Contamination of aircraft cabin air by bleed air – a review of the evidence

Expert Panel on Aircraft Air Quality
(Expert Panel)

A document reviewing evidence up to September 2009

Introduction

Cabin air in commercial aircraft can be contaminated with hydraulic fluids, synthetic jet oils or the compounds released when these fluids are heated or pyrolysed. The incidence of contaminated air events and the nature of contaminants within the cabin air are difficult to determine as commercial aircraft do not have air quality monitoring systems on board and under-reporting is common amongst aircrew. The immediate effects of exposure to contaminated air have been well documented but debate continues about causation, diagnosis and treatment of long-term effects.

For more than twenty years, concerns have been expressed in reports from Australia and overseas about a possible relationship between exposure to fumes from heated engine and hydraulic oils contaminating air drawn into aircraft air conditioning systems in certain types of aircraft, and post-exposure acute and chronic symptoms experienced by some cabin occupants. Most reports involve aircrew - both pilots and flight attendants. The term 'Aerotoxic Syndrome' has been used by some to describe the symptoms experienced, although this term is not accepted as a recognised medical diagnosis. Although a number of inquiries have been undertaken, both in Australia and internationally, the results have been indeterminate, due in part to the difficulty in finding satisfactory evidence.

In 2007, in response to persisting reports from Australia and overseas about possible links between the contamination of air supplied to the aircraft cabin and descriptions of post-exposure acute and chronic symptoms from those exposed to the contamination, the Australian Civil Aviation Safety Authority (CASA) established an Expert Panel on Aircraft Air Quality (EPAAQ).

This Panel comprised members with expertise in aircraft engineering, occupational and environmental health, aviation medicine, toxicology and epidemiology to examine concerns about cabin air contamination.

This Report describes the evidence-based review undertaken by this Expert Panel, together with recommendations for further action.

Research Assistance

The Panel engaged an Occupational and Environmental Medicine consulting group, Rumball Souter Floyd & Associates Ltd (RSF), to undertake a literature search and assist in this investigation. The Panel determined the scope of the literature search, as well as instructing RSF to seek input from a wide range of stakeholders whom RSF contacted, advising them of the Review and requesting provision of information or advice. Respondents were able to submit their documents electronically or post them directly to RSF. The Panel received a large number of personal medical reports submitted following a call from an advocacy group

Global Cabin Air Quality Executive (GCAQE). These reports were systematically reviewed, but the contents have remained confidential.

The Panel and the research team used a purpose built limited access website known as a "wiki" developed and managed by RSF. The wiki provided the Panel with access to all submissions and references, as well as enabling the Panel to participate in real time development of the report.

The Panel met on eight occasions over the past two years and examined a significant body of information and evidence, including governmental inquiries, expert opinions, incident reports, media reports, *in vitro* and animal studies and human epidemiology studies, as well as individual testimonies. The Panel recognised the concerns expressed by individuals, and some organisations, that their ill health (which they attributed to exposure to contaminated cabin air) was significant, and in some cases very debilitating. However, throughout this review the Panel adopted an evidence-based approach in assessing a wide range of material; particularly focusing on comprehensive peer reviewed scientific literature wherever possible. In addition, members of the Panel contributed information and data from their own sources to enable the Panel to explore as widely as possible the available evidence.

The detailed literature review was completed in September 2009. Subsequently, RSF has assisted the Panel in developing this report. The Panel acknowledges the ongoing research, presentations at conferences and publication of papers since that date and will seek to have CASA maintain this report as a "living document" to enable updating of the document as and when further evidence becomes available.

Limitation of this review

The Panel limited the scope of this review to cabin air contamination due to internal leakage of chemicals into the air conditioning system. The review excluded consideration of the health effects of allergens, microorganisms and chemical contamination from external sources.

Acknowledgement

The Panel acknowledges the expertise, skills, patience and diligence of our research team Rumball Souter Floyd & Associates Ltd (RSF), particularly Dr Christopher Rumball and Dr Karen Grant. As chairman, I wish to highlight and acknowledge with gratitude the enormous support, input, advice, expertise and encouragement of all members of the Panel each of whom have willingly given their services diligently, well beyond what would generally be expected of an Expert Panel. Finally I wish to recognise the support and great assistance of Dr Pooshan Navathe, Principal Medical Officer, CASA who has provided me with guidance and support throughout this project.

Michael Bollen AM
Chairman of the Expert Panel

Executive Summary

For more than twenty years a range of concerned groups, including representatives of current or former flight-crew members, have expressed concern to governments, airlines and in the media that:

- Modern passenger aircraft use heated air drawn directly from aircraft engines and auxiliary power units (APUs) for cabin air conditioning (termed "bleed air" because it is bled from the engine).
- This air can be contaminated with various substances including some arising from heated engine oils and hydraulic fluid.
- Cabin air can also be contaminated by various substances that are drawn in through the engines and, via the engine bleeds, enters the air-conditioning pack and passes into the aircraft cabin environment.
- Exposure to detectable fumes and vapours can result in acute, short-term symptoms.
- For some individuals, chronic ill health can result from long-term exposure to contaminated air (in some cases leading to long-term disability and forced retirement).
- The organophosphate, tri-ortho-cresyl phosphate (TOCP), a known contaminant of heated engine oils is a causative agent, but there are several other potential contaminants, which may also play a role.

Over the years various jurisdictions have conducted a number of reviews and inquiries including a Senate Inquiry in Australia in 2001 and an inquiry by the House of Lords in the UK. Despite the findings and recommendations of these inquiries and a range of research undertakings, the above concerns remain.

The Civil Aviation Safety Authority (CASA) requires that any matter relating to aircrew and passenger health demands serious attention, not only to protect individuals but also to ensure the safe operation of aircraft. To address these matters, CASA appointed a panel of experts to undertake a review with the following terms of reference:

"*The Expert Panel on Aircraft Air Quality (EPAAQ) will review national and international scientific research and other information into cabin air quality with the aim of:*

i. *Establishing the current state of knowledge in relation to safety and health risks from the quality of air onboard commercial aircraft;*

ii. *Recommending whether the current research initiatives being undertaken internationally are sufficient, or whether additional research is required in an Australian context and;*

iii. *Recommending any further actions that should be taken in relation to potential safety and health risks.*"

This Expert Panel structured its review on a question format using accepted scientific (and evidence-based medicine) techniques to answer well-defined questions. The Panel employed a research group, developed the questions, commissioned an extensive literature search enabling accumulation and categorising of the available evidence and called for submissions from interested parties. Throughout this report the Panel has presented pertinent scientific evidence in a style that enables the reader ready access to the evidence as part of a detailed analysis. The Panel has confined the scope of this review to the possible effects of bleed air contamination from the aircraft engines.

How can cabin air contamination occur?

The Panel acknowledged that lubricating oils and hydraulic fluids used in aircraft contain chemicals that were known to produce ill effects on both animals and humans. Pyrolysed oils and fluids as well as other gases, fumes and vapours could be mixed with the heated air intended for the air conditioning system if engine oil seals were worn, poor maintenance practices or exhaust fumes during engine start or aircraft taxiing. Oil seals are known to vary in effectiveness at different stages of aircraft operation, especially during "transient stages of operation", that is, take-off, landing or significant changes in altitude. Engine design and poor maintenance standards and practices can contribute to problems with cabin air quality.

How often do contaminated cabin air events occur?

On the available evidence, reported fumes events were quite rare, whether expressed on the basis of the number of flights or the number of hours flown. However, the Panel was unable to find consistent or systematic reporting systems which specifically targeted aircraft incidents being used by Australian or international airlines to enable statistical incidence to be verified. In addition, there was no consistency in the collection of such data between the various regulatory authorities, both locally in Australia and internationally. Reporting and investigation appeared to depend on whether flight crew considered the incident was significant or crew became seriously incapacitated during a flight. There appears to be a significantly lower rate of reporting of smoke and fumes events in civilian/commercial aviation when compared with those reported by military aviators in Australia. The Panel was made aware of several databases where an incident might be recorded but these databases were not linked and the data not verified according to any standardised methodology. For this reason the Panel had no meaningful way of interpreting information obtained from these databases.

What could potentially contaminate cabin air?

The Panel observed that aircraft cabin air contamination has been reported in both normal and abnormal operations. Contaminants could come from a range of sources including jet engines, auxiliary power units (APUs) and air conditioning machines (ACMs) as well as from de-icing fluid, condensation, smog, fog and from the engine exhausts of aircraft, including their own, whilst on the ground as well as other external environmental odours and contaminants. Contamination could also occur during the takeoff and landing stages of flight. Pyrolysis of commercial jet oils could release a range of substances into cabin air during a seal failure including cresyl- and the more volatile butyl-phosphate esters, as well as potentially irritant acid,

aldehyde and ketone volatile organic compounds (VOCs). Other potential contaminants included carbon dioxide (CO_2) carbon monoxide (CO) and fumes from oil leaks, hydraulic leaks, water leaks, and inhibiter fumes. Burning of any type including galley or electrical fires, chemical reactions, and cargo fire/smoke should be regarded as abnormal.

What contaminants are found in cabin air?

The Panel examined the available evidence for cabin air contamination during both normal operations and reported fume events and recognised the potential for contamination to occur. However, there was insufficient evidence to reach any conclusion about what could be considered the normal range of air contaminants and their concentrations in commercial aircraft during normal operation. There was also insufficient data on levels or possible interactive effects of contaminants to evaluate their toxicological significance when in aircraft air. There was no evidence that neurotoxic trimethyl propane phosphate (TMPP) was formed or it was not sufficiently volatile to be captured on air duct surfaces, despite suitable analytical techniques having been used. Carbon monoxide (CO) and organophosphate derivatives remain the most likely contaminants. The Panel understands that major research projects are currently being undertaken in the UK and the USA to seek to determine what contaminants occur in cabin air and their concentrations.

Problems with currently available tests for cabin air contaminants

The Panel had difficulty attributing any clinical outcome to specific exposure because of the large number of potential toxic chemical substances that could be involved and the lack of data documenting exposure levels in cabin air. While sampling cabin air during normal operation was feasible and equipment has been available, identifiable contamination events were infrequent and unpredictable. This reduced the opportunity to capture an event and analyse for the presence and level of possible contaminants at the time of exposure. The Panel became aware of a recent US decision to deploy testing devices in aircraft but data on the specificity or sensitivity of these tests were not readily available.

What biological evidence is available that exposure takes place?

The Panel concluded that there was insufficient evidence at present to confirm or deny biologically significant exposure to cabin air contamination that would lead to significant absorption by crew or passengers. Butyrylcholinesterase (BChE) inhibition has been the standard biological test used for OP monitoring but should only be considered a marker of acute exposure. Tests based on measuring TCP metabolites in blood and/or urine may not be sufficiently sensitive, or able to discriminate exposures to the more neurotoxic compounds (TOCP, DOCP, MOCP and TMPP). The Panel considered that exposure to other potentially toxic components of contaminated cabin air (e.g. ozone, carbon monoxide, carbon dioxide, hydrocarbons) or hypoxia (lack of sufficient oxygen) might be overlooked if the focus was solely on bio-monitoring of OPs. Further research on biomarkers of exposure and markers of contaminated cabin air is continuing in the USA. This research may shed light on possible TOCP exposure after air events because of the type of bio-marking being investigated. Genetic testing is problematic, although it may be possible to determine whether the susceptibility of subjects who have experienced symptoms might be associated with

higher levels of biomarker adducts, either through higher levels of exposure or a genetic polymorphism which results in greater production of reactive TCP metabolites.

Does sub-detectable exposure occur?

The Panel considered the term "sub-detectable" to mean the absence of visual or olfactory cues. TCP and CO are colourless and odourless toxic agents and could be considered sub-detectable according to this criterion. Though plausible, the Panel found no direct evidence available that pilots and cabin crew of aircraft were being exposed to sub-detectable level of contaminants. There was also no evidence found that ill health associated with cabin air quality contamination was related to unique individual susceptibility to low levels of airborne toxic chemicals, i.e. that adverse health effects could occur in some individuals exposed to a level of a toxic chemical that would not affect most people. The Panel could find no convincing evidence that interaction between TOCP, the alleged cabin air neurotoxin and some other factor could cause neurotoxicity at unexpectedly low doses. However, this possibility could not be excluded.

Does the cabin environment influence the effect of the contaminants?

The Panel reviewed the theories regarding possible synergistic effects between a number of compounds that, while not at a toxic level individually, together might reach a "causal" threshold but was unable to find evidence to support these theories. The Panel noted the conjectural relationship between organophosphates used in sheep dips and neurobehavioral effects observed in farmers and that this could indicate a potential for similar effects with organophosphate contaminants from engine oils. However, the Panel considered extrapolating such evidence from one setting to another could be misleading.

What are the acute symptoms of exposure to contaminated cabin air?

The Panel noted that symptoms reported in the literature and disclosed in submissions received during the review predominantly were related to the respiratory or neurological systems or mucosal irritation but generally could not be linked to any identifiable cause in cabin air or extent of the exposure. However there was some suggestion of a temporal relationship with symptoms following exposure, from a case series presented to the Panel.

The Panel noted two broad groups of acute symptoms:

Irritant effects: itchy, red, weeping eyes**:** "scratchy" sensation in throat, swelling of throat (sometimes with altered taste): respiratory symptoms, tightness in chest, red and itchy skin.
Central Nervous System (CNS) effects: loss of recent memory, poor concentration, increased lethargy, neuromuscular incoordination, confusion and headaches.

However, the Panel considered that there was no cardinal set of symptoms or signs in those who have experienced ill health that would define a toxidrome or syndrome. The Panel found this problematic when interpreting the literature and reviewing case reports and testimonies.

What contaminants may be responsible for these symptoms?

The focus on cabin air contaminants has been on neurotoxic metabolites of TOCP but the Panel found

insufficient evidence to implicate this as the sole, or even the most likely, cause of adverse health effects in aircrew or passengers. In the literature review and individual reports, symptoms were variously attributed to tri-ortho-cresyl phosphate (TOCP), carbon monoxide (CO) and other agents from the pyrolysis of oil, including organic acids (e.g. pentanoic and valeric acid). However, the Panel noted that while TOCP and CO are toxins that could potentially produce significant effects on target organs/systems including eyes, nose, throat, lungs and skin as well as the CNS:

- There were no detailed or specific scientific investigations that identified specific causes for self-reported acute symptoms.
- There were no specific features consistent with acute organophosphate poisoning (in the case of TCP) or carbon monoxide poisoning.

The Panel noted delayed sequelae of CO poisoning include apraxia (loss of the ability to execute or carry out skilled movements and gestures, despite having the desire and the physical ability to perform them), apathy/indifference, memory deficits, Parkinsonism and psychomotor retardation. While frank neurological signs such as Parkinsonism should be easily detected, personality, cognitive and memory changes are not readily apparent and could be missed unless specifically targeted.

Effects of other potential contaminants

The Panel reviewed the known effects of other potential contaminants including carbon dioxide (CO_2), nitrogen dioxide (NO_2), trimethyl propane phosphate and hydrogen cyanide (HCN) and noted:

- No known long-term sequelae from CO_2 or HCN.
- Nitrogen dioxide can cause chronic respiratory impairment, with diseases such as bronchiolitis obliterans or pulmonary fibrosis.

The Panel also noted the potential for hypoxia or reduced oxygen tension in cabin air to be a co-factor in affecting neurological function.

Who is affected by acute exposure?

The Panel reviewed the investigations of several major incidents and noted considerable variability in the response of aircrew. This variability could be explained by the location of the crew within the aircraft and the source of the air. For example in the BAe146, air for the flight attendants and passengers comes from engines 3 and 4, whereas the pilots' air comes from engines 1 and 2. If an oil seal leak were to occur in engine 1 or 2 the pilots could receive higher exposure because they received more contaminated air. The Panel noted the possibility that genetic polymorphism in metabolism of organophosphates could possibly account for some individuals having an inherent susceptibility to OP-induced toxicity. However, the Panel was unable to draw any conclusions as to whether this factor could explain individual differences between affected and non-affected aircrew because of the lack of definitive evidence. The Panel recognised that smokers were known to be more susceptible to elevated carbon monoxide levels as they have initial high carboxyhaemoglobin levels already.

What is the effect of the acute functional disabilities on the ability to control the aircraft?

The Panel noted significant concerns being expressed about the effects of fume events on the ability of pilots to control aircraft. The Panel recognised that flying an aircraft was a complex task requiring a high level of psychomotor and cognitive skills and cabin air contaminants have the potential to compromise human performance. In addition, there have been reports of catastrophic accidents where the primary cause of the accident was not determined, but where exposure to air contaminants could have played a part, but this was unproven.

The Panel noted:

- Reports of aircrew incapacitation were rare;
- There have been no recorded catastrophic events or fatal injuries directly attributable to aircraft cabin contamination;
- There had been no formal studies of aircrew function while affected by contaminated cabin air or other possible airborne contaminants however the Panel recognised that such studies would have inherent difficulties because of the infrequency and unpredictability of such episodes.

What are the regulations governing cabin air and flight safety in Australia?

The Panel identified regulations, both in Australia and internationally, that require the provision of a safe working environment in an aircraft, to ensure both safety of the aircraft and the health of aircrew and passengers. In Australia, the Air Transport Safety Board (ATSB) requires mandatory reporting of accumulation or circulation of toxic or noxious gases in the crew compartment or passenger cabin. The presence of smoke, toxic or noxious fumes inside the aircraft is considered a major defect. All major defects must be reported to the aircraft operator and an air safety incident report (ASIR) must be provided to the ATSB as soon as possible after detection. Where such a defect is reported, the operator of the aircraft must take action and a report must be furnished to CASA within two working days of the report. Where CASA considers that an unsafe condition exists, or is likely to exist/develop CASA may issue an Airworthiness Directive. Despite these strict guidelines, the Panel questioned whether all of these events were being reported to the regulatory authority or reported in a timely manner.

Some submissions suggested that full compliance with these regulations was not occurring for a range of reasons including complexities with reporting systems, time pressures and lack of management support. The Panel considered that addressing those factors that currently act as a disincentive to compliance with these regulations by aircrew and management should lead to a safer working environment for aircrew and a safer travel environment for passengers.

Does exposure to contaminated cabin air result in chronic illness?

The Panel noted a large number of papers reviewing the relationship between exposure to contaminated cabin air and reports of subsequent chronic illness but the lack of high quality epidemiological studies meant that this question could not be resolved. However, the Panel noted a recent legal decision has supported the claim that exposure to contaminated air had resulted in significant ongoing ill health.

What are the chronic toxicological effects of the contaminants?

On the evidence available the Panel was unable to resolve whether acute exposure resulted in delayed or chronic adverse health effects. The Panel identified a number of points that were inconsistent with TOCP being the sole neurotoxic agent of concern in cabin air quality incidents, including the absence of peripheral neurotoxicity in reported cases associated with cabin air contamination.

Furthermore, as noted earlier, there could be genetic polymorphisms for susceptibility to neurotoxicity, which are as yet undefined.

Is the level of exposure to contaminants that could occur in a fumes incident enough to produce chronic illness?

From the available evidence, the Panel was unable to draw any conclusions about the level of exposures during cabin air quality incidents and their relationship to threshold values in humans that might be sufficient to cause chronic adverse health effects.

What are reported chronic symptoms and signs following exposure?

This major issue was carefully examined by the Panel, including review of personal medical reports submitted by aircrew describing their chronic or ongoing symptoms. In addition, the Panel reviewed a number of case series reported by health professionals. Several papers discussed the effect of ill health on the careers of aircrew. The symptoms reported ranged across many different body systems, were a combination of acute irritant and delayed effects and included several nonspecific symptoms that have been reported as part of other syndromes. Some documents also detail symptoms suffered by passengers. The Panel considered that terminology used to describe such incidents could be confusing. For example, the Panel considered that the term 'Aerotoxic Syndrome' was based on a presupposition that symptoms experienced after aircraft cabin fume events were due to toxic effects of chemical exposures. Instead, the Panel suggests a more general term 'Aircraft-related condition' would be a more appropriate descriptor for symptoms reported in association with aircraft cabin fume events.

What is a possible case definition?

Determining suitable case definitions is an important element of public health surveillance systems and is an essential component of epidemiological studies. In reviewing the evidence associated with ill health attributed to cabin air contamination the Panel noted the lack of a formal case definition. The Panel considered possible criteria for a case definition to better identify adverse health effects related to aircraft cabin fume exposures based on published surveys and individual submissions. However a case definition for fumes exposure would require validation and appropriate refinement before being used in prospective epidemiological studies. In the absence of a validated case definition, prevalence data cannot be considered to be reliable.

The Panel considered that, in order to improve the ability to undertake formal epidemiological studies, the medical symptoms, signs and laboratory findings need to be better defined, to enable investigation of associations with exposure to cabin air contaminants. Development of a suitable case definition would

ensure comparability between epidemiological studies and also make surveillance data comparable between countries. However as noted earlier, such epidemiological studies would be difficult to implement given the relative rarity of contamination events.

What is the biological plausibility of proposed theories of causation?

The Panel considered the theory that symptoms experienced in fumes events were the result of organophosphate toxicity due to TCP exposure as well as the possibility that carbon monoxide exposure could also contribute to the symptoms experienced.

The Panel reviewed a number of papers that studied the common symptoms experienced by aircrew following exposure to cabin air contamination and noted:

- Airport workers are also exposed to jet fuel and combustion products:
- Hypoxia could be a cause of symptoms at high altitudes:
- Ozone is also a contaminant of cabin air at high altitudes:
- Exposure to insecticides may also cause symptoms:
- Odours and irritants may cause symptoms.

Which theories of causation are considered plausible?

The Panel noted that exposure to a neurotoxic OP might be a plausible biological mechanism for the neuro-behavioural and neuropsychological symptoms described but at least some of the reported symptoms attributed to the syndrome are also typical somatic manifestations of hyperventilation and anxiety.

The Panel noted

- It has not been definitely established that the putative neurotoxic agent is TOCP or its more toxic oxidative metabolites or other cresyl esters (e.g. mono-ortho congeners).
- A number of potential chemicals in pyrolysed engine oils and hydraulic fluids could cause the sensory and skin-eye irritation commonly described in cabin air fume incidents.
- There was insufficient data to establish whether air levels of any of the chemicals under consideration could reach high enough concentrations to cause such acute irritant reactions or whether such reactions at low levels might be idiosyncratic.
- There were inconsistencies between the acute presentation of the symptoms attributed to what has been referred to as the 'Aerotoxic Syndrome' and the ongoing chronic symptoms in the toxicological profile of the OPs that produce organophosphorus ester-induced chronic neurotoxicity/Chronic Organophosphate Induced Neuropsychiatric Disorder (OPICN/COPIND) experimentally.

Which theories of causation are considered to lack plausibility?

The Panel considered, on the available evidence, that malingering, primary psychiatric illness and theories based on abnormalities identified by unconventional laboratory testing (autonomic dysfunction; mitochondrial disorder; immune dysfunction; DNA damage; metabolic abnormality; autoimmune reaction; allergic reaction) lacked plausibility.

Are there effects on reproductive health?

The Panel was unable to draw any firm conclusions about effects on reproductive health associated with cabin air quality incidents from the available evidence.

What do epidemiological studies demonstrate?

Although the Panel recognised the potential for the contamination of aircraft cabin air during routine flight there remains a complete lack of comprehensive exposure data and characterisation of the environment in aircraft during smoke/fume incidents, which limits epidemiological research.

The current published epidemiological literature has added little to the Panel's understanding of the relationship between fume incidents in aircraft cabins and acute and chronic health outcomes in either cabin staff or the travelling public.

The Panel accepted that there has been consistent evidence that aircrew experience a variety of specific medical conditions both acute and chronic, associated with work in the airline industry, for example short and long-term respiratory problems. This evidence has come from well-designed cohort studies or cross-sectional studies with good response rates and comparison groups. Using the Panel's review categories, this evidence would be categorised epidemiologically as **Sufficient Evidence of an Association**.

The evidence for the existence of an 'Aerotoxic Syndrome' related to smoke/fume events is, however, still based almost entirely on case-series reviews, remains self-reported and should be categorised epidemiologically as **Inadequate or Insufficient Evidence to Determine Whether an Association Exists**. It should be noted that this view is based on the lack of adequately designed studies and the difficulties inherent in undertaking such studies rather than on the presence of evidence of no association.
The Panel observed that the existence of an 'aircraft-related condition' associated with cabin air quality during relatively rare smoke/fume incidents was likely to prove difficult to confirm or refute using standard observational epidemiological methods.

Control Mechanisms

The Panel considered that unanswered questions relating to cabin air contamination will necessitate ongoing research into detecting contaminated air, developing effective filtration systems, and identifying medical protocols for assessment and management of fumes episodes and affected people. Development of monitors and filtration systems are evolving rapidly.

Meanwhile given the need to address occupational health and safety (OH&S) issues, the Panel examined current approaches to management of exposure episodes and, more importantly preventing such episodes from occurring. These approaches included regular preventive maintenance of engines to minimise seal failure and in the event of a contamination episode, immediate use of 100% oxygen and application of smoke goggles by all exposed individuals, as required under existing regulations.

Conclusion

A circumstance where there is suggestive evidence of the potential for serious harm resulting from an occupational exposure will always generate debate about whether, how and when to intervene. In the case of cabin air smoke/fume incidents there is the added imperative of the safety of passenger aircraft where pilots and other cockpit crew may be impaired. The products of thermal degradation of engine oils and hydraulic and de-icing fluids such as CO and VOCs that are known to be generated when bleed air is contaminated are sufficient to cause concern. Assertions about "low toxicity" TCP in jet engine oils are not reassuring. An extensive environmental monitoring programme conducted during smoke/fume events would be necessary to clarify whether the exposures of concern exist before making recommendations for change. Even in the absence of definitive data on the exposures that occur during smoke/fume incidents, the Panel considered that the prudent approach would be to take whatever action is necessary to prevent these incidents through engineering means.

Despite the large amount of information available to the Panel, there remain many unanswered questions in seeking to understand the potential for exposures to engine oil in aircraft cabins and the acute and chronic effects on a person's health as the result of such exposures. The information available about the association between specific contaminants and symptoms appeared more frequently conjectural rather than definitive. The absence of a global reporting system, the lack of an agreed minimum data set (including a standard case definition), the differences in frequency of reporting (perhaps related to the apparent failure to comply with current regulations) and the lack of acceptable methods of objective testing all contributed to the inability of the Panel to reach definitive conclusions. However, a recent decision by the US Senate to have the FAA monitor aircraft cabin air, and the work being undertaken in the USA to develop a blood test to try to measure exposure, could provide higher quality information to advise passengers and crew about the likelihood of being exposed to any significant risks.

Recognising the potential for contamination of cabin air from bleed air and determining the frequency of cabin air contamination events is important. The Panel considered that, even if such events were rare, this could still represent potentially significant occupational health and safety concerns. As such, while the question of the chemicals involved in a contamination event remains unresolved at present, regulators and airline operators have an obligation to ensure that aircrew and passengers are able to have protection if a contamination event occurs, that aircrew and airline operators recognise their obligation to report such events and operators recognise the need to investigate and file reports on the finding including action subsequently taken. As this issue has international significance, the Panel considered that actions and studies undertaken in Australia as the result of this Report should be co-ordinated with those taking place in other countries.

Adelaide
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Glossary

Acroparaesthesia	Numbness, tingling or other abnormal sensations in one or more of the extremities.
Acute (symptoms or disease)	Having a rapid onset and following a short but severe course.
Acute renal tubular necrosis	A medical condition involving the tubule that transports urine to the ureters.
Adduct	The product of a reaction between molecules, where one substance is bound to another.
Aerosol	A gaseous suspension of fine solid or liquid particles.
Air-prox. event	An air proximity incident, i.e. where safety has been compromised due to two or more aircraft being too close to each other.
Allele	Any one of the alternative forms of a specified gene.
Analyte	Chemical constituent or substance determined in an analytical procedure.
Angina	Chest pain due to a lack of blood and hence oxygen supply of the heart muscle.
Apoptosis	Programmed cell death. Excessive apoptosis can cause atrophy, where as an insufficient amount can result in uncontrolled cell proliferation such as cancer.
Apraxia	Apraxia is a disorder caused by damage to specific areas of the cerebrum, characterized by loss of the ability to execute or carry out learned purposeful movements, despite having the desire and the physical ability to perform the movements.
Ataxia	The inability to control voluntary muscle movement; postural imbalance and a staggering gait.
Atrophy	Wasting away of a cell or of an organ of the body.
Auto-oxidation	A material built up from a series of smaller units e.g. polythene is a polymer made up of many ethene units joined together.
Auxiliary power unit	An independent airborne engine to provide power for supplementary equipment, electrical services, starting etc. (Walker, 1991)
Basal ganglia	An area in the brain associated with a variety of functions including learning and motor control.
Biomarker	A substance used as an indicator of a certain biological state (e.g. whether exposure to a certain toxin has occurred).

Bleed air	Air taken from the compressor unit of an engine. Bleed air is hot and at pressure.
Bronchospasm	A sudden constriction of the muscles in the walls of the bronchioles, which can make breathing difficult.
Bulbar (muscles)	The muscles supplied by the motor nerves from the brain stem, which control swallowing, breathing, speech, and other functions of the throat.
Carbonaceous	Carbon-containing material.
Carcinogenic	Cancer causing.
Cerebral aneurysm	A weak or thin spot on a blood vessel in the brain that balloons out and fills with blood.
Cholinergic synapses	Synapses where acetylcholine is the neurotransmitter.
Chronic	A persistent disease or medical condition, or one that has developed slowly.
Concurrent	Existing or happening at the same time.
Condensed	Formed a liquid from its vapour.
Congener	A member of the same kind, class or group.
Cytotoxic oedema	Swelling of brain cells due to lack of oxygen.
Delayed neuropsychiatric syndrome	A condition in CO poisoning where sufferers can appear to make a full recovery but can relapse a few days later with a range of neurological and psychiatric symptoms.
Demyelination	Loss of the myelin sheath that insulates the nerves, which can cause nerve damage.
Depolarization (of a nerve cell)	Depolarization is a change in a cell's membrane potential, making it more positive, or less negative. In neurons and some other cells, a large enough depolarization may result in an action potential.
Dermal	Pertaining to the skin.
Disinsection	The spraying of an aircraft with an insecticide for the removal of insects.
Distal paresis	Partial loss of movement, or impaired movement, in the parts of the limbs farthest where they attach to the body.
Dystonic posturing	The production of one pattern of muscle activity when a different pattern was intended.
End-plate	The flattened end of a motor nerve fibre, which transmits impulses to muscle.
Endocrine (system)	A system of glands that secrete hormones into the body.
Enzyme	A protein with catalytic activity.
Ester	A derivative of an acid formed by condensing with an alcohol.
Fasciculation	Muscle twitch.
Febrile	Pertaining to, produced by, or affected by fever.
Fire	The active principle of burning, characterized by the heat and light of combustion [Your free dictionary online]; a process in which substances combine chemically with oxygen from the air and typically give out bright

	light, heat, and smoke; combustion or burning [OUP Online]
Fumes	Cloud of airborne particles, generally visible, of low volatility and less than a micrometre in size, arising from condensation of vapours or from chemical reaction (Walker, 1991); a gas or vapour that smells strongly or is dangerous to inhale [Oxford online Dictionary of English, 2005].
Globus pallidus	Part of the basal ganglia system of the brain.
Haematocrit	A graduated capillary tube of uniform bore in which whole blood is centrifuged, to determine the ratio, by volume, of blood cells to plasma.
Haemoglobin	The red pigment of the blood whose major function is to transport oxygen from then lungs to the tissues.
Haemophysis	Haemorrhage in the lung.
Haemorrhage	Bleeding; escape of blood from a ruptured blood vessel.
Histology	The study of the minute structure of tissues and organs.
Humoral (immunity)	Specific immunity attributable to antibodies as opposed to cell-mediated immunity.
Hydraulic fluid	A fluid used in a hydraulic system.
Hyperventilation	Rapid or deep breathing that can occur with anxiety or panic. Sometimes known as over breathing.
Hypoxia	Lack of oxygen supply.
Hypoxic ischaemic encephalopathy	Damage to cells in the central nervous system (the brain and spinal cord) from inadequate oxygen.
Hysteria	A physical disability with no apparent organic cause; a condition of extreme excitement characterized by emotional disturbance, sensory and motor derangement and sometimes the simulation of organic disorders.
Incapacitate	Prevent from functioning in a normal manner; make unable to perform a certain action; unable to perform any duties.
Incoordination	Clumsiness.
Isomer	One of two or more compounds with the same formula but a different arrangement of atoms in the molecule and different properties.
Labyrinth seal	A mechanical seal composed of many straight grooves that press tightly inside an axle or a hole, so that fluid has to pass through a long and difficult path to escape. [Adapted from wiki]
Lacrimation	Shedding of tears.
Lipophilic	A substance that dissolves more easily in oil than water.
Metabolism	The complex of physical and chemical processes occurring within a living cell or organism that is necessary for the maintenance of life. In metabolism some substances are broken down to yield energy for vital processes while other substances, necessary for life, are synthesized.
Metabolite	A substance involved in metabolism, either synthesised during metabolism or taken in from the environment.

Mist	A suspension of a liquid in a gas or a suspension of water droplets (radii less than 1μm) reducing the visibility to less than 1 km (Walker, 1991).
Necrosis	Death of a cell (or group of cells) while still part of the living body.
Neurocognitive	Pertaining to or connecting the mouth and nose.
Neurotoxic	Having a poisonous effect on nerves and nerve cells.
Neurotoxic	Poisonous to nerves or nervous tissue.
Neurotransmitter	A natural chemical that transmits signals from a neuron to another cell across a synapse.
Nomenclature	Principles of naming; the systems of procedures and terms related to naming.
Nystagmus	An abnormal and involuntary movement of the eyeball seen as a flicking backwards and forwards when the eye is deviated.
Ocular	Relating to the eye.
Odour	A distinctive smell, especially an unpleasant one
Off-gas	An exhaust gas, e.g. from a combustion engine or a gas which is slowly released from a material in which it had previously been trapped (e.g. solvents released from a new carpet).
Olfactory	Pertaining to the sense of smell.
Oxidative stress	Changes in living organisms in response to excessive levels of cytotoxic oxidants and free radicals in the environment.
Palpitations	Unpleasant sensations of irregular and/or forceful beating of the heart.
Palsy	Paralysis, generally partial, whereby a local body area is incapable of voluntary movement (motor function).
Paraesthesias	An abnormal sensation, such as tingling, tickling and 'insects crawling on the skin'
Pathognomic	Specifically indicating a particular disease.
Pharmacodynamics	The science of the action of drugs.
Pharmacokinetics	The action of drugs in the body over a period of time.
Phosphorylation	The addition of a phosphate (PO_4) group to a protein or other organic molecule.
Polymorphism	The state or quality of existing in several different forms e.g. enzyme polymorphisms are different forms of the same enzyme found in different individuals.
Polyneuritis	A widespread affection of many peripheral nerves with flaccid paralysis of muscle and/or loss of skin sensibility, due to infection or poisoning with various agents.
Polyneuropathy	A neurological disorder that occurs when many peripheral nerves throughout the body malfunction simultaneously.
Potentiate	To increase or enhance the effect of a drug.
Psychomotor retardation	A slowing down of thought and a reduction of physical movements in an

	individual.
Psychosomatic	Referring to physical symptoms that are caused or significantly influenced by emotional factors.
Pulmonary aspiration	Breathing in of a foreign object, such as fluid from the lung.
Pulmonary oedema	An abnormal accumulation of fluid in the lungs, leading to shortness of breath.
Pyrolysis	Chemical decomposition of a condensed substance by heating.
Radical scavenger	An anti-oxidant capable of trapping highly reactive free radical compounds that can cause disease.
Respiration	The transport of oxygen from the air to the cells of the body, and the transport of carbon dioxide in the opposite direction.
Respiratory depression	Slowing the rate of breathing.
Salivation	An abnormal overabundance of saliva.
Sequelae	Any abnormality following or resulting from a disease or injury or treatment.
Situational awareness	A pilot's or aircrew's continuous awareness of themselves and the aircraft in relation to flight, threats, and the ability to forecast and then execute tasks based on that perception
Smell	A quality in something that is perceived by the faculty of smell; an odour or scent; an unpleasant odour.
Smoke	Visible cloud of airborne particles derived from combustion, or from chemical reaction; the particles are generally smaller than 1μm. (Walker, 1991)
Solvent	A liquid substance capable of dissolving other substances.
Spirometry	Measurement of the air breathed in and out of the lungs.
Subarachnoid haemorrhage	A form of stroke; specifically a haemorrhage into the space between the arachnoid and the pia mater surrounding the brain, especially as a result of an aneurysm of one of the arteries.
Subcutaneous	Just under the skin.
Subdetectable	Below the limits of human detection; odourless and invisible to humans.
Synapse	The junction across which a nerve impulse passes from an axon terminal to a neuron, muscle cell, or gland cell.
Synergy	The working together of two things (muscles or drugs for example) to produce an effect greater than the sum of their individual effects; Acting together.
Systemic	Relating to the body as a whole; generalised not localised.
Tachycardia	A rapid heart rate, usually defined as greater than 100 beats per minute.
Thermal degradation	Molecular deterioration of chemicals due to overheating.
Toxicant	A poison or poisonous substance.
Vacuole	An enclosed compartment in a cell, which is filled with water containing

	various substances including enzymes.
Vapour	Moisture or another substance diffused or suspended in the air, especially one normally liquid or solid. [OUP online, 2005]
Ventricular fibrillation	An abnormal irregular heart rhythm.
Volatile organic compounds	Carbon compounds which evaporate at room temperatures, (excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbonates, metallic carbides and ammonium carbonate). They often have a strong odour and can be released from many products, such as glues, carpeting, upholstery, paints, solvents, and cleaning products.
Wiki	A website which allows the easy creation of a document by multiple authors, via a web server and specialist software editing tools.
Xenobiotic	A chemical found in an organism, which is not normally produced or expected to be present in it.

Abbreviations

ACER CoE	Air Transportation Center of Excellence for Airliner Cabin Environment Research (USA)
AAIB	Air Accident Investigation Board (UK)
AAIASB	Air Accident Investigation and Aviation Safety Board (Greece)
ACP	Air conditioning pack
AD	Airworthiness Directive
AFA	Association of Flight Attendants (USA)
AIPA	Australian & International Pilots Association
AN	Air Navigation
AOPIS	Aviation Organophosphate Information Site
APH	Acetylpeptide hydrolase
APU	Auxiliary power unit
ASHRAE	American Society of Heating, Refrigerating and Air conditioning Engineers
ASIR	Air Safety Incident Report
ASR	Air Safety Report
ATSB	Australian Transport Safety Bureau
BALPA	British Airline Pilots Association
BChE	Butyrylcholinesterase
C	Celsius
CAA	Civil Aviation Authority (UK)
CAIR	Confidential Aviation Incident Report
CAQ	Cabin Air Quality
CAQPCCA	Committee on Air Quality in Passenger Cabins of Commercial Aircraft (US)
CAS No.	Chemical Abstracts Service registration number
CASA	Civil Aviation Safety Authority (Australia)
CBDP	2-(*ortho*-cresyl)-4H-1,3,2-benzodioxaphosphoran-2-one
CNS	Central nervous system
CO	Carbon monoxide
CO_2	Carbon dioxide
COPIND	Chronic organophosphate-induced neuropsychiatric disorder
COSHH	Control of substances hazardous to health
COT	Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (United Kingdom)
CWA	Communications Workers of America
DNA	Deoxyribonucleic acid
DOHA	Department of Health and Aging
DOCP	Di-ortho-cresyl phosphate
EASA	European Aviation Safety Authority
EPAAQ	Expert Panel on Aircraft Air Quality
EU	European Union
FAA	Federal Aviation Administration
GCAQE	Global Cabin Air Quality Executive
HCN	Hydrogen cyanide
HEPA	High Efficiency Particulate Air
HSE	Health and Safety Executive
ICAO	International Civil Aviation Organization
ICE	Ideal Cabin Environment
IPA	Independent Pilots Association
IRM	Immediately Reportable Matters
IMS	Intermediate Syndrome
LBA	Luftfahrt-Bundesamt (Civil Aviation Authority of Germany)
MCS	Multiple Chemical Sensitivity
MSDS	Material Safety Data Sheets
MOCP	Mono-ortho-cresyl phosphate/0,0-diphenyl-o-tolyl phosphate

MOR	Mandatory Occurrence Reporting
MOU	Memorandum of Understanding
NAA	National Aviation Authority
NIOSH	National Institute for Occupational Safety and Health (USA)
NHS	National Health Service (UK)
NJS	National Jet Systems
NO_2	Nitrogen dioxide
NSW	New South Wales
NTE	Neurotoxic esterase
OHRCA	Occupational Health Research Consortium in Aviation (USA)
OH&S	Occupational Health and Safety
OP	Organophosphate
OPIDN	Organophosphorus ester-induced delayed neurotoxicity
OPICN	Organophosphorus ester-induced chronic neurotoxicity
PDF	portable document format
PK	pharmacokinetics
PON1	Paraoxonase 1
RPT	Regular Public Transport
RSF	Rumball Souter Floyd & Associates
SPR	Surface Plasmon Resonance
TBO	Time Between Overhaul
TCP	Tricresyl Phosphate
TMPP	Trimethyl propane phosphate
TOCP	Tri-ortho cresyl phosphate
TSI	Transport Safety Investigation
TWA	Time-weighted average
UK	United Kingdom
US/USA	United States of America
USAF	United States Air Force
VOC	Volatile organic compound

1 Background

1.1 Expert Panel on Aircraft Air Quality

- Reports from Australia and overseas have indicated a possible causal association between the contamination of air supplied to the aircraft cabin through the introduction of engine oil and hydraulic fluid into the air conditioning system of certain aircraft types, and post-exposure acute and chronic symptoms in the occupants. Most reports involve aircrew - both pilots and flight attendants.
- A range of governments, institutions, professional and consumer groups/organisations, including the Civil Aviation Safety Authority of Australia (CASA), have determined the need for a greater understanding of the current evidence available on the possible contamination of the air supply into commercial aircraft with toxic substances.
- The International Civil Aviation Organization (ICAO) under Resolution A35-12 — *Protection Of The Health Of Passengers And Crews And Prevention Of The Spread Of Communicable Disease Through International Travel* — recently started reviewing the health of people who travel on aircraft (aircrew and passengers) and recommended that regulators worldwide commence work to address this wider approach to the possible health issues facing those who travel in commercial aircraft.
- CASA established the Expert Panel of Aviation Air Quality (EPAAQ) to address the concerns about cabin air contamination with the following terms of reference:

    1. Establish the current state of knowledge in relation to human safety and health risks from the quality of air onboard commercial aircraft;
    2. Recommend whether the current research initiatives being undertaken internationally were sufficient, or whether additional research would be required in an Australian context and;
    3. Recommend any further actions that should be taken in relation to human safety and health risks.

- The Expert Panel Report begins with a chapter that aims to define what is known about the exposure. It then addresses the potential flight safety effects of acute exposure, followed by the chronic health effects, before discussing potential solutions.

1.2 Cabin air contamination

- Air travel over the last one hundred years has grown from an experimental form of powered flight to a fully functional mass transit system both within and between continents.
- Cockpits became enclosed in the early 1920s, thereby separating cockpit air from the outside air.
- It has been reported that pilots, flight attendants, aircraft engineers and passengers have been exposed to varying degrees of contaminated air in both normal and abnormal aircraft operations over this time. In the latter part of the twentieth century several high profile legal cases raised the issue in the public arena. The results of some of these cases were controversial, and thus aircraft cabin air contamination remains a contentious and unresolved issue in aviation today.
- Concern for the safety and wellbeing of those who fly, either in a work environment, or for business and pleasure or for those who are charged with maintaining and repairing aircraft, has led to research and public inquiries into this area in order to assess potential risks from contaminated cabin air. The need for answers has been heightened in recent years by the increased used of air travel in most countries, coupled with concerns for public safety.

1.2.1 Previous inquiries

1.2.1.1 Australian Senate Inquiry

- The Senate Rural and Regional Affairs and Transport References Committee published a report in 2000 (Senate Rural and Regional Affairs and Transport References Committee, 2000a). The inquiry focused on the issue of chemical fumes, in particular tricresyl phosphate (TCP), in the BAe146, a medium-sized commercial aircraft, which was manufactured in the United Kingdom by British Aerospace. The Senate Committee Report noted the history of odours and fume events in the BAe146, and the likely connection with health effects. The major recommendations included further assessment of BAe146 air quality, modifications of air circulation systems, development of a test for air quality monitoring, and research programs to study the health effects of contaminated cabin air.
- The following relevant documents were available to the Expert Panel members:
    - Transcripts of the Committee meetings and the submissions received by the inquiry;
    - Government response to recommendations (Australian Government, 2002);
    - Presentation by the Chair of that Senate Committee, former Senator the Reverend John Woodley, to the British Airline Pilots Association (BALPA) Contaminated Air Conference in 2005 about the politics of the inquiry (J. Woodley, 2005);
    - Submission by the Reverent John Woodley to the Expert Panel (J. Woodley, 2009);
    - Letter to the Australian and New Zealand Journal of Public Health by Dr Andrew Harper discussing corporate bias (A. C. Harper, 2001).

1.2.1.2 Committee on Toxicity, United Kingdom (UK), 2006-7

- The Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT) was asked by the UK Department for Transport to undertake a scientific review of data submitted by BALPA (Committee on toxicity of chemicals in food consumer products and the environment, 2007k). The COT produced the *Statement on the review of the Cabin Air Environment, Ill-Health in Aircraft Crews and the possible relationship to smoke/fume events in aircraft*.
- A non-technical lay summary was also published (Committee on toxicity of chemicals in food consumer products and the environment, 2007j).
- Three sets of discussion documents, together with appropriate annexes, were considered at the COT meetings.
    - The first discussion document, TOX/2006/21, was a review of the BALPA submissions and was considered by the COT at its meeting on July 21 2006.
    - The Committee identified the following points as requiring further investigation:
        - Further assessment of incidents, particularly relating to those not reported to airlines or under regulatory schemes such as the UK Civil Aviation Authority (CAA) Mandatory Occurrence Reporting (MOR) scheme.
        - The development of approaches to measure potential exposure to chemicals during a smoke/fume incident due to oil/hydraulic fluid contamination of the bleed air.
        - Further assessment of the reported acute and chronic ill health documented by pilots to include further consideration of the neuropsychological data submitted to the COT on the 11 July 2006, and the blood/fat levels of chemicals in pilots.
        - The development of approaches to measure potential exposure to chemicals during a smoke/fume incident due to oil/hydraulic fluid contamination of the bleed air.
        - A review of all the epidemiological data contained in the BALPA submission and additional data retrieved through literature searches.
        - A full literature search to identify published data not sourced in the BALPA submission or the initial searches undertaken by the COT Secretariat.
    - The second discussion document, TOX/2006/39, presented information on the above questions, and was considered by the COT at the meeting on 5 December 2006.
        - Areas identified at the meeting for further consideration were:
            - Further information on whether the pilots making multiple reports of smoke/fume incidents were those who also documented continuing ill health.
            - Identification of any further information on exposure to pyrolysed oils and hydraulic fluids.
            - Possible approaches to investigate further the skill tests/proficiency checks for flight crew licences and ratings in relation to

the neuropsychological symptoms documented in a study of self-selected pilots.

- The third discussion document, TOX/2007/10, presented information on the above issues, and was considered at the COT meeting on 20 March 2007. In addition a full evaluation of all of the epidemiological studies was submitted (TOX/2007/10 Annex 10).

1.2.1.3 Civil Aviation Authority, UK, 2004

- The CAA initiated its research programme into cabin air quality in 2001, after a small number of events where flight crews were partially incapacitated, most likely caused by engine oil fumes (Safety Regulation Group, 2004). This report addressed the effect of cabin air contamination on the ability to safely fly and land the aircraft. It included analysis of the toxicity of aircraft lubricants and the presence of air conditioning duct contaminants.

1.2.1.4 House of Lords reports, UK, 2000 - 2008

The UK House of Lords has previously investigated this area resulting in recommendations for further research, clear guidelines for reporting events etc. *The Air Travel and Health* report was produced in 2000.

- Chapter 1: *Summary and Recommendations* (Science and Technology Committee, 2000g);
- Chapter 2: *Background to the inquiry* (Science and Technology Committee, 2000h);
- Chapter 3: *Regulatory arrangements* (Science and Technology Committee, 2000i);
- Chapter 4: *Elements of healthy cabin air* (Science and Technology Committee, 2000j);
- Chapter 5: *Providing a healthy cabin environment* (Science and Technology Committee, 2000k);
- Chapter 6: *Deep vein thrombosis, seating and stress* (Science and Technology Committee, 2000l);
- Chapter 7: *Other medical concerns* (Science and Technology Committee, 2000m);
- Chapter 8: *Wider issues* (Science and Technology Committee, 2000n);
- Chapter 9: *General conclusions* (Science and Technology Committee, 2000o).

