Contaminated aircraft cabin air

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A broad overview of the subject is presented, covering all salient aspects including the technical history, a discussion of the compounds involved in the contamination, the frequency of occurrence, a survey of attempts to measure the contamination, safety considerations, health considerations, and possible technical solutions to the problem of contamination.

1. INTRODUCTION

This paper sets out to answer the question: Is there linkage between oil fume events and flight safety and adverse health effects? Note that the term "fume" describes both visible and invisible fumes or other emanations that may or may not be detectable using the bodily senses. In particular, the term does not apply to smoke only.

"Contaminated air in aircraft" refers to the air supply within aircraft cabins contaminated by synthetic turbine engine oils, hydraulic fluids or deicing fluids; however, the focus in this paper is on the synthetic oils. Those developed after World War II are made up of an ester base stock (95% of the oil) and an additive package consisting of engine antiwear agents, most commonly tricresyl phosphate (TCP) (3%) together with corrosion inhibitors and antioxidants (1–2%) [1].

2. AWARENESS

The use of engine air compressors from which compressed air could be bled in quantities suitable to supply cabin ventilation and conditioning was said to be a *"fortuitous circumstance"* in 1946 [2]. As a consequence, the use of synthetic oils rather than mineral oils was required due to the higher operating and bearing temperatures of turbine engines [3, 4]. Oil manufacturers recognized that turbine engines with higher compression ratios and more power had forced temperatures of oils and bearings up, requiring better oil compatibility with seals if seal leakage was to be minimized [5]. In 1952, the US National Advisory Committee for Aeronautics published a report noting that synthetic engine oils were required to satisfy the requirements of future lubricants of gas turbine engines [6]. There was concern about the higher operating temperatures of the newer, more advanced engines causing thermal degradation of the lubricants. The report stated that there was *"speculation about probable toxicity and corrosiveness at elevated temperatures"* with these properties having not yet been adequately studied. The Aero Medical Association in 1953 advised that pyrolysed oil *"can contain irritant and toxic aldehydes and other dangerously toxic products of incomplete combustion ... even a small degree of bodily impairment from toxic gases would lead to increased pilot error and so be hazardous in aviation"* [7].

A 1954 United States Air Force (USAF) study [8, 9] investigated the toxic effects of animals exposed to mists derived from heated components of synthetic jet engine oil meeting the MIL-L-7808 standard. The toxicity was found to come from the breakdown of the principal ingredient, the base stock di-2-ethylhexyl sebacate. The mists produced pneumonitis and degenerative changes in the brain, liver and kidneys. In the case of the esters, aldehydes, carbonyls, carbon monoxide (CO) and undecomposed particulate matter were found in the atmosphere, while in the case of the TCP, free cresols, undecomposed TCP and CO were found. Fogs formed at 400–550 °F (204–288 °C) were *"much less toxic than those formed at 600 °F (315 °C). The products of thermal decomposition are much more toxic than the undecomposed material."* Fatalities were noted to particularly increase in animals exposed to the mists generated from the oils exposed to temperatures of 700 °F (371 °C) compared with over those of 400 °F (204 °C).

A 1967 Esso study undertook further animal inhalation toxicity testing on oils including Esso Turbo Oil 2380 (still in common use today) that were highly heated, finding that the cause of death was severe irritation to the respiratory tract [10]. In 1965 a US Navy study of hydraulic fluids containing triaryl phosphates including TCP and other similar compounds found that components other than just the *ortho* isomers of TCP appeared to have significant neurotoxic potential or were capable of synergizing or potentiating the toxic effects of triaryl phosphates [11]. A 1995 USAF study found oils containing TCP heated to high temperatures resulted in changes to the compounds, resulting in increased neurotoxicity [12].

The awareness of the bearing and lubricant problems in turbine engines operating at high speeds and temperatures was a major issue for the military in the 1950s with nontoxicity over the whole temperature range listed as one of the six lubricant general requirements [13]. Esso reported that the contamination of cabin air with

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thermally degraded oil fogs introduced the question of toxic effects from thermal decomposition products [14].

During the 1950s, there was considerable industry awareness about the critical operation of oil seals used with a bleed air system. Oil leakage problems associated with the use of engine oil bearing seals pressurized with air that are responsive to variations in engine operating conditions were clearly recognized [15]. Engine oil bearing seals are used to prevent oil leakage from the engine bearing chambers into the compressor bleed air flow. Several different factors must be accounted for in preventing oil leakage into the air supply.

Firstly the design of bleeding air from the engine compressor provides a mechanism for oil leakage as a function of system architecture. Commonly used labyrinth seals rely on pressurized air taken from the compressor acting on the external side of the seals to prevent oil leakage from the bearings. The seal prevents oil leakage by allowing the air to flow from the outside to the inside of the bearing chamber. If there is a leakage in the air system, or if the air system supply is inadequate, the pressure could be less than that of the oil pressure, allowing oil to escape and enter the air side of the engine. The Society of Automotive Engineers (SAE) reported that [16]:

"It is possible in some designs that lubricating oil may leak at greater rates when an engine or APU[1] *is started and seals not yet at operational pressure and temperature or during transient operations such as acceleration/deceleration. Some systems rely on internal air pressure to maintain the sealing interface. When an engine shuts down this interface is opened, possibly allowing some oil to exit the oil wetted side of the seal. Upon engine startup, this oil is entrained into the air entering the compressor of the engine. The seal interface is again established when the engine internal air pressure returns to operating norms."*

Secondly, operational factors further explain why it is known that *"all engines leak oil from their seals and bearings"* [17]. Labyrinth seals are known to lose performance fast when seal wear occurs or during certain thermal or transient conditions [18]. Carbon seals require very high surface finish or flatness for minimizing leakage and have a finite rate of wear [19]. Additional factors effecting oil leakage include specific maintenance practices and the operational setup of the airflow. Too much airflow is a performance penalty, while too little facilitates leakage. Maintenance failures within the engine bleed air system and other areas of the environmental control unit system should also be considered.

