenger load are given suitable consideration

AN EXPOSURE ESTIMATION / CALCULATION METHOD FOR IN-CABIN AIRBORNE CHEMICALS: A MODEL

Whatever the limits are or have been in sampling and monitoring in-cabin contamination by aircraft fluids, the estimation of in-cabin air concentrations and exposure levels are important tools for assessing risks.

Estimating / calculating these exposures rely on the following key parameters :

1. ϕ cont : contaminant leak flow rate in g.min^{-1}
2. ϕ bleed : bleed air flow (total bleed air, all PACks, in m^{3}.min^{-1})
3. α : ratio bleed air to total engine air flow ($0\% < \alpha < 20\%$)

4. β : differential in bleed air fluid ingestion according to bleed air port / failing seal port bearing (0%< β < 100%)
5. γ : oil retention ratio in the recirculation air compared to the oil concentration in the bleed air (0%< γ < 100%). example: γ = 10% for a 90% removal efficiency
6. δ : retained contaminant fraction as by inspired / expired air : retention ratio ($\delta = 0.8$)
7. V : mean inspired air flow per crew on duty = 30 liters per minute : mean inspiratory volume = 1.5 liters / mean respiratory frequency = 20 /min. A mean inspired air flow of 20 liters per minute could apply for passengers at rest.
8. t : exposure duration in minutes

Estimated contaminant concentration

$$Cfluid = (\Phi cont / \Phi bleed) \times \alpha \times \beta \times [(1+\gamma) / 2]$$

Estimated inhaled dose

$$Dfluid = (\Phi cont / \Phi bleed) \times \alpha \times \beta \times [(1+\gamma) / 2] \times \delta \times V \times t$$

Parameters do differ according to aircraft type as air flow rate (Packs on), number of engines, engine type / bleed air port, leak level within engines, conditions of hydraulic ingestion.

[(1+ γ) / 2] refers to a 50% recirculation ratio. Aircraft fluid density is estimated to be 1.

When leaking fluid is a blend, concentration / inhaled dose of a specific chemical as part of blend, D chemical = D fluid x % of contaminant in blend.

CASE STUDIES AND CONCENTRATION / INHALED DOSE ESTIMATES

In the two hereunder case studies, the estimated oil mist and OP contamination levels exceed by orders of magnitude the standards or threshold limit values.

WORSE CASE FAILURE CONDITION, HYDRAULIC LEAK – Aircraft type :narrow body ; 70 passengers ; rear engines ; 20 cfmp bleed air , no recirculated air ; 1 hour flight segment ; 20% of hydraulic leak ingested in bleed air.

α = 20 %; β = 1; γ = 100 %; δ = 80%; V= 20 versus 30 $L.min^{-1}$

Hydraulic leak (30 liters released during 1 hour flight segment), hydraulic fluid containing 20% organophosphates (OP) ; hydraulic flow rate = 500 $g.min^{-1}$, bleed air contamination rate = 100 $g.min^{-1}$, bleed air flow rate = 25.2 $m^3.min^{-1}$, concentration in bleed air = cabin air concentration.

Table 3. Concentrations and inhaled doses, worse case failure, hydraulic contamination.

Hydraulic fluid concentration in cabin air	3680 mg/m-3
OP concentration in cabin air	794 mg/m-3 (both aerosol and gas phases

Breathing volume	Inhaled hydraulic dose	Inhaled OP dose
20 $L.min^{-1}$ (Pax)	3810 $mg.hour^{-1}$	754 $mg.hour^{-1}$
30 $L.min^{-1}$ (Crew)	5716 $mg.hour^{-1}$	1143 $mg.hour^{-1}$

<u>Note 1:</u> on that flight, documented illness show initial symptoms starting 20 min after take-off, blue haze in the cabin, and caused irreversible CNS impairment, major symptoms lasting for over 6 months.

<u>Note 2:</u> Exposure standard (ACGIH) for TCP is 0.5 mg/m^3 and 0.01 mg/m^3 for TOCP. SAE's ARP 4418 allows a maximum bleed air contamination by engine oil at 5 $mg.m^{-3}$. This value is based on mineral oil, not on a synthetic oil containing toxic ingredients (including phosphated content). OP related TLVs based on a 40 hour work week vary from 0.05 to 0.2 ppm according to compound / isomer, standard or regulatory bodies.

<u>Note 3:</u> Due to the very low vapor pressures of organophosphates, in the range of 10^{-4} mm Hg (IPCS, 1990), it is expected that the OP gas phase does not exceed 0.16 ppmv at 600 hPa, well below the blank values of the used sampling and monitoring methods. Therefore, most OP in air would be in aerosol phase.

ENGINE OIL LEAK – Aircraft type :narrow body, 100 passengers, leak flow rate (l) = 6 liters oil leak per engine per day (3% TCP), 2 engines, leak over 15 hours flight per day, 50% recirculated air.