In 2007 there was an inquiry into progress since the 2000 report - *Air Travel and Health: an Update* (Science and Technology Committee, 2007). Submissions to this inquiry were also available to members of the Expert Panel.

In 2008 the UK Government responded to the update - *Air Travel and Health Update: Government Response 2008* (Science and Technology Committee, 2008).

1.2.1.4.1 **Criticisms of Reports**

Former Senator John Woodley, who chaired the Australian Senate Inquiry, made a submission to the Expert Panel in which he stated:

> "Another concern which I have is with the Report of a House of Lords Inquiry into Air Travel and Health held in 2000 which made light of the effects of fumes in aircraft. I did meet with Lady Wilcox who chaired this Inquiry and she indicated to me that she felt that the evidence her committee had received on this issue was inadequate."
>
> (J. Woodley, 2009)

- Woodley had made a similar statement that he had concerns with the House of Lords report in his address to the 2005 BALPA conference:

> "At the same time as our Inquiry was underway, the UK House of Lords was also conducting an Inquiry into various aspects of aircraft health and safety. I met in London with the Chair of the Committee and also with the public servant who was the Secretary to her Committee, a most charming gentleman, who never left her side apart from a few minutes during lunch when he went to the toilet. While he was away she confided in me that she felt she was being "conned" by the bureaucrats and, having read the House of Lord's Report, I believe she was!"
>
> (J. Woodley, 2005)

1.2.1.5 Federal Aviation Authority (FAA), USA, 2002

- The FAA established a committee to review what is known about air quality in passenger cabins, the Committee on Air Quality in Passenger Cabins of Commercial Aircraft (CAQPPCA) which provided a number of recommendations - *The Airliner Cabin Environment and the Health of Passengers and Crew* (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002).
- The FAA then responded to the report - *Report to the Administrator on the National Research Council Report, "The Airliner Cabin Environment and the Health of Passengers and Crew"* (The Airliner Cabin Environment Report Response Team, 2002).

1.2.2 Political issues

- The health effects of contaminated cabin air have been the subject of considerable ongoing political debate in both Australia and the UK. A list of relevant Hansards (transcripts of political debates and speeches) from Australia and the UK is maintained by the Aviation Organophosphate Information site (Aviation Organophosphate Information Site, 2010a). The list of Hansards runs from 1999 to October 27 2009.
    - There was a major debate held on July 1 2009, the Hansard of which provides detail of the current UK situation.
- The Reverend John Woodley (former Australian Democrats senator who chaired an Australian Senate Inquiry into cabin air contamination) commented on the politics of aircraft health and safety at the BALPA conference (J. Woodley, 2005).

1.2.2.1 Communications between ASHRAE and other parties

- The President of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) sent the FAA and the European Aviation Safety Authority (EASA) a request to investigate and determine requirements for bleed air contaminant monitoring and solutions to prevent bleed air contamination (W. A. Harrison & ASHRAE, 2009).
- These two major regulatory agencies have responded:
  - The FAA was awaiting results from the ASHRAE/Battelle and ACER-RITE research programmes before making a decision on further steps to be taken (Bahrami, 2009).
  - The EASA was awaiting results from current research projects and also had prepared an Advanced Notice of Proposed Amendment to be released for consultation in the summer of 2009 (Goudou, 2009).

1.2.3 Conferences

- A number of conferences have been held in recent years to consider cabin air quality and safety including:
  - The International Cabin Safety Symposium, Quebec in 2008:
    - Chris Witkowski, Director of Air Safety, Health and Security from the Association of Flight Attendants presented a background of the issue from the perspective of the Association of Flight Attendants (Witkowski, 2008).
  - The *Solakonferansen,* Stavanger in 2007:
    - Cliff Barrow, from the UK Civil Aviation Authority Safety Regulation Group presented a summary of the Authority's conclusions regarding TCP and short chain organic acids and their effects on Flight Deck and Cabin Air Quality (Barrow, 2007).
  - The BALPA *Air Safety and Cabin Air Quality International Aero Industry Conference* held in 2005 (British Airline Pilots Association, 2005).
  - *International Congress on Occupational Health Conference*, Brisbane, 2000. Dr Chris Winder presented a background to Aerotoxic Syndrome (Winder & Balouet, 2000).

1.2.4 Media

- There have been a number of television programs about contaminated cabin air, and numerous print and online reports. The Aviation Organophosphate Information Site (AOPIS) maintains a list of relevant media events (Aviation Organophosphate Information Site, 2010b). Some of these video and newspaper articles were made available to the Expert Panel members.

1.2.5 Legal Cases

- Legal decisions include a recent Australian case - *Turner v Eastwest Airlines Limited*, Dust Diseases Tribunal of New South Wales (NSW) (Kearns, 2009):
    - The finding was in favour of the plaintiff, who had argued that a fume exposure that occurred in 1992, while she was working as a flight attendant, had caused ongoing respiratory illness.
    - In April 2010, The Supreme Court of NSW dismissed an application by East West Airlines for leave to appeal ("East West Airlines Limited v Turner [2010]," 2010).
    - The High Court of Australia subsequently dismissed the appeal by East West Airlines in August 2010.

1.2.6 Recent review documents

- The Panel reviewed a number of recent publications documents on this issue:

1.2.6.1 Cabin Air Quality in general

- *Cabin air quality: an overview* (Rayman, 2002).
- Report by the Aerospace Medical Association - *Cabin Air Quality* (Thibeault, 1997).
- *Air Quality in Aircraft* (J.D. Spengler & Wilson, 2003).

1.2.6.2 Smoke/fumes contamination

- *Aviation Contaminated Air Reference Manual* - This book by Susan Michaelis, an former pilot, is a comprehensive summary of the topic (Michaelis, 2007a).
- *Exposure to aircraft bleed air contaminants among airline workers: A guide for health care providers* (R. Harrison, Murawski, McNeely, Guerriero, & Milton, 2009):
    - Funded by the FAA Office of Aviation Medicine, and part of collaborative project between the Occupational Health Research Consortium in Aviation (OHRCA) and Air Transportation Center of Excellence for Airliner Cabin Environment Research (ACER CoE), this document provided a review of literature and guidelines for health professionals dealing with aircrew presenting with possible symptoms of exposure to cabin air contamination.
- *Exposure to oil fumes on aircraft: the counterpoint to claims that health and safety are not compromised* (Murawski, 2009a):
    - A review of the literature, which examines the history of health effects of fume events, under-reporting of fume events, safety risks, probable toxicity of contaminants, and whether concentrations of contaminants in events may be harmful to health.
- *The Current Debate - Preliminary report on Aerotoxic Syndrome (AS) and the need for diagnostic neurophysiological tests* (M. Hale & Al-Seffar, 2008):
    - A review for medical professionals to stimulate debate and raise awareness of the possibility of an ‘Aerotoxic Syndrome’ existing.

- *Hazardous Chemicals on Jet Aircraft: Case Study - Jet Engine Oils and Aerotoxic Syndrome* (Winder, 2006b).
    - Reviews the causes, frequency, and outcomes of bleed air contamination.
- *Aircraft air quality incidents: symptoms, exposures and possible solutions* (C. van Netten, 2005b):
    - Reviews toxicology, exposure and health effects of exposure to contaminated cabin air. Also discusses a method of cabin air sampling.
    - This was also presented at the BALPA 2005 Contaminated Cabin Air conference (C van Netten, 2005).
- *In-flight smoke and fumes* (Singh, 2004):
    - Review of the frequency, causes and management of smoke and fume events.

1.2.6.3 Submissions to the Expert Panel

- Dr van Netten provided a summary of his background in this area and the barriers he has found to research of the issue (C van Netten, 2009).
- Susan Michaelis provided a briefing to the Expert Panel on behalf of the Global Cabin Air Quality Executive (GCAQE) outlining the background to this topic and the concerns of the GCAQE (Michaelis, Loraine, & Murawski, 2008).

1.2.6.4 Textbook chapters

- The Handbook of Environmental Chemistry (2005) has several chapters that review this area:
    - *Aircraft Air Quality Incidents, Symptoms, Exposures and Possible Solutions* (C. van Netten, 2005a).
    - *Crew effects from toxic exposures on aircraft.* (Winder & Michaelis, 2005b).
    - *Aircraft air quality malfunction incidents: Causation, regulatory, reporting and rates* (Winder & Michaelis, 2005a).
    - *Occupational and Public Health Risks* (Murawski, 2005b).

1.2.7 Academic Theses

- PhD thesis by N Vakas: *Interests and the Shaping of an Occupational Health and Safety Controversy: The BAe146 Case* (Vakas, 2007).
- PhD thesis by Tosten Lindgren: *Cabin Air Quality in Commercial Aircraft - Exposure, Symptoms and Signs* (Lindgren, 2003).

1.3 Submissions to this inquiry

- In addition to the documents obtained directly by the researchers, the Panel received submissions from over 100 organisations and individuals. These included personal medical records, scientific

papers, case reports, and internal documents. All were available for consideration by the Panel members.

1.4 Objectives and scope

- The Panel and the research team approached this review by:
  1. Dividing each topic into a number of specific questions
  2. Accumulating and categorising the evidence that could be used to answer these questions
  3. Enabling the Panel to have ready access to the evidence.
  4. Critically appraising the relevant scientific studies
  5. Identifying areas where the Panel considered that further research was needed

- The Panel limited the scope of this review specifically to cabin air contamination due to internal leakage of chemicals into the air conditioning system. The Expert Panel did not include the health effects of allergens, microorganisms, or chemical contamination from external sources in this review.

2 Methods

2.1 Expert Panel on Aircraft Air Quality

2.1.1 Meetings

- The Expert Panel met on eight occasions from September 2008 to May 2010.
- The following people with special areas of knowledge agreed to meet with the Panel:
    - Ms Susan Michaelis - former airline pilot and author of a treatise on cabin air quality.
    - Dr Jonathon Burdon - respiratory physician with a particular interest in people with illness attributed to exposure to cabin air contamination incidents.
    - Professor Clement Furlong (by video conference link from Washington State) – a Research Professor of Genome Sciences and of Medicine at the University of Washington, who is undertaking commissioned research to determine whether blood tests can identify exposure to toxic substances following exposure to cabin air contamination

2.1.2 Document preparation

- Each section of this report was prepared by at least two Panel members, each using their specific areas of expertise. The Panel then reviewed the whole report.

2.2 Research

- As noted earlier, the Panel contracted an Occupational and Environmental Medicine consultancy group to provide research services for the Panel. There is a significant body of literature around this topic, which includes individual testimonies, governmental inquiries, expert opinions, incident reports, media reports, *in vitro* and animal studies, and human epidemiology studies. This research project attempted to accumulate all types of evidence, with a particular emphasis on scientific literature.

2.2.1 Call for evidence

- A formal letter was posted and emailed to interested organisations and people. The first letter was sent in the week of May 4 – 8 2009. A second round of letters was sent out in the week May 18 – 22 2009, to additional contacts identified by the members of the Expert Panel. A final reminder letter was sent to all organisations that had not responded in late June. The letter was also available online. Interested parties were able to upload their documents, submissions or contributions electronically or deliver them via post.
- Parties providing responses have been listed in Section 8.3**.**

- A total of 62 personal medical reports were also submitted.
- Although the literature search was completed by September 2009, significant information subsequent to that time has been included where relevant.

2.2.2 Database searches

- To ensure complete coverage of academic literature relevant to the issue, the databases CISDOC, NIOSHTIC, PUBMED, and EMBASE were searched with the following method:

Search no	*Search terms*	*Comments*
[1]	*Aeroplane OR airplane OR aircraft OR airline OR cockpit OR "passenger cabin" OR (flightdeck OR "flight deck")*	*Only screened in combination with other terms*
[2]	*Aircrew OR "flight attendants" OR "cabin attendants" OR "stewardesses" OR "stewards" OR "cockpit crew" OR "crew members" OR "flight deck crew" OR "airline pilots" OR "aircraft pilots" OR "aeroplane pilots" OR "airplane pilots" OR "flight engineers" OR "technical staff" OR passengers*	*Only screened in combination with other terms*
[3]	*"Fume event" OR "fumes" OR (odor OR odors OR odours) OR (smell OR smells) OR (vapor OR vapors) OR dust OR smoke OR (gas OR gases) OR (aerosol OR aerosols) OR particulates OR "engine oil" OR "jet oil" OR "hydraulic fluid" OR "tricresyl phosphate" OR TCP OR "carbon monoxide"*	*Only screened in combination with other terms*
[4]	*Neuropath* OR neurotox* OR neuropsych* OR neurolog* OR ("multiple chemical sensitivity" OR MCS) OR "chemical sensitivity" OR OPICN OR OPIDN OR "chronic fatigue" OR "lung disease" OR "incapacitation"*	*Only screened in combination with other terms*
[5]	*Aerotoxic*	
[6]	*"Cabin air" OR ([1] AND "air quality")*	
[7]	*[2] AND ("cabin air" OR "air quality")*	
[8]	*[3] AND [1]*	
[9]	*[3] AND [2]*	
[10]	*[4] AND [1]*	
[11]	*[4] AND [2]*	

Table 1: Database search strategy.

- Notes: Documents reviewed were restricted to those dealing with cabin air contamination due to internal contaminants.

2.2.3 Document structure

- The Report has been structured to address what were considered to be the most pertinent questions, to demonstrate clearly how the Panel arrived at the opinions expressed in the Report and to show where the Panel considered the need for further research.
- This review has been structured in a question format; the reason being that science (and evidence-based medicine) works by designing experiments/trials to answer well defined questions. By

breaking the topic down into very specific questions, the pertinent evidence is presented in a style that allows rapid yet detailed analysis.

2.2.4 Reference Management

- A specially developed private wiki was created to allow the Panel to collaborate on the document. Through this wiki, panel members had access to the PDFs of the submissions and documents that are described and referenced in the 'Description of Evidence' sections. Successive drafts of the report were also created using the wiki.

2.2.5 Epidemiological review

- Epidemiological papers were independently reviewed by an epidemiologist, Dr D. McLean, from Massey University, New Zealand, see section 8.6 (McLean, 2009).

3 Defining the exposure

3.1 Introduction to the evidence

- The Expert Panel resolved to focus on cabin air contaminants that were introduced from within the aircraft; more specifically on cabin air contamination from the introduction of engine oil and hydraulic fluids (and their pyrolysed products) into bleed air. This first section has focused on the oils and fluids that have the potential to be introduced into cabin air.
- Reviews that address this issue included:
    - A review of reported cases in the United States Air Force (USAF) during the period 197-1980, due to a variety of sources including electrical fire or mechanical malfunction (Rayman & McNaughton, 1983)
    - An Aviation Safety Spotlight article reviewing incidents in the Australian Defence Force (ADF) (Singh, 2004).
    - A review of hazardous chemicals on jet aircraft (Winder, 2006b).
    - *The Aviation Contaminated Air Reference Manual* by Susan Michaelis provided an extensive database of literature relevant to this issue (Michaelis, 2007a). An editorial for an earlier book gave an overview of some of the relevant issues (Michaelis, 2002).
    - A review by the Office of Aerospace Medicine of the FAA in the USA reviewing Aerospace toxicology reviewed cabin air contamination issues (Chaturvedi, 2009).
- Although other potential cabin air contaminants have been identified, for example pathogens and ozone, these have not been included in this review, although they have been mentioned where relevant.
- Each topic has been divided into the component questions considered crucial to reaching a conclusion. The evidence relevant to each individual question was detailed and referenced for the Expert Panel members, who analysed and discussed the questions using their particular expertise.
- The questions were:
    1. How could cabin air contamination occur?
    2. How often do contaminated cabin air events occur?
    3. What could potentially contaminate cabin air?
    4. What biological evidence is there that exposure takes place?
    5. Does the environment influence the effect of the contaminants?

3.2 How can cabin air contamination occur?

3.2.1 What are the engineering features that allow cabin air contamination to occur?

3.2.1.1 Description of evidence

- In modern jet airlines, outside air to the aircraft cabin is supplied via the engines (or during takeoff, when air cannot be spared from the engines, air is supplied from the auxiliary power unit (APU), which is also jet powered) (van Netten, 1998).
- In some aircraft, the APU is responsible for providing power to the aircraft when it is on the ground.
- The use of 'bleed air' from the engines and APU is useful as it is a convenient source of heated, pressurised air when aircraft can be cruising at levels of up to 41,000 feet and at outside temperatures as low as -60^{o} Celsius.
- When taken from the compressor unit, the bleed air is at a temperature of at least 170^{o}C and is passed into an Environmental Control System (ECS) and an Air Conditioning Pack (ACP), which condition the air to the appropriate pressure and temperature for the aircraft cabin.
- Some aircraft contain catalytic converters for the removal of ozone from the outside air, as ozone concentrations increase at higher altitudes and certain latitudes.
- Contamination of the bleed air can occur for a variety of reasons, including failure of an oil seal in an aircraft engines or APU, or poor servicing practices.
- The design of the seals can also contribute to oil contamination.
- Contamination of the air supply can also come from outside the aeroplane, for example from de-icing fluids or exhaust fumes from other aircraft whilst still on the ground.
- A mixture of recirculated air and bleed air supplies the aircraft cabin environment. The recirculated air is often filtered using a high efficiency particulate air (HEPA). This filter removes micro-organisms and other particulate contaminants in the recirculated air but does not remove other contaminants such as volatile organic compounds (BOEING Australia Holdings Pty Ltd, 2009). However, these filters are only fitted to new generation aircraft types.
- An overview of the engineering aspects of air conditioning systems is available in the SAE aerospace information report (SAE Aerospace, 2007).
- Most of the relevant evidence has related to the design and engineering of modern pressurised aircraft. Most of the available evidence has been drawn from official government reports and inquiries, particularly in the annexes to the UK COT report (2007), accident investigation reports (AIR), and documents in submissions to the Panel from the aviation industry.

3.2.1.1.1 **Accident Investigation Reports (AIR)**

- Some of the most detailed and most easily understood evidence regarding the design of bleed air systems was found in some in-depth accident investigation reports from the UK, most notably:
    - An extremely detailed explanation of the bleed air system of the BAe146, including detailed schematic diagrams (Air Accidents Investigation Branch, 2004a, 2004b).

- Another Air Accidents Investigation Branch (AAIB) investigation report described the details of the bleed air system in the B757 aircraft (Air Accidents Investigation Branch, 2005).
- In another reported incident, cabin air taken from the APU inlet was contaminated with de-icing fluid when the APU was started soon after the aircraft was de-iced (Air Accidents Investigation Branch, 2006b).

3.2.1.1.2 **Industry Documents**

- Ullah of Allied Signal, a major manufacturer of APUs, discussed why oil seal leaks occur and proposed that this was the primary cause of odour in the cabin (Ullah, 1996) .
- BAe Systems has issued a number of Inspection Service Bulletins (Inspection Service Bulletins: BAe146 series/AVRO 146RJ series):
  - Inspection Service Bulletin 21-150 and 21-156 relates to inspection of various parts of the air conditioning packs and APU to help prevent future contamination of bleed air with engine oils/hydraulic fluids in their BAe146 aircraft (BAE Systems, 2002a, 2002b).
  - These documents formed part of the submission by Honeywell (Honeywell, 2009).
- CASA Airworthiness Directives (AD) regarding modifications of the BAe146 APU based on service bulletins issued by BAe were issued by CASA, for example AD/BAe146/105, and AD/BAe146/105 amendment 1 (Civil Aviation Safety Authority, 2003, 2005).
- Honeywell, an engine manufacturer, focused on four engine components in its attempts to reduce the number of reported cabin odour events (Honeywell, 2009) [page 4]. These components were the number 1 seal, the air diffuser, the number 2 bearing pack and the number 9 seal.

3.2.1.1.3 **Previous Government Inquiries/Government Reports**

- Several reviews included detailed information about the BAE146 aircraft, as this aircraft had been a major source of complaints about cabin air contamination.
- Senate Rural and Regional Affairs and Transport References Committee, Australia:
  - The Senate Report provided a well summarised explanation of the air supply systems in the BAe146, air flow rates and which engines supplied the cockpit and passenger cabin (Senate Rural and Regional Affairs and Transport References Committee, 2000a) [pages 9-11]. The source of cabin air odours was described as having:

> "..predominantly been determined to be due to minor systems failures such as leaks from oil seals on aircraft engines and APU."
>
> (Senate Rural and Regional Affairs and Transport References Committee, 2000a)

- Committee on Toxicity, UK:
    - The following bleed air schematics and other technical documents relating to the bleed air system were submitted to the COT in the UK and included in Annex 5:
        - Draft description of generic air conditioning system (Civil Aviation Authority);
        - Diagram of air conditioning system layout in BAe146 (Civil Aviation Authority, 2006c);
        - A brief overview of the 535E4 internal air system (Civil Aviation Authority, 2006b);
        - A document regarding B757 Engineering Issues (Rolls Royce, 2006);
        - A report of a meeting of the COT secretariat and the main aircraft/engine manufacturers (Committee on toxicity of chemical in food consumer products and the environment, 2006b).

- Committee on Air Quality in Passenger Cabins of Commercial Aircraft (CAQPCCA), USA:
    - This report made reference to a description of bleed air systems, including a diagram of a fan-jet engine demonstrating bleed port locations (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002) [pages 54-59].

3.2.1.1.4 **Scientific Publications**

- Relatively few papers described in detail potential ways in which contamination of the cabin air supply with engine oils and hydraulic fluids could occur:
    - A specific description of the bleed air system of the BAe146 aircraft was included in a paper by van Netten (van Netten, 1998).
    - A detailed explanation of the environmental control system was included in a review by Spengler and Wilson (J.D. Spengler & Wilson, 2003).
    - A book chapter by Best and Michaelis provided some examples of engineering problems that have caused fume events in the past (Best & Michaelis, 2005).
    - Murawski provided a good summary of the different ways by which cabin air contamination could occur:

> "Oil or hydraulic fluid can contaminate the air conditioning and supply systems as a result of deficient maintenance, operation, or design, or some combination thereof. For example, oil can leak through worn or defective seals that are intended to separate and seal the wet and dry sides of the engine. Or, sometimes maintenance workers will accidentally overservice an engine or APU, causing spillage. Alternatively, maintenance may spill oil or hydraulic fluid when filling a reservoir, sometimes because of broken equipment. APU failure can also cause oil to enter the ventilation air. Also, leaks and spills of hydraulic fluid can lay in areas of the cowling or fuselage and then later become ingested into the air inlet of the APU, engine, or air conditioning systems."
>
> (Murawski, 2008)[page 8]

- A report by the FAA in the US discussed the potential for dislodgement of solid particles contained within previously deposited carbonaceous deposits on air ducts during certain times during flights. This material could form solid aerosols in the cabin air (Chaturvedi, 2009).

3.2.1.2 Interpretation of evidence

- A number of contaminants resulting from mechanical and electrical failures, as well as normal environmental odours, could be responsible for aircraft cabin air contamination including odours from electrical failures (wiring etc.), galley oven smoke, fumes and odours, APU failures, engine and hydraulic fluid contaminants, and ozone.
- Modern aircraft, designed and built after the B707 era, and used in Regular Public Transport (RPT), have a system that ducts air from the engine compressor to pressurise and heat the aircraft cabin. This air is primarily unfiltered and any contaminants that enter the inlet of the engine could be ducted into the aircraft cabin environment. These contaminants include engine oil, hydraulic fluid, exhaust gases from other aircraft, or any environmental contaminant that might be introduced into the engine inlet. As the aircraft cabin is an enclosed environment, the amount of cabin air that is re-circulated can vary dependent on aircraft type. Generally between up to 75% of cabin air is re-circulated and so it would be difficult to remove all the contaminated air within a short period of time.
- Poor maintenance standards and non-compliance with manufacturers' recommendations regarding engine design or engine seals are the main problems that could result in contamination of cabin air (Kearns, 2009).
- Engine seal design is another contributing factor to the potential for fumes exposures. The main shaft-bearing seals may be labyrinth or carbon seals (depending on the engine type), and the tolerance and wear on the seals will determine the extent of the exposure to fumes (National Research Council, Committee on Air Quality in Passenger Cabins of Commercial Aircraft, & Board on Environmental Studies and Toxicology, 2001).

3.2.2 Which types of planes and engines are vulnerable to contaminated cabin air events?

3.2.2.1 Description of evidence

3.2.2.1.1 **Reviews/Books**

- *The Aviation Contaminated Air Reference Manual* contains a table of UK reported contaminated air events from the year 2006 (from all available UK sources) by aircraft type - with a total of 27 different aircraft types listed (Michaelis, 2007a) [page 233]. Four aircraft types made up nearly 80% of the reported events in the UK: Boeing 757 - 42.29%; BAe146/RJ - 22.19%; Embraer 145 - 8.86% and Airbus A320 - 6.19%

- A breakdown of 470 known US fume events by aircraft type showed that 48 types of aircraft had at least one reported contaminated air event, from small turboprop aircraft to wide-body jet aircraft (Murawski, 2008)[page 3].

3.2.2.1.2 **Scientific literature**

- The first reports of contamination of bleed air in aircraft cabins came in the 1950s, from both military and commercial aircraft during the period when the practice of drawing pressurised cabin air from 'bleed air' was first developed (Kitzes, 1956).
- Susan Michaelis mentioned 1667 incidents on the Boeing 757 (Michaelis, 2003).
- An Australian article reporting a survey of health symptoms contained a table showing reports of fume events in several different aircraft types (the main offenders being BAe146 and B757), including some incidents in Airbus, MD80, 737, 767, DC10 and DK aircraft (A. Harper, 2005a, 2005b).
- A report by van Netten contained a table of incidents on 7 aircraft types in the US (C. van Netten, 2005b).

3.2.2.1.3 **Previous Government Inquiries/Reports/Official Documents**

- The Senate Rural and Regional Affairs and Transport References Committee focused specifically upon contamination in the BAe146 aircraft and concluded that the aircraft was vulnerable to contaminated air events. The Committee made several recommendations in an attempt to address this vulnerability (Senate Rural and Regional Affairs and Transport References Committee, 2000a).
- Appendix 3 of the Senate report listed 16 Australian Transport Safety Bureau (ATSB) reports of "oil fumes" in the cabin air of BAe146, B737, Airbus A340, B747, B727, B767 and Fokker F28 aircraft from 1991-1999.
- A report by the Australian Defence Department showed evidence of cabin air contamination in the cockpits of Hawk, F-111 and Hercules C-130 aircraft (Hanhela, Kibby, De Nola, & Mazurek, 2005). This report also contained a table showing that smoke and fumes incidences occurred in a wide variety of Australian military aircraft in the years 1998-2003.
- A report investigating cabin air contamination in Hercules military aircraft found traces of TCP in air filter bags (but not in the air samples) from suspect aircraft (Kelso, Charlesworth, & McVea, 1988).
- A 2004 Airworthiness Directive from the FAA showed that, in the years prior to 2004, certain Rolls Royce engines were prone to rapid failure of the No. 1 bearing that could result in smoke in the cabin (Federal Aviation Administration, 2004).
- The FAA responded to the 2002 CAQPCCA report and acknowledged that:

> "FAA rulemaking has not kept pace with public expectation and concern about air quality and does not afford explicit protection from particulate matter and other chemical and biological hazards. 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."
>
> (Federal Aviation Administration, 2005)

- The ATSB provided the Panel with a list of reported incidents in Australia from 1999 to September 2009 (Australian Transport Safety Bureau, 2007):
    - The data indicated an upward trend in reported fume events.
    - July 2001 to June 2006: 53.4% of reported incidents involved fumes, 37.4% smoke, 7.6% fire. 4 events were due to cigarette smoke.
- Also from the *ATSB Fumes Register* 1999 to September, 2009 (Australian Transport Safety Bureau, , database):
    - There were 684 reports of smoke, fumes or fire in the Air Safety Incident Reports (ASIRs) to the ATSB from 1999 to September 2009.

3.2.2.1.4 **Air Accident Investigation Reports**

- In 1984, the National Transport Safety Board (NTSB) conducted an investigation into the possible effects of bleed air contamination on pilot incapacitation in the Garrett TPE 331, and concluded that such contamination was not likely to occur (National Transportation Safety Board, 1984).
- In 1997, an investigation by the ATSB into an incident in a BAe146, led to a recommendation by the Bureau of Air Safety Investigations that British Aerospace address the deficiencies that allowed the entry of fumes into the cockpit (Australian Transport Safety Bureau, 1997).

3.2.2.1.5 **Documents submitted to the Panel**

- Fume events on BAe146s were mentioned in many personal submissions from flight crew (for example those by Devine, Michaelis and Queen) and incidents on Boeing 757 aircraft were mentioned by Frith and Watson (Devine, 2009; Frith, 2009; Michaelis, 2009a; Queen, 2009; Watson, 2009).
    - Reports were also received regarding a range of other aircraft types:
        - A report detailed several cabin air contamination incidents in the GHC8-202/315 series (Dash-8) turboprop aircraft in Australia (Nivison, 2009).
        - An account by an air hostess detailed incidents on MD-80 aircraft (Bradford, 2002).
        - A personal submission included an engineering report on a fume incident on an A321 aircraft (Denney-Sandefer, 2009).
        - An ex-Cathay Pacific pilot reported fume events on Boeing 747 and 777 aircraft (Holmes, 2009).
        - A survey of Independent Pilots' Association (IPA) members who rang the IPA revealed that:

> "the experiences came from range of aircraft types, from B747 to Executive jets and included most civil airliner types...this questioning bore out the fact that Cabin Air Contamination occurs on most other types of gas turbine powered aircraft."
>
> (Independent Pilots Association, 2009)

- Honeywell submitted documents that showed the older Honeywell ALF502 engines were at least 5 times more prone to cabin odour events than this manufacturer's newer LF507 engine (Honeywell, 2009).

3.2.2.2 Interpretation of evidence

- In the UK, evidence from the AAIB demonstrated that the B757 aircraft (engine type RB211) had the most smoke/fumes events. In Australia, according to ATSB ASIR reports, the B767 aircraft had the highest number of incidents of smoke/fumes exposures (Australian Transport Safety Bureau, 2007). This aircraft type has two different engine types, the RB211-524 and the GF6-8OC. As the reports do not stipulate the engine type involved, it is difficult to determine which engine is implicated most often.
- The Air Transport Safety Board of Australia (ATSB) outlined the number of Air Safety Incident Reports (ASIR) per aircraft type related to fumes events (Australian Transport Safety Bureau, 2007) [page 42]. The B767 accounted for 26.4% of all fumes exposures reported to the ATSB (July 2001 to June 2006), despite having only about 24 B767s on the Australian Register (see Table 2). The B737, with about 160 aircraft on the Register, has 28.6% of the fume events reported, and the B747, with 36 aircraft on the Register, accounts for only 4.3% of the fume reports. Some foreign operators operating in Australian airspace lodged ASIRs that were included in this data.
- In summary:
    - From 1999 to September 2009 the ATSB received 684 Fumes, Smoke or Fire ASIRs.
    - The data indicated an upward trend in fumes exposures.
    - From July 2001 to June 2006 ASIRs comprised: 53.4% involving fumes, 37.4% involving smoke and 7.6% fire. There were 4 cigarette smoke events.
- Analysis of the data supplied by the ATSB, collating aircraft type and engine manufacturer with fumes events, demonstrated that the Boeing 767 represented 26.4% of regular public transport (RPT) fumes exposures and so appeared to be the aircraft responsible for the majority of cabin fume events in Australia (Australian Transport Safety Bureau, , database). Although the Boeing 737 was responsible for most reported incidents, there are approximately four times as many 737s in operation in Australia than there are 767s so the rate of incidence per aircraft for the 767 is actually higher than that for the 737.
- However, data from the UK, in Table 3 below, pointed mainly to the Boeing 757 aircraft, with a total of 444 fumes exposures and a total of 42.29% of the total fumes exposures for RPT operations (Michaelis, 2007a) [page 233].

Aircraft make and model	*Occurrences Involving Fumes*	*Percent*
Boeing Co 737	*40*	*28.6*
Boeing Co 767	*37*	*26.4*
Boeing Co 747	*6*	*4.3*
British Aerospace Plc BAe146	*24*	*17.1*
De Havilland Canada DHC-8	*13*	*9.3*
Fairchild Industries Inc SA227	*7*	*5.0*
Airbus Industrie A380	*3*	*2.1*
Other aircraft	*10*	*7.1*
Total	*140*	*100.0*

Table 2: Aircraft make and model with reported fumes events. July 2001 to June 2006 ATSB ASIR (Australian Transport Safety Bureau, 2007).

Type	*Events*	*%*	*Type*	*Events*	*%*
Airbus A300	*1*	*0.09*	*Boeing 767*	*9*	*0.86*
Airbus A319	*48*	*4.57*	*Boeing 777*	*28*	*2.67*
Airbus A320	*65*	*6.19*	*Bombardier Dash 8*	*22*	*2.10*
Airbus A321	*7*	*0.67*	*Cessna CB560XL*	*1*	*0.09*
Airbus A321	*7*	*0.67*	*Concorde*	*3*	*0.29*
Airbus A330	*1*	*0.09*	*Dornier 328*	*2*	*0.19*
Airbus A340	*2*	*0.19*	*Douglas DC-10*	*1*	*0.09*
ATR 42	*1*	*0.09*	*Embraer 145*	*93*	*8.86*
BAe146/RJ	*233*	*22.1*	*Fokker F70/F100*	*4*	*0.38*
BAe ATP	*16*	*1.53*	*Hawker HS125*	*1*	*0.09*
Boeing 737	*45*	*4.29*	*Lockheed L-188*	*1*	*0.09*
Boeing 737	*45*	*4.29*	*Saab 2000*	*2*	*0.19*
Boeing 747	*15*	*1.43*	*Saab 340*	*3*	*0.29*
Boeing 757	*444*	*42.29*	*Unknown Type*	*2*	*0.19*
			TOTAL	*1050*	*100*

Table 3: UK Reported contaminated air events by aircraft type (Michaelis, 2007b).

- The Panel considered that an investigation should be undertaken to determine engine type, age of the aircraft engines and airframes involved in the majority of fume events. The exposure rates for the B767 in Australia were far higher than those reported for the BAe146 and further investigation is required.
- The Panel was told that aircraft engines were analysed for fumes at the time of manufacture. No further testing is undertaken subsequently until either the engine fails or the engine is removed and overhauled after a component failure.
- The Panel considered that engines and the air conditioning system should be subject to a regular testing schedule to look for possible factors contributing to contamination. Currently, maintenance regimes and CASA Regulations have no provision for such testing.

- Currently, no information has been collected to determine the increased likelihood of system failures in ageing aircraft. Further data should be gathered to determine any correlation between the age of an aircraft and increased risk of system failures contributing to cabin air contamination.

3.2.3 Does cabin airflow affect exposure?

3.2.3.1 Description of evidence

- Hocking provided a detailed analysis and discussed the benefits and costs of increased outside air provision in aircraft (Hocking, 2002). This article also discussed the various measurements of airflow that were most useful in comparing aircraft cabin air quality with building air quality (volume units versus air changes per hour).
- The Strom-Tejsen group investigated the effects of airflow on symptoms in simulated aircraft (Strom-Tejsen, Wyon, Lagercrantz, & Fang, 2007).
    - Simulated seven hour flights showed that symptoms of headache, dizziness and claustrophobia increased when cabin airflow was reduced to increase relative humidity. The authors suggested this could be due to increased contaminants.
- Another group investigated ventilation effectiveness in an aircraft cabin mock-up, and found variations in airflow throughout the cabin (A. Wang, Zhang, Sun, & Wang, 2006). However, individual air ducts were not included in this study.
- The Australian Senate Report noted that modifications to cabin air flow had no effect on reports of contaminated air:

> "Since the Fox Report, Ansett has made some modifications to airflow in this area; however these modifications have proved ineffective (numbers of Fume Reports have not decreased) or have proven impractical and have had to be reversed (extraction fans in the toilet caused the smoke alarm to malfunction). It is also of note that Ansett's modification to the cabin ventilation system; the repositioning of air vents to higher on the interior fuselage, was completed by August 99 as planned. This did not produce any noticeable reduction in fume reports."
>
> (Senate Rural and Regional Affairs and Transport References Committee, 2000a) [page 91, s4.72]

- A report by the FAA discussed the potential for dislodgement of solid deposits on air ducts into the airflow during times of high demand for cabin heat or during take-off and landing (Chaturvedi, 2009).

3.2.3.2 Interpretation of evidence

- The Panel noted that levels and extent of risk in potential exposure could be dependent on the source of the air circulating in the cabin. For example, in the BAe146, different engines supply

different air conditioning packs, which then supply air to different parts of the aircraft. Therefore, as an example, there may be different levels of exposure in the cockpit compared with the cabin.

3.2.4 What are the findings from previous investigations of cabin air contamination?

3.2.4.1 Description of evidence

3.2.4.1.1 **Australia**

- The 2000 Australian Senate Inquiry found that the source of cabin air odours had:

> "..predominantly been determined to be due to minor systems failures such as leaks from oil seals on aircraft engines and APU."
>
> (Senate Rural and Regional Affairs and Transport References Committee, 2000a)

3.2.4.1.2 **UK**

- The Committee on Toxicity of chemicals in food consumer products and the environment (COT) made the following observation about fume events:

> "An oil/hydraulic fluid smoke/fume air contamination incident is an event in which a small quantity of oil/hydraulic fluid released into the compressor stage of the engine, due to an oil seal failure, is extracted into the bleed air supplying the aircraft air conditioning system resulting in the formation of an oil mist or odour in the aircraft. The leaked oil/hydraulic fluid is subject to a range of temperatures within the engine and aircraft air conditioning system that might cause thermal decomposition of the oil/hydraulic fluid. Not all odours detected within the aircraft cabin originate from oil contamination of the air supply, for example, toilet and galley odours also occur, and it is not possible to define the cause of all smoke/fume air contamination incidents. It has been estimated from information provided by three airlines that overall, smoke/fume incidents associated with possible explanatory faults identified by engineers (engineering-confirmed smoke/fume incidents) occur in around 0.05% of flights (sectors) but that the incidence may be higher than this in some circumstances, depending on airframe, engine type and servicing."
>
> (Committee on toxicity of chemicals in food consumer products and the environment, 2007k) [page 8]

- A report by the UK CAA included an analysis of aircraft conditioning duct contaminants (Safety Regulation Group, 2004) [chapter 2].

3.2.4.1.3 **US**

- The 'Committee on Air Quality Passenger Cabins of Commercial Aircraft' report found that contamination of bleed air could occur and recommended that more research should be undertaken (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002).

3.2.4.1.4 **Switzerland**

- The report on aircraft AVRO 146-RJ 100 HB-IXN, operated by Swiss International Air Lines Ltd under flight number LX1103 on 19 April 2005, regarding an incident on approach to Zurich-Kloten Airport, found that:

> "Smell and fumes in the cockpit occurred during operation of HB-IXN even before the serious incident.
>
> The indicators for bearing damage in engine No. 1 were not analysed and pursued to eliminate the defect before the serious incident.
>
> The aircraft was released for flight operations several times, even though the defect had not been rectified.
>
> The technical status of the aircraft with regard to air-conditioning pack No. 1 was not explicitly apparent to the crew of flight LX 1103 from the work orders."
>
> (Swiss Air Accident Investigation Bureau, 2006)

3.2.4.2 Interpretation of evidence

- The Australian Senate Inquiry into the BAe146 pointed to poor maintenance practices and engine design as a cause of poor cabin air quality and this has been echoed throughout previous government investigations as outlined below (Senate Rural and Regional Affairs and Transport References Committee, 2000a):
    - National Research Council: *The Airliner Cabin Environment - Air Quality & Safety,* 1986 (National Research Council, Committee on Airliner Cabin Air Quality, Board on Environmental Studies and Toxicology, & Commission on Life Sciences, 1986).
    - UK House of Lords Inquiry, 2000 (Science and Technology Committee, 2000g, 3596-609).
    - National Research Council: *The Airliner Cabin Environment and the Health of Passengers and Crew,* December, 2001 (National Research Council, et al., 2001).
    - COT: *The Cabin Air Environment, Ill-Health In Aircraft Crews And The Possible Relationship To Smoke/Fume Events In Aircraft*. 2007 (Committee on toxicity of chemicals in food consumer products and the environment, 2007k).
    - House of Lords 2007 (Science and Technology Committee, 2007).

- The Panel noted that in March 2010, the US approved an amendment that directed the FAA to investigate the use of fume detection and removal devices. As many airlines operate in US airspace and carry US citizens, this directive is likely to be adopted throughout the global industry (Feinstein, 2010).

3.3 How often do contaminated cabin air events occur?

3.3.1 What are the reporting systems in place?

3.3.1.1 Description of evidence

3.3.1.1.1 **Australia**

- ATSB requirements for Immediately Reportable Matters (IRM) under both the Air Navigation Act (AN) and the Transport Safety Investigation Act (TSI Act) included the following:

> "1.3.1 Immediately reportable matters
>
> • accidents
>
> • violations of controlled airspace
>
> • breakdown of separation and airprox occurrences
>
> • fire, smoke, explosion or fume occurrences
>
> • crew injury or incapacitation
>
> • uncontrolled engine failures
>
> • fuel exhaustion occurrences."
>
> (Office of Legislative Drafting and Publishing Australia, 1920, 2003)

- The answer to a Senate question tabled by Senator O'Brien, 31 July 2006, included that:

> "The Civil Aviation Regulations 1988 require the reporting of defects, such as noxious fumes in the cabin, to the Civil Aviation Safety Authority."
>
> (O'Brien & Campbell, 2007)

- A submission by National Jet Systems (NJS) to the Senate Committee stated that:
  - An ASIR on any aviation safety issue may be submitted directly to the ATSB by anyone involved in the operation of aircraft.
  - Individuals who wish to remain anonymous to their employer have the option of raising a Confidential Aviation Incident Report (CAIR) to the ATSB (Senate Rural and Regional Affairs and Transport References Committee, 2000j).
- Cabin air incidents reports can be submitted through a number of bodies and procedures including CASA, ATSB, ASIR, CAIR, REPCON and Individual Company reporting.
  - The Civil Aviation Act 1988 required the reporting of defects, such as noxious fumes in the cabin, to the Civil Aviation Safety Authority (Office of Legislative Drafting and Publishing, 1988).
  - An ASIR on any aviation safety issue may be submitted directly to the ATSB by anyone involved in the operation of aircraft. Individuals who wish to remain anonymous to their

employer previously had the option of raising a CAIR to the ATSB. An ASIR on any aviation safety issue may be submitted directly to the ATSB by anyone involved in the operation of aircraft.

- ATSB Australian Transport Safety Bureau – REPCON Report – Anonymous reporting system:
  - Formerly individuals who wished to remain anonymous to their employer had the option of raising a CAIR to the ATSB. This was phased out and the REPCON report was created.
- Company reporting systems incorporate service difficulty reports, incident/occurrence reports.

- A wide range of data was available but was often inconsistent or incomplete.

3.3.1.1.2 **Germany**

- A submission to the Panel by a German journalist stated:

> "According to German law crews are obliged to report such events to the respective authorities (the Civil Aviation Authority of Germany – the Luftfahrt-Bundesamt (LBA) and to the BFU), depending on the nature of the event. If a crewmember became impaired a report has to [be] filed with the BFU in order to investigate. If an unsafe condition is to be expected that may impact anybodies welfare in the future a report has to be filed with the LBA, according to § 5 of the German LuftVO."
>
> (van Beveren, 2009)

3.3.1.1.3 **New Zealand**

- The Civil Aviation Authority of New Zealand *Mandatory Occurrence Notification and Information*, states that, for all aircraft, incidents should be reported to air traffic control and then to the CAA in writing on Form CA005 (Civil Aviation Authority of New Zealand, 2007). The guidance notes gave examples of incidents that should be reported, including the following events:

> "flight crew incapacitation in flight
>
> smoke, or toxic or noxious fumes, in the aircraft
>
> contamination of the cabin, cockpit, or baggage compartment"
>
> (Civil Aviation Authority of New Zealand, 2007)

3.3.1.1.4 **United Kingdom**

- The COT report noted the official reporting systems available to pilots in the UK included use of a Tech Log, which is a means of communication between aircrew and engineers, and Air Safety

Reports (ASR), which is a formal means of report for any safety incident deemed worthy of reporting. Of note:

> "Pilots do not necessarily have to make an ASR in relation to cabin fume events. In addition, airlines screen the ASRs they receive with regard to whether a MOR should be raised and will submit any ASR a pilot considers reaches the threshold for a MOR to the CAA. The CAA classification of MORs can be conceived as a pyramid ranging from a very small number of accidents that require major and immediate intervention through incidents, undesirable events and abnormal variations to normal variations which constitute the majority of MORs received. Cabin fume events are most likely not to reach the threshold for a MOR or, if they do, they are most likely to represent a small part of the abnormal variations/normal variations. Individual airlines would consider the threshold for submitting MORs on a case-by-case basis. Most cabin fume events would, if reported, be documented as ASRs or possibly as Tech Logs but would not necessarily generate an automated Flight Data Monitoring (FDM) record."
>
> (Committee on toxicity of chemicals in food consumer products and the environment, 2007k)

- Since the COT report was published, Commission Regulation (EC) No. 859/2008; Council Regulation (ECC) 3922/91 [as last amended] regarding Occurrence Reporting has been released (European Union, 2008). This regulation has obliged pilots in the UK (and the rest of Europe) to report all defects, including fumes.
    - All cases of smoke, toxic or noxious fumes must be reported.
    - EASA incident reporting – see *article 4 & emergencies* [page 6] *DIRECTIVE2003/42/EC* (European Union, 2003).
    - Each European Union (EU) country that has adopted the EU regulation, including the UK, has a different Mandatory Occurrence Reporting (MOR) system. The wording in the UK Act mirrored the wording in this Directive and mandated that "toxic, noxious fumes" should be reported as a MOR (Civil Aviation Authority, 2009).
- The UK has two other reporting systems: an individual confidential pathway for aircrew to report incidents to the CAA without having to go through their employer or their line management and a confidential Human Factors Incident Reporting Programme (Science and Technology Committee, 2007) [Q298 and Q299]).

3.3.1.1.5 **United States**

- The FAA operates the Service Difficulty Reporting Database and Accident/Incident Data System (AIDS) and Aviation Safety Reporting System (ASRS).
    - FAA Order 8020_11c (Federal Aviation Administration, 2010).
- FAA (2006) 14 CFR 121.703 mandated reporting of defects and toxic noxious fumes:

> "(a) Each certificate holder shall report the occurrence or detection of each failure, malfunction, or defect concerning—
>
> (5) An aircraft component that causes accumulation or circulation of smoke, vapor, or toxic or noxious fumes in the crew compartment or passenger cabin during flight;"

(National Archives and Records Administration, 2010)

- Other avenues are available to crews for reporting incidents in the US, including the National Transport Safety Bureau (NTSB), the American Society of Heating and Refrigeration Engineers (ASHRAE) and the American Automotive Society Aviation Section (AAS).

3.3.1.2 Interpretation of evidence

- The Panel observed:
    - Worldwide, there were many systems in place for reporting aircraft incidents and/or accidents. Every National Aviation Authority (NAA) has a separate system. However, there is currently no global reporting system. The benefits of a global information gathering system would outweigh any initial and ongoing costs.
    - Most NAAs have compulsory reporting of aircraft incidents; however, not every administration requires aircraft cabin air contamination incidents to be recorded. The differences between reporting systems in different jurisdictions creates difficulties in capturing the data required for a detailed analysis of aircraft cabin air contamination.
    - The EASA system covers most of Europe and so mandatory reporting of aircraft incidents, including aircraft cabin air contamination events, is being implemented across Europe.
    - Australia has the REPCON system, which enables confidential collection and analysis of data about incidents, with particular emphasis on flight parameters and phases of flight.
    - To enable full determination of a cabin air contamination event, statements from several sources within the aircraft (pilots, flight attendants, passengers or engineers) should be gathered at the time of the event, in order to gain 'real time data'. Currently, this information is rarely gathered, as the requirement for an in depth investigation often depends on whether anyone was seriously incapacitated, injured or became ill during the incident.
    - Cabin air contamination events are often complicated due to multiple possible contributing factors. Gathering very precise data is essential to identify the cause and assess the gravity of the defect.
    - Some airlines and employers have implemented their own reporting systems to analyse cabin air contamination events. To be successful these need to be well-resourced, supported at all management levels, and permit confidential reporting.
    - Most companies in Australia provide their employees with reporting systems in order to adhere to the procedures set down in their systems of maintenance. In theory, this information should be passed to the authorities (CASA and ATSB), as required by legislation. However, the Panel was told about an ATSB report on a 2007 incident that concluded that there was reluctance by flight crews to report any incidents to CASA and

the ATSB, that could result in serious consequences (ATSB, 2007). The Panel was told that the company concerned was not prosecuted in relation to this lack of reporting. This could undermine the reporting system.

