Jet engine oil consumption as a surrogate for measuring chemical contamination in aircraft cabin air

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A considerable number of measurements of aircraft cabin air contamination with more or less toxic substances has been carried out to date, but there are significant differences between the reported results. This may reflect a possible reality of differences between different aircraft types at different stages in their engine maintenance cycles; unfortunately most of the reports do not give sufficient detail in this regard. On the other hand the measurements are intrinsically difficult and the lack of agreement may reflect systematic errors due to inappropriate methodologies. In the absence of any comprehensive comparative review, no definite conclusion regarding the discrepancies can be drawn. In this paper, an independent estimate of the contamination is made based on the assumption that it originates from the bleed air and using engine oil consumption as the primary parameter. An estimate is also made of the aerial concentration of contaminants in a typical fume event, which has not yet been reliably measured directly.

1. INTRODUCTION

Ever since the system of pressurizing jet aircraft cabins using hot compressed air bled off the engines ("bleed air") was introduced, aeronautical engineers have been aware of the possibility, indeed inevitability, of some contamination of the bleed air and, hence, of the ambient atmosphere in the cockpit and cabin, with engine oil [28]. The composition of jet oil is typically about 96% synthetic ester (e.g., esters of pentaerythritol and pentanoic acid), 3% tricresyl phosphate (added as an antiwear agent, as an iron-passivating agent to inhibit the iron-catalysed decomposition of the ester, and as a fire retardant) and 1% N-phenyl-α-naphthylamine (usually abbreviated as PAN, also known as N-phenyl-1-naphthylamine, added as an antioxidant) [18, 19]. In operation, the oil may be heated to several hundred °C, at which some decomposition is likely to take place, the products of which appear to be toxic [33]. Furthermore, at least some of the isomers of tricresyl phosphate (TCP) are known to be potent neurotoxins [11], notably those containing at least one *ortho* substituent.

Although the health and *a fortiori* (in severe cases) safety risks from inhaling engine oil contaminating the bleed air cannot be considered to be negligible, as with other spheres of human activity, such as motoring, the benefits have been assumed to outweigh the disbenefits.[1] Traditionally, attention to chemical contamination of aircraft cabin air has focused on small-molecule gases such as carbon dioxide, carbon monoxide and ozone [32]. Nevertheless, the recognition that bleed air contamination can occur focuses attention on the oil constituents, among which, as mentioned, tricresyl phosphate is a potent neurotoxin. The neurological (including behavioural) sequelae of TCP ingestion by humans have been documented for many tens of thousands of cases and innumerable animal experiments have been subsequently carried out [1]; inhalation is, of course, a much more effective way of dosing a subject than ingestion [25]. Documented cases of pilot ill health following a "fume event" [20], which we can define as the significant and sudden ingress of oil-based contamination into the cabin, to a degree that it is actually visible as smoke, and probably due to the catastrophic failure of one of the oil seals separating the oil from the air in the engine, has engendered the suspicion that those frequently exposed to cabin air, especially pilots, cabin attendants and perhaps frequently flying passengers as well, might suffer occupational neurological disease with an insidious onset due to the long-term, chronic exposure. This suspicion has led to attempts to measure oil contamination in the cabin, which is technically significantly more demanding than measurement of the small molecules.

The effort required to realize such measurements is considerable. For example, investigations of the Swedish Board of Accident Investigation (SHK) following a suspected fume event included collection and analysis of the cabin air, requiring the removal of 29 passenger seats from the aircraft [31]. In order to minimize the space

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[1] For example, Chaturvedi writes, "Despite health issues associated with air travel, there are enormous benefits of this mode of travel to travelers, to commerce, to international affairs, and to health" [5].

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required for the instrumentation, the most popular procedure is to collect the contamination by pumping the air through sample tubes packed with adsorbent, which is subsequently (post-flight) desorbed and analysed in a laboratory on the ground [30]. Based on the premiss that the rather involatile oil components are likely to condense on the internal surfaces of the aircraft (including the ducting leading the bleed air into the cabin), these surfaces have also been analysed [4, 30, 14], which gives at least a qualitative indication of past contamination.

Such measurements as have been carried out have been rather inconclusive.[2] Reviewing previous work, Nagda and Rector commented in 2003 that "such a limited dataset does not permit definitive conclusions" [23]. Subsequently, van Netten found up to about 100 ng/m^3 of TCP using the sample tube approach, although only two measurements were made and details of the calculation of the contamination concentration were not given [24].[3] Solbu et al., using a similar approach, failed to detect any TCP at all [30]. Denola et al., also using sample tubes, were actually able to identify four of the individual isomers of TCP, the total concentration of which was measured as 51.3 μg/m^3 in an actual fume event [8]. Unfortunately they did not give details of their actual analytical procedure, hence it is not possible to properly evaluate this result.[4] The most comprehensive (10 flight phases for each of a hundred flights) study to date was that made by Crump et al., using a combination of sample tubes and on-board particle and photoionization detectors [7]. Although this study has been subjected to some criticism [6, 22] it nevertheless provides the best data currently available. The concentration of TCP averaged over all measurements was 0.22 μg/m^3 [7].[5] An unexpected feature of the results of Crump et al. [7] is that the ratio of tri-*ortho*-cresylphosphate (T*o*CP) to total TCP was much higher than what can be deduced from the composition of the modern commercial TCP that is presumably what is blended into the base oil [27] (during the past few decades intensive efforts to eliminate T*o*CP, because of its known potent neurotoxicity, from the commercial product at reasonable cost have been made). The reason for this discrepancy is still unknown.[6]