There has been wide industry recognition that increasing compression ratios result in increasing bleed air extraction temperatures, well above the critical decomposition temperatures of conventional engine lubricating oils. There was a concerted effort in early generation bleed air aircraft to minimize the temperatures at which the bleed air was extracted, with even failure conditions restricting exposure to high critical temperatures to as short a time as possible. There was, however, recognition that the aircraft being designed in the 1960s for the future would be unlikely to pass the civilian or military bleed air purity requirements, given the hotter temperatures involved. At the time it was assumed that the *"rather vague"* Federal Aviation Administration (FAA) regulations (still in use today) would be revised in the future to become more stringent. This has never happened to the present day [20, 21].

A 1981 report noted that *"some commercially available lubricants are being stressed to the limits of the fluid's capabilities"* [22]. The dominant industry trend with regard to gas turbine engines since the 1970s had been to increase fuel efficiency, which was in part accomplished by raising engine operating temperatures, resulting in higher heat loads on the lubricant, thereby necessitating oils with greater thermal and oxidative stability [22, 23]. The ongoing need to increase fuel efficiencies in more severe operating environments, including higher operational temperatures, will require improved ester-based lubricants with increased upper temperature capabilities; however, this *"will require a careful balance of ester base stocks and improved additives"* [24].

The original synthetic oils were developed using a "type 1" base stock made from diesters, while in the early 1960s, "type 2" base stocks were developed from polyol esters, which are more hydrolytically and thermally stable [23, 25]. Type 2 and 3 polyol ester base stocks generally consist of pentaerythritol (PE) or PE and trimethylpropane (TMP) esters. Type 2 base stocks certified to specification MIL-L-23699 were developed to possess higher load-carrying characteristics and better oxidative and thermal stability, therefore reducing engine deposits and foaming, coking and elastomer swell [22, 26]. Type 2 oils include Mobil Jet Oil II and BP 2380, commonly used today, while current latest-generation oils include BP2197. The temperature capabilities of typical oils such as those specified to MIL-PRF-23699 range up to 204 °C; however, driven by the need to develop more fuel-efficient engines operating in more severe operational environments, improved ester-based lubricants will have increased

[1] Auxiliary power unit.

upper temperature capabilities of 230 °C [24]. Typical high-stage engine compressor temperatures can range from 300–650 °C [27] or 450–600 °C [28], or 650 °C for the B767 at take-off power [29].

3. SUBSTANCES

Synthetic turbine engine oil substances of interest include:

1. Organophosphates (OPs). Jet turbine oils contain tricresyl phosphate (TCP) as well as other triaryl phosphates (TAPs) [30]. TCP, practically odourless, is a mixture of tricresyl phosphate isomer molecules and other structurally similar compounds. The *ortho* isomers have long been known to be potent neurotoxins [30].

Until the late 1950s the toxicity of TCP preparations had generally been considered to be related to the tri-*ortho*-cresyl phosphate (TOCP) content, but it became apparent around that time that other *ortho* isomers were of equal or greater neurotoxic activity [31]. Nevertheless, the focus for the oil and aviation industry has always been to minimize TOCP. In 1959, the German scientist Henschler reported that TOCP was, in fact, the *least* toxic of the *ortho* isomers of TCP, with di-(DOCP) and mono-(MOCP) being 5 and 10 times more toxic, respectively [32]. Previously unreported, Mobil advised the Australian Senate in 2000 that MOCP followed by DOCP were in their product at far higher quantities than TOCP [33]. The *ortho* isomers in the TCP mixture were listed at 0.3% with the MOCP isomers comprising over 99% of the total *ortho* isomers. In 1961 it was determined that the active metabolite responsible for the toxicity of TOCP was cresyl saligenin phosphate (CBDP) a very potent inhibitor of esterases and lipases [34, 35].

While the *meta* and *para* isomers of TCP have virtually always been assumed to be nontoxic, this has been questioned on numerous occasions. Mobil studies of TCP were unable to explain the low but consistently apparent levels of neurotoxicity in *"low toxicity"* TCPs, as the substance was derived from 99.1% *meta* and *para* cresol isomers, which *"were expected to be completely inactive"* [30]. The toxicity of TCP isomers other than TOCP were again questioned by Mobil in 1993 based on the *"unexpected high neurotoxic potency of aviation oils containing 3% TCP"* with very low levels of TOCP [36].

Preliminary studies have shown that dermal exposure by not only the TOCP isomer, but also the non-*ortho* isomers (*meta* and *para*) caused sensorimotor deficits and neuropathological lesions in the brain [37]. Importantly, bioactivated Durad 125 (the TCP formulation used in gas turbine engine oils) and tri-*para*-cresyl phosphate (TPCP) have been found to be inhibitory to all enzymes tested [38].

TCP with less than 0.1% TOCP has been reported as a reproductive toxicant [39–42]. In 2009, the French oil manufacturer NYCO, after undertaking research on 15 different OPs in turbine oils including TCP (which it does not use), revised its product data sheets to include the risk phrases R 63.G3 "Possible risk of harm to the unborn child" and R 62.F3 "Possible risk of impaired fertility" [43]. Despite the research finding TCPs used in other oils to be toxic, no other oil manufacturers have as yet done this.