- This was further illustrated by comments made by the head of the ATSB, Martin Doolan, in his media statement about this report:

> "We can often learn as much or more from occurrences like this as we can from investigating tragic accidents, I would like to remind all transport operators that safety is a shared responsibility that relies, in part, on the timely reporting of accidents and incidents."
>
> (ATSB, 2007)

- The European Organisation for Safety in Air Navigation described the importance of establishing 'Just Culture' principles, which encourage reporting of safety incidents:

> "This effective reporting culture depends on how those organisations handle blame and punishment."
>
> (European Organisation for the Safety of Air Navigation & Eurocontrol, 2006)

- Most investigative procedures reflect the Maintenance Error Detection Aid system developed by the Boeing Aircraft Company for the investigation of factors contributing to maintenance errors (Rankin, 2000).

3.3.2 What is the reported incidence through official channels?

3.3.2.1 Description of evidence

3.3.2.1.1 **Australia**

- Winder and Michaelis provided a table summarising the country-specific rates of cabin air contamination (Winder & Michaelis, 2005a) [page 213-4].
- In a submission to the Australian Senate Inquiry, Qantas provided the following information concerning reported contaminated air events:

> "Since 1996-97, the number of cabin air quality reports has increased. We believe this is due mainly to the greater awareness of the issue amongst passengers and crew. Even so, in 1999, less than 0.12 per cent of all BAe146 flights resulted in a cabin air quality crew report, and that is approximately one report in every 785 flights."
>
> (Senate Rural and Regional Affairs and Transport References Committee, 2000o) [page 37]

- In response to a question by Senator O'Brien in the Australian Senate in 2002, the following figures regarding mandatory reports of cabin air contamination in the BAe146 aircraft to CASA were provided:

> "As at 27 September 2002, 51 reports of cabin air contamination have been received since the issue of Airworthiness Directive (AD) BAe146/86 on 3 April 2001."
>
> (O'Brien & Campbell, 2002)

- In response to a question by Senator O'Brien in the Australian Senate in 2007, the following figures regarding mandatory reports of cabin air contamination in the BAe146 aircraft to CASA were provided:

> "(1) A total of 90 reports were received by CASA during the period 27 September 2002 to 5 October 2006. (2) (a) Refer attached table. (b) All reports were lodged by National Jet Systems. (c) Cabin air contamination reports in BAe 146 aircraft have declined over the years. CASA has overseen a program of modifications to address air contamination problems as well as requiring changes to the flight manual to ensure that the flight crew wear oxygen masks at the first instance of cabin air contamination to minimise the possibility of flight crew incapacitation."
>
> (O'Brien & Campbell, 2007)

  - A table showing dates of all 90 reports and the corrective action taken by the airline was also included by the Minister for Transport and Regional Services in his answer to the Australian Senate. This table can be seen in Appendix 7, section 8.7.

- A table of reported fume events over the last ten years to September 2009 was provided by the Australian Transport Safety Bureau in Australia (Australian Transport Safety Bureau, 2009).

- An investigation by the Bureau of Air Safety Investigation reported that:

> "The investigation found that smoke and fume contamination of cabin air is neither a new phenomenon nor a particularly rare event and that over time, it has been experienced in many aircraft types. The Australian experience has found that many complaints have been recorded against the BAe146 type."
>
> (Bureau of Air Safety Investigation, 1997)

- The Bureau of Air Safety Investigation reports demonstrate the nature of some Australian incidents (Bureau of Air Safety Investigation, 1997, 2001, 2002a, 2002b, 2003a, 2003b, 2003c).

- An ATSB report examined the trends in reports of aircraft incidents (Australian Transport Safety Bureau, 2007). This report included a section on fire/smoke/explosions or fumes.

- Australian Defence Force data for the last 10 years shows an incidence of 0.5 events per 1,000

hours of flying (Singh, 2004).

3.3.2.1.2 **Germany**

- A submission from the German Pilots Association quoted an answer to a German Parliamentary question stating that since 2004, the German Aviation authority had received 156 incident reports related to smoke or smells in aircraft (4.3% of the total of 3620 reports) (German Air Line Pilots Association & Schewe, 2009).

3.3.2.1.3 **UK**

- A report by the Royal Aeronautical Society discussed rates, studies and probabilities of Smoke and Fume incidents in transport aircraft (Royal Aeronautical Society & Cox, 2006) [pages 12-13].
- The Committee on Toxicity reported that:

> "It has been estimated from information provided by three airlines that overall, smoke/fume incidents associated with possible explanatory faults identified by engineers (engineering-confirmed smoke/fume incidents) occur in around 0.05% of flights (sectors) but that the incidence may be higher than this in some circumstances, depending on airframe, engine type and servicing."
>
> (Science and Technology Committee, 2007), [TOX/2006/39 Annexes 13, 14 and 18].

3.3.2.1.4 **US**

- The FAA conducted a review of the SDRS (Service Difficulty Reporting System) databases from January 1999 through November 2008. There were 1013 events on this database from Jan 1999 to November 2008. From these figures, the FAA estimated the likelihood of an event occurring as being 2.7 events per million departures. However, this report had a proviso:

> "Because there is currently no requirement that crew members report 'air quality' events, however, these numbers may understate actual occurrences."
>
> (Federal Aviation Administration, 2009)

- A presentation by the FAA Director in 2006 regarding the introduction of the FSAW (*Flight Standards Airworthiness Information Bulletin 06-05*) stated that:

> "FAA data analysis indicates numerous events not being reported."
>
> (Federal Aviation Authority & Ballough, 2006)

- However, since 2006, it is mandatory for failures, malfunctions and defects to be reported in the

SDR Database, but it is not clear if reporting is mandatory in the circumstances of a fumes event without an obvious malfunction (National Archives and Records Administration, 2010).

- The specialist paper *Reducing the Risk of Smoke, Fire and Fumes in Transport Aircraft* listed some statistics regarding incident rates (Royal Aeronautical Society & Cox, 2006):
    - The probability of a passenger experiencing an in-flight smoke event is greater than 1 in 10,000. In the US alone one aircraft a day is diverted due to an in-flight smoke event.
    - IATA data estimates more than 1,000 in-flight smoke events occur annually, resulting in greater than 350 unscheduled landings per year.
    - Worldwide smoke events estimated at a rate of 1 in 5,000 flights while diversions are estimated at a rate of 1 in 15,000 flights.
    - From January 2002 to December 2004 an IATA conducted study of ASRs from 50 commercial operators found 2,526 events were in-flight occurrences of smoke, highest number within cruise phase of flight. Most official and company reports were confidential and so the information provided will be real life experiences provided directly by technical crew.
- There were 760 reports of contamination at one US airline on the MD80 aircraft from 1989 – 1998 (Association of Flight Attendants-CWA, 2003).

3.3.2.1.5 **Industry Reports**

- Honeywell supplied documents detailing reported numbers of Honeywell engine caused cabin odour events for the older ALF-502 model and the newer LF507-1F engine, showing a peak of 40 events per million engine hours (Honeywell, 2009) [Figures 5 and 6]. The figures for 2008 showed the rates to be approximately 10 events per million hours for the ALF-502 and 1.7 events per million hours for the LF507-1F engine. These figures show events reported to Honeywell by the aircraft operators. A single operator reported the majority of events in 2001-03.
- A magazine article by Boeing, which analysed data for reported smoke events 1992-2000, found that 14% of smoke events originated in the air conditioning system (Boeing, 2001).

3.3.2.2 Interpretation of evidence

- The ATSB received only a small number of reports for many types of IRM, making it impossible to provide a meaningful analysis of reporting trends for all occurrence types across the time period

impossible. Therefore, the Panel has focused on the more common occurrences that were reported under both the AN Act and the TSI Act.

- It is documented that non-compliance with reporting systems does occur (ATSB, 2007)
- The incidence of documented events through official channels has increased significantly over the last few years. For further discussion on this topic, see Section 3.3.4.
- Reporting systems have become more robust, possibly due to increased awareness of occupational health and safety (OH&S) laws.
- Cabin air contamination reports in BAe146 aircraft have declined over the years. CASA has overseen a program of modifications to address air contamination problems, as well as requiring changes to the flight manual to mandate that flight crew wear oxygen masks immediately in the event of cabin air contamination to minimise the possibility of flight crew incapacitation.

3.3.3 What is the reported incidence through unofficial channels?

3.3.3.1 Description of evidence

3.3.3.1.1 **Reviews**

- Winder and Michaelis discussed the problem of under-reporting (Winder & Michaelis, 2005a) [page 216].
- Van Netten also discussed these problems (C. van Netten, 2005a).

3.3.3.1.2 **Australia**

- In a submission from a pilot with NJS, the Expert Panel was given details of 79 incidents on Dash-8 aircraft in Australia (NJS planes), from 2003-2009. The pilot stated:

> "The majority of CAQ incidents do not get reported by aircrew and are seen by many as an occupational hazard that goes with the job. This culture is slowly changing with more aircrew suffering from serious health issues as a result of repeated exposures. The Air Safety Incident Reports and OH&S reports that are submitted by aircrew after Cabin Air Quality incidents are dealt with in house by the National Jet Systems safety department. The reports are not forwarded to CASA."
>
> (Nivison, 2009)

- The Expert Panel received a number of other personal submissions that mentioned contaminated cabin air events experienced in Australian aircraft:
    - A submission by an Australian pilot, retired due to ill health, stated:

> "I flew aircraft with bleed air systems for over 30 years and odours in the cabin and Flight Deck have always been a part of the perceived "normal" flying environment."
>
> (Knight, 2009),

- A submission by an ex-pilot (he last flew in 2002), claimed his diaries showed that about 30% of all flights he flew had contamination (Pavlinovich, 2009).
- A submission by an ex-cabin crew member related frequent cabin odour events (Williams, 2009).
- A former president of the Australian & International Pilots Association (AIPA) claimed that the true rate of fume events was higher that that reported, and that the Expert Panel should clarify this with the ATSB (Woods, 2009).

3.3.3.1.3 **Germany**

- A submission by Tim van Beveren, German Public Broadcaster, Westdeutscher Rundfunk (WDR) noted:

> "As we did receive logbook data by sources from a major German carrier operating BAe146 aircraft a comparison of the BFU database and our logbook entries showed a significant mismatch of events. This leads to the conclusion that a massive underreporting of such events is taking place."
>
> (van Beveren, 2009)

  - As a possible explanation of the discrepancies he had noted between official figures and their own logbook data he wrote:

> "We learned that for example Lufthansa does not permit its flight crews to directly report to the authorities. Usually the crew files a report on their on board laptop (with-out retaining a hardcopy) which is directed to their operations department and the crew relies upon the later to forward the report to the authorities. We learned that other German Airlines handle this matter in a similar way. We hereby became very concerned that despite regulations in place Airlines and the supervising authority, the LBA, do not properly handle this particular issue."
>
> (van Beveren, 2009)

3.3.3.1.4 **United Kingdom**

- Carter, a retired pilot wrote:

> "Who actually saw fume events? Pilots, cabin staff, engineers and passengers. You want the truth, ask the retired."
>
> (Carter, 2009)

  - Carter proposed some possible reasons for the under-reporting of incidents:

> "...pilots have the best job in the world and do not want any conflict with management. Pilots are self-centred on their own career; they will not fill out questionnaires truly [sic] even if it is supposed to be

> anonymous. Consequently the number of entries in any tech-log needs to be factored by 100."
>
> (Carter, 2009)

- The IPA contended that that under-reporting of fume events by members was due to various reasons including that:

> "..some had been 'persuaded' not to raise tech log entries as the problems were being 'investigated by other means, whilst others were convinced by more senior colleagues that such occurrences were normal for the aircraft type and had to be lived with.' ...'Of those contacted, 21% had suffered fume events involving in their experience, aircraft engine oil...only two had submitted ASRs/MORs
>
> The author has personal experience of one operator who openly admits to 'playing down' air contamination events and their effects on crews and passengers as a matter of policy, despite having a higher than average occurrence of such incidents on their fleet. Hence this Association [sic] belief of a general large degree of under-reporting."
>
> (Independent Pilots Association, 2009)

- Several personal submissions from the UK mentioned that oily smells or fumes occurred more frequently than official figures suggested (Frith, 2009; Godfrey, 2009; Poutsma, 2009).

3.3.3.1.5 **USA**

- Murawski used data from both official (Service Difficulty Reports and Accident and Incident Data System Reports to the FAA) and unofficial channels (incidents documented with airlines by flight attendants which were copied to the AFA union and newspaper clips) to determine possible under-reporting of fume incidents (Murawski, 2008). This report identified an average of 0.86 events per day over an 18-month period. The analysis showed that 74% of the cases were identified in the FAA databases.
- A report by Harrison *et al* discussed under-reporting of fume events (R. Harrison, et al., 2009) [page 2].

3.3.3.2 Interpretation of evidence

- The Panel noted that fume incident rates reported through unofficial channels were higher than those reported through official channels. Therefore, under-reporting of incidents (as noted in previous official inquiries) was likely to be of concern.
- The Panel considered that under-reporting of all cabin air contamination incidents should be of major concern for any regulatory authority. The information reviewed by the Panel suggested that

under-reporting of cabin air contamination incidents was occurring and this issue should be addressed as soon as possible.

- The Panel noted that there were a number of possible reasons for under-reporting that could require a range of solutions. Possible reasons included:
    - Lack of notification / documentation of event. For example, notification might not occur due to:
        - Time pressure of the individuals involved in the incident, both at work and when off-duty.
        - Complexity / difficulty of the reporting system.
        - Lack of easy access to provide documentation.
        - Lack of management support for documentation to be completed.
        - Fear of repercussions or retribution for reporting incidents
        - Lack of knowledge about of OH&S requirements.
        - Cultures in some airlines may be to only report incidents verbally, or not to report at all.
        - Failure to recognise a contamination event because crew members may have variable responses to the same contamination event.
        - Aircrew having no knowledge, or a poor understanding, of the potential effects of fume exposures and events.

> "For example, several engineers during interviews recalled asking the flight attendants on separate occasions as they flew the BAE146, 'What is this fog near the ceiling, it smells like engine oil?' The replies from the flight attendants ranged from, 'Oh that's here every flight' to, 'I remain seated most of the flight, it makes me dizzy'. On one particular occasion the engineer noticed the flight attendant leave her seat to enter the toilet several times during the two-hour flight and when he asked whether she was all right, she replied, 'it's the oily smell it makes me nauseous.'" [Personal communication, Paul Cousins].

- Difficulty in identifying the cause of an event. For example:
    - Failure to pinpoint the cause of an event
    - Difficulty defining events which occur intermittently
- Poor record keeping and failure in distribution of information to higher authorities
    - Information received by in-house reporting systems not being distributed to the safety authority.
    - General technical log action comments that were variable and non-specific e.g. "To be rectified at company convenience", "Not safety of flight", "For information only", "No fault found" or "Nil fault please report further".

- The practice in the airline industry that non-vital defects are only required to be reported at the end of the day or duty (Aircraft Engineers International (AEI (Aircraft Engineers International) & Bruggeman, 2009).
- Poor administration of the reporting system resulting in loss of records and failure to publish reports.

- Dr Bhupinder Singh undertook a comparison of incident data from military and aviation records (see Appendix 4: Comparison of the incidence of smoke & fumes events):
  - This appeared to show a large discrepancy in reporting rates between military and commercial aviation.
  - This discrepancy could be due to under-reporting in commercial aviation.

3.3.4 Why have incidents appeared to increase in last decade?

3.3.4.1 Description of evidence

3.3.4.1.1 **Industry & Scientific literature**

- Qantas airlines figures for reported contaminated air events:

> "Since 1996-97, cabin air quality reports have increased. We believe this is due mainly to the greater awareness of the issue amongst passengers and crew. Even so, in 1999, less than 0.12 per cent of all BAe146 flights resulted in a cabin air quality crew report, and that is approximately one report in every 785 flights."
>
> (Senate Rural and Regional Affairs and Transport References Committee, 2000o) [page 37]

- A paper by Hocking demonstrated higher rates of outside air ventilation in aircraft in the 1960s/1970s compared with aircraft in the 1980s (Hocking, 2002).
- An FAA report stated that the ventilator systems of modern jet aircraft are designed for optimum efficiency which can leave them exposed to:

> "…lapses in the recycling of clean air and blocking fumes from jet engine exhausts from entering the aircraft cabin areas."
>
> (Chaturvedi, 2009)

- Pilots in an Australian survey reported fume events from 1986 up to 2005 with a peak during the late 1990s (A. Harper, 2005a, 2005b).

3.3.4.1.2 **Personal Submissions**

- Quote from Ray Jarvis' questionnaire:

> "I believe we have seen an increased level of events for two reasons, one being an increase in air travel (therefore more aircraft). The other is due to engine maintenance reverting to an "on condition basis" rather than the original TBO [Time Between Overhaul] system. In my case it was evident that engine oil was cheaper than changing a leaking front end seal"
>
> (Jarvis, 2009)
>
> ("On condition basis" maintenance means that regular maintenance checks should be performed in order to detect the onset of mechanical component failure. The TBO maintenance regime involves removal of items from service after a certain length of service, as specified by the manufacturer, for overhaul or replacement indifferent of the items current performance condition. For further discussion of these maintenance types see the CASA website) (Civil Aviation Safety Authority, 2001).

- The Association of Flight Attendants suggested another reason for the rise in incidents:

> "We first received reports of neurological and respiratory illnesses from our members in the 1970s, but by the late 1980s, it became clearer that these symptoms were associated with reports of odorous smoke, fumes, or haze in the aircraft cabin. This started around the time that cigarette smoking was being phased out on commercial flights in the US. Presumably, when the cigarette smoke cleared, the oil smoke became more noticeable."
>
> (Association of Flight Attendants CWA & Witkowski, 2009)

3.3.4.2 Interpretation of evidence

- Although the Panel could not identify a specific reason for the increase in rates of reporting of cabin air contamination events in recent times, there were a number of possible reasons including:
    - Reporting systems becoming more accessible due to OH&S requirements and increased knowledge of airlines' responsibility and their legal liability to passengers and crew.
    - Increase in number of available reporting authorities
    - Compulsory reporting under the Transport Safety Investigation Act (Office of Legislative Drafting and Publishing Australia, 2003).
    - Greater knowledge and awareness of cabin air quality issues within companies.
    - Regulator acknowledgement of the issue that has led to the creation of study groups and committees to investigate cabin air quality. These inquiries and some high profile court cases have raised awareness of the issue, which may have led to higher reporting rates.
    - Changes in the economic climate resulting in engine maintenance reverting to an "on condition basis" rather than the original TBO system.
    - Banning of smoking on aircraft resulting in increased awareness by flight crew, cabin crew, engineering crew and passengers of unusual odours in the aircraft, especially the oily

or acrid smells associated with aircraft engine fluids, which were previously wholly or partially masked by cigarette smoke.[1]

- Widespread use of newer aircraft. Older aircraft had a higher percentage of outside airflow passing through the cabin. This reduced the possibility of 'contaminated' air from engines entering the cabin. Aircraft manufactured from the 1960s to the 1980s had higher outside air ventilation rates. More modern aircraft used a greater proportion of bleed air to ventilate the cabins with less outside air ventilation.
- Ventilator systems of modern jet aircraft have been designed for optimum efficiency, which can leave them exposed to:

> "… lapses in the recycling of clean air and blocking fumes from jet engine exhausts from entering the aircraft cabin areas."
>
> (Chaturvedi, 2009)

- Changed community attitude towards risks related to environmental exposures to chemicals.
- Increased air travel due to increased affordability and availability.

3.4 What could potentially contaminate cabin air?

3.4.1 Introduction

- The focus of the Panel has been on potential contamination of the bleed air supply by engine operating fluids. However, the Panel was aware that a variety of possible contaminants could be introduced into the aircraft cabin from routes other than through the bleed air from the engines. These potential contaminants include ozone, environmental pollution (such as exhaust gases from other aircraft on the runway) odours from electrical faults, smoke from small onboard fires and volatile organic compounds (VOCs) from aircraft components (new carpets, upholstery). Other possible contaminants include insecticides sprayed for disease prevention in accordance with local regulations.
- Hypoxia and hyperventilation were also possible explanations for the symptoms described by aircrew. For further discussion of possible explanations for symptoms in affected individuals, see Section 5.7 below. Background information and further discussion of other potential contaminants can be found in Chapter 4 of the House of Lords report undertaken in 2000 (Science and Technology Committee, 2000j).

[1] Non-smoking sections were first introduced in 1973. Cigars and pipes were banned from flights in 1979. In 1988 US domestic flights under 2 hours were made non-smoking and by 1998 all US domestic flights were non-smoking flights. In June 2000, smoking was banned by US Federal law on all scheduled passenger flights in the US and this spread across the globe.

3.4.2 What operating fluids may be involved?

3.4.2.1 Description of evidence

- Winder provided a general review of many compounds used in aviation, including additives to engine oils and lubricating fluids (Winder, 2006a).

3.4.2.1.1 **Engine Oils**

- There are some reviews of the components of engine oils:
  - Guerzoni and Bishop provided a discussion of the general components of aircraft lubricants (Guerzoni & Bishop, 1999).
  - A textbook chapter discussed the toxic ingredient of jet oils (Winder & Michaelis, 2005b).
- Material Safety Data Sheets (MSDS) provide information on ingredients and toxicity.
  - They may differ slightly depending on the country of issue.
  - Most MSDS for engine oils warn of possible adverse health effects due to inhalation of the thermal decomposition products of the oils.
    - Note: The Panel noted that material safety data sheets (MSDS) (information sheets containing data regarding the properties of a particular substance) might not necessarily be accurate. One study showed inaccuracies in 3 out of 24 Canadian MSDS submitted for evaluation (Welsh, Lamesse, & Karpinski, 2000).
- Commonly used engine oils:
  - Mobil Jet Oil II
    - MSDS for Mobil Jet Oil II from Australia (ExxonMobil, 2008) and Canada (Imperial Oil, 2007) and a Material Safety Data Bulletin from the US (ExxonMobil, 2008) showed that this oil contains 1-5% TCP and 1% P.A.N. (phenyl-alpha-naphthylamine) and <2% alkylated diphenyl amines.
    - A paper by Winder and Balouet contains an assessment of Mobil Jet Oil II with a focus on TCP and PAN (Winder & Balouet, 2002).
  - Mobil Jet Oil 254
    - Mobil Jet Oil 254 product description is a lubricant made from high quality synthetic oil with selected additives (ExxonMobil, 2007b). The MSDS from Australia lists 1-5% TCP (Exxonmobil, 2009).
  - BP 2380
    - The MSDS from Australia does not list any specific ingredients but states that the oil:

> "…may be harmful by inhalation if exposure to vapour, mists or fumes resulting from thermal decomposition products occurs."

(BP, 2006b)

- BP Turbo Oil 2197
  - The MSDS from BP Australia (BP Australia, 2006) does not mention TCP, however, the MSDS from the Netherlands (BP Australia, 2006) and Canada (BP, 2006a) both list TCP at 1-5%.
  - The memorandum from the Association of Flight Attendants relates a summary of recent research by the OHRCA-ACER study in the US included the following:

> "…a series of commonly used jet engine oils was analysed, revealing that the up to three percent content of tricresylphosphate wear additive reported by manufacturers in their data sheets was exceeded in five of eight oils tested."
>
> (Association of Flight Attendants CWA & Witkowski, 2009) [page 2]

  - Note: No further details of this research were provided in the AFA submission.
- NYCO SA produces Turbonycoil 600, which contains triphenyl phosphates rather than TCP (in a submission to the House of Lords (NYCO, 2009b)). The Panel understands that NYCO is now in the process of further development of less toxic oil that is environmentally more acceptable whilst still achieving the same certification outcomes.
  - The MSDS states that a respirator should be worn in the presence of the heated product and also that there are possible risks to the unborn child and to fertility.
  - This oil meets various standards including MIL-PRF-23699 F class and the company is to perform comparative toxicity studies (NYCO, 2008).
  - Turbonycoil 600 has over 1 million hours of use in civil aviation aircraft including Airbus 320, Boeing 737 and 757.

- Van Netten analysed the elemental content of common engine oils and hydraulic fluids (van Netten, 1999). The analysis of the elements found noted that no toxic heavy metals were detected.

What are the concentrations of the ortho isomers of TCP in engine oil?

- There are many different isomers of TCP, the most toxic of which are the ortho-isomers. For full discussion and references regarding toxicity see Section 5.2.1.1.3 below. Of these, the mono-ortho (MOCP) and di-ortho (DOCP) isomers are several times more neurotoxic than the tri-ortho (TOCP) isomer (Henschler, 1958 - English).
  - One study compared the toxicity of new 'lower-toxicity' TCPs (which have been manufactured to contain less ortho-isomers) with older TCPs in terms of 'equivalent TOCP toxicity' (Mackerer, Barth, Krueger, Chawla, & Roy, 1999). The authors concluded that the modern 'lower-toxicity' TCPs were less toxic than the older TCPs.
- Some recent studies have looked at the TOCP, DOCP and MOCP concentrations in engine oils:
  - An Australian Defence Science and Technology Organisation study analysed four engine oils (De Nola, Kibby, & Mazurek, 2008 258). This study found that the ortho-isomers were mainly in form of the more toxic MOCP isomers at concentrations of 13-150 mg/L.

- The reference sample for engine oil in a non-peer reviewed report by van Netten for a German TV station showed the main TCP isomers in engine oil were mmm-TCP, mmp-TCP, mpp-TCP, ppp-TCP (where m represents the meta form and p represents the para form of alkylation of the aromatic ring) (C. van Netten, 2009b). Thus ortho isomers of TCP were not found to be the main isomers found in engine oil.

3.4.2.1.2 **Hydraulic fluids**

- A variety of hydraulic fluids are used, including:
  - Skydrol LD4 - the MSDS listed all ingredients (Solutia Inc, 2008a):
    - Tributyl phosphate 58.2%□ dibutyl phenyl phosphate 20-30%□ butyl diphenyl phosphate 5-10%□ 2-ethylhexyl 7-oxabicyclo[4.1.0] heptane-3-carboxylate <=10%□ 2,6-di-tert-butyl-p-cresol 1-5%.
    - No TCP listed.
    - Exposure limits for individual ingredients was listed.
    - One study examined Skydrol by gas chromatography and concluded it was a mixture of butyl and phenyl esters of phosphoric acid (Spila, Sechi, & Bernabei, 1999).
  - Hyjet IV-A Plus – the MSDS listed the following ingredients (ExxonMobil, 2009):
    - Tributyl phosphate 70-80%□ aliphatic epoxide 5-10%□ triphenyl phosphate <2.5%□ calcium sulphonate 01-1%.
    - The exposure limits for individual components are listed.
    - The product description for Hyjet IV-A Plus described the typical properties of the product (ExxonMobil, 2007a).
  - Monsanto Skydrol 500B4 and 500B:
    - For Skydrol 500B4, the MSDS listed some ingredients (Solutia Inc, 2008a):
    - Tributyl phosphate 58.2 %, □dibutyl phenyl phosphate 20.0-30.0 %, □butyl diphenyl phosphate 5.0-10.0 %, □2-ethylhexyl 7-oxabicyclo[4.1.0] heptane-3-carboxylate <=10.0 %, 2,6-di-tert-butyl-p-cresol 1.0-5.0 %.
  - The MSDS for Skydrol 5 listed the following ingredients (Solutia Inc, 2008b):
    - Triisobutyl phosphate 60 - 100 %, □triphenyl phosphate 0.5 - 5.0 %, □2-ethylhexyl 7-oxabicyclo[4.1.0] heptane-3-carboxylate <=10.0 %. □
- Hewstone discussed some additives to hydraulic fluids and their toxicology, concentrating on the cold fluid, in contact with skin and eyes (Hewstone, 1994).
- One study by van Netten et al attempted to characterise the profile of two hydraulic fluids but could not do so with complete certainty as the appropriate standards could not be used due to lack of information from the manufacturers. TCP was found in the fluids, as noted in the data sheets provided for these oils at the time of analysis (van Netten & Leung, 2000).

3.4.2.1.3 **De-icing fluids**

- An investigation bulletin showed that de-icing fluid had contaminated the cabin air of an aircraft. The brand of de-icing fluid was not mentioned in this report. (Air Accidents Investigation Branch, 2006b)

3.4.2.2 Interpretation of evidence

- The Panel noted that the operating fluids that might be involved in cabin air contamination vary depending on the type of aircraft and also the manufacturer of that aircraft. The main operating fluids have been listed in the Panel's library of documents but others that may be present include de-icing fluids, operating greases and engine oil/fuel system inhibitors.

3.4.3 What is the effect of pyrolysis on the chemical composition of engine oil and hydraulic fluid?

3.4.3.1 Description of evidence

- Engine oils and hydraulic fluids are routinely tested for their toxicological effects via oral and dermal administration. However, the Panel was primarily concerned with exposure to thermalised and pyrolysed engine oils via cabin air. Pyrolysis is the chemical decomposition of a condensed substance by heating. Although much of the discussion centres on TCP, the effect of pyrolysis on the chemicals that could enter the bleed air system is not completely understood:
    - A report by the UK CAA reviewed the products of pyrolysis (Safety Regulation Group, 2004).
    - The UK Defence Evaluation and Research Agency (DERA) reported on an analysis of the thermal degradation products of turbine lubricants in the presence of oxygen (Defence Evaluation and Research Agency UK, 2001)
    - The US Navy analysed 26 oils, and found that high levels of the neurotoxin (Trimethyl propane phosphate (TMPP) formed from Exxon 2380 under laboratory conditions (Callahan, Tappan, Mooney, & Heyder, 1989). However, a later study found no TMPP formed in high temperature boilers but it was detected in residual material (Rubey, Striebich, Bush, Centers, & Wright, 1996).
    - A discussion by Shell representatives of the potential contaminants in pyrolysed aircraft lubricants stated that:

> "It is recognised that decomposition of aviation turbine oils can give rise to the formation of hazardous compounds. This may be in the form of base stock derived components such as acids, aldehydes, ketones which will be present as VOCs or by TCP found in an oil mist. Evaluation under laboratory conditions provides a valuable insight into the types of species which could be expected in the event of damage to

> seals in an aircraft engine, leading to exposure to the cabin to engine oil vapour or mists."
>
> (Guerzoni & Bishop, 1999)

- A paper by van Netten and Leung contained a table of 525 ^{o}C pyrolysis products of 2 jet engine oils (van Netten & Leung, 2000). The main products were carbon dioxide (CO_2), carbon monoxide (CO) and VOCs, with TCPs also being detected. No TMPP was found in this study.
- An analysis of pyrolysis products of Skydrol LD-4, HyJet IV-A and Mobil Jet Oil 254, showed that
    - White smoke was produced at temperatures as low as 180^{o}C (Skydrol LD-4, HyJet IV-A).
    - CO was the main toxic pyrolysis product, with 5 times more CO released by the engine oil than the hydraulic oils.
    - TBP was also present.
    - Swab samples detected both phenyl and cresyl phosphates.
    - The two hydraulic fluids showed little increase in complexity after pyrolysis, whereas pyrolysed Mobil jet oil showed markedly increased complexity compared to the bulk oil analysis (van Netten & Leung, 2001).

- A team at Honeywell measured formaldehyde, acetaldehyde, acrolein and CO levels in pyrolysed engine oils (Honeywell, 2003).
- The temperature to which the oil is subjected is an important element, since different products of pyrolysis can be formed at higher temperatures. For example, TMPP is formed at a temperature higher than 365-390 ^{o}C (Callahan, et al., 1989; Centers, 1992).
- Bleed air is taken from the compression section of the engine (before combustion occurs) and may be subjected to temperatures from around 170 ^{o}C (Science and Technology Committee, 2000e) to more than 500 ^{o}C (Chaturvedi, 2009)[part of Boeing Australia submission]; (van Netten & Leung, 2000).
- An incident investigation report from the UK stated that bleed air is cooled to 230 ^{o}C in the primary cooling area (Air Accidents Investigation Branch, 2004b).
- Annex 5 of the COT report stated that bleed air temperature is from 170 ^{o}C to 300 ^{o}C as a maximum, with the BAe146 APU having higher temperatures than the B757 - up to 350 ^{o}C (Committee on toxicity of chemical in food consumer products and the environment, 2006b).
- The report by the CAQPCCA in the USA contained a table of typical bleed air conditions (information gained from Boeing during the inquiry), which showed temperatures ranging from 170 ^{o}C on the ground to 350 ^{v}C on take-off at maximal power (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002).
- Appendix M of the submission by Honeywell analysed pyrolysis products as a function of engine temperature, relating it to a nominal 1-hour flight and found that contaminant quantities were higher at 371^{o}C than at 204 ^{o}C (Honeywell, 2003).
- Another study found that Skydrol LD-4, HyJet IV-A and Mobil 254 did not produce detectable TMPP at 525 ^{v}C (van Netten & Leung, 2001) .

3.4.3.2 Interpretation of evidence

- Pyrolysis of commercial jet oils could release a range of substances into cabin air during a seal failure, including cresyl- and the more volatile butyl-phosphate esters, as well as potentially irritant acid, aldehyde and ketone VOCs. Other significant airborne pyrolysis products include CO_2 and CO. Where suitable analytical techniques have been used, it appears that neurotoxic TMPP is either not formed, or is not sufficiently volatile to avoid capture on duct surfaces (Rubey, et al., 1996; van Netten & Leung, 2000, 2001).
- While there are potentially a large number of chemicals that could contaminate cabin air from pyrolysed engine lubricants, there is insufficient data on levels or possible interactive effects to evaluate their toxicological significance. Carbon monoxide and OP derivatives remain the most likely candidates to explore the potential for neurotoxicity to occur in aircrew or passengers (see further discussion in Sections 4 and 5).

3.4.4 What are the contaminants found in cabin air?

3.4.4.1 Description of evidence

3.4.4.1.1 **Cabin air monitoring studies**

- The submission by Honeywell included an aerospace recommended standard by SAE Aerospace which described the methods for sampling and measuring bleed air contaminants (SAE Aerospace, 2008).
- Recently a small monitor has been developed (C. van Netten, 2009a).
    - Designed for use in flight, this monitor was tested on 2 BAe-146-300 flights. The results showed exposure in those two flights to TCP levels from 31 ng/m^3 to 83 ng/m^3. The author concluded that the monitor was capable of detecting air concentrations of TCP isomers at concentrations greater than 4.5 ng/m^3.
- Honeywell submission (Richard. Fox, 2002):
    - Honeywell has developed a portable monitor and reported a case study of how this monitor could be used to locate the source of contamination in an aircraft cabin. It was reported that hydrocarbon levels increased after the aircraft environmental control system was activated. The device was also used to demonstrate that the contamination in this example emanated from the left propulsion engine.
- A report by van Netten analysed cabin air for contaminants in several aircraft in which the crew had detected air quality problems. Van Netten also collected information on symptoms suffered by crew (van Netten, 1998).
- Winder wrote a review which critiqued previous aircraft cabin air monitoring studies (Winder, 2006a).

3.4.4.1.2 **During Normal Operations**

- Christiansson *et al* found brominated flame retardants in aircraft cabin dust and elevated levels in long distance travellers immediately after travel (Christiansson, Hovander, Athanassiadis, Jakobsson, & Bergman, 2008). The authors suggested undertaking a study involving pilots/air cabin crew.
- The UK COT report reviewed the available literature regarding doses/concentrations of contaminants, reporting that:

> "Overall, the dearth of available information from exposure monitoring means that no definite conclusions can be reached on the normal range of air contaminants and their concentrations in commercial aircraft during flight."
>
> [page 13, paragraph 42] (Committee on toxicity of chemicals in food consumer products and the environment, 2007k)

- A health hazard evaluation of Mesaba Airlines in the US sampled air in the back of the passenger cabin and found very low concentrations of VOCs and CO (NIOSH & Tubbs, 2006).
- A BALPA conference paper, which was also published as a DSTO report, studied cabin air contaminants in Australian Defence Force aircraft:
    - The report demonstrated that TCP, phenyl naphthylamine (PAN) and dioctyldiphenylamine (DODPA) were present at low levels in cabin air of military aircraft during normal operations.
    - The highest levels of contaminants were found in cockpit of Hawk trainer aircraft with APU operation on the ground (TCP at 21.7 and 49 $\mu g/m^3$), but all other levels were very low (Hanhela, et al., 2005; Kibby, De Nola, Hanhela, & Mazurek, 2005).

- The Building Research Establishment measured a variety of contaminants during normal flights (Building Research Establishment (BRE) Environment, et al., 2004).
- A 2003 paper critically reviewed six previous studies, which monitored cabin air contaminants (N. L. Nagda & Rector, 2003).
- The abstract of a conference paper reported measurement of VOCs, Nitrogen oxides, CO, CO_2, O_3, temperature, relative humidity, total particulates and pressure on commercial transport aircraft. This group found that, in general, contaminant levels were low compared to standards (Waters, Bloom, Grajewski, & Deddens, 2002).
- Another group measured carbon dioxide on routine flights, and reported a maximum value of 2013 ppm CO_2 (Haghighat, Allar, Megril, Blondeau, & Shimotakahara, 1999).
- A study of cabin air quality included a cabin air monitoring study on Boeing 777 aircraft (Pierce, Janczewski, Roethlisberger, & Janczewski, 1999). This study looked at a variety of compounds including CO, VOCs and formaldehyde.
- Van Netten monitored cabin air in flights of known problem aircraft and normal aircraft (van Netten, 1998). No CO or VOCs were found on normal flights.
- An earlier report found volatile organic compounds within threshold levels, ethanol was present and further organics were emitted by passengers (Dechow, Sohn, & Steinhanses, 1997).

- A study of normal operations in Ansett BAe146 aircraft found that air quality during normal flights was acceptable (Honeywell, 1997). Levels of contaminants in the air were found to be 30 - 40% of currently accepted safety standards during normal flights. TCP was tested for but not detected.
- A health hazard evaluation of Alaska Airlines, in response to concerns about cabin air quality and health problems, found no plausible work related exposure identified that would account for the reported health problems (NIOSH, Sussell, Singal, & Lerner, 1993).
- A study by Nagda *et al*, took measurements on mainly smoking flights, main contaminants due to cigarette smoking, ozone at acceptable levels, CO_2 levels sufficiently high to pose potential comfort problems to airline occupants (Niren L. Nagda, Koontz, Konheim, & Katharine Hammond, 1992).
- A personal submission by Jon Delorme, a passenger on a flight, related concerns regarding ‘'neurotoxin’ contained in Aerosafe insecticide, which was sprayed in passengers’ faces on flight to Guyana (Delorme, 2009).

3.4.4.1.3 **During Fume Events**

- A 1983 survey of USAF cockpit contamination events demonstrated that most contamination was due to organic petroleum derivatives (Rayman & McNaughton, 1983).
- Van Netten tested two aircraft with reported fume events and found elevated CO and VOCs compared with aircraft with no reported events (van Netten, 1998) .
    - Note: The report was commissioned by an airline (Air BC, no longer in operation), which later attempted to block publication of this data in a scientific journal (C van Netten, 2009).

3.4.4.1.4 **Ongoing Monitoring Research Projects**

- In a presentation at BALPA conference in 2005, the research plans for monitoring studies to be carried out by OHRCA were explained (Kincl, Murawski, & Hecker, 2005).
- In their submission to the Expert Panel, the AFA summarised their knowledge of current research in this area (Association of Flight Attendants CWA & Witkowski, 2009). AFA is a partner in the OHRCA-ACER research project in the US and so had access to the final report recently submitted to the FAA.

> “In 18 flights on which duplicate samples were taken and analyzed by two different laboratories, samples from three of these flights were found positive for low levels of tricresylphosphate additives; in a separate round of sampling in which only one lab performed the analysis 13 of 38 air samples tested positive for these tricresylphosphate additives; in all of these cases no visible or reported air supply contamination occurred.”
>
> (Association of Flight Attendants CWA & Witkowski, 2009)

- The AFA also mentioned an ACER research project at Kansas University, which is testing re-circulated air filters removed from aircraft with reported fume events. However, they criticised this project:

> "At US Airways, we have learned that if there is a reported oil fume event on an aircraft, the recirculated air filter is replaced and 30 days later the replacement filter is sent to KSU for analysis. KSU researchers are conducting the filter analyses blind and were not aware of this arrangement until recently. However, it is difficult to understand the purpose of this work if, presumably, little if any oil residue will enter the recirculated air stream (instead settling out in the cabin/flight deck), especially after the source of the oil has been fixed and a new recirculated air filter has been installed."
>
> (Association of Flight Attendants CWA & Witkowski, 2009)

- The ACER annual report of 2007 detailed their proposed monitoring projects (Airliner Cabin Environment Research, 2007).
- A monitoring research project was commissioned by the Department for Transport in the UK, which was carried out by the late Professor Helen Muir at Cranfield University (Muir, Walton, & McKeown, 2008) .
    - This project was subjected to peer review (see comments in the manuscript).
    - However, the memorandum of submission from the Association of Flight Attendants (AFA), questions the methods used in the Cranfield study as well as the small number of flights to be monitored (in comparison to numbers suggested in the COT report) (Committee on toxicity of chemicals in food consumer products and the environment, 2007k).
    - This study was also criticised in submissions by the GCAQE and the IPA (Global Cabin Air Quality Executive (GCAQE), Loraine, & Murawski, 2009; Independent Pilots Association, 2009). The IPA expressed concern that the study would not identify contaminants in fume events and suggested chartering a BAe146 or B757 aircraft and using a gas spectrometer to analyse cabin air in normal flights and flights using a faulty engine that is known to cause fume events.
- In 2007, ASHRAE and Battelle announced a research programme to research the link between aircraft cabin air and health symptoms (ASHRAE, 2007b).
    - Qantas has agreed to be involved in this monitoring project during the second half of 2010. Twenty-four Qantas services will be monitored, from 1st July 2010. GCAQE have criticised various research programmes:

> "Some investigations have had to modify their study design because of airline refusal to allow its crewmembers to collect data without fear of discipline or reprisal (OHRCA-ACER, 2009). Still other investigations seem designed to find nothing (ACER, 2009; Cranfield 2008, NTSB, 1984). Some have purposefully either withheld or misrepresented the data they collected (Fox, 2000; Fox, 1997). Both an aircraft manufacturer and air supply system component manufacturer have made covert payments to airlines to compensate for the adverse health effects reported by airline crewmembers caused by exposure to oil fumes (PCA, 2007)."
>
> (Global Cabin Air Quality Executive (GCAQE), et al., 2009)

3.4.4.1.5 **Swab studies**

- The identification of TCP in aircraft cabins is a controversial area.
- A number of media reports referred to swabs taken by aircrew that tested positive for TCP, but this research does not appear to have been published, and the presence of TCP has been denied by airlines (Starmer-Smith, 2008).
- An unpublished report commissioned by a reporter in Germany was submitted to the inquiry (van Beveren, 2009). This report detailed results of an analysis of wipe samples taken from interior surfaces of more than one aircraft undertaken at the University of British Columbia (C. van Netten, 2009b).
    - The report stated that the samples and controls were analysed in a fashion such that the analyst was 'blinded' as to which were control samples and which had been taken from an aircraft. The report stated that the tri-ortho isomer of TCP was not found in any samples above the detection limit, but other isomers of TCP were found, corresponding to the TCP isomers found in a typical jet engine oil sample. A swab taken from a new aircraft did not show any detectable TCP.

3.4.4.1.6 **Doses of contaminants**

- There have been several studies using test rigs to estimate the potential dose of contaminants:
    - The NTSB evaluated the potential for oil contamination in the bleed air system of the Garrett TPE 331 and concluded it was not likely to happen (National Transportation Safety Board, 1984).
    - However, the Committee on Toxicity commented that these findings are not applicable to turbofan engines (Committee on toxicity of chemicals in food consumer products and the environment, 2007k)
- The Swedish authorities commissioned a test of an engine involved in a fume event (the Malmo incident) by the manufacturer, Honeywell, to investigate the contaminants present in the bleed air (Statens haverikommission (SHK) Board of Accident Investigation, 1999). Measured contaminants were found to be within exposure limits set by the CAA and FAA.
- Others have attempted to calculate potential doses of contaminants theoretically:
    - A report recorded the view of the CAA (with reference to unpublished research at Porton Down) that potential levels of contaminants could cause irritation but would not be harmful (Barrow, 2007).
    - A committee in the US attempted to calculate the amount of oil needed to produce a hazardous concentration of contaminants (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002):
        - Their calculation showed that only 1g of pyrolysed oil needed to be released into the cabin air to produce formaldehyde concentrations above safety limits.
- A submission to the House of Lords inquiry in the UK by Airbus Industrie calculated the following:

> "…the worst-case scenario of the total discharge of an engine's lubricant into the engine would result in about 0.4 kg of oil passing into the cabin

> ventilation systems. Assuming that the oil contained 3% TCP, of which 0.1% was TOCP, the peak cabin atmosphere TOCP level would be about 0.025 mg/m^3, reducing as a result of normal ventilation thereafter. The peak level would be a quarter of the workplace limit of 0.1 mg/m^3 (and less than a tenth of the emergency workplace limit of 0.3 mg/m^3). Contamination at much lower levels would result in visible smoke and odour which would normally result in the crew switching off the ventilation feed from the affected engine."
>
> (Science and Technology Committee, 2000j)[paragraph 4.39]

- Note: the above calculation only involved TOCP, The amount of the other, more toxic, ortho-isomers of TCP (MOCP and DOCP), which are also present in engine lubricants were not reported. MOCP has been reported to be 10 times more toxic than TOCP.
- Documents supplied by Mobil US to the Australian Senate Inquiry, showed that estimated concentrations in the TCP additive to their oil were:
    - TOCP < 5ppb, MOCP approximately 3070 ppm and DOCP approximately 6 ppm (Senate Rural and Regional Affairs and Transport References Committee, 2000c).
    - After addition of this TCP mixture to the oil (diluted at a concentration of 3% by weight in the oil), the above figures were reduced 33 fold, giving estimated concentrations in the oil of TOCP at less than 0.15 ppb, MOCP of approximately 93 ppm, DOCP of approximately 0.18 ppm.
- Jet Engine Oil 291 used a recently developed low toxicity TCP with lesser amounts of ortho-isomers of TCP present.
- A study reported at a conference by Shell attempted to calculate an 8-hour TCP and 8 hour TOCP level from oil mists and found the measured levels to be greater than the time-weighted average (TWA) Occupational Exposure Limit for TCP of 0.1 mg/m^3 (Guerzoni & Bishop, 1999).
- The Committee on Toxicity concluded that:

> "Overall, the COT agreed that there was considerable uncertainty regarding the identity and levels of VOCs, SVOCs and other pyrolysis products released into the cabin air during oil or hydraulic fluid smoke/fume incidents."
>
> (Committee on toxicity of chemicals in food consumer products and the environment, 2007k) [page 13; paragraph 43]

3.4.4.2 Interpretation of evidence

- The Panel noted that some studies have demonstrated the presence of multiple contaminants in the cabin environment. However the circumstances in which the contamination occurred were unclear.
- Research currently being undertaken should clarify the circumstances of cabin air contamination.
- On 22 March 2010, the US Senate passed legislation that included providing funding for research by the FAA to conduct a study of air quality in the cabins of US airliners to ensure that the FAA has the necessary information to protect the public from harmful toxins in ventilation systems on

commercial aircraft. Qantas has agreed to participate in this study, which is currently being undertaken by ASHRAE and the FAA.

- From the information available, the Panel noted some limitations in the way that Battelle , the testing organisation, proposed to utilise the monitoring devices including where monitoring devices were intended to be sited in cabins and the relatively limited time of participation given the infrequency of a cabin air contamination event. The list of substances to be monitored under the proposed ASHRAE/FAA air-sampling program appeared to be quite extensive (Section 8.9; Appendix 9) and included a range of volatile and semi-volatile chemicals, some of which would be tested on a continuous basis, but most on the basis of aggregated samples.
- Some substances on the proposed list appeared to be based on identified sources within aircraft cabins (e.g plastics, fabrics, disinsectants), but there were many for which the Panel was unable to identify a specific source, other than that they might be products of pyrolysis.
- In the absence of data on method sensitivity, the Panel considers it may be difficult to predict whether there will be any useful data on all of the listed chemicals. The Panel expects that much of the data will indicate substances are "non-detectable". It is also not clear how the air monitoring data will be interpreted. It would appear that that many of the chemicals proposed to be tested have health-based air quality standards against which the measured levels could be benchmarked, but this is unlikely to apply across all of the proposed analytes. The Panel noted the proposal to measure three tricresyl phosphates (/o/, /m/, and /p/ isomers), probably because of the focus on TOCP in the aerotoxic syndrome literature. However, the Panel considered it might be useful to measure the mono-/ortho/ and di-/ortho/ cresyl phosphates as well, given that these are relatively more toxic and can be found in engine oils and other lubricants. The Panel also identified some phenylalkylamine derivatives as being of concern because of their sensitisation potential. According to the proposed ASHRAE/FAA list these derivatives will not be monitored. Finally, the Panel notes that formaldehyde and acetaldehyde will be measured, presumably as representatives of the aldehyde class of VOCs addressed by Coleman, who listed a more comprehensive list of the irritant aldehydes that could be released into cabin air from carpets and other fabrics (Coleman, et al., 2008).
- In the absence of reliable measurements of airborne TOCP levels during a seal leakage event, various attempts have been made to calculate potential airborne levels of TOCP. These calculations have generally yielded worst-case estimates well within occupational health standards, although there is one estimate (not measured, but extrapolated from a measured TCP level) that exceeded the established occupational TWA (0.1 mg/m^3) (Guerzoni & Bishop, 1999). However, these calculations depended in part on the reliability of estimates of typical TOCP content of engine oils, and did not include estimates of the release of mono-ortho- and di-ortho cresyl phosphates (MOCP and DOCP), which were considered to be more neurotoxic, although their involvement in OPIDN (organophosphorus ester-induced delayed neurotoxicity) and organophosphorus ester-induced chronic neurotoxicity (OPICN)/Chronic organophosphate-induced neuropsychiatric disorder (COPIND) is less well understood.