It is noteworthy that none of the analytical procedures described in any of the studies hitherto reported have been validated by collecting samples in an environmental chamber containing calibrated aerial concentrations of TCP and the other contaminants that have been measured. This absence provides the primary motivation for independently estimating the likely concentration of engine oil contamination in cabin air. It is well known that a typical jet engine uses "about one quart an hour" of oil, in SI units this is 0.26 cm^3/s. The purpose of this paper is to estimate the resulting concentration of oil in the cabin air assuming that all of it is lost via the bleed.

2. FIRST CALCULATION

From data provided by Hocking the typical ingress of external air in an aircraft like the A320 (in which the maximum number of seats is 179 [13]) can be deduced to be about 1 m^3/s [12]. This aircraft has two engines, therefore the maximum oil ingress is 0.52 cm^3/s, of which about 3% = 0.016 cm^3/s is TCP. The density of TCP may be taken as 1.17 g/cm^3 [10, 29], hence the ingress is about 18 mg/s. This immediately gives us a maximum aerial concentration c_{max} = 18 mg/m^3 for total TCP.

The 8-hour workplace exposure limit (WEL) for T*o*CP is 0.1 mg/m^3 [9]; if this were indeed applicable to an aircraft cabin in high-altitude flight as implied by Crump et al. [7], although of course it is not, the actual concentration might be almost two hundred times in excess of that limit. The fact that it has been measured to be about 80,000 times less than 18 mg/m^3 [7], with the reservation that the measurements may have significantly underestimated the quantity,[5] presumably reflects the fact that the bulk of the oil continuously lost by the engine is vented into the outside atmosphere. The fraction of about 10^{-5} of the lost oil actually leaking into the cabin is a measure of the quality of the oil seals separating the oil and (bleed) air circuits [18].

In the event of a catastrophic oil seal failure, which is presumed to be the cause of fume events in which the entire cabin is filled with smoke (e.g., Figure 1 in ref. [26]), the concentration of oil is likely to increase by many

[2] See Appendix 10 of ref. [17] for a comprehensive list and summaries of published and unpublished studies between 1979 and 2006.

[3] Most investigations have focused on measuring TCP because of its well established neurotoxicity, despite the fact that partially combusted or pyrolysed base oil has been shown to be toxic [33] and may be present at a comparable concentration.

[4] The readers of the Denola et al. paper are referred to report no DSTO-RR-0292 (2005) for full details of the experimental methods, but the authors of that report, which include the authors of the paper, are unwilling to allow it to be released, on the grounds of commercial confidentiality.

[5] Crump et al.'s value is the arithmetic mean of all the individual determinations, assigning readings below the detection limit to a value of zero; hence this average must be an underestimate.

[6] One possibility, not discussed in ref. [27], is that there is an additional source of T*o*CP apart from the engine oil—TCP is used as a plasticizer in certain (vinyl) polymers [29], and this provides a possible, albeit improbable, source for the excess T*o*CP.

orders of magnitude; the mass concentration of smoke leading to a comparable visibility loss could be $c_{\text{f.e.}} = 50$ mg/m^3 [21]. This implies that the rate of loss of the oil will increase more than twofold.

Swabs taken from the internal surfaces of aircraft have revealed the presence of contamination characteristic of engine oil constituents [30, 14]. Such results are, however, only indicative of the contamination because they cannot be quantitatively related to any particular level of aerial contamination. Adsorption on surfaces will obviously tend to diminish the aerial concentration. Supposing that all these surfaces are very far from being saturated with contamination, the actual rate of adsorption R_{ads} is simply

$$R_{\text{ads}} = sF\,A \tag{1}$$

where s is the "sticking factor" (the probability that an incoming particle will stick to the surface), F is the particle flux and A is the total adsorbent area. Since these calculations are approximate we shall take $s = 1$ (the area A of course comprises different kinds of surfaces, such as metal (oxide), polymer, textile and skin, each of which would have a different s). The appropriate expression for the flux will depend on the phase of the oil, which is discussed in §3.

3. THE PHASE OF THE AERIAL OIL

The synthetic base oil and the additives are rather involatile substances and it may be presumed that oil leaking from the engine into the aircraft cabin exists as an aerosol (oil mist). If 0.2 μm is taken as the typical diameter of droplets, they have a volume of 4.2×10^{-21} m^3; hence 1.2×10^{14} oil droplets, dispersed in 1 m^3, would enter the cabin each second if all the lost oil actually leaked into the cabin.