By the 1950s and 1960s it was recognized that early TCP/TXP (tricresyl/trixylyl) production was to be neurotoxic and, in consequence, the *ortho* cresol content in the feedstock was strictly controlled at very low levels [44]. Over 90% of the phosphate ester antiwear additives used in lubricant manufacture globally are isopropylphenyl phosphates (IPPP) in Europe and Asia or tertiary butylphenyl phosphates (TBPP) in North America. Neither IPPP nor TBPP products contain TCP [45] and were reputed to have excellent health, safety and environmental properties, justifying the replacement of TCP over 40 years ago. But two sectors had TCP-containing lubricants specified and did not wish to change—military and aviation [45].

The levels of *ortho* isomers in the TCP in the engine oil are technically classified as nonhazardous according to the OSHA guidelines. However, the guidelines clearly state that when dealing with possible synergistic effects or borderline contents of selected substances (such as the *meta* and *para* TCP isomers, which are present in jet oils) it would be prudent to use caution and reassess the hazards and risk phrases [1].

2. Amine antioxidants. *N*-phenyl-α-naphthylamine (PAN, CAS 90-30-2) is used as an antioxidant at around 1% in lubrication oils, acting as a radical scavenger to prevent the autooxidation of lubricants. This meets the regulatory cutoff criteria for classification as an irritant hazardous substance for skin, eye and mucous membrane. Additionally, a risk phrase of R43 should be applied: *"May cause sensitization by skin contact."* Two named low-level PAN contaminants include β-naphthylamine (BNA), classed as a CAT 1/schedule 1 carcinogen, and phenyl-β-naphthylamine (PBN) classed as a CAT 3 carcinogen. PAN at 0.5% in an antirust oil was thought to be responsible for tumours in exposed workers [46]. PAN in jet oils meets the hazardous classification levels and therefore the jet oils must be labelled as hazardous.

3. Base stock. As previously discussed, the base stocks were long ago reported to be subject to thermal degradation when exposed to very high temperatures leading to serious toxicity and severe respiratory irritation. The higher stage bleed air extraction point (with higher temperature and pressures) will be used at certain phases

of engine operation, such as at low power settings when the engine cannot meet system needs. TMP is reported to produce respiratory and eye irritation. The base stock is decomposed to esters and carboxylic acids upon thermal degradation, which is associated with irritant effects and a smell described as "dirty" or "old socks" [47, 48].

The material safety data sheet (MSDS) for a typical jet oil states *"Product may decompose at elevated temperatures ... and give off irritating and/or harmful (carbon monoxide) gases/vapours/fumes"* [49]. As already stated in the 1954 USAF oil study, *"the thermal decomposition of these products increased their toxicity considerably"* [8]. A growing variety of studies have more recently confirmed a wide range of thermal degradation products related to oil heated to high temperatures [47, 50–53].

Apart from the early 1950s investigation of the inhalation toxicity of heated synthetic jet oils, there is no evidence that a thorough, objective examination has taken place even though the early research already indicated unacceptability of the air for inhalation. Levels of the *ortho* isomers in the TCP have been greatly reduced since the 1940s and 1950s due to changes in production methods [30]. However, neurotoxicity was still identified in Mobil oil studies in 1988 (with oils produced from 1985), despite having considerably lower *ortho* TCP isomer levels. There is no published inhalation toxicity data available from the oil companies for the product used in its intended heated, mixed state. ExxonMobil, when questioned about inhalation studies with the cold or heated oils, advised that its most recent (unpublished) oral exposure studies of animals to the cold product demonstrated that dermal and inhalation exposure testing was unnecessary as oral exposure could be considered to maximize exposure and these tests showed no neurotoxicity [54, 55].

Aviation synthetic jet engine oils are manufactured to meet very strict military specifications [24]. Until recently civilian oils were required to meet the same specifications (e.g., MIL-PRF-23699 and its successors). However, now civilian oils are required to be certified to meet a new civilian standard SAE 5780, which is now the only specification recognized by regulatory authorities such as the European Aviation Safety Agency (EASA) and the FAA. Oils developed prior to 2006 to MIL-PRF-23699 were automatically deemed to meet the new civilian standard.

MIL-PRF-23699 states: *"S 3.6 Toxicity. The lubricating oil shall have no adverse effect on the health of personnel when used for its intended purpose"* [56], but the SAE AS 5780 specification requires only that the substances in the oils must comply with all *"legal, environmental, toxicological and regulatory requirements of the countries in which the products are manufactured and sold"* [57].

In 2004 ExxonMobil was issued with a $1700 citation for inappropriate labelling and product information of its engine oils by the US Occupational Health and Safety Administration (OSHA) [58]. This was based on a complaint by a large labour union representing aircrew after the adverse neurological warnings *"prolonged or repeated breathing of oil mist or prolonged or repeated skin contact can cause nervous system effects. Avoid prolonged or repeated overexposure to the skin or lungs"* were removed from the oil cans and product information [59]. However ExxonMobil contested the citation and the penalty with OSHA, settling the case a year later [60], and the labelling was not restored.

4. FREQUENCY

Rolls Royce has reported that one of three major causes of engine oil loss is the *"loss of liquid oil arising from permissible leakage past certain seals ... made good by "topping up" the system with fresh oil ..."* [19]. It has long been accepted that the majority of contaminated air events are related to oil leaking into the cabin air supply. [1, 61, 62] EASA reports that [63]: *"the vast majority"* of fume or smoke events *"are associated with an abnormal leakage of engine or APU lubrication fluid (aviation engine oil)"*; and *"Under certain fault conditions (e.g. engine or APU oil seal or bearing failure, engine or APU maintenance error/ irregularities, or design deficiency), engine or APU oil, hydraulic fluid, fuel, de-icing fluid and the corresponding pyrolysis products may contaminate the bleed air, which then enters the cabin air supply and can be inhaled by the aeroplane occupants."*

Underreporting of contaminated air events has been widely accepted as occurring [1, 64–66]. EASA has recently stated that fume events it regards as *"more minor"* in nature and those viewed as a *"nuisance"* mostly perceived as temporary bad smells *"could probably happen more often than the rare serious events, and the Agency agrees it is possible that they are underreported"* [67]. The regulatory databases are unreliable [1] and the regulators such as EASA are not correctly interpreting the regulations, which require all suspected contaminated air events to be reported [67–69]. If EASA does not interpret the regulations as required under the European Directive, there is little hope that other regulators, airlines, manufacturers or pilots will do so.