3.5 What biological evidence is there that exposure takes place?

3.5.1 What are the biological tests available?

3.5.1.1 Description of evidence

- The role of biological testing is to determine, not only the presence of a substance, but also to determine its potential role in causation. Hence, to be of value, there must be a high pre-test probability that the substance being tested is responsible for the illness being observed. In exploring this topic information has been provided regarding testing of particular substances but for analysis of causation the reader should refer to the relevant interpretative sections of this report.

3.5.1.1.1 **Organophosphates**

- Several members of the Panel held a videoconference with Professor Clem Furlong, from Washington State university at which he reported that his group was currently close to development of a system for assessing biomarkers of TCP exposure and had obtained a bank of blood samples from potentially exposed aircrew and passengers in order to prove or disprove exposure to TCP on aircraft, and the extent of any such exposure. A DVD of this videoconference was circulated to all Panel members.
- A conference paper presented at the 2005 BALPA conference discussed the role of polymorphisms in the paraoxonase gene in modulating exposure to organophosphates (OPs) and the development of biomarkers for OP exposure using carboxylesterase (Furlong, Cole, et al., 2005).
- Recent progress in this work was reported in a book chapter, describing the development of acylpeptide hydrolase (APH) and butyrylcholinesterase (BChE) as biomarkers for OP exposure (Kim, et al., 2009).
- A paper by a group from the University of California demonstrated that blood APH was a sensitive marker for exposure to some OPs (Quistad, Klintenberg, & Casida, 2005).
- The submission by the German Air Line Pilots Association stated that it was undertaking an OP bio-monitoring study using urine sampling, having provided 50 test kits to pilots. Details of the methods of analysis were not provided in the submission (German Air Line Pilots Association & Schewe, 2009).
- A number of personal medical submissions contained test results from laboratories claiming to show TCP in the blood or fatty tissues, also deoxyribonucleic acid (DNA) adducts to various metals or chemicals.
    - Some of these tests were mentioned in the COT report:

> "The COT considered the bioanalytical methods used in the report submitted, including the presentation of results and their interpretation. Significant doubt was placed on the interpretation of reportedly increased levels of solvents in pilots due to a lack of data on

> method precision, and limitations identified in the origin and application of the population 'average' figures. Consequently, no analyte concentration could be derived for any of these individuals with confidence."
>
> (Committee on toxicity of chemicals in food consumer products and the environment, 2007b)[page 19]

- The Aerotoxic Association has collated blood results from a number of aircrew (Aerotoxic Association, 2009) that included results of tests for VOCs, OPs, mitochondrial function and ATP levels.

3.5.1.2 Interpretation of evidence

- The Panel noted that OPs, BChE inhibition has been the standard for OP monitoring. In the acute exposure, there is a decrease in the level of cholinesterase due to binding of the OP to the enzyme. However, this bond may be broken with the administration of an oxime antidote, or, given time, the cholinesterase levels will return to normal when more enzyme is manufactured and released from the liver. Hence BChE can only be considered a marker of acute exposure.
- Similarly, monitoring urinary excretion of the OP metabolites will only identify acute high-level exposures. For example, in the case of 3,5,6 trichloro-2-pyridinol (a marker for chlorpyrifos (CPS)), the metabolite is excreted for only a short period of several days after a significant exposure. In addition, due to the widespread use of CPS and continued environmental persistence of its breakdown products, the metabolites appear at a high background level in the general population (R. H. Hill, Jr., et al., 1995). Additionally, their appearance does not indicate whether the individual was originally exposed to the harmful parent compound or the harmless breakdown product.
- Researchers interested in identifying the effects of long-term low-level chronic exposure have looked at other markers. By identifying and characterizing molecular biomarkers with longer half-lives, it should be possible to clinically detect TCP and OP insecticide exposure after longer durations of time than are currently possible.
- Another serine esterase, acylpeptide hydrolase (APH), has been proposed as both a diagnostic and therapeutic target for OPs (Richards, Johnson, & Ray, 2000). APH removes N-acetyl amino acids from the ends of peptides (Fujino, Watanabe, Beppu, Kikugawa, & Yasuda, 2000). Due to its presence in red blood cells, which have a lifespan of 120 days and no protein synthesis capability, OP-modified APH should be measurable for several weeks, depending on the level of exposure. Casida *et al* showed that despite a return to baseline for BChE post injection of di-isopropyl fluorophosphate in rats by day 4, only 20% of APH activity had returned by this time (Casida, Eto, & Baron, 1961).
- Other markers have been investigated. Furlong described the use of multidimensional protein identification technology (MudPIT) to identify TCP modifications to serine residues in the liver enzyme, carboxylesterase. Furlong postulated that analysis of proteins modified by specific xenobiotics provided an approach for examining the nature of an exposure over a much longer time frame (Furlong, Cole, et al., 2005).

- A more detailed description of the mass-spectrometric method used to identify several covalently bound adducts has recently been published (Schopfer, Furlong, & Lockridge, 2010). Plasma protein targets such as albumin and butyrylcholinesterase were found to have adducts resulting from the covalent binding of the ultimate active metabolite of TOCP (2-(ortho-cresyl)-4H-1,3,2-benzodioxaphosphoran-2-one, or CBDP) to either tyrosine or serine residues.
- The likely problems with attempts to find a suitable biomarker of exposure to TOCP are:
    - Tests based on measuring TCP metabolites in blood and/or urine may not be sufficiently sensitive, or able to discriminate exposures to the more neurotoxic compounds (TOCP, DOCP, MOCP, TMPP).
    - By focusing on bio-monitoring of OPs, the studies may overlook exposures to other potentially toxic components of contaminated cabin air (e.g. ozone, carbon monoxide).
- The efforts of the University of Washington group led by Professor Clem Furlong have a greater chance of success for bio-monitoring TOCP exposure because the tests focus on CBDP, the active metabolite of TOCP covalently bound to target esterases. Such adducts are long-lasting and therefore more amenable to detection in typical bio-monitoring sampling regimens, as well as being more specific for TOCP exposure and therefore potentially able to discriminate between exposure to TOCP and other TCP isomers.
- The Panel noted that the Furlong group had not published any biomarker results using the above techniques on the blood samples they stated had been collected from aircrew and passengers following contaminated cabin air incidents. However, the interpretation of the levels of adducts found will still be likely to be problematical, although it might be possible to determine whether the susceptibility of subjects who have experienced ill health which they have attributed to aircraft cabin contamination might be associated with higher levels of biomarker adducts, either through higher levels of exposure or a genetic polymorphism which results in greater production of reactive TCP metabolites.
- Other potential causes of symptoms that should be considered included:
    - Exposure to CO
    - High levels of CO_2
    - Exposure to hydrocarbons
    - Lack of oxygen, hypoxia
- There has been insufficient testing to date to confirm or deny cabin air contamination. Aircrew who report ill health following exposure to contaminated air should be referred for further investigations, including psychology, neurology, neurophysiology, neuroimaging and respiratory tests. However, clinically, it will be important to rule out any organic pathology before ascribing symptoms as being due to industrial hysteria and psychosomatic disorders.

- Dr Rob Loblay, a member of the Panel, discussed the role of laboratory testing and immune responses in a paper Appendix" see Appendix 5:
- Many of the biological tests currently being used in this area have not been validated for the situations in which they are employed.

3.5.2 Does subdetectable exposure occur?

3.5.2.1 Description of evidence

- Since the pilots and cabin crew of aircraft spend large proportions of their working lives in the cabin environment there has been some speculation as to whether sub-detectable exposure to contaminants could occur and what the likely effects of this undetectable contamination could be. It is possible that events might occur where aircrew are exposed to contamination that is undetectable to the human olfactory system and where there is no smoke to be observed. It is therefore possible that long-term, low-level exposure to contaminants could occur. There is also the possibility that some contaminants might be invisible and odourless.
- Sub-detectable exposure (exposure which is undetectable to the human olfactory or visual systems) can occur due to very low levels of contaminants, or contaminants that are invisible and odourless.
    - Carbon monoxide (CO) is odourless and has been identified as a product of pyrolysis (Prockop & Chichkova, 2007).
    - A paper by van Netten discussed the use of CO detectors on aircraft (C. van Netten, 2005a) [page 11].
    - There are differences in sensitivity to contamination in individuals:
    - An incident report described a fume event where one flight crewmember detected an abnormal odour but other flight crew did not (Air Accidents Investigation Branch, 2006c).
    - Tristan Loraine of the GCAQE observed that possessing a sense of smell is not a requirement for pilots or flight attendants (Loraine, 2009).
    - A scientific paper discussed differences in odour detection between individuals and the olfactory detection of different VOCs (Cometto-Muniz & Abraham, 2009).

- Nivison, in a personal submission noted:

> "While some of my exposures occurred with the Mobil Jet Oil II used before approximately mid 2004, the majority of exposure has occurred since the aircraft started using the BP 2380 oil. As the oil being used since then BP 2380 is of the lower odour variety, there may have been other times I was exposed without realising I had been exposed."
>
> (Nivison, 2009)

- With regards to possible effects of long-term, low-level exposure:
    - Winder and Balouet, quoting from a 1983 US National Transportation Safety Board study, stated:

> "[T]here are certain instances in which chronic or repeated exposure may sensitize a person to certain chemicals so that later concentrations

> in the ppb range may later elicit an acute hypersensitivity type reaction."
>
> (Winder & Balouet, 2001)

- Winder provided a review of possible mechanisms for hypersensitivity to low-levels of chemicals in certain individuals (Winder, 2002).
- Jamal *et al* reviewed a variety of studies and concluded that there is a link between long-term, low level exposure to organophosphorus esters and neurotoxicity (Jamal, Hansen, & Julu, 2002).

3.5.2.2 Interpretation of evidence

- The Panel observed that the question of whether sub-detectable exposures could be associated with toxic effects was to some extent confounded by the terminology used. In reviewing the literature, it was noted that reporting of an aircraft air quality event was triggered by a smell or odour. If the exposure is sub-detectable there is no such trigger and hence there is no way of determining incidence or prevalence of these exposures (if indeed they occur). It is certainly possible that a toxicologically relevant exposure could occur to toxic agents such as TCP and CO in the absence of such visual or olfactory cues; because these toxic agents are themselves colourless and odourless i.e. they are sub-detectable according to these criteria. The Panel also noted that detection could be prevented due to olfactory overstimulation. For example, hydrogen sulphide has significant toxicity at levels of greater than 50ppm. However, at this level those exposed can no longer smell the typical "rotten egg" smell due to overstimulation of the olfactory nerves.
- For the Panel the more difficult issue was whether the reported illnesses associated with cabin air quality incidents were associated with an unusual susceptibility to airborne toxic chemicals; i.e. adverse health effects occur in some individuals exposed to a level of a toxic chemical that would be without effect in most people. This form of reaction is commonly termed Multiple Chemical Sensitivity (MCS) and it is a controversial and hypothetical concept that does not lend itself well to conventional toxicological analysis. However, MCS is a condition in which olfactory stimuli are often involved in triggering an adverse reaction, so the link between cabin air odours and adverse effects cannot be dismissed completely.
- Another factor considered by the Panel was whether an interaction between TOCP, the putative cabin air neurotoxin, and some other factor could cause neurotoxicity at unexpectedly low doses. The possibility is that OP toxicity could be potentiated by the concurrent presence of another neurotoxin (e.g. carbon monoxide), or even by the lower oxygen tension that prevails at altitude even in a pressurised aircraft cabin. There were no definitive data to resolve either of these points, but see Section 5.7 for further discussion of the interactive influences of such environmental factors.

3.6 Does the environment influence the effect of the contaminants?

3.6.1 Are there synergistic effects / interactions between contaminants or with other onboard chemicals?

3.6.1.1 Description of evidence

- Some papers have demonstrated theoretical toxic synergies between different chemicals:
    - An early paper by Abou-Donia discussed the interaction between neurotoxicities induced by OPs and long-chain hexacarbon compounds (M. B. Abou-Donia, 1983).
    - Another paper discussed the potentiating effect of a ketone on an OP (EPN), possibly due to increasing the metabolic activation to a more toxic metabolite (M. B. Abou-Donia, Lapadula, Campbell, & Abdo, 1985).
- A review of the effects of ozone noted that:

> "The airway epithelial lining serves as an efficient barrier against penetration of exogenous particles and macromolecules. Disruption of this barrier following O_3 exposure represents a state of compromised epithelial defenses leading to increased transmucosal permeability. Although the barrier disruption following an acute exposure is transient in nature, the brief period of disruption caused by O_3, an oxidant air pollutant, provides an opportunity for facilitated entry of a potentially toxic particulate copollutant(s) across the airway epithelia."
>
> (Bhalla, 1999)

- PAN, an ingredient of some engine oils (e.g. Mobil Jet Oil II), has been shown to be a skin sensitizer (Winder & Balouet, 2002).
- Van Netten analysed the constituents of insecticides and discussed the potential interaction with bleed air contamination by engine oil (van Netten, 2002).
- Another paper by van Netten discussed methods to identify synergistic agents (C. van Netten, 2005a) [page 16].
- In his submission to the COT inquiry, Professor Furlong discussed the synergistic effects of mixed exposures and provided some references (Furlong, 2007b) [page 2]:
- It has been noted that TOCP potentiates the toxicity of malathion (Casida, et al., 1961).
- Van Netten noted that the inhibition of carboxyesterase by TOCP may potentiate the toxic effects of permethrin (C. van Netten, 2005b) [pages 463-4].
- Methods for studying the effects of complex mixtures have been proposed:
    - Verhaar *et al* proposed a theoretical framework for modelling the pharmacodynamics and pharmacokinetics of petroleum mixtures (Verhaar, et al., 1997).

3.6.1.2 Interpretation of evidence

- Many theories and claims regarding which chemicals could be responsible for alleged symptoms have been put forward, pointing towards toxic products of pyrolysed oil or a synergistic effect between a number of compounds that may not be at a toxic level individually but together may reach a "causal" threshold (Karalliedde, Edwards, & Marrs, 2003).
- Animal studies have shown that when two chemicals are combined (e.g. an OP plus DEET), severe neurotoxic effects were seen in the peripheral and central nervous system and increased mortality even though safe levels of each chemical were chosen (M. B. Abou-Donia, 2003; M. B. Abou-Donia, et al., 1996). Clearly, proving causation under these conditions is even more difficult.
- The Agency for Toxic Substances and Disease (ATSDR), a branch of the Centres for Disease Control (CDC) in the United States, has a legislative mandate to investigate priority hazardous substances in the environment. This includes the interactions of mixtures of hazardous substances that might occur in the environment and to which human populations might be exposed (Agency for Toxic Substances and Disease Registry, 2004). The question of the consequences of low-level chronic exposure to toxins was examined (using heavy metals as the prototype).
- An analytical method was used to estimate the interactions between these metals in the setting of chronic human exposures for each target organ of concern. First, an exposure-based hazard index (HI) is developed for each metal for each target organ.
    - Hazard Index$_{AS}$ = $E_{As} \square TTD_{Neuro\ AS} \square$
        - Where E_{As} is the measured dose of arsenic (expressed as mg/kg/day) and $TTD_{Neuro\ AS}$ is the target organ toxicity dose for arsenic on the neurological system (3 x 10-4mg/kg/day). The measured dose of arsenic ingested, expressed as mg/kg/day, can be derived from the measured level of arsenic in the urine. These individual hazard indices are then added together.
- The ATSDR was careful to emphasise that the methodology is only valid when the hazard quotients of at least two of the metals equal or exceed 0.1. □A qualitative 'weight of evidence' (WOE) approach is then used to determine the character of the interactions between binary metal pairs, and these estimates or quotients (derived numbers) are then applied to the total added hazard indices for each target organ. When applying this methodology the ATSDR concluded that in the case of arsenic, lead and cadmium there was a slightly greater than additive effect of the agents alone, but this was not substantial.
- In the current case, to document any ongoing chronic effect of potential air cabin pollution, one needs to identify the toxin (hazard), and measure its concentration in the body in relation to the dose exposed. This has not been done and is unlikely to be successfully done, given the lack of consistency and agreement on the "supposed" agent of exposure, the infrequent nature of the exposure itself and the lack of any measurement of dose and tissue concentrations (Agency for Toxic Substances and Disease Registry, 2004).

3.6.2 Are there interactions between contaminants and other aspects of the cabin environment?

3.6.2.1 Description of evidence

- It is well known that the low humidity of aircraft cabins can cause a variety of symptoms:
    - Norback *et al* evaluated the influence of air humidification on ocular and nasal symptoms (Norback, Lindgren, & Wieslander, 2006).
    - Strom-Tejsen *et al* studied the effects on passengers of different ventilation rates of fresh air, which alters the humidity (Strom-Tejsen, et al., 2007).
- Lindgren *et al* studied the influence of air humidification on perception of cabin air quality (Lindgren, Norback, & Wieslander, 2007).
- Nagda and Hodgson reviewed the relationship between low humidity and drying symptoms (N. L. Nagda & Hodgson, 2001).
- The Ideal Cabin Environment (ICE) Project international aviation conference produced a few papers on this subject. These mainly studied the interaction between altitude and comfort and noted that sleep was not normal at any altitude:
    - Perera gave an overview of the ICE project (Perera, 2009).
    - Another paper described two studies that investigated the effects of 8000 feet altitude on symptoms, neurobehavioral performance, and sleep (Muhm, 2009) .
    - Bagshaw reviewed the question of what is the most appropriate cabin altitude in pressurised aircraft (Bagshaw, 2009).
    - Gruen discussed the studies done at the Fraunhofers Flight Test Facility looking at the impact of cabin climate on comfort (Gruen, 2009).
- One study found that noise had a negative impact on perception of flight-related symptoms and subjective assessment of performance with crews reporting more awareness of symptoms such as swollen feet when conditions were noisier than when conditions were more quiet (Mellert, Baumann, Freese, & Weber, 2007).
- Honeywell's report in 1997 contains the following note:

> "Note that current safety standards differ from air-quality levels, that will provide a perceived, acceptable level of customer and crew satisfaction. Contaminant levels may be well below recommended levels in currently accepted safety standards - yet generate complaints, because they can act in synergy with other contaminants - or because some standards may be outdated and not have incorporated more recent scientific and medical evidence. In addition, extenuating circumstances on board aircraft (including humidity and cabin pressure), have not been studied to the extent that a new standard can be proposed - that incorporates these factors or identifies interactions between factors."
>
> (Honeywell, 1997)

- There are other sources of chemicals in aircraft:
    - Chemicals can be produced from reactions between ozone and aircraft cabin materials and clothing fabrics (Coleman, Destaillats, Hodgson, & Nazaroff, 2008).

- The impact of air pressure on volatile organic compound (VOC) emissions from aircraft carpet was evaluated (Gao, Deng, Lin, & Yang, 2009).
- There appear to be no formal studies looking at any toxic interaction between cabin air contaminants and aspects of the cabin environment.
- Winder and Balouet discussed the role of altitude and lower cabin pressure, suggesting that increased respiratory rate could contribute to increased exposure to contaminants (Winder & Balouet, 2002) [pages 18-21].

- In a submission to the Australian Senate inquiry, Thom and Burdon pointed out the possible interaction between inhaled oil mist and the hypoxia of altitude (Thom & Burdon, 1999).

3.6.2.2 Interpretation of evidence

- The Panel considered that currently there were insufficient data to determine whether there were interactions between contaminants and other aspects of the cabin environment, however, it would be reasonable to expect the cabin environment to have an impact on symptom expression.
- In addition to the physical layout in the cabin, other factors relating to the physical environment should be considered. The cabin environment is characterized by low relative humidity (10 - 20%), high air-exchange rate (10–20 h^{-1}) and reduced cabin air pressure (0.8 atm) (National Research Council, et al., 2001).
- While the percentage of oxygen at any altitude is the same (21%), the pressure varies with altitude. At the maximum cabin altitude of 8,000 feet the reduced pressure is equivalent to about 15% oxygen. That is a level at which the healthy human body is perfectly able to function. However, Winder suggested that this level of oxygen may be significant if the respiratory rate increases to compensate, predisposing the lungs to increased exposure to contaminants (Winder & Balouet, 2002). Others have argued that acceptable levels of exposure from industry cannot be applied to enclosed environments such as submarines or aircraft cabins, or where air is significantly recirculated.
- Coleman *et al* examined the effect of ozone consumption and volatile organic compound production (Coleman, et al., 2008). Saturated aldehydes (C1 through C10), acetone, and 6-methyl-5-hepten-2-one (6-MHO) were the compounds most commonly detected. These compounds reflect the plastic, carpet and seat fabric within the cabin. The detection of VOCs increased with an increase in atmospheric ozone, in particular formaldehyde. However, these levels were not in the toxic range. Other factors that have been studied include humidity as an independent variable; sleep patterns, climate control and noise.

3.7 Recommendations

1. That the Australian Government, through CASA and the ATSB, sponsor and fund the development of a single, central, internet-based, confidential reporting system on cabin air

contamination incidents to be co-ordinated and operated jointly by CASA and the ATSB. To improve the reporting and monitoring of cabin air contamination incidents, this system should have web-based forms to facilitate the collection and collation of data from all authorities and companies responsible for cabin air contamination incidents that would enable the data to be tabulated into a de-identified and unalterable uniform document that could be accessed and utilised by all stakeholders.

2. That the internet reporting system of cabin air contamination incidents utilise a common agreed database developed in consultation with all relevant parties, incorporating a minimum data set of variables applicable throughout Australia, but allowing scope for additional fields of entry.

3. That CASA resolve to enforce fully the mandatory reporting of all aircraft contamination incidents and alerts all operators that it is mandatory for the reporting of all aircraft cabin air contamination incidents and the outcomes of investigations and management to CASA using Form 404 within the required timeframe no matter how apparently insignificant the event to enable a more accurate determination of the frequency of such incidents.

4. That CASA alerts all operators that failure to comply with reporting requirements of cabin air contamination incidents will result in significant penalties, including the ability of CASA to suspend AOCs (Airline Operator Certificates) and inform the public through a well publicised website using a safety rating system based on that system currently operating in the USA.

5. That CASA issue specific guidelines for all aircrew, engineers and other ground crew regarding their responsibilities in reporting Mandatory Occurrences (MOs) with particular attention to aircraft cabin air contamination incidents.

6. That CASA mandate full disclosure of internal reporting and management systems of cabin air contamination incidents by airlines operators to improve the external reporting of all cabin air contamination incidents including followup investigations and subsequent management.

7. That Australia seeks immediate support of the International Civil Aviation Organisation (ICAO) for the implementation of a worldwide common agreed database incorporating a minimum dataset for the mandatory reporting of cabin air contamination incidents.

4 Do acute episodes of contaminated cabin air compromise flight safety?

4.1 Introduction to the evidence

This topic focused on the implications for flight safety of acute exposure to contaminated air, and has been divided into the components that are considered crucial for drawing conclusions. The evidence relevant to each individual question was described for the Panel members, who analysed and discussed the questions. Previous inquiries have looked at the effects of acute exposure in varying levels of detail.

- The UK Civil Aviation Authority conducted an investigation in 2004 which addressed the effect of cabin air contamination on the pilot's ability to safely fly and land the aircraft (Safety Regulation Group, 2004).
- The Committee on Toxicity focused on the potential irritancy of the contaminants and felt that further research was needed to define the potential irritants, as well as the effects of other aspects of cabin air environment such as low humidity and air pressure (Committee on toxicity of chemicals in food consumer products and the environment, 2007k) [paragraphs 78, 92].
- The US National Research Council report of 2002, *The Airline Cabin Environment and the Health of Passengers and Crew*, did not specifically focus on the acute effects of exposure (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002).
- The Australian Senate Committee report of 2000 made the effects of acute exposure on flight safety a central focus. Chapter 5, *Impact of air quality on air safety,* included a detailed review of the Kolver incident and the subsequent investigation, as well as several other incidents. Although it did not draw specific conclusions as to the risk to flight safety of fumes exposures, the Senate Report did recommend engineering changes to minimise the possibility of fume events (Senate Rural and Regional Affairs and Transport References Committee, 2000a).
- Murawski noted that the FAA had previously acknowledged the potential effects of acute exposure on flight safety:

> "In 2004, the FAA issued an Airworthiness Directive (AD) requiring BAe146 operators to prevent the accumulation of oil residue in the air supply system ductwork. The FAA stated that these procedures were necessary "to prevent impairment of the operational skills and abilities of the flight crew caused by the inhalation of agents released from oil or oil breakdown products, which could result in reduced controllability of the airplane." "
>
> (Murawski, 2009a)

The Panel considered this question under the following topics:

1. What were the acute symptoms and disabilities that occur with exposure to contaminated cabin air?
2. What contaminants might be responsible for the acute symptoms?
3. Who was affected by acute exposure?
4. What was the effect of the acute functional disabilities on the ability to control the aircraft?
5. What regulations govern cabin air and flight safety?

4.2 What are the acute symptoms and disabilities that occur with exposure to contaminated cabin air?

4.2.1 Description of evidence

4.2.1.1 Reviews

- A paper by van Netten included a review of the reported acute symptoms experienced following an exposure (C. van Netten, 2005b).
- The CAA has provided a classification of acute effects:

> **"Incapacitation** – Unable to perform any duties.
>
> **Partial Incapacitation** – Able to perform duties but with great difficulty
>
> **Impairment** – Able to perform duties with some difficulty and/or minor mistakes made (e.g. missed ATC calls)□Slight Impairment – Able to perform duties with little difficulty but with reduced efficiency (e.g. light-headed, dizzy)."
>
> (Barrow, 2007)

4.2.1.2 Medical reports

- Descriptions of acute symptoms following exposure were present in many of the personal medical reports submitted to the Panel. There was generally no attempt to identify the cause of the exposure. The symptoms described were predominantly respiratory, neurological or descriptions of mucosal irritation.
- Panel member, Dr Bhupinder Singh, provided the Panel with a list of cases with a history of exposure to toxic fumes that demonstrated the temporal link between exposure and effects (Singh, 2009).

4.2.1.3 Incident reports

- There were a number of incident reports where both the cause of the exposure and the subsequent effect have been more closely investigated:
    - Several incidents were described in the Australian Senate Inquiry [chapter 5] (Senate Rural and Regional Affairs and Transport References Committee, 2000a). Kolver described his symptoms in his submission to the inquiry (Senate Rural and Regional Affairs and Transport References Committee, 2000m) [Submission 1].
- Other incident reports described the acute symptoms following a probable fume exposure (Air Accidents Investigation Branch, 2004b, 2005, 2006c)
    - AAIB in the UK conducted a comprehensive investigation of fume events following a 2004 event (Air Accidents Investigation Branch, 2004b) .
        - Pages 21 - 34 reviewed incidents on a range of aircraft (Air Accidents Investigation Branch, 2004b)
        - On page 49, section 2.3.2, summarised the effects on crewmembers and discussed the likely causes.
    - A 1977 paper discussed a single case of a military navigator who suffered acute gastrointestinal and neurological symptoms while flying, thought to be due to inhalation of pyrolysed engine oil (Montgomery, Wier, Zieve, & Anders, 1977) .
- Several papers reviewed the causes of aircraft accidents, including the role of pilot incapacitation:
    - Buley reviewed the causes of non-fatal pilot incapacitation from 1960-66 (Buley, 1969).
    - DeJohn *et al* reviewed the literature in this area from 1968-2000 (DeJohn, Wolbrink, & Larcher, 2006).
    - Kulak *et al* described an epidemiological study of pilot incapacitation (Kulak, Wick, & Billings, 1971).
    - Smith *et al* described the toxicological findings in a series of aircraft accidents in 1970 (P. W. Smith, Lacefield, & Crane, 1970).

4.2.1.4 Case Series

- Van Netten noted the symptoms experienced by crew from planes with a recent history of fume events, as well as reports on air monitoring studies (van Netten, 1998).
- Winder and Balouet described seven cases of pilots with both acute and chronic symptoms (Winder & Balouet, 2001).

4.2.1.5 Surveys

- Michaelis surveyed Boeing 757 pilots and collated reports of fume incidents and short-term symptoms ((Michaelis, 2003).
- Harper also surveyed aircrew (predominantly flying on the BAe146) and reported the frequency of symptoms (A. Harper, 2005a, 2005b).

- Winder and Balouet surveyed US and Australian pilots, and reported the frequency of acute symptoms experienced (Winder, Fonteyn, & Balouet, 2002).
- Cox and Michaelis surveyed BAe146 aircrew (21 subjects) and then described the range and frequency of symptoms experienced (Cox & Michaelis, 2002).
- The Toxic Free Airlines website conducted an online survey in which people could leave comments. A total of 640 completed surveys were submitted (mainly by BA cabin crew) and the data collated. The results showed the raw data only, with no analysis. The survey form was online and it was unclear how the identity of respondents was verified (it would appear to rely wholly on the integrity and veracity of respondents) (Toxic Free Airlines, 2009).

4.2.2 Interpretation of evidence

- The Panel noted that reported frequencies of air quality incidents were not uniform across aircraft type. Hence in evaluating the literature it could not be assumed that all aircraft should and could be studied as a homogenous group.
- Table 4 and Table 5 show frequencies of air quality incidents and symptoms from North American carriers (C. van Netten, 2005b).

	Average number of incidents per aircraft	
Aircraft Type	***Per Year***	***Per 1000 cycles***
BAe146	*6.4*	*3.88***
MD-80	*1.01***	*1.02***
A-320	*1.67*	*1.29*
B-747	*0.34*	*1.25*
DC-10	*0.38*	*1.04*
B- 767	*0.21*	*0.63*
B- 737	*0.07*	*0.09*

A cycle is defined as take-off, flight and landing sequence
*** Incomplete data, estimate only*

Table 4: Air Quality Incident frequencies, based on flight incident reports submitted by three North American air carriers by flight crew. Reproduced from Van Netten (C. van Netten, 2005b)

	Air carrier		
Symptom	***X(%)***	***Y(%)***	***Z(%)***
Any Symptom	*58*	*78*	*82*
Eye, ears, nose and throat	*38*	*16*	*25*
Central nervous System:	*45*	*72*	*63*
Intoxication	*45*	*70*	*63*
Neuropsychological	*3*	*3*	*2*
Other	*6*	*19*	*8*
Respiratory	*9*	*16*	*28*
Gastrointestinal	*16*	*30*	*21*
Skin	*7*	*10*	*3*
Cardiovascular	*2*	*3*	*2*
Total incident reports (Number)	*128*	*598*	*299*

Table 5: Outline of symptoms associated with these reports. Reproduced from Van Netten (C. van Netten, 2005b).

- These data were obtained from only North American Air Carriers and have not been scrutinised for scientific merit.
- What was consistent across the three carriers was the preponderance of central nervous system (CNS) "intoxication" with upper respiratory tract symptom and gastrointestinal symptoms being reported less frequently.
- Toxicologists define toxidromes as the pattern of symptoms and signs that develop as a result of an exposure to a toxin. A syndrome is defined as a set of symptoms, which occur together. It follows that there should be a set of consistent symptoms which together make up a given condition. Where these signs and symptoms describe a toxic condition the term toxidrome is used. The more specific the signs and symptoms are for the condition the more suitable is the label toxidrome.
    - A simple example is the patient who has ingested heroin and presents with decreased conscious state, "pin point" pupils and decreased respiratory effort. In life threatening clinical situations the treatment may be mandated before the diagnosis is fully known. Hence in our example the patient would receive the antidote for heroin overdose before any investigations or corroborating history was obtained. 'Aerotoxic Syndrome' has not been officially recognised as a syndrome
- The term ''Aerotoxic Syndrome' was first proposed in 1999, and many people believe this condition is caused by contaminated air circulating in the cabins of jet aeroplanes (Balouet, Winder, & Hoffman, 1999). So far, the earliest relevant article identified was published in 1956 (Kitzes, 1956). There are 2 references on Medline under the term 'Aerotoxic Syndrome' (Abeyratne, 2002; M. A. Hale & Al-Seffar, 2009), yet there are 11,400 hits on Google. Three decades ago, cabin air quality was apparently not an issue in commercial aviation and the incidence of disease through airborne vectors or toxic fumes was uncommon among passengers and crew.
- Claims have been made that modern jet airliners generally carry the threat of disease through the ventilator systems of these aircraft, which have been designed for optimum efficiency. This may

allow lapses in the recycling of clean air and allow blocking fumes from engine exhausts of the jets to enter the inhabited parts of the aircraft (Chaturvedi, 2009).

- It has been claimed that 'aerotoxic' fumes are most common in the cockpit and that the technical crew are the most susceptible to the 'Aerotoxic Syndrome'.
- Individuals reporting that they suffer from 'Aerotoxic Syndrome' describe a wide range of non-specific symptoms and signs with insufficient consistency to fulfil the requirements for the definition of a medical syndrome.
- The non-specific nature of the signs and symptoms are such that many of the reported symptoms are largely the same as those reported by participants in all phase-1 drug trials. It is recognised that 70% of the population experience one or more of these symptoms every day (Bagshaw, 2008).
- Khan and Khan looked at trials of 12 weeks to 12 months duration, and found that 79 percent of patients on placebo remained well compared to 93 percent of anti-depressant responders (Khan & Khan, 2008).
- In the clinical effects described above and elsewhere there are 2 broad groups:

Irritant effect

- Irritated eyes (itchy, red, weeping etc), irritated throat (tightness, "scratchy", swelling, altered taste), and irritated skin (red and itchy).

CNS effect

- Described in terms of memory loss, poor concentration, increased lethargy, sleepiness, tiredness, lack of libido, headaches etc.

- These were the predominant symptoms from review of the medical reports of individuals who voluntarily submitted their own symptoms to this Panel Review. Additionally, many also claimed MCS and chronic fatigue.
- These symptoms are non-specific, do not tightly define any toxidrome and are common to a number of clinical conditions, which could be toxicological, non-toxicological and mental health related.

4.3 What contaminants may be responsible for the acute symptoms?

4.3.1 Description of evidence

- The Panel noted a number of studies that contended that the precise identification of chemicals responsible for the acute symptoms was not a pre-requisite for determining whether there were effects on flight safety.

4.3.1.1 Investigations

- An investigation by the CAA included an analysis of pyrolytic products and air conditioning duct contaminants. It also discussed the potential effects of the chemicals detected (Safety Regulation Group, 2004).
- A 1984 investigation by the National Transportation Safety Board (USA) evaluated the potential for turbine oil leakage into the bleed air system to cause pilot incapacitation in the Garrett TPE 331. It concluded that:

> "..contamination of compressor bleed air by the ingestion of engine oil is not possible"
>
> (National Transportation Safety Board, 1984)

  - This report did not show any increase in CO levels.
- Crane *et al* investigated the toxicity of thermal degradation products from aircraft lubricating oil and related products in rats, and concluded that it was the CO levels that were the source of the acute toxicity (Crane, Sanders, Endecott, & Abbott, 1983).
- Davies suggested that for totally enclosed environments a lower maximum permissible exposure level must be specified (Davies, 1975).
- A UK AAIB investigation concluded that there was exposure to some kind of irritant (and likely a mixture of chemicals), but could not be more specific (Air Accidents Investigation Branch, 2004b) [section 2.3, Pages 46-52].
- A National Institute of Occupational Safety and Health (USA) investigation into an Alaska airlines report on cabin air contamination attempted to elucidate the causes for symptoms suffered by some flight attendants on an MD-80. The investigation concluded that CO was unlikely to be a cause, and overall could not identify a work-related cause (Sussell, Singal, & Lerner, 1993).

4.3.1.2 Air Accident reports

- Very high levels of CO in post-mortem samples from victims of air accidents were thought to indicate an exhaust leak as a possible cause of the accident (Canfield, Chaturvedi, & Dubowski, 2005).

4.3.1.3 Scientific studies

- Kinkead *et al* investigated the acute toxicity in animals of a hydraulic fluid (which included TCP). Inhalation caused acute symptoms of rapid breathing, eye irritation and lethargy, with high mortality at high concentrations (E. R. Kinkead, Wolfe, Bunger, & Leahy, 1992). There are a number of other studies by the same group:
  - A 1986 study compared the short-term toxicity of several hydraulic fluids (Gaworski, Kinkread, Horton, Bashe, & Einhaus, 1986).

- In 1998 they evaluated the acute toxicity in animals of hydraulic fluids used in submarines (E.R. Kinkead, et al., 1988).
- A previous study evaluated the acute toxicity in animals of two operational Air Force hydraulic fluids given via inhalation, dermal and oral routes, and found one caused mild skin irritation (E. R. Kinkead, Horton, Gaworski, & Salomon, 1985). No other toxicity was identified.
- Another study by this group investigated the toxic effects in rats of a 90-day continuous inhalational exposure to hydraulic fluid, and found no effect at the concentrations tested (E. R. Kinkead, Wolfe, Bunger, Leahy, & Kimmel, 1991).

4.3.1.4 Reviews

- Van Netten has suggested that the acute effects are predominantly CO related (C. van Netten, 2005a).
- Bobb *et al* reviewed the known effects of the constituents of jet oil smoke (Bobb, Still, & Kenneth, 2003).

4.3.2 Interpretation of evidence

- The Panel noted that while much of the focus on cabin air contaminants has been directed towards the neurotoxic metabolites of TOCP, there was insufficient evidence to implicate this as the sole, or even the most likely, cause of adverse health effects in aircrew or passengers.
- The recent publication of the Furlong group which has been working to develop a biomarker of TOCP exposure cited in section 3.5.1.3, acknowledged that exposure to CBDP, the active metabolite of TOCP, was simply the "leading scenario for the cause of aerotoxic syndrome" (Schopfer, et al., 2010).
- According to Van Netten, aircraft air contamination incidents related to engine oil occurs at a frequency of 3.8-0.09 per 1000 cycles in crewmembers, depending on the aircraft. A cycle is defined as a take-off, flight and landing sequence. (C. van Netten, 2005b)
- The cause has been variously attributed to tri-ortho-cresyl phosphate (TOCP), carbon monoxide (CO) and other off-gassed agents from the pyrolysis of oil, such as organic acids (e.g. pentanoic and valeric acid). TCP is used as an anti-wear agent and constitutes 3% or less of the engine oil.
- In those aircraft with filtering systems, TCP has been extracted and others have shown the presence of CO in the air cabin at 60ppm ((R. Harrison, et al., 2009; C. van Netten, 2005b). Cigarette smoke is a source of CO and it is important to note that smoking in planes was banned in a "stepwise manner" over the last 30 years:

  1973: No-smoking sections introduced.

  1979: Cigars and pipes banned on planes.

  1987: Air Canada offers no-smoking flights between New York and Montreal

  1988: No-smoking on all U.S. domestic flights less than 2 hours.

  1990: No-smoking on all U.S. domestic flights under 6 hours.

1996: The Australian Government banned smoking on all passenger flights operated by Australian carriers.

1998: No-smoking on all U.S. domestic flights.

1999: Japan Airlines bans smoking.

2000: U.S. Federal Law 106-181 sec. 252.3, passed on 4/5/00, took effect in June 2000. It says, "All carriers shall prohibit smoking on all scheduled passenger flights."

- The type of aircraft might be an important independent variable to this discussion.
- The Panel noted a lack of scientific investigation into causation for these self-reported symptoms. The Panel acknowledged that TCP and CO were toxins that produce a significant effect on target organs/systems. The Panel also acknowledged that these target systems included those listed in Table 5.
- The Panel also recognised that the predominant system affected by these two agents was the CNS. However there were specific features of acute OP poisoning (in the case of TCP) and carbon monoxide poisoning that were absent.

4.3.2.1 Specific Agents

4.3.2.1.1 **Tricresyl phosphate (TCP)**

- TCP poisoning occurs acutely as a result of the inhibition of the enzyme acetylcholinesterase, resulting in an accumulation of the neurotransmitter, acetylcholine at the autonomic and motor synapses, which leads to initial stimulation and eventual exhaustion of cholinergic synapses. The mechanism of action of paralysis is persistent depolarization of the neuro end-plate eventually leading to desensitization.

- There are three distinct phases:

  a. Acute cholinergic crisis

  b. Intermediate syndrome (IMS)

  c. Delayed polyneuropathy (OPIDN)

a. Acute cholinergic crisis

- In the acute cholinergic crisis, those who have been exposed develop lacrimation, salivation, bronchospasm and objective muscle weakness. Other symptoms and signs include vomiting, respiratory distress, abdominal pain, depressed level of consciousness, seizures, muscle fasciculations and muscle paralysis. Progression of paralysis may affect the muscles of respiration necessitating ventilatory support.
- The cholinergic phase usually passes within 48-72 hours but complete clinical recovery from all the effects may take up to a week. Treatment is supportive with oximes, atropine and mechanical ventilation, in addition to decontamination.

b. Intermediate Syndrome (IMS)

- After the acute cholinergic phase, a second stage of weakness occurs 1 - 4 days later, with or without a symptom-free interval, and, if left unrecognized, can lead to fatal respiratory depression. First termed by Wadia *et al* in 1974 as type II paralysis, IMS is a syndrome characterized by muscle paralysis following the acute cholinergic phase (Wadia, Sadagopan, Amin, & Sardesai, 1974). IMS develops 12-96 hours after exposure and reflects a prolonged action of acetylcholine on the nicotinic receptors. The clinical features are muscular weakness in the ocular, neck, bulbar, proximal limb and respiratory muscles with occasional dystonic posturing, requiring mechanical ventilation in an intensive care unit for several days. Cranial-nerve palsies are common. The risk of mortality is due to the associated respiratory depression. The sensory functions characteristically remain normal and full recovery is evident in 4-18 days. The incidence of IMS in different studies has been reported to be between 20-68% (Leon, Pradilla, & Vesga, 1996).

c. Delayed Organophosphate Induced Polyneuropathy (OPIDN)

- OPIDN is an uncommon clinical condition. It occurs in association with the ingestion of large amounts of OP and manifests as limb weakness persisting long after the acute cholinergic symptoms have subsided. The clinical picture is characterized by a distal paresis in lower limbs (Brent, Wallace, Burkhart, Phillips, & Donovan, 2005).

4.3.2.1.2 **Carbon Monoxide**

- The clinical features of CO poisoning are less defined. Blumenthal described an acute exposure state and a delayed neurological deterioration post exposure (Blumenthal, 2001).
- The acute symptoms were subdivided into CNS and constitutional symptoms. CNS symptoms included amnesia, confusion, difficulty concentrating, dizziness, loss of consciousness and Parkinsonism. Constitutional symptoms included fatigue, personality change, seizures and weakness.
- Gastrointestinal symptoms included abdominal cramps, diarrhoea and nausea and vomiting. Cardiorespiratory symptoms were listed as angina, palpitations and shortness of breath. Delayed sequelae of CO poisoning were described as consisting of apraxia, apathy/indifference, memory deficits, Parkinsonism and psychomotor retardation.
- These symptoms and signs, which are most common in the elderly, occur within a month in 10-30% of patients (Raub, Mathieu-Nolf, Hampson, & Thom, 2000). Some of the frank neurological signs such as Parkinsonism are easily detected. Personality, cognitive and memory changes are not readily apparent and can be missed unless specifically targeted. Children may present with behaviour or education problems (Tomaszewski, 1999).

- Most neuropsychiatric signs resolve within a year (Choi, 1983). In one study, review at 3 years revealed persistent signs in 11% of patients (J. S. Smith & Brandon, 1973). There is no means of predicting recovery. Advances in neuro-imaging have been helpful in diagnosing delayed sequelae.'
- The initial toxic insult may manifest as diffuse hypoxic ischemic encephalopathy (as a result of oxygen debt) or focal cortical injury with a predilection for the temporal lobe and the hippocampus and necrosis of the globus pallidus and other basal ganglia.
- Diffusion-weighted Magnetic Resonance Imaging (MRI) of patients with CO poisoning have shown the development of delayed and slowly progressive cytotoxic oedema in the cerebral white matter, possibly as the result of delayed cell death and demyelination. The interval also parallels the development of delayed neuropsychiatric syndrome. Later, diffuse brain atrophy is present (Lo, et al., 2007).
- There are no documented cases of neuroimaging being performed on pilots or cabin crew exposed to air contamination episodes.

4.3.2.1.3 **Other Agents to consider**

- N-Phenyl-1-naphthylamine, (CAS No 90-30-2), a component of Mobil Jet Oil, also known as Phenyl-alphanaphthylamine (PAN), is a lipophilic solid used as an antioxidant in lubrication oils and as a protective agent in rubber products. In these products, the chemical acts as a radical scavenger in the auto-oxidation of polymers or lubricants. It is usually used in these products at a concentration of about 1%. PAN has many metabolites that are active. Chronic exposure to naphthylamine has potential carcinogenic properties (notably bladder cancer) but has not been implicated in acute toxicity (International Agency for Research on Cancer (IARC), 1987).
- Hydrocarbons and other solvents.
    - The following symptoms may occur with hydrocarbon exposure:

Mild to Moderate Toxicity	***Moderate to severe toxicity***
Nausea	*Pulmonary aspiration*
Dizziness	*Impaired memory*
Respiratory irritation	*Incoordination*
Headache	*Tachycardia*
Drowsiness	*Ventricular fibrillation*
Abdominal pain	*Acute renal tubular necrosis*
Vomiting	*Tremors*
Diarrhoea	*Convulsions*
	Unconsciousness
	Death

Table 6: Severity of poisoning. Adapted from Hydrocarbons listing on TOXINZ website (TOXINZ)

- While symptoms reported are similar to those listed above, they are non-specific and none are pathognomonic for solvent toxicity alone.

- Miscellaneous contaminants include CO_2, nitrogen dioxide (NO_2), TMPP and hydrogen cyanide (HCN) (Bobb, et al., 2003). There are no expected long-term sequelae from CO_2, or HCN. Nitrogen dioxide may cause chronic respiratory impairment, with diseases such bronchiolitis obliterans or pulmonary fibrosis. TMPP is known to reduce sperm motility in rats, which worsens with the duration of exposure.
- The UK Science and Technology Committee's 2007 report, *Air Travel and Health: An Update,* concluded that, given the scientific uncertainty regarding the potential hazards of inhalation of pyrolysed engine oil, further research into the full range of health effects from inhalation of heated or pyrolysed synthetic jet oils was definitely warranted (Science and Technology Committee, 2007). This research should consist of:
    - On board monitoring to determine the contaminants and level of each contaminant that enters the aircraft.
    - An epidemiological survey to determine the incidence and prevalence of ill health in aircrew and any association there might be with exposure to contaminated air.
    - A medical records review of aircrew concerning any long-term effects from exposure to the aircraft cabin environment.
    - A survey to determine whether passengers are affected by exposure to engine oil fumes on board aircraft.
    - Toxicological tests that take account of the potential synergistic effects of the range of different chemicals found in engine oil (Science and Technology Committee, 2007).
- The recommendations stated that whilst this research was being undertaken, the Government and regulators should re-consider whether there was a need to supply only fresh air to the flight deck and/or installing filters to minimise the risk to aircrew and passengers of engine oil fumes.

4.3.2.1.4 **What tests are available?**

- In ascribing cause and effect, the evidence should be considered critically and dispassionately before reaching any conclusion. Even when there has been a reported apparent temporal link between the two (80% reported personally by Singh), this does not constitute evidence of cause and effect (Singh, 2009).
- In addition, when dealing with a number of potential chemicals, it becomes even more difficult to attribute any specific clinical outcome to a particular exposure. Verhaar *et al* suggested a predictive tool that modelled the expected behaviour of a compound to an expected effect on a biological system (Verhaar, et al., 1997). However, as the authors noted, this approach was still limited in the presence of an increasing number of compounds. They note that, where there was a general lack of experimental data on an individual compound, predictive modelling of its effect in a mixture was impossible, despite techniques such as lumping analysis or outcome integration[2].

[2]Lumping analysis and outcome integration are specialist mathematical/statistical methods used for toxicological analysis of complex chemical mixtures.

- Its use in a clinical setting where the symptoms are non-specific is further limited, as the biological effect is difficult to ascribe in any case. Table 7 lists the possible ways evidence can be collected when investigating a potential toxicant:

• *Self-reporting.* • *Clustering of reports.* • *Industry reports.* • *Air quality sampling during normal aircraft operations.* • *Air filter examination.* • *Engine and APU, low pressure ducting examination (Safety Regulation Group, 2004).* • *Examination of the "coalescer bags" (placed between the bleed air and the cabin air to remove excess water content.* • *Air quality sampling during incidents in aircraft.*	• *Blood and/or urine testing in crew and passengers after normal operational flight (M. A. Hale & Al-Seffar, 2009).* • *Blood and/or urine sampling in crew and passengers during or immediately after an incident has been reported.* • *Sampling of objects throughout the plane after landing (uniforms, seats, etc).* • *Simulate the engine environment and collect and review the oil constituents and breakdown products, i.e. at altitude, in a reduced oxygen environment, after being subjected to extreme temperature [CAA-commissioned research project into Cabin Air Quality, Phase 1].*

Table 7: Methods of collecting evidence of exposure.