The boiling points of the various isomers of TCP range from 200 to 400 °C [11, 10, 29, 3]. The vapour pressure P_{TCP} is 10–100 μPa at room temperature; aircraft cabins are usually pressurized to about $P = 75$ kPa (corresponding to an altitude of 8000 feet above sea level), hence the expected aerial equilibrium concentration in the presence of liquid TCP, P_{TCP}/P, would be only 1.3×10^{-9} ppm, which corresponds to a mass concentration of $(P_{\text{TCP}}/P)\,M_r/V_{\text{NTP}}$, where the molecular weight M_r of TCP is 368 and V_{NTP} is the volume of 1 mole of gas at normal temperature and pressure (24.45 dm^3), about 20 pg/m^3. Therefore, we may safely deduce that TCP will not be inhaled as a vapour but as an aerosol, in all probability dissolved in the base oil.

Ultrafine particle counts as measured by Crump et al. typically fell in the range 10^9–10^{11} m^{-3} [7]. The lower end of this range would agree with the fraction of lost oil actually leaking into the cabin deduced from the TCP measurements (§2). The precise number, of course, depends on the size of the droplets, which is only estimated in this calculation.

4. ADSORPTION ONTO INTERNAL SURFACES

The Brownian flux of aerosol particles to the internal surfaces could be estimated using

$$F = Dc/\delta \tag{2}$$

where D is the diffusivity of the particle, which can be calculated using the Stokes–Einstein relation,[7] $= 11 \times 10^{-11}$ m^2/s (keeping the particle radius $r = 100$ nm as before), c is the particle concentration and δ is the thickness of the aerodynamic (Blasius) boundary layer. The aerodynamics of the airflow in the interior of an aeroplane cabin is of course an exceedingly complicated matter and, not surprisingly, resort has been had to computational fluid dynamics for studying it (e.g., refs [2, 16]). We shall take an average value of $\delta = 10$ mm. This yields $F = 10^7$ m^{-2}s^{-1} for $c = 10^{14}$ m^{-3}.

Taking the A320-200 as a typical aircraft example, the fuselage is (approximately[8]) 40 m long and has a radius of 2 m [13, 12], giving a volume of 500 m^3 (of which half is occupied by the passenger cabin and the cockpit). The inner surface of the fuselage has an area of approximately 500 m^2. The actual surface is much greater because the cabin is filled with seats and passengers. Let us approximate this additional surface by the area of the 179 passengers who could be accommodated; the average area of the human body is approximately 2 m^2, giving a total of about 360 m^2, and a grand total of 860 m^2.

From eqn (1) we therefore calculate the rate of loss of particles as 8.6×10^9 s^{-1}. This is many orders of magnitude less than the maximum oil ingress (under normal operation); if c is taken as 10^{10} m^{-3}, (roughly the middle of the range found by Crump et al. [7]) we shall have a rate of loss of particles of ~10^5 s^{-1}, from which we can conclude that adsorption onto the internal surfaces within the aircraft cabin does not significantly diminish the aerial concentration.

Lamb et al. found TCP deposits of about 30 μg/m^2 [14].[9] Using $F = 10^3$ m^{-2} s^{-1} for $c = 10^{10}$ m^{-3}, and keeping other variables the same (3% TCP), the rate of deposition of TCP is about 1.5×10^{-13} g m^{-2} s^{-1}, implying that exposure

[7] $D = k_B T/(6\pi\eta r)$, where η is the viscosity of the air, taken to be 20 μPa s [15].
[8] Numbers here and elsewhere are appropriately rounded.
[9] Depending on aircraft type and location. This result is typical for the B757.

for 2×10^8 s would be needed to accumulate the amounts found, assuming that the TCP is irreversibly deposited and does not decompose on the surfaces. This estimate seems to be perfectly reasonable; it corresponds to 555 flying days of 10 h flying per day. Unfortunately no details of the aircraft, other than type, are given in Lamb et al.'s study [14].

5. CONCLUSIONS

Comparison of the known rate of loss of engine oil during jet engine operation with measurements of ultrafine particle concentration (assumed to consist of oil droplets) and tricresyl phosphate (the most significant minor component of the oil) suggests that a fraction 10^{-5}–10^{-4} of the oil leaks into the aircraft cabin, where it can be inhaled by aircrew and passengers.

This is during normal operations. The oil concentration in an actual fume event, in which visible smoke appears in the cabin, is estimated at 50 mg/m^3. The corresponding concentration of TCP is about 1.5 mg/m^3. If the ratio of T*o*CP to total TCP found in ref. [7] is representative [27], this corresponds to a T*o*CP concentration of 0.5 mg/m^3—well exceeding the short-term workplace exposure limit (15 minute reference period) [9], which is, as already pointed out, applicable to a terrestrial factory environment.

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