There is a variety of other reasons why contaminated air event fail to be reported as required. The USAF recognized the difficulty associated with getting pilots to report matters related to adverse effects, when they have *"a profession, hobby or aircraft investment to* *protect"* [70]. Lack of education and awareness about the health and flight safety implications of exposure to contaminated air is another factor along with job security. In Europe, there is additionally a terminology problem, with "fumes" signifying visible smoke only, when in fact they refer to airborne particles that may or may not be visible (dispersed nanoparticles would be invisible), and with or without a noticeable odour. Hence, the problem has gone on for decades unresolved, with people affected differently.

The UK Committee of Toxicity stated that, based on information supplied by UK airlines, contaminated air ("fume") events were reported by the pilots in 1% of flights, while a confirmed engineering source reported in 0.05% of flights [71]. There is a clear contradiction how fume events are viewed within the aviation industry. Leaking oil at transient engine operation settings and the issue of engine oil seal bearings providing an incomplete seal over the whole engine operating range, provides the basis for frequent low level oil leakage—it is part of the engine operation process. However, varying interpretations are provided from within the aviation industry of what constitutes an oil seal leakage or a contaminated air event, with many suggesting that only a major malfunction will lead to a contaminated air event or that only *"Dense visible fumes or concentrations of toxic products sufficient to incapacitate crew or passengers"* need to be reported [67]. Oil seal leaks apart from failure are seen as normal and generally accepted and ignored, with bleed air contamination being far more common than the aviation industry acknowledges. The true extent of contaminated air events cannot be known as there are no detection systems in aircraft and the aviation industry is relying upon a reporting system that is not working.

Internationally, there are a number of reporting regulations that are required to be met. Any defect that the captain becomes aware of must be reported in the aircraft technical log [72]. Toxic and noxious fumes (visible and invisible) are required to be reported to the aviation regulator under the mandatory reporting occurrence scheme [73]. Additionally, *"Any person involved who has knowledge of the occurrence of an accident or serious incident shall notify without delay the competent safety investigation authority of the State of Occurrence"* [74]. As such, EU member states require pilots to report defects in the aircraft technical log; contaminated air suspected to be related to oil leakage is required to be reported to the regulator as a mandatory reportable occurrence and noxious fumes or toxic air requiring the use of oxygen should be reported to the BFU as a serious incident. Underreporting is, however, a systemic industry-wide problem [1].

5. SAFETY

Exposure to contaminated air is without doubt a flight safety issue. Firstly, the regulations indicate this is the case. The EASA airworthiness regulation CS 25.831 requires that each crew compartment has enough fresh air to enable crew members to perform their duties without undue discomfort and fatigue and that crew and passenger compartments must be free of harmful and hazardous concentrations of gases or vapours. Therefore, the extensive evidence of adverse health effects suspected to be related to contaminated air in flight indicates a breach of the airworthiness regulations and safety of the flight. There is, additionally, a variety of European regulations and specifications that can be related to aircraft contaminated air and which must be met at the design stage and on an ongoing continuing airworthiness basis [75, 76]. EASA CS 25 1309 requires aircraft systems and components to be designed so that the probability of occurrence of any major failure condition (causing physical discomfort for flight crew) is assessed as *"remote"*; that is, less than 10^{-5} per flight hour. EASA CS E510 requires a safety analysis of the engine, including the compressor bleed systems. The analysis must show that hazardous engine effects, which include toxic products of engine bleed air, are predicted to occur at a rate not in excess of that defined as *"extremely remote"* (i.e., less than 10^{-7} per engine flight hour). Hazardous engine effects include *"concentration of toxic products in the engine bleed air sufficient to incapacitate crew or passengers, no effective means to prevent flow of toxic products to crew or passenger compartments"* and *"degradation of oil leaking into the compressor air flow."* Major engine effects must be predicted to occur at a rate not in excess of that defined as *"remote"* ($< 10^{-5}$ per engine flight hour) and include *"concentration of toxic products in the engine bleed air sufficient to degrade crew performance."* Similar regulations apply to the APU under CS APU-210. Continuing airworthiness requirements necessitate that aircraft are maintained throughout their operating life in the condition to which they have been certified [75, 76].

Contaminated air events are occurring at a far higher rate than acceptable under the design standards, indicating the regulations are not being met. EASA (unreliably) suggests that minor contaminated air events may be occurring at a rate of 1 in 10 000 (10^{-4}) based on FAA figures, as well as 1 in 10^{-6} (1 in 1 000 000), while the UK COT suggested contaminated air occurrences being reported at 1 in 100 flights (10^{-2}) [71]. The underreporting problem and the design and operational practice of using bleed air, allowing smaller oil leakage to occur on a frequent or even continuous basis, also supports the fact that the safety analysis requirements and regulations relating to bleed air are not being met.

In 2002 the FAA reported that *"No present airplane design fulfills the intent of 25.831 because no airplane design incorporates an air contaminant monitoring system to ensure that the air provided to the occupants is free of hazardous contaminants"* [77]. The EASA and FAA airworthiness regulations CS and FAR 25.831b require that it can be demonstrated in flight that the air is free of harmful and hazardous levels of contaminants, yet at present there is only the human nose. The UK Air Accidents Investigation Branch (AAIB) in 2007 and again in 2009 recommended that EASA and the FAA consider requiring sensors be installed in the flight deck to detect smoke or oil mist from the air conditioning system, yet this recommendation was ignored on both occasions [78, 79]. EASA regulation (CS 25.1309 c) requires that *"information concerning unsafe system operating conditions must be provided to the crew to enable them to take appropriate corrective action. A warning indication must be provided if immediate corrective action is required."* Therefore it is necessary for EASA and FAA to recommend detection systems be developed and installed in order to make the aircraft properly airworthy and to significantly improve safety.