ϕ bleed air = 180 l per person/min (10 cfmp) ; total bleed air flow 18 $m^3.min^{-1}$

α = 10%; $\beta = 1$; γ =10 %; δ = 80%; V = 20 versus 30 $L.min^{-1}$

Table 4. Concentrations, engine oil contamination

Engine oil concentration in bleed air	147 mg/m^{-3} (both aerosol and gas phases)
TCP concentration in bleed air	4.43 mg/m^{-3} (both aerosol and gas phases)
Engine oil concentration in cabin air	80 mg/m^{-3} (both aerosol and gas phases)
TCP concentration in cabin air	2.4 mg/m^{-3} (both aerosol and gas phases)

Table 5. Inhaled doses, engine oil contamination

Breathing volume	Inhaled engine oil	Inhaled TCP dose
20 L.min^{-1} (Pax)	77 mg.hour^{-1}	2.3 mg.hour^{-1}
30 L.min^{-1} (crew)	115 mg.hour^{-1}	3.5 mg.hour^{-1}

According to above case study, crew (30 L.min^{-1}) annual and life exposures (in g) can be estimated to :

Table 6. Estimated total inhaled engine oil/TCP, as based on above leak conditions

Equivalent dose (in g) of contaminant/OP	Flying 700 hours/year	Flying 900 hours/year
40 hours work week	4.6 / 0.14	4.6 / 0.14
1 year	80 / 2.4	103 / 3.15
5 years	400 / 12	515 / 15.7
10 years	800 / 24	1030 / 31
15 years	1200 / 36	1545 / 47
20 years	1600 / 48	2060 / 62

The above given examples are not under « normal operations ». Case n° 1 typically is an incidental condition while case n°2 corresponds to existing flight conditions considered as « normal » by the airline whereas over 800 complaints have been logged by this company.

REGULATORY ISSUES IN CABIN AIR QUALITY

Cabin air quality is regulated by Federal Aviation Authority (FAA) in the USA and Joint Aviation Authority (JAA) in Europe. Requirements deal with four contaminants only : O_3, CO, CO_2, NO_2. Pressure and air flow are also controlled. These requirements apply to both aircraft manufacturers (FAR part 25) and operators (FAR part 121).

It is noted that requirements for contaminants by FAA and JAA markedly differ to other recommendations for workplace exposure standards such as Threshold Limit Values (TLVs) or Maximum Acceptable Concentrations (MACs). Recommended values are available for hundreds of compounds and isomers. General aviation air quality recommendations apply to the above four compounds only, except for:

- Canadian Civil Aviation where Aviation Occupational Safety and Health has integrated the ACGIH's (American Conference of Governmental and Industrial Hygienists) TLVs and MACs
- US Air Force has its own AFOSH (Air Force Occuptional Safety and Health) standard
- NASA and ESA (1992) have established Spacecraft Maximum Acceptable Concentrations (SMACs).

Consideration of inclusion of recommended exposure standards for other contaminants likely to be found in aircraft is needed. This also needs to take into account factors such as altitude and recirculation of air.

Over 130 lawsuits have been filed by civil aviation air crew worldwide for cabin air contamination events.

- Recommendations
- Use less toxic compounds in aviaton as recommended for safety risk management, and by the Cleaner Production Program of the United Nations Environment Program (UNEP), or the World Health Organization (WHO-International Program on Chemical Safety).
- Ensure regulatory/standard consistency and compliance
- Introduce recommended exposure standards for contaminants likely to be found in airplane environment, most especially toxic contaminants
- Reduce avoidable risks of exposure at source : leaks, design, operation control, maintenance
- Increase awareness, training and medical care

CONCLUSIONS

Aviation has a been a pioneering industry for decades.

Still, this industry has not fully investigated airborne chemicals in an exhaustive manner, despite flight safety issues and health risks associated to the use of toxic compounds and cabin-air contamination.

Priority tasks include :

- Delineating the level of toxic contaminants in airplane environments
- Developing recommendations for permissible exposure in airplane environments
- Ensuring that effects of altitude, humidity, work load, rates of ventilation and other air quality factors are considered in exposure standard development
- Ensuring that in-cabin airborne chemicals are estimated on at least additive principles used for estimating hazards as by exposure to mixtures

It is thus a necessary preliminary to document chemical compounds and concentration ranges, in an exhaustive measurement and analytical/synthetic approach.

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DEFINITIONS

Airborne chemicals refer to chemical contaminants in gas and aerosol (liquid or particulate) phases.

Aircraft fluids include de-icing fluids, hydraulics, lubricating oil (engines and Auxillary Power Unit – APU), jet fuel, coolants, fire fighting fluids.