- The Panel noted that one of the particular difficulties was that, although it was possible to sample cabin air during normal operation, events of contamination were infrequent and unpredictable and there has not been the opportunity, nor suitable equipment, to capture an event and analyse exactly to what the crew might have been exposed (Science and Technology Committee, 2007).

- Table 8 outlined some testing results using gas chromatography-mass spectrometry. The Panel noted that TCP was identified, but so too were recreational drugs. The Panel considered that presence did not signify toxicity, as the Panel could not infer concentration or dose from this test. Similarly, it is not established that sampling such as this is in any way related to cabin air quality. In addition, these tests were performed on craft not associated with an incident, so the temporal relevance was unclear.

Aircraft	*Type of analysis*	*TCP presence*	*Comment*
B-757	*Flight deck roof filter*	*Positive*	
B-737	*Lavatory Filter*	*Negative*	*Positive for cocaine and amphetamines*
B-757	*Pre-filters from recycled air*	*Positive*	
B-757	*HEPA filter analysis*	*Positive*	*930 mg TCP/filter (total area 4.5m^2)*
BAe146	*Forward lavatory ceiling filter*	*Positive*	
BAe146	*Flight deck walls near side vent*	*Positive*	
BAe146	*Pilot's trousers*	*Positive*	*0.17mg/pair of trousers*

Table 8: Results of tests for presence of TCP in aircraft (C. van Netten, 2005b).

- However, the above concerns about scientific methodology do not detract from the need to provide crew and public alike with an "expert consensus" opinion regarding the "cause and effect" discussion outlined above. A systematic investigation by the UK CAA, initiated as a result of a November 2000 aircraft incident, noted strong circumstantial evidence toward oil contamination of cabin air from engine/APU oil seal leaks (Safety Regulation Group, 2004).
- There are many potential toxicants circulating in the air of an aircraft cabin. These can be both biological and chemical. The enclosed environment of the aircraft promotes exposure and, with respect to chemicals, the nature of the air circulation via the engine or the APU raises questions about design. There are many case histories and testimonies regarding illness and many in the aircraft industry believe that their illnesses, acute, chronic or acute on chronic are as a result of occupational exposure. There are also sporadic cases of passengers being similarly affected.
- There are a number of barriers preventing definitive conclusions regarding cause and effect in the context of this discussion including:
    - The number of potential agents and the lack of appropriately performed investigations addressing the toxicity of a single agent let alone a combination.
    - The lack of knowledge regarding acute versus low-level exposure.
    - The lack of monitoring, either environmental or biological.
    - The potential danger of extrapolating from one setting to another (i.e. the use of an OP as an insecticide versus its use as an engine coolant).
    - The lack of robustness in the levels of evidence that have been collected to date. In considering the hierarchy of evidence there is very little in the literature on this topic that would be considered anything above level IV (Australian Government, 2009).
- There appears to be significant variability in both the detection of a possible exposure, and its effects.

4.4 Who is affected by acute exposure?

4.4.1 Description of evidence

- Some of the major incidents that have been investigated demonstrate the variability in response:
    - In one incident, 2 of the 3 pilots experienced symptoms (Bureau of Air Safety Investigation, 1997).
    - In another incident all crew detected fumes, but only the pilot suffered symptoms (Bureau of Air Safety Investigation, 2002b). The co-pilot was unaffected.
    - In a third incident, only the co-pilot detected an odour and experienced symptoms (Air Accidents Investigation Branch, 2006c).

4.4.1.1 Location in cabin

- The 2001 AAIB investigation reviewed the air conditioning system of the BAe146 noting that the air for the flight deck comes from only one of the air conditioning packs (Air Accidents Investigation Branch, 2004b)[pages 8-9].
- The 2002 Australia Senate inquiry also discussed this area (Senate Rural and Regional Affairs and Transport References Committee, 2000a)[pages 9-11], and received submissions by the Australian Federation of Air Pilots (Senate Rural and Regional Affairs and Transport References Committee, 2000c) [Submission no 14] on this topic. In addition, Professor van Netten pointed out to the inquiry that:

> "... the flight attendants and the passengers are serviced by air coming from engines 3 and 4, whereas the pilots are serviced from engines 1 and 2, ...
>
> The pilots get air from engines 1 and 2 under normal conditions ... as soon as you get an oil seal leak in engine 1 or 2 then the pilots get higher exposure than anybody else because they get more fresh air."

4.4.1.2 Genetics

- There is proven genetic variation in individual metabolism of OPs:
    - Furlong's group described biomarkers for sensitivity to OPs (Furlong, Cole, et al., 2005).
    - Another Furlong paper described the genetic variability in cytochrome P450 pathway responsible for OP detoxification (Furlong, 2007a).
    - Tiffany-Castiglioni et al reviewed the role of polymorphisms in neurotoxicity (Tiffany-Castiglioni, Venkatraj, & Qian, 2005).
    - Cherry showed that farmers with ill health attributed to sheep dip were more likely to have certain polymorphisms of paraoxonase 1 (PON1) than farmers in good health that also used sheep dip (Cherry, et al., 2002).

4.4.2 Interpretation of evidence

- The Panel noted that case reports and the lay media identified both passengers and crew as being at risk of being affected by acute exposure. This suggested that there was no single cause. The Panel questioned the reason why some passengers would be affected and not others. Possible factors might include the nature of the individual, the result of seating or air circulation or was this dependent on the aircraft? The Panel was unable to find answers to these questions and considered that further research needed to be open and comprehensive before any specific syndrome could be clearly defined.

- If OPs were the source of cabin air contamination one should consider the impact of genetic make-up of individuals, which may play a role in susceptibility (Cherry, et al., 2002; Costa, et al., 2003; Mackness, et al., 2003). Other factors needed to be considered, for example, smokers were more susceptible to elevated CO levels. CO levels have been studied in submariners and results demonstrate there is a significant increase in CO levels within contained spaces, which is exacerbated in smokers (Davies, 1972; Lambert, 1972; Lawther, 1969; Lightfoot, 1972).

4.5 What is the effect of the acute functional disabilities on the ability to control the aircraft?

4.5.1 Description of evidence

- According to the EASA, there have been no catastrophic events or fatal injuries as a result of fume exposure (European Aviation Safety Agency, 2009) [page 6].
- From the database of incident investigations (Appendix 2: Fume event investigations), aircrew incapacitation was very rare, although some reports described the need to relinquish control of the aircraft:
    - In an Australian incident, the pilot described a loss of situational awareness and relinquished control to the co-pilot (Bureau of Air Safety Investigation, 1997).
    - In an incident in Sweden, the pilot felt dizzy and groggy and handed over control to the co-pilot (Statens haverikommission (SHK) Board of Accident Investigation, 1999).
    - In a UK investigation, both pilots were affected by lightheadedness and the commander became confused (Air Accidents Investigation Branch, 2007a). An emergency was declared, the pilots donned oxygen masks, and an automatic landing was performed. It was noted that:

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

- Michaelis hypothesised that the failure of the flight crew to react to hypoxia warnings in the cabin prior to a fatal crash near Athens might have been linked to acute effects of a contaminated air event

(an intermittent smell from the APU was noted in the log book a few weeks prior to the crash but mechanics could find no obvious leak) (AAIASB, 2006; Michaelis, 2007a) [page 103].

- No formal studies have been reported on aircrew function while affected by contaminated cabin air.

4.5.2 Interpretation of evidence

- The Panel recognised that aircrew were required to perform complex tasks, which require a high level of psychomotor and cognitive skills in the course of their duty. A continuous cycle of monitoring the situation, assessing the state of events, then taking actions and re-evaluating the results is required. Maintaining a continuous state of situational awareness involves complex neural processes (Benson, 2006; Civil Aviation Authority UK., 2006; Flin, O'Connor, & Crichton, 2008a, 2008b; O'Hare, 1997; Seamster, Redding, & Kaempf, 1997).
- These high level psychomotor and cognitive skills were very vulnerable to insult from contaminants that have the potential to compromise human performance. Although there are no reports of catastrophic events or fatal injuries following exposure to smoke and fumes, there were a number of reports where an aircrew member had become severely incapacitated, resulting in handing over the controls to the co-pilot, or an inability to perform the task at hand.

4.6 What are the regulations governing cabin air and flight safety?

4.6.1 Description of evidence

4.6.1.1 Australia

- The 2000 Australian Senate inquiry summarised the applicable Australian Regulatory requirements (Senate Rural and Regional Affairs and Transport References Committee, 2000a) [pages 1-5]:
  - Civil Aviation Regulations on crew health:

CAR 2 (major defect)

> ".... as in relation to an aircraft, means a defect of such a kind that it may effect the safety of the aircraft or cause the aircraft to become a danger to person or property."

CAR 48.0 (Flight time limitations)

> "1.4: Notwithstanding anything contained in these orders, a flight crew member shall not fly, and an operator shall not require that person to fly if either the flight crew members is suffering from, or considering the circumstances of the particular flight to be undertaken, is likely to suffer from fatigue or illness which may affect judgement or performance to the extent that safety may be impaired;"

Civil Aviation Advisory Publication (CAAP) 51-1 (O) states:

> "(c) smoke, toxic or noxious fumes inside the aircraft is considered a major defect."

- Other potentially relevant Civil Aviation Regulations include:
  - CAR 6.16A (Holder of a medical certificate; impaired efficiency due illness)

    "**(1)**The holder of a medical certificate must not do an act authorised by the flight crew licence…. To which the certificate relates while his or her ability to do the act efficiently is, or is likely to be, impaired to any extent by an illness or injury, no matter how minor."

  - CAR 233 (responsibility of pilot in command before flight)

    "(1) An aircraft shall not commence a flight unless evidence has been furnished to the pilot in command and the pilot has taken such action as is necessary to ensure that:

    a. The required operating and other crew members are on board and in a fit state to perform their duties.

    g. The aircraft is safe for flight in all respects"

  - CAR 256 (Intoxicated persons not to act as pilots etc. or be carried on aircraft)

    "(2)A person acting as a member of the operating crew of an aircraft,……..shall not, while so acting…., be in a state in which, by reason of his/her having consumed, used or absorbed any alcoholic liquor, drug, pharmaceutical or medicinal preparation or other substance, his/her capacity so to act is impaired."

- Civil Aviation Regulations relating to Airworthiness:
  - CAR 21 (Certification & airworthiness requirements for aircraft & part)

    "21.3 (4) *The following occurrences must be reported as provided in subreg 1 & 2*

    (c) The accumulation or circulation of toxic or noxious gases in the crew compartment or passenger cabin."

  - CAR 25 (Airworthiness standards for aeroplanes in the transport category)

    "25.1(1) The airworthiness standards for an aeroplane in the transport category are

    a. the airworthiness standards set out in part 25 of the FARs…… or

    b. the airworthiness standards set out in JAR-25….

(1) An aeroplane in the transport category that meets the airworthiness standards….in (1) a or b is taken to meet the airworthiness standards for an aeroplane in the transport category under these regulations"

- Civil Aviation Regulation relating to Reporting and Defects - CAR248 (Reporting of defects)

"(1) At the termination of each flight, or in any urgent case, during the currency of the flight, the Pilot in command shall report, to the persons specified by CASA, all defects in the aircraft…. which have come to the pilot's notice-

(2) Where a defect in the aircraft is reported in accordance with subreg (1), the operator of the Aircraft shall take such action…as is required under these regulations.

CAR 50 (Defects and major damage to be endorsed on maintenance release)50- where the holder of the certificate of registration, or operator, or flight crew member

a) becomes aware of the existence of a defect in the aircraft or b) becomes aware that the aircraft has suffered damage that in the opinion of the holder, the operator or the flight crew member is major damage; he / she shall enter on the maintenance release… an endorsement signed … setting out the particulars of the defect or damage."

- Definitions
  - CAR 2 □-Major defect:

"In relation to an aircraft, means a defect of such a kind that it may affect the safety of the aircraft or cause the aircraft to become a danger to person or property Defect - (dictionary) - shortcoming/failing CAAP 51 - Defect-imperfection that impairs the structure, composition or function of an object or system"

  - CAR 51 (Reporting of defects in Australian Aircraft-general)

"(1) Where a person who, in the course of employment with an employer, is engaged in the maintenance of an Australian aircraft becomes aware of the existence of a defect in the aircraft, the person shall report the defect to the employer. (2) If a person engaged in the maintenance of an Australian aircraft becomes aware of the existence of a major defect in the aircraft, the person must report the defect to the holder of the Certificate of registration and to CASA. (4) If the holder of the Certificate of Registration for an Australian aircraft becomes aware of the existence of a defect in the aircraft, he/ she must a. have an investigation made of the defect b. If the defect is a major defect - have a report made to CASA with respect to the defect and to any matters revealed by the investigation."

- *Civil Aviation Advisory publication*, CAAP 51-1(1) described the preferred method of complying with the directions given under CARs 51, 51A, 51B & 52. *2. Defect Reports 2.3.* Listed below are representative examples of major defects -

  "smoke, toxic or noxious fumes inside the aircraft"

- CAR 52A How must reports to authority be made:

  "(1) A report of a defect to CASA under reg 51,51A or 52 a) must be made in accordance with this regulation: (3)…A report to CASA in relation to a defect must be sent to CASA within 2 working days of the discovery of the defect"

- *The Occupational Health and Safety Act 1991* prescribed the employer's responsibilities:

  "16 Duties of employers in relation to their employees etc.(1) An employer must take all reasonably practicable steps to protect the health and safety at work of the employer's employees. Note: An employer who breaches subsection (1) may be subject to civil action or a criminal prosecution (see Schedule 2).(2) Without limiting the generality of subsection (1), an employer breaches that subsection if the employer fails to take all reasonably practicable steps: (a) to provide and maintain a working environment (including plant and systems of work): (i) that is safe for the employer's employees and without risk to their health; and (ii) that provides adequate facilities for their welfare at work; and (b) in relation to any workplace under the employer's control, to: (i) ensure the workplace is safe for the employees and without risk to their health; and (ii) provide and maintain a means of access to, and egress from, the workplace that is safe for the employees and without risk to their health; "

  (Office of Legislative Drafting and Publishing Australia, 2009)[Part 2, Div 1, 16 - page 22]

- *The National OHS Compliance and Enforcement Policy* detailed the methods of enforcement (Heads of Workplace Safety Authorities, 2008).
- A report by WorkCover outlined the public comment consultation on a draft national standard for the control of workplace hazardous chemicals (WorkCover NSW, 2008).
- Australian Registered Aircraft with VH registration are regarded as Australia Sovereign Territory and therefore OH&S legislation applies to the work place of the Technical and Cabin Crew [personal communication from Graeme Cleary].
- *National Code of Practice for the Control of Workplace Hazardous Substances* [NOHSC:2007(1994)];
- *List of Designated Hazardous Substances* [NOHSC:10005(1999)];
- *Approved Criteria for Classifying Hazardous Substances* [NOHSC:1008(2004)];
- *Exposure Standards for Atmospheric Contaminants in the Occupational Environment - Database* [NOHSC:3008(1995)];
- *National Model Regulations for the Control of Workplace Hazardous Substances* [NOHSC:1005(1994)];

- *National Code of Practice for the Preparation of Material Safety Data Sheets 2nd Edition* [NOHSC:2011(2003)];
- *National Code of Practice for the Labelling of Workplace Substances* [NOHSC:2012(1994)].

4.6.1.2 Europe

- CS 25.831 Ventilation

> "(a) Each passenger and crew compartment must be ventilated and each crew compartment must have enough fresh air (but not less than 0.28 m^3/min. (10 cubic ft per minute) per crewmember) to enable crewmembers to perform their duties without undue discomfort or fatigue. (See AMC 25.831 (a).)
>
> (b) Crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapours. In meeting this requirement, the following apply:
>
> > (1) Carbon monoxide concentrations in excess of one part in 20 000 parts of air are considered hazardous. For test purposes, any acceptable carbon monoxide detection method may be used.
> >
> > (2) Carbon dioxide concentration during flight must be shown not to exceed 0·5% by volume (sea level equivalent) in compartments normally occupied by passengers or crewmembers. For the purpose of this subparagraph, "sea level equivalent" refers to conditions of 25° C (77° F) and 1 013·2 hPa (760 millimetres of mercury) pressure.
>
> (c) There must be provisions made to ensure that the conditions prescribed in sub-paragraph (b) of this paragraph are met after reasonably probable failures or malfunctioning of the ventilating, heating, pressurisation or other systems and equipment. (See AMC 25.831 (c).)
>
> (d) If accumulation of hazardous quantities of smoke in the cockpit area is reasonably probable, smoke evacuation must be readily accomplished, starting with full pressurisation and without depressurizing beyond safe limits.
>
> (e) Except as provided in sub-paragraph (f) of this paragraph, means must be provided to enable the occupants of the following compartments and areas to control the temperature and quantity of ventilating air supplied to their compartment or area independently of the temperature and quantity of air supplied to other compartments and areas:
>
> > (1) The flight-crew compartment.
> >
> > (2) Crew-member compartments and areas other than the flight-crew compartment unless the crewmember compartment or area is ventilated by air interchange with other compartments or areas under all operating conditions.
>
> (f) Means to enable the flight crew to control the temperature and quantity of ventilating air supplied to the flight-crew compartment independently of the temperature and quantity of ventilating air supplied to other compartments are not required if all of the following conditions are met:

(1) The total volume of the flight-crew and passenger compartments is 22.65m3 (800 cubic ft) or less.

(2) The air inlets and passages for air to flow between flight-crew and passenger compartments are arrange to provide compartment temperatures within 2.8°C (5ºF) of each other and adequate ventilation to occupants in both compartments.

(3) The temperature and ventilation controls are accessible to the flight crew."

- European Parliament and Council, *Directive 2003/42/EC* - Reportable occurrences in civil aviation:
  - Include: "Fire, explosion, smoke or toxic or noxious fumes;"
  - JAR-E 690 - *Engine Bleed*

    Contamination Tests of Bleed Air for Cabin Pressurisation or Ventilation.

    "Tests to determine the purity of the air supply shall be made."

4.6.1.3 UK

- Committee on Toxicology 2006 *Annex 4*:

  "Throughout the life of an aircraft regulatory oversight seeks to ensure the continued airworthiness of that aircraft through approved maintenance practice and system modifications that are compatible with the original certification specification."

  (Committee on toxicity of chemicals in food consumer products and the environment, 2006i)

- *Air Navigation Order 2005- CAP 393*, *Air Navigation Order* and the *Regulations amendment 1/2005* came into effect.
- Article 142: mandatory reporting of occurrences. Article 142(3) states:

  "This article shall apply to occurrences which endanger or which, if not corrected, would endanger an aircraft, its occupants or any other person". Part 4 states that: "a list of examples of these occurrences is set out in Annexes I and II (and their Appendices) of Directive 2003/42 of the European Parliament and of the Council of 13th June 2003 on occurrence reporting in civil aviation."

- Mandatory Occurrence Reporting (MOR): *CAP 382* - Mandatory reportable incidents include:

  "Smoke, toxic or noxious fumes in the aircraft"

- *Health & Safety at Work Act: 1974*:
  - Not applied to aircraft due to a Memorandum of Understanding (MOU) with CAA leaving OH&S matters to CAA. The CAA advised that it had no direct responsibilities for passenger health or comfort (Michaelis, 2007a) [page 280].
  - The functions of the CAA were amended to include the health of persons on board aircraft, leading to establishment of the Aviation Health Working Group and later the Aviation Health Unit. Later this lead to the COT Inquiry and the Cranfield monitoring studies.
- *Control of Substances Hazardous to Health Regulations* (COSHH): These are applicable to aircraft using substance in synthetic jet engine oils e.g.:

> Regulation 6 *Assessment of Health Risks Created by Work Involving Substances Hazardous to Health*;
>
> Regulation 7 *Prevention or Control of Exposure to Substances Hazardous to Health;*
>
> Regulation 10 *Monitoring Exposure at the Workplace;*
>
> Regulation 11 *Health Surveillance* and
>
> Regulation 12 *Information, Instruction and Training*.

- *CAA Act 2006*: Secretary of State for Transport charged with:

> "the general duty of organising, carrying out and encouraging measures for safeguarding the health of persons on board aircraft"

4.6.1.4 USA

- **1970:** *Occupational Safety & Health (OSH) Act*, passed & to be carried out by OSHA intending:

> "to assure safe and healthful working conditions for working men and women."

- **1975:** FAA claimed exclusive jurisdiction over the safety and health of crewmembers:

> "Pursuant to its complete and exclusive responsibility for the regulation of the safety of civil aircraft operation … the FAA prescribes and enforces the standards and regulations affecting occupational safety or health with respect to U.S. registered civil aircraft in operation."

- (*40 Fed.Reg. at 29114,1975*) As a result of this federal regulation crewmembers were exempted from the protections of the 1970 OSH Act (Submission by Association of Flight Attendants to US Department of Transportation Dockets, 1999).

- *14 CFR 43.13 (b)* maintenance work be done "in such a manner" so as to restore the aircraft to its "original or properly altered" condition with regard to qualities affecting airworthiness (National Archives and Records Administration, 2001)
- *29 CFR § 1910.1200 - Toxic and Hazardous Substances - Hazard Communication*
- *29 CFR § 1910.1020 - Toxic and Hazardous Substances - Access to employee exposure and medical records*
- A memorandum of understanding between FAA & OSHA was signed in 2000, although to date the FAA has not extended the OSHA standards to aircraft in operation (Association of Flight Attendants-CWA, 2010; Federal Aviation Administration & Occupational Safety and Health Administration, 2000)
- *CFR 14: PART 21—CERTIFICATION PROCEDURES FOR PRODUCTS AND PARTS Subpart A—General*:

  "§ 21.3 Reporting of failures, malfunctions, and defects.

  (a) Except as provided in paragraph (d) of this section, the holder of a Type Certificate (including a Supplemental Type Certificate), a Parts Manufacturer Approval (PMA), or a TSO authorization, or the licensee of a Type Certificate shall report any failure, malfunction, or defect in any product, part, process, or article manufactured by it that it determines has resulted in any of the occurrences listed in paragraph (c) of this section.

  C3) The accumulation or circulation of toxic or noxious gases in the crew compartment or passenger cabin. (to FAA)"

- *Title 14 CFR 703 a (5)*

  "Mechanical reliability reports: Each certificate holder shall report the occurrence or detection of each failure, malfunction, or defect concerning: An aircraft component that causes accumulation or circulation of smoke, vapor, or toxic or noxious fumes in the crew compartment or passenger cabin during flight;" [to FAA].

- *Title 14 CFR 121.219*.

  " Each passenger or crew compartment must be suitably ventilated. Carbon monoxide concentration may not be more than one part in 20,000 parts of air, and fuel fumes may not be present."

- *Title 14 CFR 121.563 – Reporting mechanical irregularities*.

  "The pilot in command shall ensure that all mechanical irregularities occurring during flight time are entered in the maintenance log of the airplane at the end of that flight time. Before each flight the pilot in command shall ascertain the status of each irregularity entered in the log at the end of the preceding flight."

- FAR 25.831 (Ventilation and heating) 1997 amendment:

  Ventilation

> "a) Under normal operating conditions and in the event of any probable failure conditions of any system which would adversely effect [*sic*] the ventilation air, the ventilation system must be designed to provide a sufficient amount of uncontaminated air to enable the crewmembers to perform their duties without undue discomfort or fatigue and to provide reasonable passenger comfort. For normal operating conditions the ventilation system must be designed to provide each occupant with an airflow containing at least 0.55 pounds of fresh air per minute.
>
> b) Crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapours."
>
> FAR 25.831 - 1965
>
> "(a) Each passenger and crew compartment must be ventilated, and each crew compartment must have enough fresh air (but not less than 10 cu. ft. per minute per crewmember) to enable crewmembers to perform their duties without undue discomfort or fatigue. (b) Crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapors."

- Bobb Hoy wrote in the CASA Flight Safety Magazine:

> "By international agreement, the aircraft design must meet very searching design standards as specified by the design rules, for example US federal aviation regulations (FAR) 23 or FAR 25…. Continuing airworthiness is a complex subject but it involves simple philosophies to ensure that an aircraft continues to meet the design standard and therefore the airworthy state of the aircraft."
>
> (Hoy, 2000)

- Aircraft Air Quality Standard 161-2007.

> "This standard defines the requirements for air quality in air-carrier aircraft and specifies methods for measurement and testing in order to establish compliance wit the standard." (ASHRAE, 2007a)

- A report by SAE Aerospace described the procedure for sampling bleed air supplies from aircraft engines (SAE Aerospace, 2008).

4.6.1.5 Comments on regulations

- Some concerns were expressed by the workers union Unite (UK) that the safety regulations (COSHH) are acknowledged by the authorities as not being applied to aircrew, and so their welfare is not sufficiently protected. Unite is:

> "…aware of many UK airlines which have not carried out any risk assessments in these matters." (Unite the Union, 2007)

4.6.2 Interpretation of evidence

- The Panel considered that both the US (FAR 25.831 (Ventilation and heating) 1997 Amendment), and the EU (CS 25.831 Ventilation) regulations were very comprehensive, and mandated the supply of sufficient amounts of uncontaminated air to crewmembers and passengers at all times during the flight. The regulations specifically mandated that the crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapours.
- AIPA have made a number of comments in their submission about international and national regulations, and the current Regulatory Reform Programme. They are concerned that:

> "Australia therefore appears to have limited aviation specific regulatory options available to enforce air carrier compliance of internationally accepted crew and passenger health standards."
>
> (Australian & International Pilots Association (AIPA), 2009)[pages 2-3]

- There needs to be a testing procedure and a time scale that places a requirement on the operator or the AOC holder to regularly test their aircraft for cabin air quality.
- The Panel identified regulations; both in Australia and internationally, that require the provision of a safe working environment in an aircraft to ensure both safety of the aircraft and the health of aircrew and passengers. In Australia it is mandatory to report accumulation or circulation of toxic or noxious gases in the crew compartment or passenger cabin. The presence of smoke, toxic or noxious fumes inside the aircraft is considered a major defect, and any major defect must be reported by the pilot to a person specified by CASA, as soon as possible after detection. Where such a defect is reported, the operator of the aircraft must take action and a report must be furnished to CASA within two working days of the report. Where CASA considers that an unsafe condition exists, or is likely to exist/develop, then CASA may issue an Airworthiness Directive.

4.7 Recommendations

8. That CASA utilise ATSB data together with any other available data to maintain an ongoing comprehensive study of cabin air contamination incidents using available data collected in Australia by operators collating all relevant information including, but not limited to, numbers of incidents, types of incidents, aircraft types involved, engine types involved, flight phases involved, companies involved, dates and times, witness statements, to create and maintain a solid base of consolidated cabin air contamination incidents data to enable analysis of trends and common features.

9. That CASA obtain and utilise ATSB data to collate the ATSB Fumes Data Records of cabin air contamination incidents from Forms 404 lodged by the airlines and publish the collated results annually.

10. That CASA collate and follow up information collected both through the proposed Internet database and from any other cabin air contamination recording systems submitted to the regulators (NAAs) and safety boards (NTSB, ATSB, BSTB etc) for reporting to the Minister.

11. That CASA negotiate with ATSB for ATSB to undertake an in-depth analysis of all aircraft air contamination incidents at regular intervals and over a set period of time, to document trends over time, changes in the incidence of categories of cabin air contamination, identify common features and provide deidentified overall results and conclusions which could be used to design measures to eliminate cabin air contamination risks to aircrew and passengers.

12. That CASA negotiate with ATSB for ATSB to review past reported incidents of cabin air contamination incidents using the agreed case definition to determine if data recorded previously could be defined more accurately and entered into the new system to strengthen research or to highlight any deficiencies in recording.

5 Does exposure to contaminated cabin air result in chronic illness?

5.1 Introduction to the evidence

- There are a large number of papers looking at the relationship of contaminated cabin air and chronic health effects, but relatively few high-quality epidemiological studies. Given the lack of definitive studies, this question has been broken down into a number of components, the answers to which enabled the Expert Panel to draw preliminary conclusions and plan for definitive research

Component Topics

1. What are the chronic toxicological effects of the contaminants?
2. Is the dose of contaminants that it is possible to receive in a fume incident enough to produce illness?
3. What are the reported chronic symptoms and signs following exposure to contaminated cabin air?
4. What is the temporal relationship between exposure and symptoms?
5. What is a possible case definition?
6. What is the biological plausibility of proposed theories of causation?
7. Are there effects on reproductive health?
8. What do epidemiological studies demonstrate?

5.2 What are the chronic toxicological effects of the contaminants?

5.2.1 Description of evidence

5.2.1.1 Engine Oil

5.2.1.1.1 **Reviews**

- Winder and Balouet reviewed the ingredients of engine oil and their known toxicology (Winder & Balouet, 2002).
- A textbook chapter also reviewed the toxicology of engine oil (Winder & Michaelis, 2005b).
- There are toxicological studies of engine oil by itself, as well as some of the constituents.

5.2.1.1.2 **Studies with engine oil**

- There are a number of animal studies that evaluate the toxicity of engine oil directly. Mobil has sponsored a research program.
    - Mackerer *et al* evaluated the neurotoxic effects of conventional and low-toxicity jet engine oil in rats and hens (Mackerer, et al., 1999).
    - Daughtrey *et al* compared the effects of engine oil, TOCP and corn oil on a group of 20 hens over 90 days. TOCP induced clinical impairment but MJO 254 engine oil and corn oil did not (Daughtrey, Biles, Jortner, & Ehrich, 1996).
    - Feudenthal *et al* also studied the toxicity in hens, and concluded that the neurotoxicity caused by oil containing 3% TCP could not be accounted for by the amount of TOCP present (Freudenthal, et al., 1993).
- The effect of pyrolysis on toxin formation has also been investigated:
    - Centers described the formation of TMPP, a potent neurotoxin, by the high temperature reaction of TCP and trimethylopropane esters (Centers, 1992).
    - Callahan *et al* found significant amounts of TMPP were generated from Exxon 2380 Engine oil (Callahan, et al., 1989).
    - Van Netten and Leung studied the pyrolysis products of engine oil. They did not find TMPP, but did find significant amounts of CO (van Netten & Leung, 2001).
    - Wyman *et al* demonstrated TMPP formation in the conditions of a shipboard fire (Wyman, et al., 1992).
    - An inhalational study analysed effects of thermally degraded engine oils and hydraulic fluids on time-to-incapacitation and time-to-death in rats and chickens (Crane, et al., 1983). They also observed the animals for further 40 days and concluded that the oils were not more toxic than would be expected from the carbon monoxide production alone.

5.2.1.1.3 **Tricresyl phosphate**

- TCP is a mixture of isomers. A number of references reviewed the composition of commercially available mixes of TCP isomers (Michaelis, 2007a):
    - Winder and Balouet extensively reviewed the classification, manufacture, nomenclature, and toxicity of TCP (Winder & Balouet, 2002) [pages 7 – 17].
    - Part of the submission by Boeing reviewed the use of TCP in lubrication fluids (Goode, 1999).
- The WHO International Programme on Chemical Safety provided substantial toxicological background on the toxicology of TCP (International Programme on Chemical Safety, 1990).
- The ortho isomers are regarded as the most toxic, and subsequently the ortho content of TCP in engine oils has been minimised by the producers (Supresta and Chemtura) (Michaelis, 2007a).
    - De Nola *et al* found that the o-cresyl isomers of TCP exist almost exclusively as the more toxic mono-o-cresyl isomers rather than less toxic tri-o-cresyl phosphate isomers (De Nola, et al., 2008).

- Learmount conducted an interview with Tim van Beveren and Professor Dietrich Henschler discussing toxicity of the mono-ortho esters (Learmount, 2009).

- Much of the early work on the toxicity of the TCP isomers was published in German:
  - Using animal experiments Henschler evaluated the toxicity of the various isomers of TCP (Henschler, 1958 - English). He concluded that:

    > "Only tricresyl phosphates with ortho-cresyl radicals were found to have toxic paralytic effects. Their toxicity decreases in the order mono-, di-, and tri-ortho-cresyl esters in the proportions 10:5:1"

  - It was also noted that different types of poisoning were caused by chemically different TCPs.
  - Studies were made of the toxicity of triaryl phosphates (Henschler & Bayer, 1958 - English).
  - Another paper in German (no English translation obtained) compared triphenylphosphate and tricresylphosphate (Hierholzer, Noetzel, & Schmidt, 1957).
  - Henschler also studied the paralysing ability of triaryl phosphate (Henschler, 1959 - English).
- The toxicokinetics of TCP have been evaluated in hens by oral, dermal and subcutaneous administration:
  - Abou-Donia *et al* evaluated the pharmacokinetics (PK) of oral administration (M. B. Abou-Donia, Suwita, & Nomeir, 1990).
  - The same group evaluated the PK of TOCP and its metabolites in hens (Suwita & Abou-Donia, 1990) and rats (Somkuti & Abou-Donia, 1990).
  - The absorption of TOCP following subcutaneous administration in hens was also investigated (Carrington, Burt, & Abou-Donia, 1988).
  - Nomeir and Abou-Donia studied the metabolism in cats of a dermal dose of TOCP (Nomeir & Abou-Donia, 1986a). They also studied the synthesis and identification of TOCP metabolites (Nomeir & Abou-Donia, 1986b).
  - Hodge and Sterner evaluated the PK following dermal administration of TCP in humans (Hodge & Sterner, 1943).

- Metabolism in the liver is crucial in TCP toxicity:
  - Casida *et al* found that rats administered TCP excreted aryl phosphates, and suggests that the ataxia in animals following TCP administration is due to metabolites that act as esterase inhibitors (Casida, et al., 1961).
- It was found that 'subtoxic' doses of TCP could depress humoral immunity in albino rats and concluded that the mammalian immune system may be a sensitive target for TCP (Banerjee, Saha, Ghosh, & Nandy, 1992).
- A number of *in vitro* studies have looked at the effects of TCP:

    - One group looked at the effects of different TCP isomers on NTE (neurotoxic esterase) inhibition (Sprague & Castles, 1985).
    - Flaskos *et al* studied the effect of TCP on mouse neuroblastoma and pheochromocytoma cell lines (Flaskos, McLean, Fowler, & Hargreaves, 1998) and compared the effects of different TCP isomers on mouse neuroblastoma cells (Fowler, Flaskos, McLean, & Hargreaves, 2001).
- Attempts to set workplace exposure standards are difficult because of the different toxicity of the isomers:
    - Craig and Barth reviewed the literature around the hazards and exposure standards for TCP (Craig & Barth, 1999).
    - Hewstone discussed the health effects of lubricant additives, briefly touching on TCP (Hewstone, 1994).

Animal studies

- There is known to be considerable variation in response to TCP between different animal species:
    - Henschler reviewed the different responses of lab animals (Henschler, 1958 - English) [pages 5-6].
    - Somkuti found differing reactions between individual strains of rat, with certain strains of rat being unsusceptible to delayed neurotoxic effects of TOCP (Somkuti, et al., 1988).
- Abou-Donia made a detailed presentation to the GCAQE outlining the mechanism of action of OPs and showed results of studies using different isomers of TCP to induce neurotoxicity in rats (M.B. Abou-Donia, 2009).
- Many of the studies have analysed oral ingestion of either engine oil alone, or both engine oil and TCP separately:
    - Mackerer *et al* studied oral ingestion of engine oil and TCP, using inhibition of NTE and neurological symptoms as end points (Mackerer, et al., 1999).
    - Another group found TCP caused reproductive and endocrine toxicity in rats (Latendresse, Brooks, & Capen, 1994) (Latendresse, Brooks, Flemming, & Capen, 1994).
    - The phosphorylation of brain proteins in roosters in response to TOCP has also been investigated (Suwita, Lapadula, & Abou-Donia, 1986).
    - Another paper studied the relationship of TOCP and OPIDN in hens and changes in CNS protein phosphorylation (Patton, Lapadula, & Abou-Donia, 1986).
    - The same group also described changes in CNS protein phosphorylation in hens (Patton, Lapadula, O'Callaghan, Miller, & Abou-Donia, 1985).
    - Padilla and Veronesi described the development of a rodent model for OPIDN using rats exposed to TOCP (Padilla & Veronesi, 1985).
    - Another study used TCP-containing hydraulic fluid (Carpenter, Jenden, Shulman, & et. al., 1957).

- Aldridge compared the *in vitro* and *in vivo* effects of orally administered TOCP on cholinesterase function (Aldridge, 1954).
- The US National Toxicology Program conducted an extensive investigation of the toxicity and carcinogenicity of orally-administered TCP in rats and mice:

> "Under the conditions of these 2-year feed studies, there was no evidence of carcinogenic activity of tricresyl phosphate in male or female F344/N rats that received 75, 150, or 300 ppm. There was no evidence of carcinogenic activity of tricresyl phosphate in male or female B6C3F1 mice that received 60, 125, or 250 ppm. Nonneoplastic lesions associated with exposure to tricresyl phosphate included cytoplasmic vacuolization of the adrenal cortex and ovarian interstitial cell hyperplasia in female rats, increased incidences of clear cell focus, fatty change, and ceroid pigmentation of the liver in male mice, and increased severity of ceroid pigmentation of the adrenal cortex in female mice."
>
> (National Toxicology Program, 1994)

- Other studies have analysed the effects of other routes of administration:
  - Siegel *et al* administered TCP by inhalation. Their experiment studied neurotoxic effects in various animals over a 90-day period with concentrations ranging from 1.8 to 100 mg/m^3 (Siegel, Rudolph, Getzkin, & Jones, 1965).
  - Another study shows areas of neural degeneration in the CNS following SC administration of TOCP to cats (Cavanagh & Patangia, 1965).
  - Ahmed used dermal application (Ahmed, 1973):
    - Dermal administration to primates produced ataxia and paralysis. The pathological changes were mitochondrial swelling, large membrane-bound vacuoles, and deterioration of the myelin sheath.

Humans

- There have been numerous human poisonings by TCP.
  - Early reports described symptoms of probable widespread TCP poisoning in the 1930s, and the subsequent public health investigation – 'the Ginger Paralysis' (Maurice I. Smith & Elvove, 1930) (M.I. Smith, Elvove, & Frazier, 1930).
  - Morgan and Tulloss historically reviewed 'the Ginger Paralysis' (Morgan & Tulloss, 1976).
  - One paper reported on poisoning in a four year old (Goldstein, McGuigan, & Ripley, 1988).
  - Another paper reported on three workmen who developed polyneuritis (Hunter, Perry, & Evans, 1944).
  - An Indian group reported on an outbreak of poisoning in India (Srivastava, Das, & Khanna, 1990).

- There are reported instances of toxic polyneuropathy in girls following TCP poisoning (Senanayake & Jeyaratnam, 1981).

- More recent research has focused on the individual variability of response to OP:
  - Furlong has studied polymorphisms of the P450 system that relate to OP metabolism (Furlong, 2007a).
  - His group described biomarkers for sensitivity to OPs (Furlong, Cole, et al., 2005).
  - Tiffany-Castiglioni *et al* reviewed the role of polymorphisms in neurotoxicity (Tiffany-Castiglioni, et al., 2005).
  - Richter, Jarvik and Furlong studied the effects of PON1 polymorphisms on the hydrolysis of OPs (Richter, Jarvik, & Furlong, 2009).
  - Richter and Furlong reported on the development of high-throughput method for assessing PON1 status, and the PON1 allele frequencies for specific populations (Richter & Furlong, 1999).
  - One group defined inter-individual variation for five enzymes involved in OP toxicity (Mutch, Blain, & Williams, 1992).

5.2.1.1.4 **Toxicology of organophosphorus compounds in general**

- There has been significant research in defining the chronic effects of OP exposure:
  - Wilson provided a background to cholinesterase inhibition (Wilson, 2005).
  - Tang *et al* reviewed metabolism of OP pesticides in a textbook chapter (Tang, Rose, & Chambers, 2006).
  - Costa discussed the current debates in this area (Costa, 2006).
- Some studies have focused on the effects of chronic, low-level OP exposure:
  - Ray and Richards discussed the effects and mechanisms of chronic low-dose OP exposure (Ray & Richards, 2001).
  - Ray reviewed the mechanisms of the neurotoxic effects of chronic low-level OP exposure (Ray, 1998).
  - Prendergast, *et al* studied the effects of chronic low-level OP exposure in monkeys and rats (Prendergast, Terry, & Buccafusco, 1998).
  - De Silva *et al* commented on OP poisoning in developing countries and suggested that the adverse health impacts of chronic low-level OP exposures may have been underestimated, due to the focus on acute intoxications (De Silva, Samarawickrema, & Wickremasinghe, 2006).
- Chronic neurotoxicity and delayed neurotoxicity has been reviewed by a number of people:
  - Abou-Donia reviewed and discussed OPIDN and OPICN (M. B. Abou-Donia, 2003).
  - Jamal reviewed studies that investigate the relationship between long-term low levels of exposure to OP (i.e. no history of acute exposures) and symptoms of neurotoxicity (Jamal, et al., 2002).

- Moretto reviewed the acute and chronic toxicity of anticholinesterase agents (Moretto, 1998).
- Geyer *et al* reviewed the molecular mechanisms of OP toxicity, including the potential enzyme targets associated with acute, chronic and delayed neurotoxicity (Geyer, Evron, Soreq, & Mor, 2009).
- Jamal reviewed different neurological syndromes that can follow exposure to OPs (Jamal, 1997).
- Another review looked at the history and possible mechanisms (Barrett, Oehme, & Kruckenberg, 1985).
- Abou-Donia gave a presentation to the BALPA conference outlining OPICN (M. B. Abou-Donia, 2005).

- In addition there has also been speculation of links to motor neuron disease:
  - Chang and Wu discussed the role of NTE mutations in OPIDN and motor neuron diseases (Chang & Wu, 2009).
- Much of the debate has been around the underlying mechanisms of the chronic neurotoxicity, in particular the role of NTE:
  - Johnson looked at the role of NTE measurements in biological evaluations (Johnson, 1990).
  - Abou-Donia and Lapadula discussed the specific mechanisms of OPIDN (M. B. Abou-Donia & Lapadula, 1990).
  - Johnson suggested that the mechanism for organophosphorus neurotoxicity is phosphorylation of neurotoxic esterase (Johnson, 1975).
  - Ray reviewed the mechanisms of the neurotoxic effects of chronic low-level OP exposure (Ray, 1998).
- There has been considerable discussion about the relationship between the symptoms suffered by aircrew and other multisystem diseases:
  - Hooper discussed the symptoms, definitions, and diagnosis of multi-system diseases (Hooper, 2005).
- Epidemiological studies to substantiate the chronic effects of OP exposure have focused on agricultural workers:
  - Pilkington *et al* found a strong link between exposure to concentrated OP and neurological symptoms and a possible weak link between cumulative exposure and chronic effects (Pilkington, et al., 2001). The editorial in the journal also discussed this report (Blain, 2001).
  - Rosenstock *et al* performed a retrospective cohort study of agricultural workers who had OP poisoning (Rosenstock, Keifer, Daniell, McConnell, & Claypoole, 1991). The study found that two years later the exposed group had significantly worse neuropsychological functioning compared to controls.
  - Stephens *et al* demonstrated decreased neuropsychological performance in sheep-dip workers (Stephens, et al., 1995).

- Steenland *et al* demonstrated neurobehavioral deficits in people who had suffered acute pesticide poisoning (Steenland, et al., 1994).
- Stallones and Beseler studied depressive symptoms in farm residents exposed to pesticides (Stallones & Beseler, 2002).
- A 1985 study compared levels of biochemical markers between agricultural workers and controls (Misra, Nag, Bhushan, & Ray, 1985).

- Some reviews have linked the symptoms of agricultural OP poisoning and those of aircrew:
  - A review by Julu, Hansen and Jamal found similarity in the symptoms suffered by farmers exposed to sheep dip and aircrew (Julu, Hansen, & Jamal, 2005).
    - Note: There have been some papers published that express concerns regarding some reported neurological toxicological effects, with some papers by Abdel-Rahman and Abou-Donia at Duke University (reporting effects of Sarin and synergistic effects of the insecticides DEET and permethrin) coming in for particular mention (Jortner, 2005; Jortner, 2006; Garman, 2006) and criticism of their histological analysis. Although this particular research group was singled out, the authors point out that these histological errors are common throughout toxicology.

5.2.1.1.5 **N-phenyl-1-naphthylamine**

- Wang *et al* demonstrated a carcinogenic risk in animal studies with N-phenyl-1-naphthylamine (H. W. Wang, Wang, & Dzeng, 1984).
- Boman *et al* described a case study of dermatitis and guinea pig studies of sensitisation (Boman, et al., 1980).
- Carmichael and Foulds also discussed naphthylamine allergy (Carmichael & Foulds, 1990).

5.2.1.2 Hydraulic fluids

- Hydraulic fluids have been suspected of contaminating cabin air:
  - Hodges discussed the different hydraulic fluids used in military and aerospace applications (Hodges, 1996).
  - Hanhela *et al* surveyed the contamination of cabin air in military aircraft and suspected hydraulic fluid as the source of trialkyl phosphates (Hanhela, et al., 2005).

- The effects of high-temperature on hydraulic fluids:
  - The Committee on Toxicity (Committee on toxicity of chemicals in food consumer products and the environment, 2007k) (Page 6, paragraph 30) reviewed the papers on thermal degradation of hydraulic fluid.
  - Phillips discussed the mechanism of formation of carbonaceous material in hydraulic fluids (Phillips, 2006).

- Van Netten and Leung analysed the products of pyrolysis of aircraft hydraulic fluids, as well as engine oils (van Netten, 1999) (van Netten & Leung, 2001).

- There have been several reviews of the toxicity of hydraulic fluids:
  - Hewstone discussed the health effects of several lubricant additives, briefly touching on TCP (Hewstone, 1994).
- Carpenter *et al* studied Cellulube 220, which is a hydraulic fluid composed of a mixture of triaryl phosphate compounds, with less than 3% TOCP (Carpenter, et al., 1957).
  - This paper described experiments on various animals using various routes of administration and concluded that neurotoxicity is related to TOCP content, there is a wide species variation, there is a latent period for development of paralysis, with a cumulative effect, and that TOCP causes neurotoxicity.
- The toxicology of hydraulic fluids has been assessed in animals:
  - Mattie *et al* assessed the oral toxicity in rats of 4 hydraulic fluids (Mattie, et al., 1993).
  - One group studied the toxic effects of Skydrol. The mist resulted in nasal irritation (Healy, Nair, Ribelin, & Bechtel, 1992). High-exposure female rats also had reduced body weights, increased relative liver weights, and decreased haemoglobin and haematocrit levels, and decreased plasma cholinesterase levels. High exposure males had increased liver weights and decreased haematocrit.
  - Siegel *et al* performed an experiment that studied neurotoxic effects in various animals over a 90 day period with concentrations ranging from 1.8 to 100 mg/m^3 (Siegel, et al., 1965).
  - A report for the Naval Medical Research Institute evaluated the oral, dermal, and inhaled toxicity of 4 hydraulic fluids used in submarines (E.R. Kinkead, et al., 1988).
  - Another official report investigated the animal toxicity of 2 Air Force hydraulic fluids, and found that one was a skin irritant but neither caused neurotoxicity (E. R. Kinkead, et al., 1985).
  - The same group investigated the animal toxicity of candidate hydraulic fluid for Strategic Air Command aircraft (E. R. Kinkead, et al., 1992).
  - Kinkead *et al* also investigated the toxic effects in rats of a continuous inhalational exposure (E. R. Kinkead, et al., 1991).
  - Lipscomb *et al* used rats to study the inhalational toxicity of TOCP and several lubricant oils containing TOCP after heating to 650^{o}C to volatilise the oils (Lipscomb, Walsh, Caldwell, & Narayanan, 1995). The rats were exposed for 4 hours to the equivalent of 5 mg/L oils in air. These doses were sufficient to produce 35-50% inhibition of NTE, a sensitive marker of OP-induced OPIDN.