A review of contaminated air event records indicates that 32% mentioned some degree of crew impairment (ranging from minor to full incapacitation) [1], despite crew impairment not being directly listed as reportable under the mandatory reporting system. 20% of contaminated air events involved impairment to at least one pilot, with 9% of events involving adverse effects in both pilots [1]. An AAIB review of the UK CAA database found that 40 of 153 (26%) reports (of which 119 resulted *"probably"* from contaminated air) showed *"adverse physiological effects on one or both pilots, in some cases severe"* [78].

There are a growing number of air accident bureau investigations and other reports clearly showing that exposure to contaminated air is a safety hazard. In 2006, the Swiss Aircraft Accident Investigation Bureau attributed a serious incident on an Avro RJ100 (i.e., the BAe 146) to the cockpit filling with fumes on approach, which *"caused a toxic effect leading to a limited capability of acting of the co-pilot."* [80]. *"The fumes were caused by an oil leak as a result of bearing damage in engine no 1. The indicators for impending bearing damage were not correctly interpreted before the incident."* The smell and fumes in the cockpit occurred even before this serious incident and the aircraft was released for further service several times before the event took place despite the defect not having been rectified. The captain did not use his oxygen mask, while medical examination of the co-pilot showed that a toxic event had taken place. Similar events have been clearly and frequently identified elsewhere, internationally [1].

In 2006 a German-registered Embraer 145 departed the runway at Nuremberg after landing with visibility reduced to 20 cm due to smoke. Subsequent engine inspection found engine oil entered the air supply after a significant bearing failure (BFU report 5X008-0/06).

In 1999 two pilots of a Swedish airliner suffered temporary incapacitation apparently related to exposure to contaminated air [81]. The investigation after the event [52] positively identified a wide variety of contaminants, including TCP and engine oil pyrolysis products, along with oil leaks identified upon inspection. The air accident report [81], however, stated that the event was due to *"probable polluted cabin air"*. In the absence of sensors monitoring contamination, a more precise result can scarcely be expected, even though circumstantial evidence strongly suggests a "fume event" due to an oil leak.

ICAO Annex 13 advises that a serious incident, which *must* be investigated, includes the use of emergency oxygen. Aircraft emergency checklists (in some cases) list the use of emergency oxygen when contaminated air events are suspected or when smoke occurs, yet not all checklists *require* its use or make it the initial action. The UK CAA recommends that airlines ensure that flight crew are trained to immediately don oxygen masks if smoke or other fumes are suspected [82]. However, pilots are generally failing to use oxygen during contaminated events, with data indicating both pilots using oxygen in 9% of suspected contaminated air events and one pilot in only 4% of cases [1]. In the European situation, pilots will generally fail to use oxygen as required by some of the aircraft emergency procedures checklists as most will not consider that there is a need to use oxygen for fumes unless visible smoke is present, given the terminology problem associated with the word *"fumes"*. Passengers are not provided with oxygen to protect against contaminated air exposures and do not need to be advised an event has taken place—this is up to the airline to determine [83].

There are many admissions that exposure to contaminated air is a flight safety issue [1]. A few of the many recognizing this fact include: The FAA acknowledges that exposure to oil fumes can cause impairment of flight deck crew and impair flight safety, that it is an unsafe condition and that oil leakage is a design flaw [84 ,85]; Rolls Royce (Germany) reported that oil leaking from an engine entering the air supply was hazardous [86]; The German Luftfahrt-Bundesamt (LBA) in 2003 reported that *"oil leakage ... and oil residues ... may lead to harmful contamination of the cabin air and cause intoxication of the flight crew"* [87]. The German

Parliament, when asked if it believed inhalation of heated engine oil fumes was harmless to crew and passengers, simply said: *"No!"* [88]. EASA CS E 690 concerns the suitability of compressor engine bleed air for direct use in the aircraft cabin pressurization or ventilation system and requires *"tests to determine the purity of the air supply."* To date this has not occurred independently to an acceptable standard. Boeing's synthetic jet oil material safety data sheet for MIL-PRF-23699 reports that [89]:

- *This material is classified as hazardous.*
- *This material may cause irritation of the skin and eyes*
- *Inhalation: Respiratory irritant, particularly if vapors are from heated or burning liquid.*
- *Signs and symptoms of exposure: exposure may cause irritation, characterized by tears, redness and burning sensation (eyes), redness, swelling or cracking of the skin, or burning sensation in the nose, throat and lungs (inhalation). Neurotoxicity may be characterized by dizziness, headache, confusion and intoxication.*

In reality flight safety concerns include a variety of factors including that *"complete incapacitation could result in loss of the aircraft, while even modest impairment can reduce the crew's ability to deal with adverse operating conditions or high workload phases of flight ... crew incapacitation or performance degradation may potentially be aggravated by chronic low dose or prior contaminant exposure events"* [16].

6. MONITORING

A range of studies reviewing air quality generally have been undertaken within the aviation industry suggesting that the substances found are within set government standards or guidelines. One of the most recent is the Cranfield University air quality study [90, 91]. Where contaminated bleed air substances leak into the cabin air supply, people will be exposed to the contaminants and there is the potential for subsequent adverse effects in flight and for health problems to arise. Evidence is available to show this is not infrequent.

A close review was carried out of the 53 air quality studies [1]. Of these, 33 (62%) of the studies were undertaken specifically to look at bleed air contamination, while 20 (38%) assessed general air quality standards only and did not use suitable techniques to detect bleed air contaminants such as oil. Effectively none of the studies were undertaken during a contaminated air event. Of the contaminated air studies no epidemiological studies were undertaken at the time of the monitoring, with follow-up epidemiology of a very limited nature undertaken in 15% (5) of the studies. 27% of the specific contaminated air studies (all with a strong industry affiliation) suggested the air quality was acceptable. Of the general air quality studies that were not using techniques suitable to detect contaminated air, 60% deemed the air was acceptable, again with all having a strong industry affiliation. Such conclusions have repeatedly been used to suggest all air quality is acceptable, even covering contaminating substances not sought by the studies.

TCP was identified in 16 (48%) of the contaminated air studies, while oil was identified as the source or part of the problem in 21 (60%) of them. TCP was more recently reported (in the Cranfield University study) even during normal operations [90].

Recent Norwegian aircraft monitoring studies under normal conditions (no contaminated air events) using specific methods to detect TCP found low levels of TCP in 4% of air samples, in 39% of swab samples and in all HEPA filter samples [92]. The research revealed that TCP detected during ground testing in an aircraft that experienced leakage of turbine oil into the cabin and cockpit air supply was *"substantially higher"* than during normal operations, indicating organophosphate contamination is of relevance to contaminated air events. Traditional volatile organic compound (VOC) measurements were clearly identified as less suitable than tailored organophosphate (OP) measurements for oil aerosol/vapour sampling [92, 93]. Aviation technicians and loaders were also identified as at risk to OP exposure from oils and hydraulic fluids.

While ground-based exposure standards such as European OSHA occupational exposure limits and the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values (TLVs) are very often used to suggest substances found in aircraft cabin air studies are safe and below government-set levels, these standards should not be utilized in the aircraft environment [1]. They are not intended for use by the public, they protect *"nearly all"* workers from a limited number of individual substances only and establish a clear demarcation between safe and dangerous exposures [94]. The standards will not protect workers from adverse physiological effects above 5000 feet [95] and exposure standards should only be applied in environments where the atmospheric pressure is between 900 and 1100 mbar [96]. 900 mbar equates to just under 3000 feet. The levels to which most commercial aircraft cabins are pressurized is between 6000 and 8000 feet (810–750 mbar). Exposure standards do not take into account the unique environment of the aircraft cabin [97–99].

Environmental toxins are generally encountered in complex mixtures but most will have been tested individually only, ignoring additive, synergistic and other emerging challenges to conventional toxicology [100].

Furthermore, the type of combined action or interaction found at toxic effect levels may not predict what will happen at low levels [101].

TCP has not been assigned an occupational exposure limit. In 1958 Henschler reported that the toxicity of the total TCP mixture was far greater than TOCP alone with *meta* and *para* isomers implying the presence of the more toxic mono- and di-*ortho* isomers, which were respectively 10 and 5 times more toxic than TOCP [32]. It was therefore no longer permissible to relate an analysed proportion of *ortho*-cresol to tri-*ortho*-cresol phosphate, with the *"old method of calculation"* being *"invalid"* and *"the term TOCP poisoning should no longer be used."* Mobil advised that the adequacy of the TOCP exposure standard ought to be questioned, given the greater toxicity of the mixed isomers of TCP, recognizing that OSHA may have incorrectly used the TOCP standard to cover TCP as a whole [102]. The Australian Defence Forces have suggested that an exposure standard for TCP as a whole should be 100 times less than the present standard for TOCP [103]. However, this still does not take into account that exposure standards should not be applied in aircraft cabins and that they do not take account of the heated synergistic effects of the combined exposures. Back in 1966 Esso recognized (correctly) that the mineral oil exposure standard of 5 mg/m^3 did not apply to synthetic jet oils, for which no standard had been set; however, as there was no standard the mineral oil standard could be used [104]. In other words, the adoption of the mineral oil exposure standard for polyol ester-based synthetic oils was deemed (incorrectly) to be acceptable given that no synthetic oil exposure standard was ever adopted [105]. The misuse of the mineral oil standard is commonplace within the aviation industry.

The monitoring studies undertaken cannot be used to suggest that air quality is acceptable and therefore unrelated to adverse health effects on aircraft occupants. The analysis and interpretation of substances found relying upon ground-based industrial exposure limits cannot be appropriated to suggest all levels found are safe. There is a growing body of data available indicating exposure to contaminated air can have adverse health effects.

7. ADVERSE HEALTH EFFECTS

Exposure to turbine engine oils including TCP have repeatedly been connected with a range of short term effects including skin, eye and respiratory irritation along with neurotoxicity [89] and with a range of *"dangerously toxic"* substances from pyrolysed oil [7]. The oils contain irritants, sensitizers and neurotoxins [1, 106]. Irritation to the mucous membranes and chemical pneumonitis was reported by the USAF in 1954 along with degenerative changes of the brain [8]. According to a 2004 UK Civil Aviation Authority (CAA) study, the *"symptoms of irritation could be induced by short chain organic acids formed during pyrolysis of aircraft lubricants"* [47]. Decomposition products of the base stock were listed as causing *"severe irritation of eyes and throat and can cause eye and lung injury. Cannot be tolerated even at low concentrations"* [47, 107].

TCP is listed as *"toxic by inhalation, ingestion or by absorption through the skin, with symptoms of exposure including: irritation of the skin and eyes, flaccid paralysis without anesthesia, motor activity changes and muscle weakness. It may cause respiratory tract and mucous membrane irritation. It may also cause serious damage of the nervous and digestive systems and muscular pain. Other symptoms include gastrointestinal upset, discomfort in distal portions of the arms and legs, soreness, aching, numbness, headache, vertigo, loss of appetite, parethesias and decrease of strength in the arms and legs. It may cause vomiting, diarrhea and abdominal pain ... exposure may also lead to tingling sensations of the hands and feet and cramps"* [108].