5.2.2 Interpretation of evidence

5.2.2.1 Engine Oil

- The Panel recognised that seal failure events have generally yielded information on acute health effects characterised by irritation of the eyes and respiratory tract, and acute disturbances of cognition and CNS functions (see Section 4.2). The Panel reviewed whether such acute exposures could lead to delayed adverse health effects or whether chronic low-level exposure to chemicals released during normal aircraft operations was associated with adverse health effects in aircrew or passengers. The Panel concluded that currently available information did not allow either of these possibilities to be assessed with any reasonable certainty.
- The Panel noted that much of the literature on the adverse health effects of cabin air contamination focused on TOCP, derived from jet engine oils, as the probable causative agent for both acute and chronic adverse health effects because the neurotoxic effects of TOCP were well established, particularly through the epidemic of human poisonings associated with adulterated liquors during the 1930s (Morgan & Tulloss, 1976; Maurice I. Smith & Elvove, 1930).
- Organophosphonates (OPs) classically produce three types of neurotoxic effect with sufficient exposure:
    - An acute cholinergic response associated with inhibition of acetylcholinesterase (AChE), resulting in excessive and prolonged cholinergic neurone activity. TOCP is a relatively weak inhibitor of AChE, but OP active metabolites are generally more potent than the parent molecules.
    - OPIDN – a progressive neuronal degenerative disease characterised by demyelination and axonal loss, primarily in peripheral and spinal nerves, but also occurring in the medullary region of the brain; TOCP is a relatively potent inhibitor of neuropathy target esterase, the putative site of action of those OPs which produce OPIDN.
    - OP-induced chronic neurotoxicity (OPICN), also called Chronic Organophosphate Induced Neuropsychiatric Disorder (COPIND) – a neurodegenerative disease which primarily affects brain neurons (mainly in the cerebral cortex, cerebellum and hippocampus) and results in chronic behavioural and cognitive dysfunctions; it normally occurs after an acute large toxic exposure, but there is speculation that it can also occur with sub-clinical dosing; the key features are progressive neuronal cell death associated with apoptosis, and possibly exacerbated in the presence of cellular oxidative stress.
- The possible involvement of TOCP in acute toxic events is discussed in Chapter 4. This section focuses more on the possible involvement of TOCP in more chronic adverse health effects.
- There are a number of points which are inconsistent with TOCP being the sole neurotoxic agent of concern in cabin air quality incidents:
    - There are significant species- and organophosphate-structural differences relating to potencies for producing the three types of neurotoxicity; while TOCP is implicated in producing both OPIDN and OPICN, it has relatively low potency as an AChE inhibitor. Since the classical acute signs of AChE inhibition appear to be absent in the

adverse health effects associated with cabin air quality incidents, this would be consistent with TOCP exposure being involved.

- While TOCP is relatively potent in causing OPIDN in humans and in classical animal models, the peripheral neurotoxicity, which is characteristic of OPIDN, is generally not described in the reported syndrome associated with cabin air contamination incidents.
- The adverse health effects described are more consistent with OPICN or COPIND, which is a chronic and essentially irreversible syndrome rather than an acute intoxicating event. A key piece of evidence, which is currently lacking, would be a clear indication that the chronic neuronal cell death can occur after chronic low-level exposure to TOCP. At present, such evidence in humans is limited to studies with farmers and others occupational exposed primarily to OP pesticides with AChE inhibitory potency. If such a mechanism for chronic neurotoxicity could be demonstrated for TOCP, it might explain why aircrew appear to be more susceptible than passengers because of the potential for repeated low-level occupational exposures.
- Potency differences between OPs in AChE inhibition are often associated with differences in the rates of metabolic activation and inactivation; such differences may be influenced by induction and/or inhibition of the activating CYP450 enzymes, or by genetic polymorphisms influencing the activity of OP detoxifying enzymes (e.g. the CYP450 enzyme paraoxonase 1).
- Furthermore, there are likely to be genetic polymorphisms for susceptibility to neurotoxicity, which are as yet undefined. In the case of TOCP, oxidative conversion to saligenin cyclic-o-tolyl phosphate appears to activate TOCP in producing OPIDN (Suwita & Abou-Donia, 1990). It remains to be established that differences in individual susceptibility to cabin air fumes containing TOCP have a metabolic component, whether genetic in origin or associated with the interaction of chemicals in the fumes.

- A potentially confounding factor in evaluating the role of TOCP in the cabin air quality debate is that engine oils generally report total levels of TCPs. Efforts have been made to reduce the level of TOCP in such oils, but ignore that fact that substantially higher levels of mono-ortho (MOCP) and di-ortho (DOCP) cresyl phosphate isomers remain in the oils. Both MOCP and DOCP are assumed to be more neurotoxic than TOCP in causing OPIDN, although their role in causing OPICN/COPIND is much less well studied. The relative potency estimates for TOCP (1x), DOCP (5x) and MOCP (10x) appear to be based on Henschler's 1958 studies with commercial and semi-purified TCP compounds, using paralysis in chickens as the test model (Henschler, 1958; Henschler, 1958 - English translation).
- There are still many unknowns in relation to phosphorylation targets and other reactions with brain proteins and enzymes that can be demonstrated with OP esters. Ray and Geyer have reviewed the range of potential brain and immune system targets for interaction with OPs having quite diverse toxicological profiles (Ray & Richards, 2001; Geyer, et al., 2009). A better understanding of the significance of low-dose interactions with such targets will be needed to unravel the full story on the complete spectrum of OP chronic neurotoxicity.

5.2.2.2 Hydraulic Fluid

- The animal evidence confirms the potential for hydraulic fluids to have local toxic (irritant) effects as well as various systemic toxic effects, including neurotoxicity. Studies using the oral route of administration do not provide much assistance in resolving issues around cabin air quality.
- There are several reports where inhalation of hydraulic fluid mists was included as an exposure route (Healy, et al., 1992; E. R. Kinkead, et al., 1992; E. R. Kinkead, et al., 1991; Siegel, et al., 1965). These studies aimed to assess hydraulic fluid toxicity by a range of exposure routes. The inhalational studies are likely to be more relevant for assessing the potential toxicity of hydraulic fluids in aircraft cabin air. However, of the hydraulic fluids studied, only some were stated to contain TOCP and only these demonstrated neurotoxicity in chickens, an OPIDN-susceptible species, while rats, monkeys and dogs showed little or no neurotoxicity at levels up to 50-100mg/m^3. Irritancy to nose, respiratory tract and eyes was demonstrated in some experiments, and in the studies reported by Kinkead (1992) with a TOCP-containing fluid, relatively low levels (1.5 – 2.1 mg/L) were lethal to rats, although the cause of death was pulmonary oedema (a direct irritancy effect) rather than neurotoxicity.

5.3 Is the level of exposure to contaminants that could occur in a fumes incident enough to produce chronic illness?

5.3.1 Description of evidence

- There are difficulties in addressing this question in terms of both the dose and effect. The animal studies described above can only give a very general idea of the dose-response relationship:
    - See Section 3.4.4.1.6 for discussion of doses and concentrations.
    - Craig and Barth reviewed the literature around TCP toxicity and the levels required to produce neurotoxicity (Craig & Barth, 1999).
    - A report for the UK CAA analysed the levels of TOCP required to induce OPIDN (Safety Regulation Group, 2004) [*Appendix C*].

5.3.2 Interpretation of evidence

- The Panel was unable to draw any conclusions about the exposures in cabin air quality incidents and their relationship to threshold values in humans that would result in adverse health effects.
    - TOCP has been well studied in classical models (hen and cat) for OPIDN. Extrapolation of these dose-response data suggests a safe human dose of 2.5 mg/kg for a single dose and 0.13 mg/kg/day for repeated exposures (Craig & Barth, 1999). These extrapolations incorporate standard safety factors from dermal and oral studies in hens and cats. They also appear to be consistent with systemic dose estimates following inhalational exposures. However, these authors caution that such safety estimates are based on exposure to relatively pure TOCP, and they note that TOCP-caused OPIDN may be more associated with the presence of more toxic mono-ortho- and di-ortho-ester contaminants.
    - The current occupational exposure standard for airborne TOCP is 0.1 mg/m^3 8 h-time weighted (American Conference of Governmental Industrial Hygienists, 1997), although it has been noted that this standard may be overly conservative since exposures of hens at 3.75 times this exposure standard produced no OPIDN (Siegel, et al., 1965). It is also noted that the ACGIH standard may have been set using data from a human study in which exposures were poorly documented.
    - Since the levels of TOCP (or more toxic mono-*ortho*- and di-*ortho*-isomers) in cabin air during mist incidents has been inadequately characterised, exposure comparisons with estimated human safe doses are probably not reliable at this time.

5.4 What are the reported chronic symptoms and signs following exposure to contaminated cabin air?

5.4.1 Description of evidence

- Sixty-two personal medical reports were submitted to this inquiry, many of which described chronic symptoms suffered by aircrew.
- See Table 24 in Appendix 6 for relevant epidemiological studies.
- A number of case series have been described by various medical professional:
    - As noted earlier, Panel member Associate Professor Bhupinder Singh provided the Panel with a list of cases with a history of exposure to toxic fumes that demonstrate the temporal link between exposure and effects (Singh, 2009).
    - Mackenzie Ross described a series of 27 pilots who underwent neuropsychological and mental health assessments (Sarah MacKenzie Ross, 2008):
        - Data on the same series of pilots was presented to the Committee on Toxicity in 2006, but this included extensive appendices detailing the results of blood tests in the pilots (S. MacKenzie Ross, 2006).

        - Professor Morris, of Kings College Hospital in London, provided a commentary on the submission by Mackenzie Ross that was included in the COT report (Committee on toxicity of chemicals in food consumer products and the environment, 2006w). Morris was impressed with the quality of the research, and expressed concern about the neuropsychological damage detected in the subjects of the research, but suggested that a much larger epidemiological study would be required before any link with contaminated air could be shown. He did, however, acknowledge that such a large study would be difficult to carry out and agreed with Mackenzie Ross that the possibility of an association with contamination had not been ruled out and thus further investigation should be carried out.
        - The COT report included a further commentary by Professor Morris about the findings of Mackenzie Ross, with a focus on whether routine simulator proficiency tests for pilots would detect the neuropsychological dysfunction (Committee on toxicity of chemicals in food consumer products and the environment, 2007g).
    - Coxon, an Australian psychologist, reported neuropsychological test results on two pilots and six flight attendants (Coxon, 2002):
        - She also provided a submission to this inquiry alerting the Expert Panel to her research (Coxon, 2009) .
- Burdon *et al* prepared a paper describing the respiratory symptoms and test results of a series of 14 BAe146 aircrew (J. Burdon & A. Glanville, 2005):
        - The authors presented the same research to the *BALPA Contaminated Air Protection Conference* (J. Burdon & A. R. Glanville, 2005).
        - Dr Burdon also sent a submission to this inquiry, which included his CV and a background to his research and later made an invited presentation to the Expert Panel (Burdon, 2009a, 2009b).
    - Heuser *et al* made a presentation to the BALPA conference describing the results of physical exams, neuropsychological exams, and PET scans on 26 flight attendants (Heuser, Aguilera, Heuser, & Gordon, 2005).
        - An earlier paper that discussed the role of PET scans in the demonstration of long-term functional abnormalities following neurotoxic injury (Heuser & Mena, 1998).
    - Dr Moira Somers made a presentation to the BALPA conference detailing her experience in seeing 39 aircrew since 1999. It included an analysis of the symptoms suffered. (Somers, 2005)
        - Dr Somers has also made a submission to this inquiry which included a letter outlining her concerns (Somers, 2009).
- There were a number of case descriptions:
    - Mackenzie Ross *et al* described the case of a pilot with an 11-year history of symptoms (Mackenzie Ross, Harper, & Burdon, 2006).

    - Winder and Balouet described 7 cases of pilots with both acute and chronic symptoms (Winder & Balouet, 2001).
- There were a number of surveys of aircrew focused on the chronic symptoms experienced following possible exposure to contaminated cabin air:
    - Michaelis described the results of a survey of 106 pilots who were members of BALPA (Michaelis, 2003).
    - Cox and Michaelis surveyed 21 aircrew that had flown on the BAe146 (Cox & Michaelis, 2002).
    - Winder *et al* reported a survey of 50 Australian aircrew (Winder, et al., 2002).
    - Harper reported a survey of 60 aircrew that had experienced a fume event (A. Harper, 2005a).
    - Toxic Free Airlines, a lobby group, submitted a selection of quotes from and the results of a survey of 640 British Airways pilots (Toxic Free Airlines, 2009).
- Some documents also detailed symptoms suffered by passengers:
    - Holiday Travel Watch, a British consumers organisation made a submission which included details of symptoms reported to have been suffered by passengers following fume events (Holiday Travel Watch, 2009).
    - A personal submission by Alice O'Neil gave a detailed account of a fumes event that occurred while she was a passenger on an Airbus A330-300 flight, and the effects on her health during and after the flight. She mentions that paramedics informed her that several other passengers suffered ill health due to the fumes during the flight (O'Neil, 2009).
- A submission by the Independent Pilots Association stated that nine of their members had lost their aviation medical certificates following exposure to contaminated cabin air (Independent Pilots Association, 2009).
- Review papers that discussed the signs and symptoms following possible cabin air contamination included:
    - A wide-ranging review of the causes and mechanisms of contamination, and the subsequent effects by Winder (Winder, 2006b).
    - A discussion of the symptoms and signs with which they defined Aerotoxic Syndrome by Winder and Balouet (Winder & Balouet, 2000).
- Current research in this area included:
    - Preliminary results of an ongoing survey of the health of flight attendants by Occupational Health Research Consortium in Aviation (OHRCA) (Occupational Health Research Consortium in Aviation (OHRCA), 2008).
    - Results of the OHRCA-ACER research teams as quoted in the memorandum of the Association of Flight Attendants:

> "The **OHRCA-ACER** aviation health research teams in the US recently completed and submitted to FAA its final report on oil fume sampling data collected in the cabin on 56 flights, health survey data collected from 4011 cabin crew (48% response rate to mailed survey), and a health care providers' guide intended to educate physicians about

> the acute and chronic symptoms associated with exposure to oil fumes. Briefly, the teams were unable to collect sampling and health survey data on the same flights because airlines would not cooperate. However, several findings are of particular interest: 1) In 18 flights on which duplicate samples were taken and analyzed by two different laboratories, samples from three of these flights were found positive for low levels of tricresylphosphate additives; in a separate round of sampling in which only one lab performed the analysis 13 of 38 air samples tested positive for these tricresylphosphate additives; in all of these cases no visible or reported air supply contamination occurred. 2) There was a startlingly high prevalence of self-reported neurological symptoms. For example, 23% of flight attendants who completed a survey reported seeking medical attention for headaches in the past year, followed by 19% for dizziness/lightheadedness, 17% for numbness/tingling, 16% for muscle weakness, and 14% for memory loss/lack of concentration. The ultimate study design makes it impossible to correlate these first two sets of findings, but both deserve attention. 3) Finally, as part of this study a series of commonly used jet engine oils was analyzed, revealing that the up to three percent content of tricresylphosphate wear additive reported by manufacturers in their data sheets was exceeded in five of eight oils tested."
>
> (Association of Flight Attendants-CWA, AFL-CIO, & Witkowski, 2009)

- *Retrospective Study of 1500 pilots* (Dr Sarah MacKenzie Ross, Neuropsychological Toxicology Unit - Clinical Health Psychology: Aviation Division, UCL):
    - A survey of 1500 UK commercial airline pilots. The Independent Pilot Association invited its members to fill in questionnaires regarding work history and health, then a subsample of around 60 pilots were to be invited to undergo neuropsychological assessment. Work has been completed but is as yet unpublished.

5.4.2 Interpretation of evidence

- The advocacy group Aerotoxic Association listed the following symptoms:
    - Fatigue – feeling exhausted, even after sleep
    - Blurred or tunnel vision
    - Shaking and tremors
    - Loss of balance and vertigo
    - Seizures
    - Loss of consciousness
    - Memory impairment
    - Headache
    - Tinnitus
    - Light-headedness, dizziness
    - Confusion / cognitive problems
    - Feeling intoxicated
    - Nausea

- Diarrhoea
- Vomiting
- Coughs
- Breathing difficulties (shortness of breath)
- Tightness in chest
- Respiratory failure requiring oxygen
- Increased heart rate and palpitations
- Irritation of eyes, nose and upper airways.

- While symptoms were said to be "acute or chronic", data was not provided to support this assertion.
- Another advocacy group, Toxic Free Airlines, submitted a document to the Panel (the data is publicly available from their website) that included data from 640 aircrew documenting symptoms and frequency (see Figure 1) (Toxic Free Airlines, 2010, 2009):

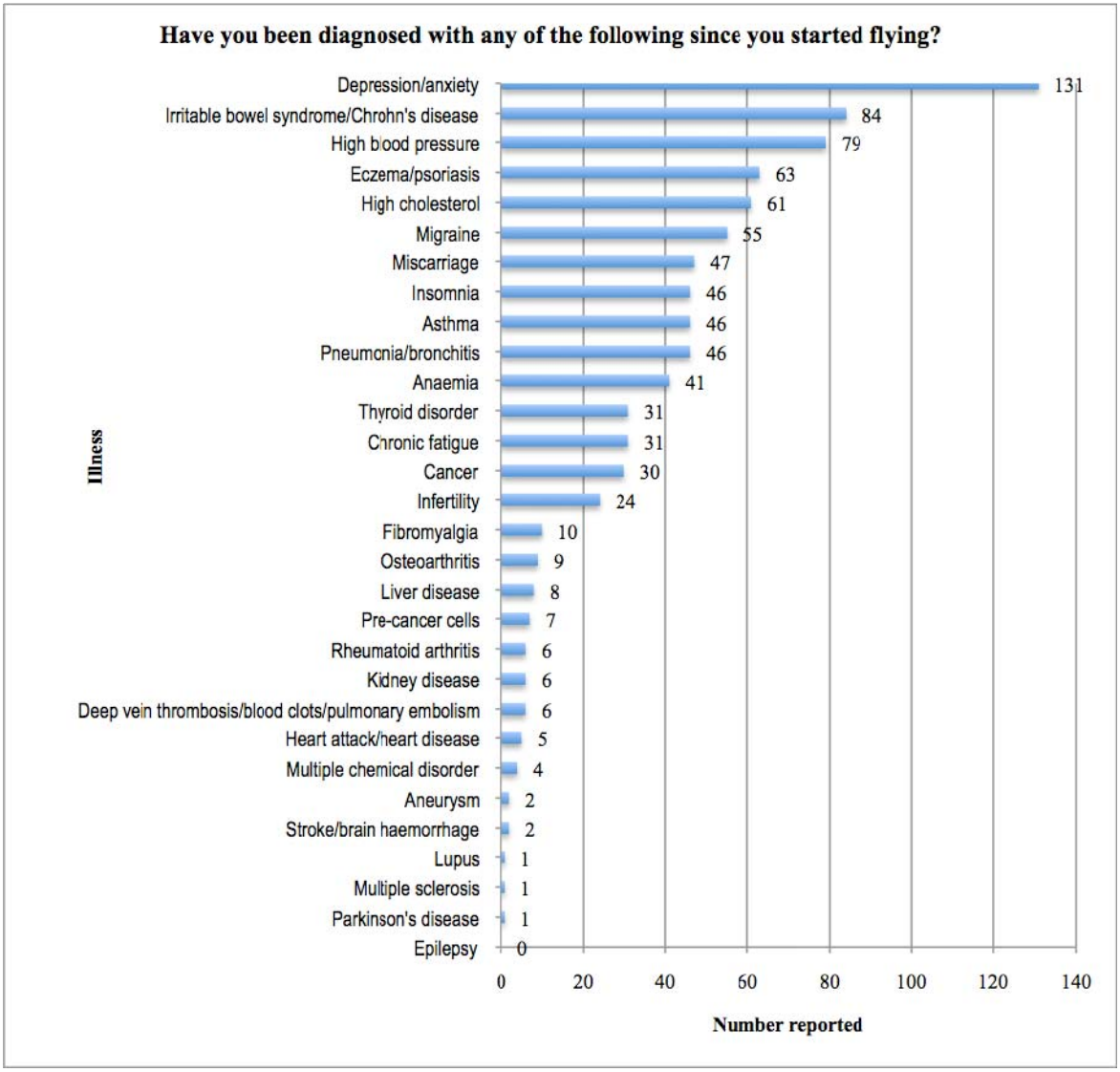

Figure 1: Symptoms reported in survey of 640 aircrew by Toxic Free Airlines (Toxic Free Airlines, 2009)

- Cox and Michaelis published the results of a survey of aircrew who been flying on the BAe146. The number of questionnaires sent out was not given, but the response rate (19 pilots and 2 flight attendants) was described as "low". Symptom frequency and severity were tabulated, in addition to the proportion reporting "long-term" symptoms (Table 9). (Cox & Michaelis, 2002).

Symptom Severity	*No answer*	*Occasional*	*Sometimes*	*Often*	*Long term*
Headaches, light-headedness, dizziness	*32%*	*21%*	*21%*	*10%*	*16%*
Irritation of eyes, nose and throat	*16%*	*16%*	*32%*	*16%*	*21%*
Disorientation	*74%*	*5%*	*5%*	*0%*	*16%*
Memory impairment (short-term)	*53%*	*10%*	*5%*	*5%*	*26%*
Concentration difficulties, confusion	*53%*	*16%*	*10%*	*0%*	*21%*
Blurred vision, tunnel vision	*90%*	*5%*	*0%*	*5%*	*0%*
Nausea, vomiting, gastrointestinal problems	*90%*	*0%*	*0%*	*5%*	*5%*
Fatigue, weakness, decreased performance	*32%*	*21%*	*26%*	*0%*	*21%*
Respiratory distress/difficulties	*63%*	*0%*	*26%*	*0%*	*10%*
Numbness (head, limbs, lips, fingers)	*74%*	*5%*	*0%*	*10%*	*10%*
Balance/coordination difficulties	*74%*	*0%*	*16%*	*0%*	*10%*
Joint pain, muscle weakness	*84%*	*5%*	*5%*	*0%*	*5%*
Intolerance to chemicals/odours	*53%*	*5%*	*16%*	*0%*	*26%*
Intolerance to foods/alcohol	*84%*	*0%*	*0%*	*5%*	*10%*
Skin irritations	*79%*	*5%*	*16%*	*0%*	*0%*
Immune system disorders	*79%*	*0%*	*0%*	*0%*	*21%*
General increase in feeling unwell	*53%*	*5%*	*16%*	*5%*	*21%*
Diarrhoea	*90%*	*0%*	*5%*	*0%*	*5%*
Cancer	*100%*				

Table 9: Symptom Severity from survey responses of Cox and Michaelis (Cox & Michaelis, 2002)

- Winder *et al* categorized self-reported symptoms from a survey of 50 Australian aircrew. One of the aims of the survey was "to identify whether aerotoxic syndrome was definable and, if so, the symptoms that might be considered indicative of such a condition".
    - Symptom clusters were described as follows:
        - Neurological dysfunction immediately after intense exposures
        - Skin, eye, nose and respiratory irritation immediately after exposure
        - Gastrointestinal discomfort immediately after exposure
        - Neuropsychological impairment immediately after exposure

- General symptoms of exhaustion progressing to chronic fatigue
- General symptoms of immune suppression developing some time after exposure, including food and alcohol intolerances, allergies and chemical sensitivity.

These clusters are tabulated in Table 10 (Winder, et al., 2002).

Eye & skin	***Respiratory & cardiovascular***	***Gastrointestinal & renal***	***Neuropsychological***	***Neurological***	***Reproductive***	***General***
*Hair loss^*	*Tachycardia**	*Polyuria**	*Memory impairment**	*Loss of taste*	*Genetic problems^*	*Chemical sensitivity*
Rash	*Palpitations**	*Diarrhoea**	*Memory problems**	*Loss of consciousness**	*Neonatal death+*	*Altered immune problems+*
Itch	*Chest pain**	*Nausea*, vomiting*	*Sleep problems**	*Seizures**	*Miscarriage^*	*Allergies^*
Skin problems+	*Chest tightness* wheezing*	*Abdominal spasms*	*Depression*	*Tremors**	*Infertility^*	*Chronic fatigue*
Skin irritation	*Breathing problems**	*Abdominal pain**	*Anxiety**	*Uncontrolled eye movement+*	*Ovarian problems^*	*Exhaustion**
*Vision problems**	*Chronic cough**	*Salivation*	*Performance decrement**	*Impaired nerve conduction**	*Menstrual dysfunction^*	*Glandular fever^*
Eye irritation	*Nasal polyps^*		*Altered coordination**	*Tingling**	*Hormonal irregularity^*	*Joint pain*
	Rhinitis		*Confusion**			*Muscle weakness*
	Haemoptysis		*Balance problems**			
	Nose bleed					
	*Respiratory irritation**					

Table 10: Winder *et al*. (adapted from (Winder, et al., 2002)– symptom clusters

***Key**:*

**Common somatic manifestations of acute hyperventilation and anxiety.*

^Common problems in the general community – association with fume events lack plausibility.

+Too ill-defined to be useful

5.4.2.1 Case reports submitted to Expert Panel

- A total of 62 individual submissions regarding symptoms were made to Expert Panel. In most cases there was insufficient detail provided to allow firm conclusions to be drawn concerning causation. However, the following themes emerged:
    - Acute symptoms:
        - Many reports described symptoms of acute mucosal irritation in association with fume events.
        - Descriptions were of a pungent odour followed by immediate onset of eye, nose and upper respiratory tract irritation, associated in some cases with headache and nausea.
        - In most cases the symptoms resolved rapidly after cessation of exposure.
        - Some reports included typical symptoms of anxiety and the somatic manifestations of acute hyperventilation (palpitations, chest pain, tremor, breathing difficulty, dizziness, feeling faint, cognitive impairment, weakness, fatigue, acroparaesthesia, muscle cramps, syncope). There were no reports of serious disease or hospitalization associated with acute symptoms.
    - Unrelated conditions:
        - Several reports attributed unrelated conditions to fume exposure (e.g. cerebral aneurysm with subarachnoid haemorrhage; acute febrile illness; non-Hodgkins lymphoma; glioblastoma; toxic goitre; viral encephalitis; degenerative myopathy; motor neurone disease; Parkinson's disease; smoking related COPD; Crohn's disease).
    - Chronic illness:
        - Reports of chronic illness, usually but not always following fume events, had a number of common features:
            - Consultation with environmental medicine practitioners.
            - Diagnosis of 'Aerotoxic Syndrome', together with 'Chronic Fatigue Syndrome' (ME/CFS), 'fibromyalgia' (FMS) and/or MCS.
            - Referral for unconventional laboratory testing (not available in the public health sector; without validated reference ranges, and/or not approved by relevant specialist bodies).
            - Neuropsychological test results reported as indicative of 'toxic brain damage'.

5.5 What is the temporal relationship between exposure and symptoms?

5.5.1 Description of evidence

5.5.1.1 Medical reports

- A number of personal medical reports were submitted (62 in total), many of which provide information about the time between exposure and symptoms.
- As noted earlier, Panel member Associate Professor Bhupinder Singh provided the Panel with a list of cases with a history of exposure to toxic fumes that demonstrate the temporal link between exposure and effects (Singh, 2009).

5.5.1.2 Epidemiological studies

- The description of evidence lists the epidemiological studies relevant to assessing the effects of contaminated cabin air. In particular:
- Mackenzie Ross studied 27 pilots assessed following self-reported exposure, where both acute and chronic effects are noted (Sarah MacKenzie Ross, 2008). There is significant variability in the latency of chronic effects, including an observation that in some pilots a viral infection precipitated severe fatigue [page 117].
- Winder *et al* reported that a large number of respondents reported symptoms that started at the time of exposure and persisted for more than a month (Winder, et al., 2002).

5.5.2 Interpretation of evidence

- A number of aircrew members have reported developing a variety of acute symptoms on exposure to a fumes event in-flight. The number of such reported cases are very small when compared to the total number of aircrew that fly every day around the world. Nevertheless, the number is large enough to warrant an investigation into such claims. In fact, this Panel was established primarily as a result of such reports and the media response to them.
- The Panel accepts the likelihood of exposure to fumes in an aircraft cabin. This is well described, and is not contested (see Chapters 3 & 4 of this report). The development and report of symptoms by aircrew members, being of a subjective nature, are also not contested (ref. survey reports). However, questions that were unresolved were whether:
    a. Were the reported symptoms caused by some toxic elements in the fumes in particular, or in the cabin environment in general?
    b. Do toxic elements in the fumes have the potential to cause the reported symptoms?
    c. Could some other factors in the flight and/or the cabin environment be responsible for the reported symptoms?

d. Should other explanations be sought for the occurrence of the reported symptoms?

- The aircraft cabin environment is largely artificial and differs significantly from terrestrial and home/office environment, with a number of unique stressors including:
    a. Mild hypoxia (reduced oxygen partial pressure)
    b. Mild hypobaria (reduced atmospheric pressure)
    c. Low humidity
    d. Circadian disruption
    e. Noise
    f. Vibration
    g. Cosmic and other radiation
    h. Magnetic fields generated by the aircraft system
    i. Cabin air quality
- The stressors listed (a) through (f) have been studied extensively in the last four or five decades, and the effects of these stressors on humans are well known to be highly specific. The pattern and range of symptoms reported by aircrew on exposure to fumes do not fit the toxicity profile of these stressors. Also, the fact that these stressors are present throughout the duration of most flights is incompatible with the reported symptoms, which are periodic, acute and relatively uncommon.
- The effects of cosmic and magnetic radiation too have been studied extensively in recent years, but are less well known. The effects of these stressors reported in the literature are generally ill defined, and may range from none, to vague, general symptoms (not very dissimilar to those being reported by aircrew), to being carcinogenic (cancer causing). Day to day exposure to low level ambient radiation, mostly emanating from mobile phones, television and radio broadcast, household electrical and electronic equipment etc, is currently generally considered to be safe. In the event that symptoms on exposure to radiation have been reported, these were generally of sub-acute or chronic nature.
- Radiation in large doses is known to be toxic, and can cause acute symptoms, described in the literature as "radiation sickness" (dose equals magnitude of radiation multiplied by the duration of exposure). Examples of situations where exposure to high levels of radiation is likely to occur are: in the vicinity of radar equipment, X-ray equipment, and high voltage power lines.
- In the aircraft cabin, the likelihood of exposure of aircrew to high doses of radiation is very unlikely, but exposure to low levels of radiation cannot be ruled out. However, the acuteness of the reported symptoms is not compatible with the symptom profile of exposure to low level radiation. Hence, on balance, it is difficult, if not impossible, to explain the symptoms reported by aircrew as being caused by exposure to radiation.
- The Panel considered that cabin air quality, the last stressor listed above, is the most confounding, and certainly a possible culprit in the causation of the symptoms reported by aircrew. The factors supporting this view are:
    - Exposure to visible fumes or smell precedes symptoms in a majority of cases (80%, (Singh, 2009).

- The symptoms are not inconsistent with the known toxicity profile of some of the constituents of the bleed air, which is known to leak into the cabin at times.

5.6 What is a possible case definition?

- Determining suitable case definitions is an important element of public health surveillance systems and is an essential component of epidemiological studies. In reviewing the evidence associated with ill health attributed to cabin air contamination, the Panel noted the lack of a formal case definition. The Panel considered possible criteria for a case definition to better identify adverse health effects related to aircraft cabin fume exposures based on published surveys and individual submissions. However, a case definition for fumes exposure would require validation and appropriate refinement before being used in prospective epidemiological studies. In the absence of a validated case definition, prevalence data cannot be considered to be reliable.
- The Panel considered that in order to improve the ability to undertake formal epidemiological studies the medical symptoms, signs and laboratory findings need to be better defined, to enable investigation of associations with exposure to cabin air contaminants. Development of a suitable case definition would ensure comparability between epidemiological studies and also make surveillance data comparable between countries. However as noted earlier, such epidemiological studies would be difficult to implement given the relative rarity of contamination events.

5.6.1 Description of evidence

- The term 'Aerotoxic Syndrome' has been used to describe the constellation of symptoms associated with cabin air exposure:
  - In 2000, Winder and Balouet outlined the symptoms experienced by aircrew and used the term "Aerotoxic Syndrome" in a conference presentation (Winder & Balouet, 2000).
  - Winder *et al* presented an epidemiological survey of aircrew, and concluded by outlining the symptoms that define Aerotoxic Syndrome (Winder, et al., 2002).
  - Hooper, in a submission to the Expert Panel, discussed the relationship of Aerotoxic Syndrome to other Chronic Multisystem Illnesses (M. Hooper, 2009).
  - The Australian Senate Committee report in 2000 concluded that Aerotoxic Syndrome should be recognised:

> "Recommendation 4 That the issue of cabin air quality be reviewed by the National Occupational Health and Safety Commission with a view to including aerotoxic syndrome in appropriate codes as a matter of reference for future Workers Compensation and other insurance cases."
>
> (Senate Rural and Regional Affairs and Transport References Committee, 2000a) [page 106]:

- Professor Bagshaw of the Kings College London discussed the biological basis of Aerotoxic Syndrome in a conference paper, and concluded that:

> "…there is insufficient consistency and objectivity to support the establishment of a clearly defined syndrome"
>
> (Bagshaw, 2008)

- Like the Committee on Toxicity, the US National Research Council report of 2002, *The Airline Cabin Environment and the Health of Passengers and Crew,* believed that there was insufficient evidence for definition of a syndrome:

> "Balouet and Winder have argued in a series of documents for the existence of a stereotypical symptom complex, "aerotoxic syndrome," which attends exposure of cabin crew to hydraulic fluids, engine oil, and their pyrolysis products (Balouet 1998; Balouet and Winder 1999, 2000a,b; Winder and Balouet 2000b). Their papers repeat many data, so the committee's evaluation of them focuses on the one document (Balouet and Winder 2000b) that has the clearest presentation of the authors' contention that such a syndrome exists. The authors argue that in-cabin leaks, smoke, and fume events could expose up to 40,000 passengers and crews worldwide each year, although the committee was unable to verify the source for this assertion.
>
> Support for the existence of the syndrome is derived from the work of Rayman and McNaughton (1983), Tashkin et al. (1983), and Van Netten (1998), which is evaluated above. Balouet and Winder (2000b) state that there "are common themes in symptom clusters in these studies." However, that claim does not appear to be supported by the data presented. For example, of the three most common symptoms (eye irritation, pain on deep breathing, and shortness of breath) in Tashkin et al. (1983) (the largest of the three studies), at least two are not reported in either of the other two studies. In fact, only three symptoms (headache, sinus congestion, and nausea) are reported in all three studies, and there is rather little agreement on their prevalence. Six case studies are also cited; however, the committee found it difficult to interpret them, given the lack of selection criteria, the sources of the material used in the case summaries, and the incomplete and qualitative nature of the summaries. Thus, the committee concludes that evidence does not warrant the designation of a specific syndrome related to exposure to various physical agents (e.g., mists and smoke) and decomposition products derived from leaks of engine oil and hydraulic fluids. The committee recommends that until such information is available, the designation "aerotoxic syndrome" not be used for symptoms reported in coincidence with cabin air contamination."
>
> (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002) [page237]

- A recent review of Aerotoxic Syndrome discussed the need for diagnostic neurophysiological tests (M. Hale & Al-Seffar, 2008). This generated some discussion:
    - The paper was included in a submission from the editor of the *Journal of Neurophysiological Scientists,* who is one of the authors, discussing the above paper and surrounding debate (Al-Seffar, 2009).
    - A response to the Hale & Al-Seffar paper questioned the scientific and medical basis for Aerotoxic Syndrome (J. Smith, et al., 2009).
- A paper funded by the FAA provides a case definition for an acute health event [page 9] in a guide for health care providers (R. Harrison, et al., 2009).

5.6.2 Interpretation of evidence

5.6.2.1 Is there a unique syndrome associated with aircraft cabin fume events?

- Given the non-specific nature of most of the symptoms reported by certain individuals following aircraft cabin fume events (see Section 5.4) the Panel found difficulty identifying a 'unique' syndrome for the purpose of case definition:
    - Some symptoms are also characteristic of acute hyperventilation (*acroparaesthesia [numbness/tingling of hands, feet, lips]; palpitations; breathing difficulty; cognitive impairment; weakness; ataxia; dizziness; feeling faint; tetany; syncope*).
    - Many of the reported symptoms were also common in the general community (*Severe headache, head pressure; behaviour modified, depression, irritability; nausea, vomiting, gastrointestinal symptoms; abdominal spasms cramps, diarrhoea; joint pain*).
    - Other reported symptoms were too ill defined to be useful. (*Rashes, blisters (uncovered body parts); change in urine*).
    - In those who reported chronic symptoms the description overlapped substantially with Chronic Fatigue Syndrome.
    - Some also described symptoms triggered by environmental smells and fumes (not associated with aircraft); consistent with what has been described as Idiopathic Environmental Intolerances (IEI) or Multiple Chemical Sensitivity.
- However, 'uniqueness' might not be an essential attribute for the valid design of future studies. A similar question arose in relation to Gulf War Syndrome:

> "The question of whether the multisymptom illness affecting Gulf War veterans should be considered a "unique Gulf War Syndrome" has been widely discussed and interpreted….What is meant by the question has often been unclear, as have attempts to answer it. For some observers, a "unique syndrome" has meant that there should be just one constellation of symptoms affecting Gulf War veterans—a single symptom complex constituting a single syndrome. For others, a "unique syndrome" has meant that a single, unique *cause* for the symptoms should be demonstrated. For still others, a "unique syndrome" has meant that similar symptoms would not be found in people who did not serve in the Gulf War. And for several researchers, the question has hinged on whether a

> particular statistical technique, factor analysis, identifies symptom correlations in Gulf War veterans that are not found in other groups.
>
> However the question of a unique syndrome in interpreted, extensive descriptive and analytic research has clearly demonstrated that an illness, characterized by a complex of multiple symptoms, resulted from service in the Gulf War …
>
> …But this syndrome might not be considered unique, from different perspectives. That is, there could be more than one type of patho-physiological process affecting Gulf War veterans that leads to similar, overlapping symptom profiles. There could also be more than one cause for these symptoms."
>
> (Binns, et al., 2008) [page 41]

5.6.2.2 Use of the term 'Aerotoxic Syndrome'

- The fact that similar chronic symptoms are present in patients diagnosed with Aerotoxic Syndrome as in those with Chronic Fatigue Syndrome and Multiple Chemical Sensitivity argues against the introduction of a specific diagnostic label for patients who attribute the same symptoms to exposure to noxious fumes in an aircraft cabin environment (Myhill, 2007).
- The term Aerotoxic Syndrome is based on a presupposition that symptoms experienced after aircraft cabin fume events are due to toxic effects of specific chemical exposures. However, this is only one of several possible explanations, of which some other explanation may be more plausible.
- The Panel considered that "Aircraft Related Illness" would be a more appropriate descriptor for symptoms reported in association with aircraft cabin fume events.

5.6.2.3 Neuropsychology testing

- A number of patients had been referred for neuropsychological testing. Sarah Mackenzie Ross submitted to COT a case series of 27 symptomatic pilots referred for neuropsychological assessment (findings subsequently published in JNEM, 2008 (Sarah MacKenzie Ross, 2008)). The findings were put forward as being consistent with neurotoxicity. However, in a solicited commentary on this submission, Professor Robin Morris pointed out that although the:

> "…neuropsychological deficits reported were similar to those found in the literature on exposure to organophosphates and organic solvents, they are also not at all specific in this regard."
>
> (Committee on toxicity of chemicals in food consumer products and the environment, 2006w)

- The Panel noted that the 'Current Debate' contribution, *Preliminary report on aerotoxic syndrome (AS) and the need for diagnostic neurophysiological tests*, is based on a single case report (M. Hale & Al-Seffar, 2008). In this case report, there was no documented fume event; the woman concerned was well before, during and after the flight. Ten days later she experienced the acute onset of respiratory symptoms that her GP diagnosed as chest infection and treated with antibiotics; because of lack of response she underwent investigation for pulmonary embolism with negative results. Over the subsequent 2 years, multiple respiratory, cardiac, neuromuscular and sleep studies were performed with negative results. Eventually a presumptive diagnosis of obstructive sleep apnoea

was made and she was provided with a CPAP machine, with some benefit. Meanwhile, the patient made a self-diagnosis of 'Aerotoxic Syndrome' based on an Internet search. Her neurologist had been contemplating a "second diagnosis" of CFS which the patient thought might have been caused by "exposure to organophosphates", citing the claims of Myhill posted on the Aerotoxic Association website (Myhill, 2007).

- Based on this case study, and her own review of the literature, Hale endorsed the view of Myhill that patients with 'Aerotoxic Syndrome' require clinical neurophysiological studies and should be referred for unconventional testing in "non-National Health Service (NHS)" facilities.
- Winder *et al* published a case series from which they attempted to categorize symptom clusters characteristic of 'Aerotoxic Syndrome' (Winder, et al., 2002). However, the analysis suffers from a number of design problems which make it difficult to identify a specific toxidrome that could be used as a case definition:
    - Participants were self-selected ("… those aircrew who took the effort to identify themselves to the research project team…") and there were no appropriate comparison groups.
    - Symptoms were self-reported based on a "3-page structured questionnaire".
    - There was no accompanying clinical examination, so descriptors were too vague to be able to distinguish between various possible causes.
    - Relationship to reported exposures was not documented.
    - There was no distinction made between acute and chronic symptoms.
    - Some symptoms attributed to neurotoxicity are more characteristic of acute hyperventilation/anxiety.
    - Most other symptoms were non-specific and are common in the general population.
- The Panel noted a case series of chronic illness labelled as 'aerospace syndrome' in 53 workers at a large US aircraft manufacturing facility, which was reported by Sparks (Sparks, et al., 1990). Despite the different chemical exposures, there were some significant parallels with the chronic features of Aerotoxic Syndrome:
    - A number of aerospace workers developed symptoms after starting to use composite plastic materials in the manufacturing facility. Despite an industrial hygiene evaluation showing workplace chemical exposures well below those typically considered risks to health, an increasing number became chronically ill and disabled.
    - There was no difference in exposure between those who were symptomatic and those who were not. Of the 56 workers who developed chronic symptoms, most had been referred by colleagues, or the union, to a local allergist in the community, who ordered a range of non-standard immunological tests. Some workers were referred by the allergist to a psychiatrist, who diagnosed "permanent organic brain damage" said to be "typical of toxic chemical exposure". Most workers were led to believe that their chemical exposures had been "high" and that their symptoms were due to "chemical poisoning", "allergy to chemicals" or "chemical AIDS". One third were diagnosed with "multiple chemical sensitivity".

- The allergist concerned announced to the media the presence of a new disease, the "aerospace syndrome". There followed several months of local and national media coverage, intense union-management deliberations, and a US Senate subcommittee hearing on the issue.
- Thorough medical evaluation failed to reveal objective abnormalities that might explain the workers' disabling symptoms. However, psychiatric evaluation found a 74% prevalence of major depression and/or panic disorder, which were not explained by pre-existing psychiatric illness.

- Sparks *et al* concluded that:

> "Unfortunately, the label 'aerospace syndrome' … may only perpetuate illness and reinforce disability."
>
> (Sparks, et al., 1990)

- The case reports of chronically ill and disabled aircrew submitted to Expert Panel suggest that the conclusion of Sparks *et al* may also apply to use of the diagnostic term Aerotoxic Syndrome.
- In its 2002 report, the US Committee on Air Quality in Passenger Cabins of Commercial Aircraft did not consider the evidence warranted the designation of a specific syndrome (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002)[pages 236-7].

5.6.2.4 What criteria can be used to determine whether there is a causal relationship between aircraft cabin fume events and subsequent illness?

- Criteria for making judgements about the likelihood of a causal relationship between environmental exposure and illness were first clearly articulated by Bradford Hill (A. B. Hill, 1965). The widely cited 'Bradford Hill criteria' for inferring causality are based on:

1. Strength of association
2. Consistency
3. Specificity
4. Temporality
5. Biological gradient
6. Plausibility
7. Coherence
8. Experiment
9. Analogy

- In his discussion of these criteria, Bradford Hill concluded:

> "Here then are nine different viewpoints from all of which we should study association before we cry causation. What I do not believe – and this has been

> suggested – is that we can usefully lay down some hard-and-fast rules of evidence that *must* be obeyed before we accept cause and effect. None of my nine viewpoints can bring indisputable evidence for or against the cause-and-effect hypothesis and none can be required as a *sine qua non.* What they can do, with greater or less strength, is to help us to make up our minds on the fundamental question – is there any other way of explaining the set of factors before us, is there any other answer equally, or more, likely than cause and effect?"

5.6.2.5 What is a suitable case definition for future epidemiological studies?

- For the purpose of identifying adverse health effects of aircraft cabin fume exposures, the following criteria for a case definition are suggested:

1. One or more defined exposures or fume events:
    - These are events where visible fumes and/or noxious odours in the aircraft cabin are noticed by two or more passengers or crew members, and are reportable as a fume event.

2. Acute irritation symptoms:
    - 'Acute symptoms' are defined as being of sudden onset (during or shortly after exposure, usually within 30 minutes), and resolving rapidly after cessation of exposure (usually within 1-2 hours; no more than 24 hours).
    - 'Irritant' symptoms include: Mucosal irritation of eyes, nose, throat; loss of voice; acute nasal/sinus congestion; cough, wheeze, difficulty breathing, chest tightness.
    - Symptoms due to pre-existing or intercurrent illness are excluded (e.g. allergic rhinitis/sinusitis, vasomotor rhinitis, chronic asthma, upper or lower respiratory tract infection, conjunctivitis, cardio-respiratory disease).
    - Clustered symptoms characteristic of acute hyperventilation/anxiety are excluded (*acroparaesthesia [reversible numbness/tingling of hands, feet, lips]; palpitations; breathing difficulty; cognitive impairment; weakness; ataxia; dizziness; feeling faint; tetany; syncope*).

3. Persistence/progression of symptoms without a 'well' interval (in the absence of further exposure).
    - Symptoms are excluded if there is a 'well' interval of more than 48 hours between recovery from acute irritant symptoms and onset of chronic symptoms.
    - Persistent symptoms following an aircraft cabin fume event should be medically documented.
    - They should include either:
        - Two or more major symptoms
        - One major symptom and two or more minor symptoms.
        - For major/minor symptoms to be included, they should have no other known or likely medical or psychiatric explanation.

- MAJOR SYMPTOMS:
  - Neurocognitive symptoms;
  - Fatigue;
  - Musculoskeletal aches/pains.

- MINOR SYMPTOMS:
  - Non-specific headache;
  - Nausea, functional gastrointestinal symptoms;
  - Non-specific respiratory symptoms (cough, transient chest pains, chest tightness);
  - Non-specific skin rash.

- If re-exposure were to occur, exacerbation/progression of symptoms would be expected to occur within 24 to 48 hours.

- This suggested case definition is based on published surveys and individual submissions, as referred to above. This would require validation and appropriate refinement before use in future epidemiological studies.

5.7 What is the biological plausibility of proposed theories of causation?

5.7.1 Description of evidence

- A prominent theory is that of OP toxicity due to TCP exposure:
  - A paper by Lotti *et al* reviewed the pathogenesis of OP polyneuropathy (Lotti, Becker, & Aminoff, 1984).
  - Furlong *et al* discussed the role of paraoxonases as a marker for sensitivity to OPs (Furlong, Cole, et al., 2005).
  - In his submission of the COT, Furlong briefly discussed several aspects of TCP toxicity (Furlong, 2007b).
  - The *in vitro*, animal and human studies of TCP toxicity are discussed above.
  - The Committee on Toxicity concluded in the report on the health effects of exposure to contaminated cabin air:

> **"Consideration of the neuropsychological symptoms reported in pilots and OP exposure.** The COT considered the evidence presented in the BALPA conference proceedings and in the additional papers submitted by BALPA. Members agreed that, on the basis of the available evidence, it was important to keep an open mind regarding the possible identity of potential risk factors and health effects in pilots. It was the view of Members that there had been an emphasis on the

> potential involvement of OPs in health symptoms reported by commercial airline pilots in the BALPA submission. The COT consider that there might be a number of candidate chemicals, one of which are OPs, and the Committee felt that focusing on OPs drew attention away from other potential chemical causes. The COT in 1999 concluded that the balance of evidence is not supportive of an association between chronic low level exposure to OPs and neuropsychological deficits in tests or the occurrence of OPICN. Members noted that similar patterns of symptoms have been reported in studies of other syndromes such as 'sick-building syndrome' not involving OP exposure. Members consider that, irrespective and independent of chemical exposure, the combination of odour perception, discomfort, involuntary exposure and stressful working conditions in a commercial aircraft cabin environment could lead to long-term health effects through non-toxic mechanisms in a small proportion of individuals."
>
> (Committee on toxicity of chemicals in food consumer products and the environment, 2007k)[page 17]

- Carbon monoxide exposure may also contribute to the symptoms experienced:
  - The Committee on Toxicity reviewed the possible role of carbon monoxide in the neuropsychological deficits reported in pilots (Committee on toxicity of chemicals in food consumer products and the environment, 2007e).
  - Prockop and Chichkova provided an up-to-date review of carbon monoxide poisoning (Prockop & Chichkova, 2007).
- Although the relationship to the effects of contaminated cabin air is unclear, there has been discussion on the similarities with MCS and Gulf War Syndrome (GWS):
  - Hooper discussed the symptoms, definitions, and diagnosis of multi-system diseases (Hooper, 2005).
  - A paper by Winder discussed the pathophysiology, diagnosis and effects of MCS (Winder, 2002).
  - The definitions and relationships between functional somatic syndromes, including MCS were discussed by Wessely *et al* (Wessely, Nimnuan, & Sharpe, 1999).
  - One report studied the levels of VOCs in Sick Building Syndrome (Weschler, Shields, & Rainer, 1990).
  - Terr discussed the difficulties in defining new syndromes/diseases that may involve environmental and occupational toxins (Terr, 1990).
  - One study reported neuromuscular symptoms in Gulf War veterans (Sharief, et al., 2002).
  - Another paper also studied neuromuscular symptoms in Gulf War veterans (Rose, et al., 2004).
  - A comprehensive report of the scientific findings of Gulf War Syndrome research was published in 2008 (Research Advisory Committee on Gulf War Veterans' Illnesses, 2008).
- There are a number of papers that study the common health symptoms experienced by aircrew:
  - Symptoms in aircrew, nurses and teachers were compared by Sveinsdottir *et al* (Sveinsdottir, Gunnarsdottir, & Friethriksdottir, 2007).