Inhalation of PAN is reported to cause short-term effects including: blue lips, skin or fingernails, confusion, convulsions, dizziness, headache, nausea and unconsciousness. Repeated or prolonged contact may cause skin sensitization [109].

Three case study surveys were undertaken over 10 years by Michaelis [1]. An extensive 4 year case study was undertaken for BAe 146 pilots in the UK on a non-self-selected basis. Of the 274 past and present pilots in the survey, 238 consisted of working pilots with the remainder no longer retaining medical certification. Identifiable trends of pilots being unwilling to talk about contaminated air were evident; health effects are effectively denied by the airline industry and indicate operation contrary to aviation legislation—despite the high degree of awareness of exposure to contaminated air in the workplace, acknowledged as predominantly originating from oil by aircraft manufacturers, the CAA and others. 63% of the pilots advised they had experienced adverse effects consistent with occupational factors (the work environment). 32% reported medium- to long-term effects and 44% reported immediate or short-term effects. 13% of those surveyed were no longer able to maintain pilot medical certification, were retired with a consistent pattern of long-term ill health or deceased for reasons considered relevant to the study.

There was a clear pattern of adverse effects, including a range of neuropsychological, neurological, respiratory, cardiovascular and gastrointestinal irritancy and general symptoms reported in the immediate and short-term aftermath of putative exposure with a clear development into the medium or longer term for a considerable number of those reporting specific symptoms. A key chronic ill health pattern was also identified in a smaller subset.

For example, the main immediate or short-term symptoms were upper airway irritation and breathing problems (17%) and eye irritation and vision problems (10%); neuropsychological symptoms reported include performance decrement (13%), intense headaches (11%), memory impairment (10%), dizziness (10%), confusion (8%), fatigue and exhaustion (15%) and nausea (11%). These represent a considerable risk to flight safety.

In the longer term, the main symptoms reported were: upper airway and respiratory symptoms (17%); cardiovascular symptoms (10%) such as palpitations, altered heart rate and chest pain; skin irritation, rash or blisters (8%); memory impairment (14%); performance decrement (11%); intense headaches (8%); tingling in the extremities and other peripheral nerve problems (8%); exhaustion and fatigue (9%); chronic fatigue (10%); and others, including the development of chemical sensitivity.

Of the 13% (36) of pilots no longer able to fly due to chronic ill health the symptoms reported (substantiated with diagnosis) included: neuropsychological (64%); neurological (53%); general (53%); respiratory (39%); and cardiovascular (25%). The rate of permanent ill health or loss of flying ability or both found in this study ranged between 37% and 433% higher than the published rate of loss of pilot medical certification within the civil and military aviation industry for all reasons [1].

The majority of affected pilots associated their symptoms with exposure to contaminated air, while all pilots surveyed are acknowledged to be operating in a contaminated air environment by the aircraft manufacturer.

There was sufficient commonality between the symptoms seen in the surveys and similar patterns noted internationally to support a symptom basis for aerotoxic syndrome, a distinctive occupational syndrome. The close temporal relationship between exposure and ill health was supported by an extensive exposure history, industry documentation and, in the medium- to longer-term cases, medical records with all three case studies supported by other published studies. Features of this syndrome are that it is associated with aircrew exposure at altitude to atmospheric contaminants from engine oil or other aircraft fluids, temporarily juxtaposed with the development of a consistent symptomology of irritancy, sensitivity and neurotoxicity. These symptoms may be reversible following brief exposures; however, following repeat exposures a longer-term irreversible pattern develops, consisting of neuropsychological, neurological, respiratory/cardiovascular effects along with immune system effects, chemical sensitivity and chronic fatigue. Passengers are exposed to the same air, with adverse effects of a similar nature reported in a number of cases [1].

A recently published case study describes 87 smoke/fume events over two years with one US airline that likely or definitely involved cabin occupant exposure to oil or hydraulic fluid fumes [110], reported on 47 aircraft and on every aircraft type in the fleet. Most events were characterized only by an unusual odour (most commonly described as “dirty socks”) without any visible smoke or haze. Still, after 27 of the flights, one or more crew members had symptoms serious enough to require emergency medical care, after 43 flights one or more crew members required additional medical care, and after 37 flights one or more crew members lost work time due to prolonged illness. Although the odours were reported prior to take-off on 44 of the flights, only 20 of those flights were either cancelled or delayed, while the rest flew to their planned destinations, many with crew health and potential flight safety consequences. Mechanical records confirmed that oil would have contaminated the air supply on 41 of the 87 flights. After 30 flights, no mechanical cause was identified but oil was suspected as the cause based on the event characteristics. Some of the pilots and cabin crew in this dataset developed chronic neurological symptoms post-flight, including two pilots who lost their FAA medical licence to fly because of ongoing neurological symptoms after in-flight exposure to oil fumes that they did not smell and had not been trained to associate with their acute symptoms.

Contamination of the cabin air sufficient to cause symptoms of irritation, fatigue, toxicity or discomfort indicates that the aviation airworthiness ventilation legislation FAR/CS 25.831 a/b is not being met. Therefore the aircraft is not airworthy. In 2000, BAe Systems advised the Australian Senate that [17]:

> *“There is absolutely no doubt in our minds that there is a general health issue here. The number of people who have symptoms indicates that there is a general issue ... it is very clear that there is an issue here ... it is a health and safety issue, it is not a safety issue. With the weight of human evidence and suffering, which is quite clear, there must be something there.”*

In 2000, a year-long Australian Senate inquiry into cabin air contamination found that contaminated bleed air was occurring with no real possibility to eradicate it totally while air was drawn in via the engines [65]. The problem was occurring on aircraft types other than just the BAe 146; health problems were occurring that appeared linked to the leaking oil and there was serious underreporting. Oil leakage into the air supply clearly contravened civil aviation regulations, rendering the aircraft unfit to fly until the defects were fixed, with a clear link between crew health and flight safety—given that almost any impairment can have an impact on the crew's capacity to operate an aircraft. In 2010 the Australian High Court upheld an earlier decision that stated, with regard to a flight attendant claiming adverse effects from exposure to leaking jet engine oils, that: *"Smoke from pyrolysed oil can be hazardous to the eyes, mucous membranes and lungs"* [111]. In 2008, an FAA-funded medical document was published providing a protocol for health care providers on how to deal with exposure to bleed air contaminants for aircrew and passengers [112].

The health effects being reported should be reviewed with some urgency given some recent findings, including: exposure to jet oil fumes being linked to organophosphorus-induced chronic neurotoxicity (OPICN) [37, 113]; TOCP detected in airline passengers not exposed to fumes and with no immediate symptoms but slow neurodegeneration [114, 115]; and techniques being developed for exploiting biomarkers for exposure to jet engine oil triaryl phosphates [116]. Note that less toxic triaryl phosphates have recently been identified [38, 43].

8. PROBLEM AREAS

Contaminated air is an airworthiness and flight safety issue. The very extensive amount of data available [1] indicates that the aviation industry has, in effect, viewed air free of oil contamination not as a mandatory requirement, although the industry has known for decades that air was being contaminated from leaking heated turbine engine oil. There was considerable awareness in the 1950s and 1960s that this was a serious problem with significant toxicity hazards and flight safety at stake; however, this was pushed aside in the 1970s as fuel efficiency and engine/aircraft performance took priority. From the 1970s until the late 1990s there was almost total denial that contaminated air posed a problem; there is now an almost industry-wide concerted effort to marginalize and control how the contaminated air issue is addressed.

In 2000 a UK House of Lords inquiry, reviewing cabin air contamination, called for research to *"refute"* the *"common allegations"* and inspire public confidence regarding aircraft air quality [117]. This resulted in a wide variety of government- and industry-funded projects that have, in fact, dealt not at all or inappropriately with the issue. The European Commission (EU) and the European aviation industry have spent almost 60 million euros (shared roughly equally) since 2001 on these projects [118]. As an example, the EU CabinAir study, which ran from 2001 to 2004, failed to use techniques to monitor contaminated cabin air, nor indeed did it intend to, however the findings were used to suggest cabin air quality was suitable for human inhalation. The study was used as the basis of the European cabin air quality standard EN 4618, which fails to address cabin air contaminated by oils and hydraulic fluids [119]. A further joint EU-industry-funded study, the Ideal Cabin Environment (ICE), formed the basis of a further air quality standard (prEN 4666), still in draft stage [120, 121], which relies on EN 4618 and in effect totally ignores oil contamination.

Both EASA and the FAA, and other regulators, have thus far avoided responding to the call for contaminated air detection systems to be fitted to aircraft and the common-sense need for bleed air filtration to be developed and introduced, despite a growing number of authoritive bodies calling for this, including the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), the National Research Council (NRC), AAIB, the Australian and US Senates, the SAE and Defence Force Australia. Both the FAA and EASA have stated they are waiting for the outcomes of industry and Government research, such as the Cranfield University study [90], the FAA-funded Airliner Cabin Environment Research (ACER) and the Occupational Health Research Consortium in Aviation (OHRCA) and ASHRAE work. This is despite the fact that contaminated air is an airworthiness issue that must be addressed for an aircraft to be deemed airworthy, a fact ignored by the FAA and EASA. Industry has moved from a fragmented approach to a powerful coalition that ignores or manipulates external data and works towards a solution agreeable to its partners, in a manner previously seen with the tobacco and asbestos industries. Effectively all data that implies there is a problem has been brushed aside in favour of commissioning yet more research that has reached the stage of going around in circles, and ignoring the fact that the toxicity of heated jet engine oil was already recognized in 1954.

9. SOLUTIONS

Some of the practical solutions include: *inhalation toxicity* research into heated synthetic turbine oils, including triaryl phosphate additives, and modern research into the thermal degradation (pyrolysis) of ester base stocks; biomonitoring techniques for assessing human exposure to contaminated air; better designed engine and APU oil seals; bleed air systems that do not allow oil to leak; introduction of real time monitoring systems and filtration technology for bleed air; research into health effects related to contaminated cabin air; less toxic oils; correct labelling of the oil product information; better engineering practices, especially concerning engine maintenance; adherence to existing aviation and occupational health and safety (OH&S) legislation (including education on the recognition of, and requirement to report, all suspected contaminated air exposures); the requirement for pilots to use oxygen and emergency procedures when crew suspect contaminated air; appropriate medical procedures implemented for crew and passengers exposed to contaminated air; all future aircraft to be designed to no longer use bleed air. Furthermore, a full scale epidemiological study into contaminated air exposure would be very timely.

Every worker has the right to working conditions which respect his or her health, safety and dignity. It is not acceptable to knowingly expose crew and passengers to contaminated bleed air, to risk their health and safety and to allow such exposures to degrade a person's right to live with dignity, respect and freedom, which ill health and jeopardized flight safety can take away. It is a human right to breathe clean air.

There is a large volume of clear and convincing evidence that there is a link between cabin air contamination by leaking synthetic turbine oils and subsequent adverse health and compromised flight safety. To ignore this evidence with assertions that there is none or no link is highly reprehensible. The failure of the industry to react appropriately to this volume of evidence is indicative of *"manufacturing uncertainty"* to delay regulation [122].

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