- Lindgren and Norback surveyed aircrew and office workers (Lindgren & Norback, 2005).
- Whelan *et al* surveyed flight attendants and teachers (Whelan, et al., 2003).
- The reported causes and rates of permanent medical retirements from cabin crew duties at a Portuguese airline were discussed by Pombal *et al* (Pombal, Peixoto, Lima, & Jorge, 2005).
- An FAA document summarised fatigue in aircrew (Nesthus, Schroeder, Connors, Rentmeister-Bryant, & DeRoshina, 2007).
- Parker *et al* studied morbidity in US pilots as deduced from records of the Aviation Medicine Advisory Service (Parker, Stepp, & Snyder, 2001).

- Airport workers are exposed to jet fuel and combustion products:
  - Radican *et al* studied the mortality of more than 14000 aircraft maintenance workers (Radican, Blair, Stewart, & Wartenberg, 2008).
  - Tunnicliffe *et al* demonstrated respiratory problems in male airport workers, possibly due to exposure to jet fuel and/or exhaust (Tunnicliffe, et al., 1999).
  - Ritchie *et al* reviewed the neurotoxic risk of exposure to hydrocarbon fuels (Ritchie, et al., 2001).
  - Tesseraux reviewed the exposure to jet fuel combustion products at airports (Tesseraux, 2004) .
  - Struwe, Knave and Mindus did a neuropsychiatric evaluation of workers exposed to jet fuels (Struwe, Knave, & Mindus, 1983).
  - Sparks *et al* described an outbreak of skin and respiratory symptoms in an aircraft manufacturing facility (Sparks, et al., 1990).
  - Sparks also replied to comments about the above paper (Sparks, 1990).
- Studies of flight comfort:
  - Nagda and Koontz reviewed 21 studies of the effect of the cabin environment on comfort and health (N. L. Nagda & Koontz, 2003) .
  - A comparison of the perception of the work environment between office workers and aircrew was performed by Lindgren *et al* (Lindgren, Norback, Andersson, & Dammstrom, 2000).
  - Norback studied the effects of air humidification on symptoms experienced by aircrew (Norback, et al., 2006).
  - Lindgren and Norback measured pollutants present in cabin air on smoking and non-smoking flights (Lindgren & Norback, 2002).
  - Strom-Tejsen studied the effect of humidity levels on patient comfort (Strom-Tejsen, et al., 2007).
  - This group then demonstrated that using a gas phase absorption air purifier improves passenger comfort (Strom-Tejsen, Zukowska, Fang, Space, & Wyon, 2008).
  - SAE Aerospace provided a table of the possible causes of occupant symptoms (SAE Aerospace, 2007)(Page 17).

- An ASHRAE study measured physical environment parameters and correlate these with passenger comfort (Murphy, 2008).

- Hypoxia could be a cause of symptoms at altitude:
  - Professor Mehrishi of Cambridge University, considered that hypoxia may be a cause of the symptoms suffered (Mehrishi, 2009). In his submission to the Expert Panel he cited the following papers:
    - Wolff discussed the symptoms experienced due to hypoxia (M. Wolff, 2006).
    - Muhm *et al* described a controlled hypobaric chamber study of 502 volunteers (Muhm, et al., 2007).
    - Muhm also presented a paper to the 2009 ICE conference (Muhm, 2009).
    - Harding and Mills discussed the similarity in symptoms of hypoxia and hyperventilation (Harding & Mills, 1983).
  - The ICE group is continuing to research the effects of hypoxia (C. Wolff & Mayer, 2009).
- Ozone is also a contaminant of cabin air at high altitudes:
  - Ozone may be present in greater quantities in cabin air due to the altitude (Tashkin, Coulson, Simmons, & Spivey, 1983).
  - Studies have assessed its affect on symptoms (Strom-Tejsen, et al., 2008).
  - Recommendations are for improved monitoring and ozone converters, as ozone converters were found not to perform well (J. D. Spengler, Ludwig, & Weker, 2004) .
  - Weschler *et al* studied the chemicals produced in an aircraft cabin due to ozone (Weschler, et al., 2007).
  - Bhangar *et al* studied variations in ozone levels in aircraft, showing seasonal variations (Bhangar, Cowlin, Singer, Sextro, & Nazaroff, 2008).
  - Apte *et al* studied the relationship between ozone levels and building-related symptoms and found a positive relationship between levels of ozone in buildings and upper respiratory symptoms (Apte, Buchanan, & Mendell, 2008).
- Infection acquired onboard aircraft might also result in symptoms:
  - Mangli and Gendreau reviewed the transmission of infectious during air travel (Mangili & Gendreau, 2005).
  - Zitter *et al* evaluated the role of recirculated cabin air as a predictor of post flight respiratory infection (Zitter, Mazonson, Miller, Hulley, & Balmes, 2002).
- Exposure to insecticides might also cause symptoms:
  - The background, agents and toxicity of disinsection were reviewed by Rayman (Rayman, 2006).
  - Sutton *et al* reviewed US cases of illness following disinsection (Sutton, Vergara, Beckman, Nicas, & Das, 2007).
  - Kilburn studied a self-selected group of 33 flight attendants who had been exposed to insecticides (Kilburn, 2004).
  - Van Netten analysed the constituents of insecticides and discussed their potential interactions with OPs from engine oil (van Netten, 2002).

- Murawski reviewed insecticide use in aircraft (Murawski, 2005a).

- Simple odours could cause symptoms:
  - Odours can cause lightheadedness through association with previous hyperventilation (Van Diest, et al., 2006).
- A general review of health and safety issues for airline cabin crew was performed by Boyd and Bain (Boyd & Bain, 1998).

5.7.2 Interpretation of evidence

5.7.2.1 Theories of causation considered plausible

- The Panel recognised that:
  - Many of the symptoms attributed to aerotoxic syndrome were also typical somatic manifestations of hyperventilation and anxiety. *Blurred vision, loss of visual acuity; chest pains; respiratory distress, shortness of breath, breathing problems requiring oxygen; fainting, loss of concentration, 'grey out'; shaking, tremors, tingling; numbness (fingers, lips, limbs), loss of sensation; dizziness, loss of balance; light-headedness, feeling faint or intoxicated; disorientation; trouble thinking or counting, word blindness, confusion, coordination problems; memory loss, memory impairment, forgetfulness; muscle weakness, muscle cramps; fatigue, exhaustion.*
  - Exposure to a neurotoxic OP is a credible biological mechanism for the neurobehavioral and neuropsychological symptoms described in 'Aerotoxic Syndrome'. However, there is inconsistency between the acute presentation of the neurotoxic symptoms of 'Aerotoxic Syndrome' and chronicity in the toxicological profile of the OPs that produce OPICN/COPIND experimentally. Furthermore, whether the putative neurotoxic agent is TOCP, its more toxic oxidative metabolites or other cresyl esters (e.g. mono-ortho congeners) remains to be clearly established.
  - In relation to the sensory and skin-eye irritancy that is commonly described in cabin air fume incidents, there might be a number of potential chemical candidates in pyrolysed engine oils and hydraulic fluids. There were insufficient data to establish whether air levels of any such candidate chemicals could reach high enough concentrations to cause such acute irritant reactions. Much of the attention has been focused on N-phenyl-1-naphthylamine because of its known sensitisation potential. However, this requires a prior exposure to prime the immune system, so it could not explain sensory irritation where it may occur in naïve subjects.

- *Theories of causation considered unlikely and/or lacking plausibility:*
  - Malingering.
  - Primary psychiatric illness

- Theories based on abnormalities identified by unconventional laboratory testing (autonomic dysfunction; mitochondrial disorder; immune dysfunction; DNA damage; metabolic abnormality; autoimmune reaction; allergic reaction).

5.8 Are there possible effects on reproductive health?

5.8.1 Description of evidence

- Some papers have described investigating the risks to the unborn child:
  - Howard discussed the process for assessing the risk to the unborn child of exposure to contaminated cabin air (Howard, 2005).
  - Brimijohn is a short review of risks that some OP pesticides may have negative effects on neuronal development (Brimijoin, 2005).
  - Aspholm found evidence for a slightly elevated risk of spontaneous abortion in flight attendants (Aspholm, et al., 1999).
  - The effects of ingested TCP on the reproductive performance of mice has been studied (Chapin, George, & Lamb, 1988).
  - TOCP damaged rat Sertoli cells *in vitro* (Chapin, Phelps, Burka, Abou-Donia, & Heindel, 1991).
  - Oral TCP had significant effects on male reproductive performance in rats (Latendresse, Brooks, Flemming, et al., 1994).
  - Oral TCP (less than 9.0% TOCP) decreased live births in female rats and showed a dose-dependent increase in abnormal sperm morphology (Carlton, Basaran, Mezza, & Smith, 1987).
- With regards to the newer jet engine oil, Turbonycoil 600, the MSDS notes that that there are possible risks to the unborn child and to fertility (NYCO, 2009b).

5.8.2 Interpretation of evidence

- In general, studies in animals using high doses of OPs make no useful contribution to evaluating the question of whether cabin air fume incidents could affect reproductive capacity or harm an unborn child. Since animal studies constitute the main database relating to effects on reproduction possibly associated with OPs, the Panel was unwilling to draw any firm conclusions about this aspect of potential toxicity associated with cabin air quality incidents.
- In a paper presented to the 2005 conference on cabin air quality, Prof Vyvyan Howard outlined the potential for neurotoxicity in a developing foetus resulting from maternal exposure to an OP, but conceded that there were still significant data gaps which would prevent the conduct of any realistic risk assessment (Howard, 2005).
- In a single study on the rate of spontaneous abortions reported in a cohort of Finnish flight attendants, an Odds Ratio of 1.3 was reported, although this was not statistically significant (95%

CI 0.9 – 1.8) after adjustment for age, parity and induced abortions when flight attendants flew during their first trimester (Aspholm, et al., 1999). They were unable to exclude excessive exposure to cosmic radiation or any other possible cause, but they did note that the spontaneous abortion rates appeared higher in 1978-94 than in 1973-77, which may reflect increased hours on long-haul jet flights since the proportion of time spent on such long-haul flights is negligible during the first years of work experience. It would be inappropriate to use this study to draw any conclusion about any link between cabin air quality and reproductive performance.

- In a survey of flight attendants reported by Winder *et al*, female staff were questioned about possible effects on reproductive functions (Winder, et al., 2002). Winder noted that 33% of the respondents reported difficulty in conceiving or infertility. However, while it was noted that this appeared to be above community norms, there were no comparative statistics cited, so no definite conclusions could be drawn about any relationship with cabin air quality. It was also conceded that working women tend to regulate their fertility for employment reasons and thus tend to have higher rates of infertility.

5.9 What do epidemiological studies demonstrate?

5.9.1 Description of evidence

- The Panel commissioned Dr David McLean of Massey University New Zealand to provide an independent epidemiological report on the evidence for an aerotoxic syndrome related to aircraft cabin contamination (Section 8.6 Appendix 6: Epidemiology Report). See Table 24 (Appendix 6: Epidemiology Report) for a summary of epidemiological studies studying exposure to contaminated cabin air.
- Other epidemiology studies looking at the overall morbidity of aircrew and aircraft maintenance workers include:
    - A recent review analysed a variety of studies on overall mortality and cancer mortality in aircrew (Hammer, Blettner, & Zeeb, 2009).
    - Radican *et al* studied 14,455 workers, evaluating mortality risk from trichloroethylene and other chemicals – they found no substantial change to mortality rates but positive associations with several cancers. Interpretation was limited due to small numbers of events for specific exposures (Radican, et al., 2008).
    - Buja *et al* performed an analysis of published data on cancer in pilot and cabin crew. They found a slightly elevated risk of several cancers including prostrate cancer and melanoma (Buja, et al., 2005).
    - Kilburn reported a study comparing neurobehavioral symptoms in flight attendants to control subjects (non-flight attendants without chemical exposures); the study found more symptoms in flight attendants but attributed these to disinsection on the aircraft (Kilburn, 2004).

- Zeeb *et al* investigated mortality patterns in more than 44,000 cabin crew in Europe (Zeeb, et al., 2003).
- Blettner *et al* studied mortality among male pilots in Europe (Blettner, et al., 2003).
- Pukkala *et al* assessed the incidence of cancer in Nordic pilots over five decades (Pukkala, et al., 2002).
- Recent studies of cancer risk in aircrew were reviewed by Blettner, Grosche and Zeeb (Blettner, Grosche, & Zeeb, 1998).
- A cohort study of Air Canada pilots looked at mortality, cancer incidence and leukaemia (Band, et al., 1996).
- Grayson and Lyons investigated the risk of brain cancer in USAF aircrew (Grayson & Lyons, 1996).
- A Finnish group assessed the risk of cancer in Finnish aircrew (Pukkala, Auvinen, & Wahlberg, 1995).
- A cohort study of over 900 pilots looked at mortality and cancer incidence (Band, Spinelli, Ng, Moody, & Gallagher, 1990).
- A case control studied breast cancer risk in cabin aircrew (Rafnsson, Sulem, Tulinius, & Hrafnkelsson, 2003).
- Paridou *et al* performed a cohort study of pilots and aircrew in Greece (Paridou, et al., 2003).

5.9.2 Interpretation of Evidence

5.9.2.1 Summary of the review of epidemiological studies relating to health effects from aircraft cabin fume incidents

- The Expert Panel noted the following:
  - The quality of the published epidemiological studies relating to both acute and chronic effects following fume incidents is poor.
  - These studies have used weak study designs such as case series and cross-sectional studies, while there is an absence of stronger study designs such as prospective cohort studies.
  - Many of the populations used in these studies are self-selected, rather than based on well-defined sampling frames and random sampling techniques.
  - Most of the health outcomes in these studies are based on self-reported symptoms, rather then objective biological indicators.
  - There has been little attempt to standardise the definition of the health outcomes under study, including the poorly defined entity of 'Aerotoxic Syndrome'.
  - Potentially confounding factors, such as personal and lifestyle characteristics, are usually poorly described.
  - In these studies, both the nature and the level of exposure occurring during cabin fume incidents has been poorly characterised, making it difficult to investigate associations with health outcomes.

- For these reasons, the Panel considered that the current published epidemiological literature adds little to our understanding of the relationship between fume incidents in aircraft cabins and acute and chronic health outcomes in either cabin staff or the travelling public.

5.9.2.2 Recommendations for future epidemiological research

- Unless based on sound epidemiological study designs, either longitudinal in nature and including well-defined 'at risk' study populations or case control studies, future epidemiological studies are unlikely to provide more insight to our understanding of the acute and chronic health effects resulting from cabin fume incidents.
- Suitable epidemiological definitions for the health outcomes under study need to be developed, including biological indicators.
- Better quality exposure data, preferably on a personal level, are needed to better document both the type and level of exposure occurring during fume events, but the random nature of such events will make it difficult to collect such data in a comprehensive way for any population enrolled into an epidemiological study.
- In addition to developing these essential components of analytical epidemiological studies, more effort should be given to improving surveillance systems and registries to gather better quality descriptive epidemiological data relating to fume events, which will provide better estimates of the extent of the problem and potentially identify exposed populations for future epidemiological study.

5.10 Recommendations

13. That CASA establish and/or maintain contact with research groups active in the field of investigating cabin air contamination, including Cranfield University in the UK and the Furlong Group at the University of Washington in the USA, to ensure that Australia receives relevant and timely information from these research projects.

14. That CASA in association with the Department of Health and Ageing (DOHA), the Institute of Health and Welfare or the NHMRC sponsor a project to define possible criteria for case definitions for short term and longer term health outcomes following episodes of cabin air contamination.

15. That CASA assists DOHA, the Institute of Health and Welfare or the NHMRC to submit this proposed case definition to other jurisdictions for comment and appropriate refinement before being used for any future epidemiological studies and in clinical settings.

16. That CASA seek the assistance of DOHA to facilitate future research by using the agreed case definition to evaluate all present and future cases of ill health reported through the proposed internet reporting system or after assessments of aircrew following a cabin air contamination incident and that CASA seek the cooperation of ATSB in this undertaking.

17. That CASA request ATSB to facilitate the gathering of good quality exposure data on cabin air contamination incidents, preferably directly by aircrew, to enable documentation of both the type and level of exposure occurring during an episode of cabin air contamination.

18. That CASA seek the assistance of DOHA to ensure that as soon as possible following exposure to a cabin air contamination incident, experienced medical personnel assess aviation personnel involved to enable detailed documentation of signs, symptoms and test results using agreed case definitions, with this information forming the basis for the CASA directive regarding recording of information and subsequent action following fumes incidents.

19. That CASA seek the assistance of DOHA to establish an independent suitably qualified expert panel of clinicians to review reports of exposure to cabin air contamination, where relevant request additional clinical assessments and /or investigations and report to ATSB and CASA regarding any further action required.

6 Control mechanisms

6.1 Introduction

- There is ongoing research in all areas: detecting contaminated air, filtration systems, and the medical protocols for assessment and treatment. In particular, the development of monitors and filtration systems are evolving rapidly. The documents presented here are up-to-date as of October 2009.

6.2 What should the aircrew do in an acute event?

6.2.1 Description of evidence

6.2.1.1 Industry guidance

- The procedure to be followed in the event of smoke/fumes in the cockpit is described in some of the incident reports:
    - One incident report described the use of the *Smoke-Fumes Airconditioning Checklist* from the Quick Reference Handbook in a Boeing 757 (Air Accidents Investigation Branch, 2007a).
    - Another incident report described the use of the *Fuselage Smoke Or Fire - Smoke Checklist* in a Bombardier (Air Accidents Investigation Branch, 2007d).

- In 2001, BAE Systems released a Flight Safety Bulletin which included the following instructions:

> "If smoke or fumes (smells) do appear from the air-conditioning systems, follow the appropriate abnormal crew procedure - Smoke from the Air Conditioning System - and don the oxygen masks.
>
> If at any time the crew is unsure as to the air quality they should don an oxygen mask.
>
> If at any time one crewmember appears to be unwell and uses oxygen all crewmembers should use oxygen as a precaution against any unidentified contaminant. Cabin crew should be encouraged to remind the flight crew of this requirement - follow crew resource management (CRM) principles."
>
> (BAE Systems, 2001)

- Boeing analysed in-flight smoke events and presented a review of their recommended procedures (Boeing, 2001).

- Boeing also recently produced a *Single Integrated Checklist For Response To Non-Alerted Fume Events* (Boeing, 2009).

6.2.1.2 Criticisms

- Several parties were concerned about the procedures in the event of a fume incident:
  - An ex-pilot commented in his submission to the Expert Panel:

> "Despite the findings of the 1999-2000 Australian Senate Investigation, serious failures in flight safety have resulted from exposure to contaminated air as few crews actually use oxygen when they suspect the air is contaminated as they ought to. The airlines and CASA know this, but do nothing to rectify this hazardous condition."
>
> (Loraine, 2009)

- In his submission to the Panel, referring to DHC8-202/315 series (Dash-8) aircraft, pilot Rob Nivison stated:

> "There is no protective equipment supplied to observer aircrew or passengers in the event of a CAQ event. Current oxygen bottles supplied for cabin use are trickle fed, only effective above 10,000' in the event of cabin depressurisation."
>
> (Nivison, 2009)

6.2.2 Interpretation of evidence

- The Panel noted the following:
  - In an acute event, the best procedure is to follow the standard recommended practice for pilots in the case of fumes events i.e. immediate donning of oxygen masks if a caustic substance is detected, donning of smoke masks (full face), shutting down of all operating systems and contacting of the emergency services (BAE Systems, 2001; Federal Aviation Administration, 2006; R. Harrison, 2008; R. Harrison, Murawski, McNeely, Guerriero, & Milton, 2008; Institute of Aviation Medicine & Royal Australian Air Force, 2003; Federal Aviation Administration, 2006; R. Harrison, 2008; R. Harrison, et al., 2009; Institute of Aviation Medicine & Royal Australian Air Force, 2003; BAE Systems, 2001).
  - The immediate management of in-flight smoke and fumes has two main objectives:
    - To cease or minimise exposure of aircrew members and passengers to smoke and fumes;
    - To maintain control of the aircraft and prevent any occurrence that might threaten the safety of the aircraft and its occupants.
  - The immediate actions taken by the operating crew (aircraft captain, and co-pilot) fall in the domain of operational actions and are invariably included in the pilots' emergency

checklist. These actions are aircraft specific, but the general principles are similar, as listed below:

- Aircrew to breathe 100% oxygen (closed system), or use an oronasal mask with a filter.
- Aircrew to use eye protection.
- Passengers to breathe supplemental oxygen.
- Below 10kft - Depressurise, and ventilate the aircraft cabin.
- Above 10kft - Depressurise and ventilate the aircraft cabin, but be prepared for the twin problems of hypoxia and decompression. Descend immediately to an altitude below 10,000 feet.
- Divert, and land as soon as possible.
- Medical management of the exposed individuals (aircrew, passengers). Mainly administration of 100% oxygen and symptomatic treatment.
- Documentation and reporting of the incident.

The Panel noted that currently there appeared to be no obligation for operators to inform passengers that a cabin air contamination event had occurred during a flight.

The Panel considered that:

- Passengers should have the right to be made aware of a cabin air contamination event by the aircraft captain (with a suitable apology and where possible an explanation)
- Passengers should have the opportunity to report and record any symptoms experienced at the time on a pre-agreed standardised report form obtainable from cabin crew or from the service desk or ground crew.
- Safeguards should include the provision of CASA approved information sheet for passengers with the requirement for staff to assist passengers to read and understand the information provided before they filled in the report form.
- Passengers reporting symptoms could opt to provide contact details for follow up after the event and deidentified reports and follow up information could be sent to the appropriate authority.
- Passengers on an aircraft involved in a cabin air contamination incident might also be offered the option to have their details entered into a confidential registry to enable ongoing health surveillance from which they would be able to opt out at any time.

6.3 What is the appropriate medical treatment following an exposure?

6.3.1 Description of evidence

- Harrison *et al* have developed a guide for medical professionals funded by the FAA Office of Aviation Medicine, part of a collaborative project between OHRCA and ACER, and provided a

review of the literature and guidelines for health professionals dealing with aircrew presenting with possible symptoms of exposure to cabin air contamination. The paper also discussed the appropriate disability management and follow up [pages 13-15]. (R. Harrison, et al., 2009).

  - The FAA has also provides a quick reference guide for medical professionals (R. Harrison, et al., 2009 - quick reference guide).

- Burdon and Glanville provided a list of respiratory tests that should be performed on individuals following an exposure (J. Burdon & A. R. Glanville, 2005) [page 6].
- Mackenzie Ross has described a number of neurophysiological tests that have been done on patients, but these were for research purposes and currently there is no defined set of neurophysiological tests that should be done (Sarah MacKenzie Ross, 2008).
- The Institute of Aviation Medicine, RAAF, provided guidelines for the medical management of aircrew after exposure to smoke and fumes (Institute of Aviation Medicine & Royal Australian Air Force, 2003).

6.3.2 Interpretation of evidence

- Medical management of the exposed individuals (aircrew, passengers), should comprise administration of 100% oxygen and symptomatic treatment.
- In a large majority of cases, symptoms are usually absent or are mild and transitory. In a few instances, the symptoms might persist for a time, but disappear after the first line treatment in a matter of minutes. In a still fewer individuals, the symptoms might be serious and persistent, requiring transfer to a medical facility (a clinic or a hospital) for second line and tertiary treatment.
- The nature of such second line and tertiary medical management will depend on the precise nature of symptoms, their severity, and the results of medical assessment, including any investigations.
- Consideration of treatment that should be provided in a medical facility is outside the scope of the this report. That CASA incorporate into the aircraft operational procedures (as a matter of airmanship), the requirement for the aircrew to turn off air conditioning packs in known areas of potential exposure during ground operations or at known times of potential cabin air contamination e.g. when the aircraft is taxiing to the holding point and exhaust gases from other aircraft could enter the cabin via the engine and ram air conditioning inlets.

6.4 What is the role of regulations in addressing contaminated cabin air?

6.4.1 Description of evidence

6.4.1.1 Authorities / Regulators

- Australian regulations for flight safety and occupational health have been described in Section 4.6.
- The USA is in the process of reassessing their regulations:

- A proposal is before by the US Senate regarding regulating the use of cabin air filters and monitors (Lautenberg, 2009).
- A similar proposal is before the House of Representatives (US House of Representatives, 2009).
- Abeyratne discussed the legal aspects of 'Aerotoxic Syndrome' from the perspective of US law (Abeyratne, 2002).
- Murawski summarised the FAA regulatory response to this issue in recent years (Murawski, 2009b).

- ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.) has recently published new standards regarding cabin air quality (ASHRAE, 2007a):
  - A representative from Honeywell reviewed the development of recent Cabin Air Quality standards in the US and discusses issues surrounding their implementation (Richard Fox, 2009).
  - Pierce *et al* described a study to support the development of ASHRAE's standards for cabin air (Pierce, et al., 1999).
  - Murawski presented advice from the AFA to flight crew about how to use the standard (Murawski, 2007).
- Consultation is occurring for a new European regulation concerning cabin air quality.
  - The minutes from the most recent meeting are available (Lessmann, 2009a).
    - Lessmann opened the meeting with information about the Aerospace and Defence Standards (ASD-STAN) (Lessmann, 2009b).
    - Hooper presented to this meeting on OP poisoning and 'Aerotoxic Syndrome' (M. Hooper, 2009).
    - Adriaensen presented the concerns of pilots and cabin crews (Adriaensen, 2009).
    - Michaelis presented about her research and concerns about the proposed standards (Michaelis, 2009c).
    - Schwanhaeuser presented on behalf of the GCAQE (Schwanhaeuser, 2009).
    - Wolff and Mayer presented about the work of ICE (C. Wolff & Mayer, 2009).
    - Von Groote provided a background to the European Committee on Standardization (von Groote, 2009).
- The European Aviation Safety Agency (EASA) has issued advance notice of proposed amendment (A-NPA) regarding cabin air quality in large aircraft (European Aviation Safety Agency, 2009).

6.4.1.2 Interested parties

- A number of interest groups made comments on regulation (and other potential solutions):
  - AIPA made a number of comments and suggestions in their submission, in particular:

> "AIPA believes that the first stage of any Australian response to aircraft environment health concerns should centre on the introduction of appropriate aviation specific health and safety legislation, which is

> harmonised with international best practice. The way to accomplish this is to immediately develop legislation that implements the 'spirit and intent' of the above ICAO standards. Case must have the relevant power to monitor and take enforcement action against operators that fail to implement internationally recognised protection measures that prevent passengers and crew from aircraft fume exposures."
>
> (Australian & International Pilots Association (AIPA), 2009)

- GCAQE recommended the training and educating of crewmembers, and improved understanding of the medical community of the possible effects of contaminated cabin air (Global Cabin Air Quality Executive (GCAQE), et al., 2009).
- Michaelis concluded her submission to the Panel with a comprehensive list of suggested solutions (see section 8.8, Appendix 8) (Michaelis, 2009a).
- In the submission to the Panel, van Netten commented about the need for access to aircraft for research, and:

> "The only way that I can see at present that will address these problems is to take away the apparent power that the aircraft industry appears to have regarding access to their aircraft. Access to monitor the air in ground-based industries is mandated by the Worker's Compensation Board and similar agencies in most countries. If an aircraft company decides to operate in such a country, the same rule should apply. Unless and agency such as the Australian Civil Aviation Authority mandates access to aircraft similar to the access that exists in ground based industries where it concerns workers and public health, health risks in aircraft cannot be addressed properly. I believe that Australian Civil Aviation Authority is currently in an unique position to resolve these issues. All it takes is one country to break this "monopoly" on access, once that is done, from my perspective, other countries will follow suit very quickly as they have been wrestling with this problem for years."
>
> (C van Netten, 2009)

- The Association of Flight Attendants made a number of recommendations in its submission to the Panel:

> "We feel strongly that the Australian government needs to mandate bleed air cleaning and monitoring with flight deck indication, giving industry reasonable time to comply (perhaps three years).
>
> In the meantime, the government needs to fund necessary research and development of bleed air cleaning and monitoring options to enable industry to meet its responsibilities of providing clean supply air to passengers and crew.
>
> Furthermore, we call for regulators to require airlines to train cabin and flight deck crews to recognize and respond to exposure to oil fumes."
>
> (Association of Flight Attendants CWA & Witkowski, 2009).

6.4.1.3 Air Safety Incident Reporting

- AIPA made several comments in their submission about incident reporting and point out that:

> "CAR 21 stipulates maintenance regulations for aircraft components that control introduction of toxic or noxious gases in the crew compartment or passenger cabin. Defects of these components are considered 'major defects' and are Australian Transport Safety Bureau (ATSB) reportable matters requiring the submission of an ASIR.□- CAR 21 CERTIFICATION & AIRWORTHINESS REQUIREMENTS FOR AIRCRAFT & PART CAR 21.3- Reporting failures, malfunctions & defects. 21.3 (4) The following occurrences must be reported as provided in subreg 1 & 2 (c) The accumulation or circulation of toxic or noxious gases in the crew compartment or passenger cabin.
>
> The Transport Safety Investigation Act 2003, Section 18 states: - (1) If a responsible person has knowledge of an immediately reportable matter, then the person must report it to a nominated official as soon as is reasonably practicable, by the means prescribed by the regulations and including those of the particulars prescribed by the regulations that are known to the responsible person."
>
> (Australian & International Pilots Association (AIPA), 2009)

- They also believe that:

> "… all ASIRs should be sent to the ATSB for processing. This would increase transparency of the reporting process and ensure all reports are provided to the ATSB for review and investigation."

6.4.2 Interpretation of evidence

- The Panel noted that:
  - There were a number of regulations already in place, although the observation and interpretation of these regulations varied by country, airline and personnel.
  - Potential fixes to the contaminated air issue lie in the systems and regulations involved in the source of the air for the cabin and the elimination of the possibility of abnormal occurrences. The first involves removal of 'bleed' air conditioning systems from modern aircraft, as is the case with the design for the Boeing 787; the second is more difficult as it involves pre-empting service difficulties in advance. Specific and detailed preventative maintenance would contribute greatly in assisting and ultimately eliminating this problem.

6.5 What is the role of filtration technologies in addressing contaminated cabin air?

6.5.1 Description of evidence

6.5.1.1 Reviews of cabin air filtration

- Michaelis and Loraine reviewed the current situation of cabin air filtration, and discussed new technologies and their potential efficacy (Michaelis & Loraine, 2005).
  - With respect to plasma technology, Michaelis considered that the following questions should be addressed:
    - "What are the effects of air flow rate/residency time on efficacy?
    - What are the effects of plasma depth/throw (i.e. what is the relationship between the plasma size and the volume of air that can be filtered?)
    - What is the range of contaminants that can be decomposed?
    - When bleed air is contaminated with engine oil, hydraulic fluid, or pyrolysis products of these, what reaction products are produced and how safe are they?"

      (Michaelis & Loraine, 2005)

- A report by SAE Aerospace reviewed the different filtration methods available (SAE Aerospace, 2007) [page 21].
- A recent review by the GCAQE included an overview of the new Quest Air Manager (Global Cabin Air Quality Executive, 2009).

6.5.1.2 Photocatalytic filters

- Wisthaler *et al* analysed the efficacy of photocatalytic and sorption-based purification of cabin air (Wisthaler, et al., 2007).
- Ginestet *et al* discussed the development and effectiveness of a photocatalytic filter for cabin air (Ginestet, Pugnet, Rowley, Bull, & Yeomans, 2005).

6.5.1.3 Carbon filters

- Sofrance made a presentation to the BALPA conference on the effectiveness of activated carbon filters (Contini, 2005).
- Pall Aerospace, together with Airbus, has developed carbon filter elements that adsorb VOCs, and fit with the current HEPA filters (Bull, 2008).
- Pall Aerospace also presented to the BALPA conference on filter technology (Bull, 2005).

6.5.1.4 Plasma field

- Quest International and BAE Systems have recently introduced 'The Quest Air Manager' (BAE Systems & Quest International UK, 2009):
  - This system uses a non-thermal plasma field, which breaks down long chain molecules, and has been tested on the Volatile Organic Compounds that may be present in cabin air, including TCP.

- A frequently-asked questions document was provided by the manufacturers (Quest International (UK) Limited, 2009).
- The system is currently available for BAe146 and Boeing 757.
- Table 11 below shows the claimed effectiveness of this system for VOCs:

Laboratory Reference	*99436*	*9440*		*94439*	
Client reference	*No filter (x10) ug/m^3*	*1 pass ug/m^3*	*% Removal*	*3 pass ug/m^3*	*% Removal*
Hexanal	*1400*	*47*	*97*	*15*	*99*
4-methyloctane	*1600*	*56*	*97*	*16*	*100*
N,N-dimethyllacetamide	*130,000*	*660*	*100*	*261*	*100*
Phenol	*7300*	*210*	*98*	*61*	*100*
N-dodecane	*590*	*4.2*	*100*	*1.1*	*100*
Dodecamethylcyclohexasiloxane	*2600*	*25*	*99*	*12*	*100*
Total organics	*450,000*	*2,700*	*99*	*980*	*100*

Table 11: How effective CCFT is against VOCs (BAE Systems & Quest International UK, 2009)

- Michaelis discussed some concerns with the Air Manager system in an email to GCAQE.

> "Plasma oxidation units generate ozone gas which is a respiratory irritant. Also, it is not clear how the unit handles liquids (like oil mist) or "semi-volatiles" (like TCPs). Regarding oil fumes, Air Manager is intended for the recirculated air stream, but on its website, the company claims that it will protect occupants from oil fume exposures because any such exposures will be transient and then the recirculated air supplied to the cabin will be clean! Quest has partnered with an aircraft interiors company called Aeropair which specifically claims that the Air Manager "removes 98% of TCPs"[2]. On its website, Quest reports that it challenged the Air Manager with pyrolyzed Mobil Jet Oil II, Skydrol hydraulic fluid, and a deicing fluid, although it only reported on the reduction in the chemical concentrations of five oil pyrolysis products, so it is still not clear how much of the oil fumes were removed. And anyway, the unit is installed in the recirculated air stream, so if pyrolyzed oil contaminates the bleed air, crew and passengers will still be exposed, although arguably carbon monoxide and some other VOCs may not get recirculated."
>
> (Michaelis, 2009b)

- In addition to filtration, there have been recommendations to increase the ventilation rate in aircraft cabins:
  - Hocking recommended increased air ventilation, and using CO_2 levels as a marker for adequacy of ventilation (Hocking, 2000a, 2000b).

6.5.2 Interpretation of evidence

- There are several technologies with potential utility in filtration, however further study is needed to prove their relative effectiveness.

6.6 What are the monitoring technologies available?

6.6.1 Description of evidence

- The ASHRAE Committee is presently developing guidance for users of the ASHRAE standard to meet the requirement to monitor bleed air and provide flight deck indication.
- Provisional recommendations are that each source of bleed air (APU and each engine) be equipped with a sensor so that the pilot can quickly identify the location of the contamination (ASHRAE, 2008).
- In 2006, a prototype Cabin Air Sensor monitoring unit was developed by Owlstone Nanotech in the Cambridge, England under a US Air Force grant (Owlstone Nanotech Inc, 2006, 2007).
    - It was designed to measure a variety of contaminants in the bleed air system in order to distinguish between sources of air supply contamination (e.g., oil, hydraulic fluid, exhaust fumes, etc.).
    - Specifically, the goal was to provide real-time information on the nature of air supply contamination in-flight.
    - Toxic concentrations for chemical species of concern range from the few hundreds parts per million (e.g. carbon monoxide) down to the sub-parts per million (e.g. OPs, such as tricresyl-phosphate oil additives). As such, monitoring systems need not only be chemically selective in their response over a broad linear range, but also remarkably sensitive.
    - It was deemed that when flight crew need not waste any time on troubleshooting the source or nature of fumes in-flight, there should be a protective effect on aviation safety and the health of aircraft occupants and diversion costs may be reduced.
    - A prototype device was developed, but the USAF did not proceed with this project.
- Some members of the ACER group have published on TCP sensors, although it is not currently known how sensitive, expensive, durable, or appropriate they are (Pedrosa, Epur, Benton, Overfelt, & Simonian, 2009).

6.6.1.1 Reviews

- Van Netten reviewed the various methods of obtaining air quality measurements in aircraft (C. van Netten, 2005a) [pages 12-15], and methods for identifying synergistic agents [page 16].
- The Committee on Toxicity has previously reviewed the possible approaches to the monitoring of cabin air:

- A discussion with Dr O'Hare, Reader in Sensor Technologies focussed on technologies for exposure monitoring (Committee on toxicity of chemicals in food consumer products and the environment, 2006m).
- The development of an approach to exposure monitoring (Committee on toxicity of chemicals in food consumer products and the environment, 2006v).

6.6.1.2 VOC contamination monitors

- A variety of approaches and technologies for monitoring VOC contamination have been proposed and developed (see COT review (Committee on toxicity of chemicals in food consumer products and the environment, 2006v) for discussion of some of these techniques):
  - Swab samples:
    - Van Netten has analysed swab samples taken from inside aircraft (C. van Netten, 2009b).
    - As part of his research into cabin air contamination, Professor Van Netten has developed a portable personal air monitor (C. van Netten, 2009a).
  - Solid phase microextraction.
  - BRE Grab sampler.
  - Diffusive sampler.
  - Photoionisation.
  - Electrochemical gas sensor:
    - Pedrosa *et al* described an electrochemical method for rapid identification of TCP in air and fluids (Pedrosa, et al., 2009)).
  - Mass spectroscopy:
    - Griffin 450 mass spectroscopy mobile air sampler. No information is available for its application on aircraft (Griffin Analytical Technologies, 2009).
  - Surface Plasmon Resonance (SPR):
    - A presentation to BALPA conference described the technology of SPR and its potential use in cabin air monitoring (Furlong, Stevens, et al., 2005).
    - Another paper described the methods underlying SPR (Soelberg, Stevens, Limaye, & Furlong, 2009).
  - Infrared spectrophotometer
    - The “oil sniffer" detection kit by Boeing is intended for use on the ground and not for continuous, real -time monitoring. This kit may be able to distinguish between different sources of oil fumes (for example, APU, engine, air conditioning machine, etc)

> “In response, Boeing has developed an oil detection kit that can be used to quickly identify the source of oil leaks or aerosol odors. The kit includes a bleed air sampler and portable infrared spectrometer. Ground crews connect the air sampler to the 3-inch pneumatic ground cart connector and

> run engine or APU bleed air through the sampler for 10 minutes. The spectrometer and a laptop computer are used to analyze the sample. The kit's software alerts the user when the sample matches a known contaminant, such as oil or hydraulic fluid"
>
> (Holley, 2009)

- Lufthansa Technik has something similar, again intended for troubleshooting an aircraft for oil fumes on the ground (Lufthansa Technik, 2006).

- Part of the submission by Honeywell described the development of a real-time bleed air contamination monitor, developed from a carbon dioxide analyser, which performed well for ground-use only but notes that further development may allow for in-flight use (Richard. Fox, 2002).
  - Richard Fox of Honeywell (R. Fox, 1998) has also patented an air-monitoring device.
- Following the COT inquiry, monitoring research was started at Cranfield University:
  - *Functionality test of four types of monitoring equipment* (Muir, et al., 2008). Concluded that pumped thermal tube desorption technology is the most appropriate technique for cabin air monitoring.
  - A major study involving a number of airlines is presently underway (Civil Aviation Authority UK & Johnston, 2009).
- The approach taken by the COT and Cranfield University has received some criticism:
  - The lobby group GCAQE criticised both the tendering process and the research techniques (Global Cabin Air Quality Executive, 2008).
- A paper by Solbu investigated the best method to assess exposure to airborne trialkyl and triaryl OPs (Solbu, et al., 2007).

6.6.1.3 Carbon monoxide monitors

- These are available but seldom used:
  - One paper discussed the prevention of CO exposure in aviation and the use of active warning devices (Zelnick, Lischak, Young, & Massa, 2002).
  - Professor van Netten discussed the role of CO monitoring in evaluating contaminated air events, and proposed that this could be an early warning system for bleed air contamination (C. van Netten, 2005a) [pages 10-11].

6.6.2 Interpretation of evidence

- The Panel was informed that the most significant research of monitoring systems is that undertaken by Cranfield University.
- The Cranfield University study should provide the most robust evidence to date about cabin air monitoring.

- The report was due to be published before the end of 2010 however the lead investigator, Professor Helen Muir, died in March 2010.

6.7 What is the potential role for engine oils that do not contain TCP?

6.7.1 Description of evidence

- Oils are available that do not contain TCP:
    - NYCO submitted a memorandum to the COT stating that their Turbonycoil 600 is available for use and contains TPP not TCP (NYCO, 2007).
    - The MSDS for Turbonycoil 600 stated a content of triphenyl phosphate of less that 2.5% (NYCO, 2009b).
    - A presentation by NYCO described their products and the necessary approval processes (NYCO, 2008).
    - In a submission to EASA, NYCO discussed research by Professor Furlong's laboratory into the amount of BChE inhibition caused by various OPs. The conclusions were:

> "(1) Commercial TCP (as used in most jet engine oils) presents a non-negligible potential of BChE inhibition in the test, comparatively with TOCP (tri-ortho-cresyl-phosphate), a potent neurotoxic, albeit this isomer is not detected in commercial TCP.
>
> (2) TIPP (anti-wear used in "Turbonycoil 600") does not present a significant improvement over TCP within the repeatability of this test.
>
> (3) General rules between the chemical structure and BChE inhibition have been found, and specific organo-phosphates inducing a much lower inhibition have been identified."
>
> (NYCO, 2009a)

    - In addition, the submission outlined that NYCO have patented some low toxicity OPs with good anti-wear properties. This is further discussed in a submission to the Expert Panel which also states that there new formulations are currently undergoing testing with expected qualification to civil specifications in July 2010 (NYCO, 2010).

- AIPA commented in their submission that:

> "The Government should also investigate the possibility of replacing Tricresyl Phosphate **(**TCP**)** based oils with TCP free oil that may be available on the market. These oils are currently in use in military aviation and are likely to meet the manufacturers requirements for use in commercial aviation environments."
>
> (Australian & International Pilots Association (AIPA), 2009)

6.7.2 Interpretation of evidence

- Nyco oil is already in use across Europe as a possible replacement for Mobil Jet II, which was not constructed for engines operating at very high temperatures.
- It is not clear whether Turbonycoil 600 has a lower potential for health effects compared with TCP-containing oils.
- Formulations with additives that have lesser inhibition on BChE may become available in the near future.

6.8 Recommendations

20. That CASA incorporate into the aircraft operational procedures (as a matter of airmanship), the requirement for the aircrew to turn off air conditioning packs in known areas of potential exposure during ground operations or at known times of potential cabin air contamination (e.g. when the aircraft is taxiing to the holding point and exhaust gases from other aircraft could enter the cabin via the engine and ram air conditioning inlets).

21. That CASA review regulations for standard emergency procedures in regard to cabin air contamination incidents during flight, taxiing and testing stages of operation to ensure consistency throughout all airline operators and the general aviation industry.

22. That CASA collaborate with the relevant OH&S authorities to issue a directive requiring airline operators to instruct aircrew and engineering staff in the protocol to be followed regarding taking suitable precautions and adopting safe work practices when working both within and around aircraft to minimise exposure to the hazard of fumes from heated jet engine oils, hydraulic fluid and other possible contaminants.

23. That CASA collaborate with the relevant OH&S authorities issue a directive requiring operators to seek a review of engineering maintenance practices and determine a mandatory timeframe after engine shutdown before inspections are permitted to take place, to minimise risk of exposure to the hazard of fumes from heated jet engine oils, hydraulic fluid and other possible contaminants.

24. That CASA incorporate new maintenance standards in CASA Regulations, with enforceable legislation if necessary, to ensure that operators remain alert to problems associated with cabin air quality and comply accordingly.

25. That CASA examine the need for any additional actions to improve compliance with CASA regulations related to cabin air contamination incidents with consideration of heavier penalties for non-compliance.

26. That CASA recommend to the Commonwealth Minister for Transport that CASA seek participation with the US Federal Aviation Authority (FAA) in the trial of monitoring devices

in aircraft cabins and review the outcomes of the trial to determine the benefits of making mandatory the fitting of fumes monitoring devices in all aircraft.

27. That CASA incorporate ICAO Resolution A35-12, regarding 'Protection of the health of passengers and crews and prevention of the spread of communicable disease through international travel', into the CASA regulations to make this resolution applicable to Regular Public Transport Operations.

28. That CASA recommends to the Commonwealth Minister for Transport the implementation of part 6 of ICAO Resolution A35-12, supporting further research on the consequences of air transport on the health of passengers and crew.

29. That CASA incorporate into legislation, regulations that mandate aircraft operators to notify, at the time of occurrence, all individuals involved in a cabin air contamination incident, which would include flight crew, cabin crew, ground crew and passengers.

30. **T**hat CASA mandate operators to require that the captain of an aircraft in which a cabin air contamination incident had occurred to provide passengers experiencing any symptoms at the time of the incident with a CASA approved report form to complete and return to CASA to enable documentation and establishment of a database to facilitate follow up.

31. That CASA alert all operators, aircrew and engineering staff to the regulations concerning cabin air contamination and the action needed to be taken in the event of a cabin air contamination incident.

32. That the operators of aircraft known to be prone to cabin air contamination incidents, or any particular aircraft that has a high incidence of cabin air contamination incidents, be required to fit an approved fumes removal device or develop filtration systems for existing aircraft to minimise any possible exposure of aircrew or passengers to potential health effects.

33. That CASA recommends to the Commonwealth Minister for Transport that uniform national OH&S legislation regarding cabin air quality be developed and implemented to cover atmospheric contaminants within the internal cabin air space.

34. That aircraft manufacturers be required by regulation to install developed air conditioning and pneumatic filtration systems on all future aircraft.

35. That CASA adopt and implement the cabin air quality standard for aviation developed by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) for USA aviation.

36. That CASA support the move for future commercial aircraft to have airconditioning and pressurisations systems that do not use engine bleed air (for example the Boeing B-787 Dreamliner).

37. That CASA require aircraft operators to use Tricresol Phosphate (TCP)-free oils that comply with the engine manufacturers' requirements, pending absolute determination of the potential or otherwise for contamination by TCP of bleed air used in aircraft cabin air conditioning and issue explicit guidelines on the use and recording of TCP free oils.

7 Recommendations

1. That the Australian Government, through CASA and the ATSB, sponsor and fund the development of a single, central, internet-based, confidential reporting system on cabin air contamination incidents to be co-ordinated and operated jointly by CASA and the ATSB. To improve the reporting and monitoring of cabin air contamination incidents, this system should have web-based forms to facilitate the collection and collation of data from all authorities and companies responsible for cabin air contamination incidents that would enable the data to be tabulated into a de-identified and unalterable uniform document that could be accessed and utilised by all stakeholders. .

2. That the internet reporting system of cabin air contamination incidents utilise a common agreed database developed in consultation with all relevant parties, incorporating a minimum data set of variables applicable throughout Australia, but allowing scope for additional fields of entry.

3. That CASA resolve to enforce fully the mandatory reporting of all aircraft contamination incidents and alerts all operators that it is mandatory for the reporting of all aircraft cabin air contamination incidents and the outcomes of investigations and management to CASA using Form 404 within the required timeframe no matter how apparently insignificant the event to enable a more accurate determination of the frequency of such incidents.

4. That CASA alerts all operators that failure to comply with reporting requirements of cabin air contamination incidents will result in significant penalties, including the ability of CASA to suspend AOCs (Airline Operator Certificates) and inform the public through a well publicised website using a safety rating system based on that system currently operating in the USA.

5. That CASA issue specific guidelines for all aircrew, engineers and other ground crew regarding their responsibilities in reporting Mandatory Occurrences (MOs) with particular attention to aircraft cabin air contamination incidents.

6. That CASA mandate full disclosure of internal reporting and management systems of cabin air contamination incidents by airlines operators to improve the external reporting of all cabin air contamination incidents including followup investigations and subsequent management.

7. That Australia seeks immediate support of the International Civil Aviation Organisation (ICAO) for the implementation of a worldwide common agreed database incorporating a minimum dataset for the mandatory reporting of cabin air contamination incidents.

8. That CASA utilise ATSB data together with any other available data to maintain an ongoing comprehensive study of cabin air contamination incidents using available data collected in Australia by operators collating all relevant information including, but not limited to, numbers of incidents, types of incidents, aircraft types involved, engine types involved, flight phases involved, companies involved, dates and times, witness statements, to create and maintain a solid base of consolidated cabin air contamination incidents data to enable analysis of trends and common features.

9. That CASA obtain and utilise ATSB data to collate the ATSB Fumes Data Records of cabin air contamination incidents from Forms 404 lodged by the airlines and publish the collated results annually.

10. That CASA collate and follow up information collected both through the proposed Internet database and from any other cabin air contamination recording systems submitted to the regulators (NAAs) and safety boards (NTSB, ATSB, BSTB etc.) for reporting to the Minister.

11. That CASA negotiate with ATSB for ATSB to undertake an in-depth analysis of all aircraft air contamination incidents at regular intervals and over a set period of time, to document trends over time, changes in the incidence of categories of cabin air contamination, identify common features and provide deidentified overall results and conclusions which could be used to design measures to eliminate cabin air contamination risks to aircrew and passengers.

12. That CASA negotiate with ATSB for ATSB to review past reported incidents of cabin air contamination incidents using the agreed case definition to determine if data recorded previously could be defined more accurately and entered into the new system to strengthen research or to highlight any deficiencies in recording.

13. That CASA establish and/or maintain contact with research groups active in the field of investigating cabin air contamination, including Cranfield University in the UK and the Furlong Group at the University of Washington in the USA, to ensure that Australia receives relevant and timely information from these research projects.

14. That CASA in association with the Department of Health and Ageing (DOHA), the Institute of Health and Welfare or the NHMRC sponsor a project to define possible criteria for case definitions for short term and longer term health outcomes following episodes of cabin air contamination.

15. That CASA assists DOHA, the Institute of Health and Welfare or the NHMRC to submit this proposed case definition to other jurisdictions for comment and appropriate refinement before being used for any future epidemiological studies and in clinical settings.

16. That CASA seek the assistance of DOHA to facilitate future research by using the agreed case definition to evaluate all present and future cases of ill health reported through the proposed internet reporting system or after assessments of aircrew following a cabin air contamination incident and that CASA seek the cooperation of ATSB in this undertaking.

17. That CASA request ATSB to facilitate the gathering of good quality exposure data on cabin air contamination incidents, preferably directly by aircrew to enable documentation of both the type and level of exposure occurring during an episode of cabin air contamination.

18. That CASA seek the assistance of DOHA to ensure that as soon as possible following exposure to a cabin air contamination incident, experienced medical personnel assess aviation personnel involved to enable detailed documentation of signs, symptoms and test results using an agreed case definitions, with this information forming the basis for the CASA directive regarding recording of information and subsequent action following fumes incidents.

19. That CASA seek the assistance of DOHA to establish an independent suitably qualified expert panel of clinicians to review reports of exposure to cabin air contamination, where relevant request additional clinical assessments and /or investigations and report to ATSB and CASA regarding any further action required.

20. That CASA incorporate into the aircraft operational procedures (as a matter of airmanship), the requirement for the aircrew to turn off air conditioning packs in known areas of potential exposure during ground operations or at known times of potential cabin air contamination (e.g. when the aircraft is taxiing to the holding point and exhaust gases from other aircraft could enter the cabin via the engine and ram air conditioning inlets).

21. That CASA review regulations for standard emergency procedures in regard to cabin air contamination incidents during flight, taxiing and testing stages of operation to ensure consistency throughout all airline operators and the general aviation industry.

22. That CASA collaborate with the relevant OH&S authorities to issue a directive requiring airline operators to instruct aircrew and engineering staff in the protocol to be followed regarding taking suitable precautions and adopting safe work practices when working both within and around aircraft to minimise exposure to the hazard of fumes from heated jet engine oils, hydraulic fluid and other possible contaminants.

23. That CASA collaborate with the relevant OH&S authorities to issue a directive requiring operators to seek a review of engineering maintenance practices and determine a mandatory timeframe after engine shutdown before inspections are permitted to take place, to minimise risk of exposure to the hazard of fumes from heated jet engine oils, hydraulic fluid and other possible contaminants.

24. That CASA incorporate new maintenance standards in CASA Regulations, with enforceable legislation if necessary, to ensure that operators remain alert to problems associated with cabin air quality and comply accordingly.

25. That CASA examine the need for any additional actions to improve compliance with CASA regulations related to cabin air contamination incidents with consideration of heavier penalties for non-compliance.

26. That CASA recommend to the Commonwealth Minister for Transport that CASA seek participation with the US Federal Aviation Authority (FAA) in the trial of monitoring devices in aircraft cabins and review the outcomes of the trial to determine the benefits of making mandatory the fitting of fumes monitoring devices in all aircraft..

27. That CASA incorporate ICAO Resolution A35-12, regarding 'Protection of the health of passengers and crews and prevention of the spread of communicable disease through international travel', into the CASA regulations to make this resolution applicable to Regular Public Transport Operations.

28. That CASA recommends to the Commonwealth Minister for Transport the implementation of part 6 of ICAO Resolution A35-12, supporting further research on the consequences of air transport on the health of passengers and crew.

29. That CASA incorporate into legislation, regulations that mandate aircraft operators to notify, at the time of occurrence, all individuals involved in a cabin air contamination incident, which would include flight crew, cabin crew, ground crew and passengers.

30. **T**hat CASA mandate operators to require that the captain of an aircraft in which a cabin air contamination incident had occurred to provide passengers experiencing any symptoms at the time of the incident with a CASA approved report form to complete and return to CASA to enable documentation and establishment of a database to facilitate follow up.

31. That CASA alert all operators, aircrew and engineering staff to the regulations concerning cabin air contamination and the action needed to be taken in the event of a cabin air contamination incident.

32. That the operators of aircraft known to be prone to cabin air contamination incidents, or any particular aircraft that has a high incidence of cabin air contamination incidents, be required to fit an approved fumes removal device or develop filtration systems for existing aircraft to minimise any possible exposure of aircrew or passengers to potential health effects.

33. That CASA recommends to the Commonwealth Minister for Transport that uniform national OH&S legislation regarding cabin air quality be developed and implemented to cover atmospheric contaminants within the internal cabin air space.

34. That aircraft manufacturers be required by regulation to install developed air conditioning and pneumatic filtration systems on all future aircraft.

35. That CASA adopt and implement the cabin air quality standard for aviation developed by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) for USA aviation.

36. That CASA support the move for future commercial aircraft to have air conditioning and pressurisations systems that do not use engine bleed air (for example the Boeing B-787 Dreamliner).

37. That CASA require aircraft operators to use Tricresyl Phosphate (TCP)-free oils that comply with the engine manufacturers' requirements, pending absolute determination of the potential or otherwise for contamination by TCP of bleed air used in aircraft cabin air conditioning and issue explicit guidelines on the use and recording of TCP free oils.

8 Appendices

8.1 Appendix 1: Official inquiries

8.1.1 Australia

8.1.1.1 Air Safety and Cabin Air Quality in the BAe146 Aircraft

Report by the Senate Rural and Regional Affairs and Transport References Committee (Senate Rural and Regional Affairs and Transport References Committee, 2000a)

Year	***Document type***	***Description***	***Reference***
2000	*Submission*	*1. Mr Frank Kolver*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*2. Dr Mark Donohoe, Environmental & Nutritional Medicine NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*3. Dr Richard Teo NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*4. Mr Stephen Tyrell ACT*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*5. Dr Jean Christophe Balouet, FRANCE*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*6. Dr Chris Winder NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*7. Dr Judith Ford, Genetic Consulting & Testing SA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*8. Dr C Van Netten, CANADA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*9. Mr Andrew Thom & Mr Jonathon Burdon VIC*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*10. Ms Deborah Carter QLD*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*
2000	*Submission*	*11. British Aerospace Australia Limited NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000m)*

Year	*Document type*	*Description*	*Reference*
2000	*Submission*	*11E. British Aerospace Australia Ltd NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000b)*
2000	*Submission*	*12. The National Industrial Chemicals Notification and Assessment Scheme NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000b)*
2000	*Submission*	*13. Mobil Oil Australia Ltd VIC*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000c)*
2000	*Submission*	*14. Australian Federation of Air Pilots VIC*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000c)*
2000	*Submission*	*15. Department of Public Health WA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000c)*
2000	*Submission*	*16. Ms Robin May SA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000c)*
2000	*Submission*	*17. Ms Judy Cullinane WA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000d)*
2000	*Submission*	*17A. Ms Judy Cullinane WA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000h)*
2000	*Submission*	*17. Appendix 1*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000e)*
2000	*Submission*	*17. Appendix 2*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000f)*
2000	*Submission*	*17. Appendix 3*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000g)*
2000	*Submission*	*18. Ansett Pilots Association VIC*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000i)*
2000	*Submission*	*19. Association of Flight Attendants USA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000i)*
2000	*Submission*	*20. Civil Aviation Safety Authority Australia ACT*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000j)*
2000	*Submission*	*21. Qantas Airways Limited NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000j)*
2000	*Submission*	*22. Ansett Australia VIC*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000j)*
2000	*Submission*	*23. National Jet Systems Pty Ltd SA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000j)*
2000	*Submission*	*24. Flight Attendants Association of Australia QLD*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000k)*

Year	*Document type*	*Description*	*Reference*
2000	*Submission*	*25. American Society of Heating Refrigerating & Air- conditioning Engineers (ASHRAE) USA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000l)*
2000	*Submission*	*26. Ms Susan Michaelis NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000n)*
2000	*Submission*	*27. Ms Lesley Williams ACT*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000n)*
2000	*Submission*	*28. Captain Richard Buncher NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000n)*
2000	*Submission*	*29. Ms Belinda Hall WA*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000n)*
2000	*Submission*	*30. Mr Richard Best NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000n)*
2000	*Submission*	*31. Ms Kerri Allison NSW*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000n)*
2000	*Meeting transcript*	*1 February 2000 - Sydney*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000o)*
2000	*Meeting transcript*	*2 February 2000 - Brisbane*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000q)*
2000	*Meeting transcript*	*14 March 2000 - Canberra*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000s)*
2000	*Meeting transcript*	*10 April 2000 - Canberra*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000r)*
2000	*Meeting transcript*	*1 May 2000 - Canberra*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000p)*
2000	*Meeting transcript*	*17 August 2000 - Canberra*	*(Senate Rural and Regional Affairs and Transport References Committee, 2000t)*

Table 12: Documents associated with the Report by the Senate Rural and Regional Affairs and Transport References Committee, 2000, Australia

8.1.2 UK

8.1.2.1 House of Lords, UK, Air Travel and Health, 2000

Chapter 1: Summary and Recommendations (Science and Technology Committee, 2000g)

Chapter 2: Background to the inquiry (Science and Technology Committee, 2000h)

Chapter 3: Regulatory arrangements (Science and Technology Committee, 2000i)

Chapter 4: Elements of healthy cabin air (Science and Technology Committee, 2000j)

Chapter 5: Providing a healthy cabin environment (Science and Technology Committee, 2000k)

Chapter 6: Deep vein thrombosis, seating and stress (Science and Technology Committee, 2000l)

Chapter 7: Other medical concerns (Science and Technology Committee, 2000m)

Chapter 8: Wider issues (Science and Technology Committee, 2000n)

Chapter 9: General conclusions (Science and Technology Committee, 2000o)

Date	***Document type***	***Description***	***Reference***
2000	*Appendix 1*	*Members of subcommittee*	*(Science and Technology Committee, 2000a)*
2000	*Appendix 2*	*Call for evidence*	*(Science and Technology Committee, 2000b)*
2000	*Appendix 3*	*Witnesses*	*(Science and Technology Committee, 2000c)*
2000	*Appendix 4*	*Summary of individual submissions*	*(Science and Technology Committee, 2000d)*
2000	*Appendix 5*	*Note of visit to British Airways Maintenance, Cardiff*	*(Science and Technology Committee, 2000e)*
2000	*Appendix 6*	*Abbreviations and technical terms used in this report*	*(Science and Technology Committee, 2000f)*

Table 13: Appendices of House of Lords' report 'Air Travel and Health' 2000

8.1.2.2 Air Travel and Health: an Update

In 2007 there was an inquiry into progress since the 2000 report (Committee on toxicity of chemicals in food consumer products and the environment, 2007g).

Date	***Document type***	***Description***	***Reference***
2007	*Oral evidence*	*Tuesday 26 June 2007*	*Website link*
2007	*Oral evidence*	*Tuesday 10 July 2007*	*Website link*
2007	*Oral evidence*	*Tuesday 17 July 2007*	*Website link*
2007	*Written evidence*	*Memorandum by the Aerospace Medical Association*	*(Aerospace Medical Association, 2007)*
2007	*Written evidence*	*Letter from the Aerotoxic Association*	*(Aerotoxic Association, 2007)*
2007	*Written evidence*	*Memorandum by Airbus*	*(Airbus, 2007)*
2007	*Written evidence*	*Memorandum by Aviation Organophosphate Information Site (AOPIS)*	*(Aviation Organophosphate Information Site, 2007)*
2007	*Written evidence*	*Memorandum by Boeing*	*(Boeing, 2007)*

Date	*Document type*	*Description*	*Reference*
2007	*Written evidence*	*Memorandum by the British Airline Pilots Association's (BALPA) Occupational & Health Group*	*(British Airline Pilots Association, 2007)*
2007	*Written evidence*	*Memorandum by the Building Research Establishment*	*(Building Research Establishment, 2007)*
2007	*Written evidence*	*Memorandum by Dr Clement E Furlong*	*(Furlong, 2007b)*
2007	*Written evidence*	*Memorandum by the Global Cabin Air Quality Executive (GCAQE)*	*(Global Cabin Air Quality Executive, 2007)*
2007	*Written evidence*	*Memorandum by the Health Protection Agency*	*(Health Protection Agency, 2007)*
2007	*Written evidence*	*Memorandum by Ideal Cabin Environment (ICE) project*	*(Ideal Cabin Environment project, 2007)*
2007	*Written evidence*	*Letter from Dr G A Jamal*	*(Jamal, 2007)*
2007	*Written evidence*	*Letter from Dr Peter Julu, Specialist Autonomic Neurophysiologist and Consultant Physician*	*(Julu, 2007)*
2007	*Written evidence*	*Memorandum by NYCO*	*(NYCO, 2007)*
2007	*Written evidence*	*Letter from Mr Ian Panton*	*(Panton, 2007)*
2007	*Written evidence*	*Memorandum by the Research Institute for Sport and Exercise Sciences, Liverpool John Moores University*	*(Research Institute for Sport and Exercise Sciences, 2007)*
2007	*Written evidence*	*Memorandum by Ms Christine Standing MA*	*(Standing, 2007)*
2007	*Written evidence*	*Memorandum by Thomsonfly*	*(Thomsonfly, 2007)*
2007	*Written evidence*	*Memorandum by Unite the Union - Transport and General Workers' Section*	*(Unite the Union, 2007)*
2007	*Written evidence*	*Letter from H&S Representative T&G section of Unite the Union*	*(Transport and General Workers Union, 2007)*
2007	*Written evidence*	*Memorandum by Association of Flight Attendants*	*(Association of Flight Attendants-CWA, 2007)*
2007	*Written evidence*	*Letter from Captain Susan Michaelis*	*(Michaelis, 2007c)*

Table 14: Documents associated with 'Air Travel and Health: an Update'

8.1.2.3 Air Travel and Health Update: Government Response 2008

This document outlines the UK Government response to the 'Air Travel and Health: an Update', and the Committee's comments about those responses (Science and Technology Committee, 2008).

8.1.2.4 Committee on Toxicity, UK, 2006-7

Statement on the review of the Cabin Air Environment, Ill-Health in Aircraft Crews and the possible relationship to smoke/fume events in aircraft. (Committee on toxicity of chemicals in food consumer products and the environment, 2007k)

Also published a non-technical lay summary (Committee on toxicity of chemicals in food consumer products and the environment, 2007j).

8.1.2.4.1 **Discussion documents**

TOX-2006-21:

Discussion paper on the cabin air environment, ill health in aircraft crews and the possible relationship to smoke/fume events in aircraft (Committee on toxicity of chemicals in food consumer products and the environment, 2006y).

Provides background to the inquiry, and a full discussion of BALPA submissions and data.

Date	***Document type***	***Description***	***Reference***
2006	*Annex 1A*	*Overview of papers submitted June 2005*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006b)*
2006	*Annex 1A Addendum*	*Inquiry into Air Safety - BAE146 Cabin Air Quality*	*(Senate Rural and Regional Affairs and Transport References Committee, 2006)*
2006	*Annex 1B*	*Reference list B, Overview of papers submitted 11 November 2005*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006c)*
2006	*Annex 1C*	*Additional background information*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006d)*
2006	*Annex 2*	*Summary BALPA conference held at Imperial College, London, April 2005*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006f)*
2006	*Annex 3*	*Meeting between COT Secretariat and the British Airline Pilots Association (BALPA) held on 22 February at DH 140 Skipton House*	*(Committee on toxicity of chemical in food consumer products and the environment, 2006a)*
2006	*Annex 3 evaluation*	*Analysis of BALPA fume database*	*(Committee on toxicity of chemicals in food consumer products and*

Date	*Document type*	*Description*	*Reference*
			the environment, 2006g)
2006	*Annex 4*	*Pyramid*	*(Building Research Establishment, 2006)*
2006	*Annex 4 meeting note*	*Meeting between COT secretariat and Civil Aviation Authority (CAA) held on 5th April at 508 Wellington House*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006i)*
2006	*Annex 4 CAA*	*Analysis of the CAA database submissions*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006j)*
2006	*Annex 5 meeting notes*	*Meeting between COT Secretariat and BAe Systems, Boeing, Rolls Royce, Honeywell, held on 2 June 2006 at the offices of the Building Research Establishment (BRE)*	*(Committee on toxicity of chemical in food consumer products and the environment, 2006b)*
2006	*Annex 5*	*B757 Engineering Issues - Cabin fume events, input to COT*	*(Rolls Royce, 2006)*
2006	*Annex 5 addendum*	*Draft description of generic air conditioning system*	*(Civil Aviation Authority)*
2006	*Annex 5 additional*	*BAe146 & RJ Bleed & Air conditioning System Layout*	*(Civil Aviation Authority, 2006c)*
2006	*Annex 5 additional material*	*535E4 Internal Air System*	*(Civil Aviation Authority, 2006b)*
2006	*Annex 6*	*Exchange of e-mails between COT secretariat and British Airways*	*(Committee on toxicity of chemical in food consumer products and the environment, 2006c)*
2006	*Annex 7*	*Secretariat summary - Neuropsychology evaluation of airline pilots*	*(Committee on toxicity of chemical in food consumer products and the environment, 2006d)*
2006	*Annex 8*	*Preliminary information on TCP in filters from B 757*	
2006	*Annex 9*	*Summary data on potential exposures in aircraft*	
2006	*Annex 10 BRE*	*Standalone capture device for measuring transient incidents on board aircraft*	*(Building Research Establishment, 2006)*
2006	*Annex 11*	*Comparison of neurotoxic effects and potential risks from oral administration or ingestion of tricresyl phosphate and jet engine oil containing tricresyl phosphate*	*(Mackerer, et al., 1999)*
2006	*Annex 12*	*Data on blood tests from 13 pilots*	

Table 15: Documents associated with TOX-2006-21

TOX-2006-39:

Update discussion paper (December 2006) on the cabin air environment, ill health in aircraft crews and the possible relationship to smoke/fume events in aircraft (Committee on toxicity of chemicals in food consumer products and the environment, 2006z).

Addresses topics identified by the COT at their July 2006 meeting

- Further assessment of fume incidents
- Development of approaches to measure potential exposure
- Further assessment of the reported acute and chronic ill health effects in aircrew
- Review of the epidemiological data
- Full literature search to identify additional data

Date	***Document type***	***Description***	***Reference***
2006	*Annex 1*	*Minutes of COT meeting held 11 July 2006.*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006a)*
2006	*Annex 2*	*Minutes of meeting held between BALPA and HPA COT secretariat, 25 July 2006*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006e)*
2006	*Annex 3*	*Minutes of meeting held between BATA and HPA COT secretariat, 3 August 2006*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006h)*
2006	*Annex 4*	*Minutes of meeting held between CAA and HPA COT secretariat, 3 August 2006*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006k)*
2006	*Annex 5*	*Minutes of meeting held between BRE and HPA COT secretariat, 21 September 2006*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006l)*
2006	*Annex 6*	*Minutes of meeting held between Dr D O'Hare (Imperial College) and HPA COT secretariat, 25 September 2006*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006m)*
2006	*Annex 7*	*Minutes of meeting held between FlyBe and HPA COT secretariat, 2 October 2006*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006n)*
2006	*Annex 8*	*Minutes of meeting held between BA and HPA COT secretariat, 9 October 2006*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006o)*
2006	*Annex 9*	*Formulation details of jet oils and MSDS data*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006p)*
2006	*Annex 10*	*For members use only. Presentation by Shell Global Solutions 1999.*	

Date	*Document type*	*Description*	*Reference*
2006	*Annex 11*	*Thermal decomposition of oils submitted by Honeywell Aerospace*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006q)*
2006	*Annex 12a*	*For members use only. Society of Automotive Engineers report on pyrolysis of two jet oils and exposure determination in cabin air.*	
2006	*Annex 12b*	*Summary of published test-rig study using Garrett turboprop engine*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006r)*
2006	*Annex 12c*	*Overview of published exposure data*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006s)*
2006	*Annex 13*	*Information submitted by FlyBe on incident monitoring*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006t)*
2006	*Annex 14*	*Information submitted by British Airways on incident monitoring*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006u)*
2006	*Annex 15*	*Development of an approach to exposure monitoring*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006v)*
2006	*Annex 16*	*Commentary on neuropsychology data submitted to COT. Professor R Morris, Professor of Neuropsychology at the Institute of Psychiatry, Kings College Hospital, London.*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006w)*
2006	*Annex 17*	*In-confidence for members use only. Review of analyses undertaken by Biolab Medical Unit on pilots.*	
2006	*Annex 18*	*Meeting between DHL Air Ltd and the HPA COT Secretariat held on 22 November 2006*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2006x)*

Table 16: Documents associate with TOX-2006-39

TOX/2007/10:

Update discussion paper on the cabin air environment, ill health in aircraft crews and the possible relationship to smoke/fume events in aircraft (Committee on toxicity of chemicals in food consumer products and the environment, 2007g)

Addresses topics identified by the COT at the December 2006 meeting:

- Information on whether pilots making multiple complaints about contaminated cabin air were also experiencing ill health
- Identify any further information on exposure to pyrolysed oils and hydraulic fluids
- Possible approaches to investigate the skills checks for flight licences in relation to neuropsychological effects in pilots

Date	***Document type***	***Description***	***Reference***
2007	*Annex 1*	*Minutes of COT meeting held 5 December 2006.*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2007a)*
2007	*Annex 2.1*	*Further consideration of sensory irritant potential of air contaminants potentially present in commercial aircraft, plus selected paper Nielsen GD, Wolkoff P and Alarie Y (2007). Sensory irritation: risk assessment approaches. Regulatory Toxicology and Pharmacology*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2007b)*
2007	*Annex 2.2*	*Selected papers on prediction of sensory irritation*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2007c)*
2007	*Annex 3*	*Minutes of meeting held between Dr M Abraham (University College, London) and HPA COT Secretariat, 20 February 2007*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2007d)*
2007	*Annex 4*	*Further consideration of neuropsychological effects reported in pilots – exposure to carbon monoxide.*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2007e)*
2007	*Annex 5.1*	*Pilot skill tests and proficiency checks.*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2007f)*
2007	*Annex 5.2*	*Civil Aviation Authority Standards Document 24, Version 05. Guidance to examiners: multi-pilot aeroplanes (MPA) type rating skill tests and proficiency checks.*	*(Civil Aviation Authority, 2005)*

Date	*Document type*	*Description*	*Reference*
2007	*Annex 5.3*	*Civil Aviation Authority document CAP 737. Crew resource management (CRM) training. Guidance for flight crew CRM instructors (CRMIS) and CRM Instructor-Examiners (CRMIES). (Chapters 1, 2, 4 and 7 selected.)*	*(Civil Aviation Authority, 2006d)*
2007	*Annex 5.4*	*Civil Aviation Authority forms: 1) LST/LPC MPA Issue 2 (SRG\1158). MPA (multi-pilot aeroplanes) type rating, skill test and proficiency check schedule – examiner's record and guidance, 2) LST/LPC SPA/MPA Issue 9 (SRG\1119). Type/instrument/class ratings (aeroplane), licensing/ATPL skill test and proficiency check – application and guidance.*	*(Civil Aviation Authority, 2006e)*
2007	*Annex 6*	*In-confidence for Members only. British Airways pilot training, checking and grading.*	
2007	*Annex 7*	*In-confidence for Members only. FlyBe pilot checking and grading.*	
2007	*Annex 8*	*Ryan JJ and Schnakenberg-Ott SD (2003). Scoring Reliability on the Wechsler Adult Intelligence Scale – Third Edition (WAIS-III). Assessment 10(2):151-159.*	
2007	*Annex 9*	*Commentary on the applicability of pilot test/check data for neuropsychological assessment purposes. Professor R Morris, Professor of Neuropsychology at the Institute of Psychiatry, Kings College Hospital, London.*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2007g)*
2007	*Annex 10*	*Further evaluation of epidemiological data.*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2007h)*
2007	*Annex 11*	*Selected epidemiological papers.*	*(Committee on toxicity of chemicals in food consumer products and the environment, 2007i)*

Table 17: Documents associated with TOX-2007-10

8.1.3 USA

The Airliner Cabin Environment and the Health of Passengers and Crew (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002)

In this 2002 report, the Committee on Air Quality in Passenger Cabins of Commercial Aircraft review what is known about air quality in passenger cabins, and provides a number of recommendations.

FAA response to the report:
Report to the Administrator on the National Research Council Report, "The Airliner Cabin Environment and the Health of Passengers and Crew" (The Airliner Cabin Environment Report Response Team, 2002).

8.2 Appendix 2: Fume event investigations

Date	*Country*	*Plane type*	*Exposure*	*Symptoms*	*Causes*	*Reference*
10/7/1997	*Australia*	*BAe146*	*Smell of oil fumes*	*Difficulty concentrating, vertigo, nausea. Prolonged headaches.*	*Probable oil leak No 4 engine*	*(Bureau of Air Safety Investigation, 1997)*
31/05/2001	*Australia*	*BAe146*	*Oil smell*	*Headache, itchy eyes, nausea, bad taste, poor concentration*	*Probable oil fumes from APU and No 4 engine*	*(Bureau of Air Safety Investigation, 2002b)*
18/07/2001	*Australia*	*BAe146*	*Smoky, burning smell*	*Only one crew affected. Poor concentration, almost passed out. Persistent anxiety. Elevated COHb.*	*Worn bearing seal in No 3 engine causing oil contamination*	*(Bureau of Air Safety Investigation, 2001)*
07/08/2001	*Australia*	*BAe146*	*Smell of fumes*	*Sore eyes, sore throats, headaches*	*Worn bearing seal in No 3 engine*	*(Bureau of Air Safety Investigation, 2002a)*
29/06/2002	*Australia*	*BAe146*	*Smoke on flight deck*	*Eye irritation*	*Leaking bearing seals in No 1 engine*	*(Bureau of Air Safety Investigation, 2003b)*
20/10/2002	*Australia*	*BAe146*	*Oil-type fumes in cockpit*	*Headache, nausea, irritated eyes, nose and throat*	*Possible leaking bearing seal No 4 engine*	*(Bureau of Air Safety Investigation, 2003c)*
02/12/2002	*Australia*	*BAe146*	*Strong fumes in cockpit*	*Some crew members 'unwell'*	*Probable leaking bearing seal No 3 engine*	*(Bureau of Air Safety Investigation, 2003a)*
05/07/2007	*Australia*	*Saab AB 340B*	*Pungent curry-like fumes in cockpit/cabin*	*None described - oxygen masks used*	*Likely to be residual ZOK 27 compressor wash fluid remaining in right engine bleed air system*	*(ATSB, 2008)*

Date	*Country*	*Plane type*	*Exposure*	*Symptoms*	*Causes*	*Reference*
12/11/1999	*Sweden*	*BAe146*	*No smells or visible fumes*	*Multiple crew affected. Faintness, pressure in head, nasal itching, ear pain, nausea*	*No specific cause found, but presumed to be cabin air contamination*	*(Statens haverikommission (SHK) Board of Accident Investigation, 1999)*
19/05/2005	*Switzerland*	*Avro 146*	*Acrid smell, visible fumes - had occurred on earlier flights also*	*Co-pilot unwell*	*Bearing leakage engine No 1*	*(Swiss Air Accident Investigation Bureau, 2006)*
05/11/2000	*UK*	*BAe146*	*'Oily' smells.*	*Aircrew nauseated, lightheaded.*	*Oil leak from APU. Note: This report includes a significant investigation into the possible of the contamination and provides recommendations*	*(Air Accidents Investigation Branch, 2004b)Appendices: (Air Accidents Investigation Branch, 2004a)*
04/08/2004	*UK*	*DHC-8-400*	*Oily smell, then smoke throughout aircraft*	*Crew immediately donned smoke hoods. Emergency landing performed*	*Oil leak from cracked compressor support*	*(Air Accidents Investigation Branch, 2007d)*
12/11/2004	*UK*	*Boeing 757*	*Several incidents of fumes in cockpit. Various smells.*	*Sore throats, poor concentration, headaches*	*Inconclusive - possible leaking hydraulic fluid*	*(Air Accidents Investigation Branch, 2005)*
07/12/2005	*UK*	*BAe146*	*Acrid smelling fumes*	*Nausea, vomiting, light-headed, burning eyes*	*De-icing fluid*	*(Air Accidents Investigation Branch, 2006b)*
02/02/2006	*UK*	*BAe146*	*Smell - 'central heating boiler'*	*Co-pilot: dry throat, burning eyes, tingling fingers. No one else affected*	*Probable engine oil from APU*	*(Air Accidents Investigation Branch, 2006c)*

Date	*Country*	*Plane type*	*Exposure*	*Symptoms*	*Causes*	*Reference*
10/03/2006	*UK*	*Boeing 757-236*	*Unusual odour in cockpit*	*Both pilots felt unwell - light-headed, euphoric. Co-pilot partially incapacitated. Did not take off, co-pilot used oxygen during tow*	*Suspect leakage in left engine but no leak found, aircraft returned to service.*	*(Air Accidents Investigation Branch, 2006a)*
20/09/2006	*UK*	*Avro 146*	*2 events of visible smoke in cockpit*	*None described - oxygen masks used*	*Failure of no. 1 bearing causing seal damage and oil leak*	*(Air Accidents Investigation Branch, 2007b)*
04/10/2006	*UK*	*Boeing 757-236 (same aircraft as 10/3/2006)*	*Transient oily smell in cockpit on takeoff*	*Flight crew 'felt unwell' - dry mouths. Commander - headache; co-pilot - 'raw throat'. During descent both pilots disorientated and commander confused - oxygen used during descent and automatic landing used.*	*No leak discovered at time of event, several more events occurred and left engine removed and repaired.*	*(Air Accidents Investigation Branch, 2007a)*
22/10/2006	*UK*	*Boeing 757*	*Blue haze, unusual smell*	*Passengers felt unwell*	*Fractured No 1 bearing floating seal ring causing oil leak into compressor air flow path*	*(Air Accidents Investigation Branch, 2009)*
1902/2007	*UK*	*BAe146*	*'Burnt' or 'exhaust' smell*	*Tunnel vision, loss of balance, loss of feeling in hands and arms*	*Engine oil leakage no. 1 engine*	*(Air Accidents Investigation Branch, 2007c)*

Table 18 List of fume event investigations.

8.3 Appendix 3: Submissions

Date received	***Name***	***Date received***	***Name***
8-May	*David H J Bowman*	*15-Jun*	*Susan Michaelis*
15-May	*David Coppard*	*15-Jun*	*Janette Burt*
16-May	*British Airline Pilots Association (BALPA)*	*15-Jun*	*John Hoyte, Aerotoxic Association*
16-May	*Rona-patrice Stevens*	*15-Jun*	*Lesley Ann Williams*
16-May	*Deby Bradford*	*15-Jun*	*Michel Mulder MD*
20-May	*FAAA*	*15-Jun*	*Melissa Dray*
20-May	*Anna Denney-Sandefer*	*15-Jun*	*John Hoyte*
25-May	*Rolls-Royce Australia Services Pty Ltd*	*15-Jun*	*Eileen Burton*
29-May	*Mario Fernandes*	*15-Jun*	*Anonymous, E*
3-Jun	*Robert Harrison, Clinical Professor, UCSF*	*15-Jun*	*Alan Carter*
5-Jun	*Ian Panton*	*15-Jun*	*Mike Parker-Stow*
5-Jun	*Mike Pivac*	*15-Jun*	*Dr Sarah MacKenzie Ross*
7-Jun	*Mrs R. Dixon*	*15-Jun*	*David Hall*
8-Jun	*Andrew Birtle*	*15-Jun*	*Dr Darren Jakubec*
9-Jun	*Reverend Jim Woodley*	*16-Jun*	*Ronald Devine*
10-Jun	*Anthony Watson*	*16-Jun*	*Ross Coulthart, Channel 7, Australia*
10-Jun	*Ines Dieckmann*	*16-Jun*	*Dr Sarah Myhill*
10-Jun	*Jon Delorme*	*16-Jun*	*Anonymous, F.*
10-Jun	*Dee Passon*	*16-Jun*	*Dr J. Mehrishi*
10-Jun	*Ray Jarvis*	*17-Jun*	*Anthony Poutsma*
10-Jun	*Andreas Beusen*	*17-Jun*	*Judith Al-Seffar, Journal of the Association of Neurophysiological Scientists*
10-Jun	*Anne Krauss*	*17-Jun*	*Alice O'Neill*
11-Jun	*Angela Estes*	*17-Jun*	*Alan Griffiths*
11-Jun	*Exxon-Mobil*	*18-Jun*	*Dr Andrew Harper*
12-Jun	*Independent Pilots Association*	*18-Jun*	*Mai-Britt Corsini*
12-Jun	*Anonymous, A*	*18-Jun*	*Professor Malcolm Hooper*
12-Jun	*Anonymous, B*	*19-Jun*	*Unite the Union, Aviation Health and Safety*
12-Jun	*Marta Bodi*	*22-Jun*	*Ruth Medina*
12-Jun	*Leonie Coxon, Clinical and Forensic Psychologist*	*24-Jun*	*Claudia Mercer*
13-Jun	*Ben Holmes*	*26-Jun*	*William Reder*
13-Jun	*Anonymous, C.*	*26-Jun*	*Anonymous, G.*
13-Jun	*Nickolas Vakas*	*27-Jun*	*Prof. Helen Muir*
13-Jun	*Richard Fox, Honeywell Aerospace*	*28-Jun*	*Judy Cullinane*
13-Jun	*Andy Queen*	*30-Jun*	*Linda Plourde*
14-Jun	*Tristan Loraine*	*1-Jul*	*Greg Marshall, Cobham Aviation Services, Australia*

Date received	***Name***	***Date received***	***Name***
14-Jun	*Professor Clem Furlong*	*2-Jul*	*Dr Raymond Johnston, Civil Aviation Authority, UK*
14-Jun	*Association of Flight Attendants*	*2-Jul*	*Richard Jones, Policy and Technical Director, Institution of Occupational Safety and Health*
14-Jun	*GCAQE*	*11-Jul*	*Joanne Turner*
14-Jun	*Leonard Lawrence*	*13-Jul*	*Christoph Schewe, Technical Director German Air Line Pilots Association,*
14-Jun	*Susan Campbell*	*14-Jul*	*Thomas Finlay, Boeing Company*
14-Jun	*Kate Frith*	*15-Jul*	*Ken Wallingford, NIOSH, USA*
14-Jun	*Gerry McCann*	*16-Jul*	*Professor Christiaan van Netten*
14-Jun	*Toxic Free Airlines.com*	*17-Jul*	*Captain Barry Jackson, President Australian & International Pilots Association (AIPA)*
14-Jun	*Johanna Stewart, Teamsters Canada*	*22-Jul*	*International Federation of Air Line Pilots' Associations (IFALPA)*
14-Jun	*Rob Nivison*	*24-Jul*	*Mike Pivac*
14-Jun	*Brian Buchanan, CUPE local rep*	*29-Jul*	*Boeing Australia*
14-Jun	*Dr Jonathan Burdon, Consultant Respiratory Physician*	*10-Aug*	*Rex Hoy, Safe Work Australia*
14-Jun	*Captain Peter Knight (retired)*	*7-Sep*	*Frederick E. Tilton, M.D. Federal Air Surgeon, Federal Aviation Administration (FAA)*
14-Jun	*Arie Adriaensen*	*14-Sep*	*J. Kneepkens, Rulemaking Director, European Aviation Safety Authority*
14-Jun	*Nevan Pavlinovich*	*24-Sep*	*Global Cabin Air Quality Executive (GCAQE)*
14-Jun	*Cara Watt*	*7-Oct*	*Global Cabin Air Quality Executive (GCAQE)*
14-Jun	*HolidayTravelWatch*	*9-Oct*	*Global Cabin Air Quality Executive (GCAQE)*
14-Jun	*Dr Moira Somers*	*12-Oct*	*Westdeutscher Rundfunk Koln, Germany*
15-Jun	*Susan Michaelis/Ray Godfrey*	*22-Nov*	*Ian Woods, Aviation Economics*

Table 19 Submissions received by the Panel

8.4 Appendix 4: Comparison of the incidence of smoke & fumes events

The following is an analysis performed by Dr Bhupinder Singh, a member of the Expert Panel:

- It is well known that there are no reliable or robust reporting systems for smoke and fumes events in the commercial civil aviation arena (details elsewhere in this report). Many authors have reported that there is wide spread under-reporting of such events due to a variety of reasons. The claims of such under-reporting itself are untested and unproven. It was suggested that since the military (Australian Defence Force) has a good reporting system, and the incidence of in-flight smoke and fumes events in the ADF is well known, it may be worthwhile to compare the rates in military with that in civil aviation. It is pertinent to point out that the ADF operates many aircraft types, including some that are also in operation in the commercial aviation sector.

8.4.1 Incidence in ADF aviation

- The Australian Defence Force has a robust reporting system for all in-flight smoke and fumes events with a high level of compliance. The data for the last 10 years shows an incidence of 0.56 events per 1,000 hours of flying (Singh, 2004).
- This incidence level is for all aircraft types in the ADF inventory, which includes aircraft of many categories, i.e., transport, cargo, maritime reconnaissance (MR), fighters, bombers, helicopters etc. The transport, cargo, and MR type aircraft in the ADF mostly engage in operations that are roughly similar to the commercial passenger aircraft operations, in terms of length of flight and number of take offs and landings. However, the fighter aircraft and helicopter operations involve sorties which are usually of shorter durations, and may involve frequent changes to power settings, with a number of take-offs and landings during a single sortie. Therefore, an attempt was made to tease out the smoke and fumes incidence data pertaining to transport, cargo, and MR type aircraft in the ADF, which includes aircraft like Boeing B-737, Lockheed P-3 Orion, BAe HS-748, DHC-4 Caribou, Dassault Falcon 900, Lockheed Hercules C-130, Kingair B-200/350, DHC-6 Twin Otter, Bombardier Challenger CL-604, etc. It was found that the incidence of smoke and fumes events in the ADF pertaining to transport, cargo, and MR type aircraft in the ADF was 0.46 per 1,000 hours of flying, a figure which is only slightly lower than the total incidence.

8.4.2 Incidence in Civil Aviation

- There is very little reliable data regarding the incidence of in-flight smoke and fumes events in commercial civil aviation.

- However, the US FAA reports an incidence of 2.7 events per million departures (Federal Aviation

Administration, 2009). Apparently, a departure equals one flight or one sector.

8.4.3 Comparison

- The FAA rate is reported as events in a certain number of departures (sectors), while the ADF rate is reported as events in a certain number of flight hours. To compare the two, the FAA rate must be converted to events in flight hours. To achieve that, we need to know the average length of a commercial civil flight. Again, no reliable information could be sourced. General information from the internet indicates the following:
    - The average length of a domestic flight is reported to be 2.5 – 3 hours, approximately.
    - The average length of an international flight is reported to be 6-7 hours, approximately.
- The FAA data is apparently from a mixture of domestic and international flights. Therefore it makes sense to take the average length of *all* flights (domestic and international), which works out to be about 5 hours.
    - FAA rate = 2.7 events in ONE million *departures*
      = 2.7 events in ONE million *flights*
      = 2.7 events in FIVE million *hours*
      = 0.54 events in ONE million *hours*

8.4.3.1 Summary

- ADF rate = 0.56 per 10^3 hours (1,000 hours).
- ADF rate for transport, cargo, and MR types = 0.46 per 10^3 hours (1,000 hours).
- FAA rate = 0.54 per 10^6 hours (1,000,000 hours).

- **The ADF rate is 1000 times greater than the FAA rate.**
- With such a vast difference in the two rates, various assumptions made in the calculations are of little significance.

8.4.3.2 Comparison with Australian Data

- The Aviation Safety Transportation Board (ATSB), in a 2007 report (Australian Transport Safety Bureau, 2007), has documented the reported events of "fire/explosion/fumes" from 2001 to 2006. It must be borne in mind that the incidence documented by ATSB pertains to all reported events involving "fire/explosion/fumes", not all of which necessarily resulted in exposure of crewmembers to smoke/fumes. The number of reported events where aircrew members were exposed to smoke/fumes will obviously be a fraction of the total rate as reported. Nevertheless, analysis of this data is rather revealing.
- The report shows that during the five-year period from July 2001 to June 2006, there were 206 reported events involving "fire/explosion/fumes". The average number of aircraft movements

during the same period was 550,000 *per year*, whereas the average number of scheduled hours was 380,000 *per year*. The figures for aircraft movements and scheduled hours were extrapolated from graphical data, and are thus approximate. However, any errors in the figures are likely to be insignificant when compared with the overall numbers.

- From the ATSB data, the following can be summarized:

a. Total number of reported "fire/explosion/fumes" events during the 5 year period = 262
b. Number of reported "fire/explosion/fumes" events during the period = 52.4 per year
c. Number of aircraft movements during the period = 550,000 per year
d. Number of aircraft scheduled hours flown during the period = 380,000 per year
e. Average length of a scheduled sortie = 0.69 hours (from c and d)
f. Incidence of reported "fire/explosion/fumes" = 9.5 events per 100,000 movements
   = 13.8 events per 100,000 hours
   = 138 events per 1,000,000 hours.

- To summarise, the rate of smoke and fumes events in the three organisations is:
  - ATSB = 138 events per million hours
  - FAA = 0.54 events per million hours
  - ADF = 560 events per million hours

- The ATSB rate of 138 events per million hours is much higher than the FAA rate, but is about quarter of the ADF rate. It is likely that the relatively lower rates reported by FAA, and to some extent by ATSB (as compared to those in the ADF) are more likely to be due to **under-reporting** than any real differences in the rates of occurrence of such events.

8.4.4 Conclusion

- The reported rates of in-flight smoke and fumes events in commercial aviation are far lower than that reported by the ADF. The likely reasons for this difference could be:
  1. An actual low incidence of events in the civil as compared to that in the military, or
  2. A significant level of under reporting in the civil.
- Given the clear evidence of the ratio of military to civilian reporting rates and the fact that it is unlikely that military aircraft are 'more susceptible' to fume events than civilian aircraft, and given the often strictly required levels of adherence to regulation, compliance and manufacture in the military sector, it can be concluded that there appears to be a culture of significant under-reporting of smoke and fumes events in the civilian/commercial aviation.
- The likely reasons for under-reporting of smoke and fumes events in the civilian/commercial aviation can only be conjectured. Some of these reasons may be:
  - Commercial pressures on civil aircrew to maintain flight schedules, and thus ignore incidents that are considered "minor" by aircrew, thus avoiding the risk of a diversion.

There are no such commercial pressures on military aircrew.

- The implications of reporting an incident may include diversion and emergency landing. Military aircraft are required by regulations to divert and land whenever it is warranted, and it is done quite frequently in response to events of in-flight smoke and fumes. On the other hand, diverting a commercial aircraft with a large number of passengers requires many more facilities on the ground, and is usually not undertaken except in a dire emergency.

8.5 Appendix 5: Laboratory testing and immunological responses in patients considered to have 'Aerotoxic Syndrome'

This is a discussion by Dr Rob Loblay, a member of the Expert Panel

8.5.1 Laboratory testing

Many of the individual submissions to Expert Panel included the results of various laboratory tests. The following observations are relevant:

- One UK laboratory offers diagnostic testing services for patients with 'Aerotoxic Syndrome', chronic fatigue syndrome and related conditions (Myhill, 2010). Tests include an "ATP profile" performed on peripheral blood neutrophils (whole cell ATP; ADP to ATP conversion efficiency; mitochondrial ADP-ATP translocator). They are done in the presence and absence of various inhibitors and co-factors.
- Performance of these tests is supported by an article that documented results in 71 patients and 53 normal controls, and showed that "only 1 of the 71 patients overlaps with the normal region" (Myhill, Booth, & McLaren-Howard, 2009). The authors concluded:

> "The 'ATP profile' test is a powerful diagnostic tool and can differentiate patients who have fatigue and other symptoms as a result of energy wastage by stress and psychological factors from those who have insufficient energy due to cellular respiration dysfunction. The individual factors indicate which remedial actions, in the form of dietary supplements, drugs and detoxification are most likely to be of benefit, and what further tests should be carried out."
>
> (Myhill, et al., 2009)

- Several points are noteworthy.
  - There has been an unwarranted assumption, without supportive evidence, that the differences seen between patients and controls were due to mitochondrial 'dysfunction'.
  - The conditions under which blood was collected were not described in the paper. Any cause of tachycardia could wash neutrophils from the marginated pool into the peripheral blood, as with lymphocytes. Patients with CFS often develop tachycardia from relatively minor exertion, due to deconditioning and/or changes in cardiovascular reflexes. This could increase the ratio of activated to resting cells, which could account for differences in mitochondrial metabolic activity.
  - The conditions of storage and transportation of the cells were not described in the paper. Neutrophils are known to be highly metabolically active cells. When collected and stored in

a test tube they rapidly utilize and deplete metabolic precursors in the serum, especially if kept at room temperature for any length of time. This could lead to a cellular energy deficit with death by apoptosis.

- The authors attributed the patients' subjective sensation of fatigue to an energy deficit from defective "cellular respiration". If this were true there should be an associated lactic acidosis. Despite an extensive discussion of mitochondrial energy metabolism in the paper, there was no mention of serum lactic acid measurement, acid-base status, or arterial blood gas sampling in the patients.
- No evidence was presented to support the assertion that "remedial actions, in the form of dietary supplements, drugs and detoxification, were likely to be of benefit…" other than further extrapolation from the "5 individual factors" measured in the "ATP profile" test. Justification of such a claim would normally require an extensive randomised clinical trial of these therapies in relation to the "factors" being measured.
- The first author is medical adviser to the Aerotoxic Association, and the senior author is head of the laboratory where the tests were performed.
- In this paper, an earlier Australian study is cited as a rationale for measuring mitochondrial function in patients with CFS (Vernon, et al., 2006). The latter was a prospective peripheral blood lymphocyte gene expression study (microarray) of patients following acute infectious mononucleosis. In those who developed persistent post-infectious fatigue, 24 genes were differentially expressed. Of these, 12 were associated with mitochondrial functions (fatty acid oxidation; apoptosis; DNA repair; mitochondrial membrane). It was speculated that these changes might lead to altered immune function and may be responsible for the altered pattern of humoral immune response against EBV antigens in patients with prolonged fatigue.
- The study of Vernon *et al* also has the potential confounding factor of tachycardia at the time of blood collection (during follow-up clinic visits) in patients with prolonged post-infectious fatigue. Entry of lymphocytes from the marginated pool into the peripheral blood may alter the distribution of T cell subsets in patients compared to controls; differences in activation state of these cells could account for the observed changes in gene expression. It is probably not warranted to consider the reported changes in gene expression as evidence of "dysfunction".
- From the above, it can be concluded that:
    - Changes in mitochondrial parameters may be a consequence rather than causally related to disease (termed an epiphenomenon).
    - They have not been validated as diagnostic tests (by evaluating their sensitivity, specificity and predictive value in a CFS population or in those considered to have 'Aerotoxic Syndrome').
    - Extrapolation to treatment with "dietary supplements, drugs and detoxification" is not warranted.

- In many individual submissions, the Expert Panel observed that some individuals had undergone more than 50 different laboratory tests. In such circumstances, the probability of finding one or more 'abnormalities' of no clinical relevance is >90%.

8.5.2 Pathological immune response or immunotoxicity

- Pathological immune responses characteristically leave detectable clinical and laboratory evidence. This can be local (inflammatory infiltrate) or general (evidence of systemic inflammatory response, fever, lymphadenopathy, mediator release, increase in acute phase reactants, vasculitic changes, complement consumption etc). Tissue damage should be evident on biopsy and/or imaging studies.
  - Immunotoxicity causing humoral or cellular immune deficiency is asymptomatic unless complicated by recurrent infections with pyogenic bacteria or opportunistic infections, respectively. No published study on 'Aerotoxic Syndrome' or individual case report submitted to the Expert Panel has documented immunopathology of this kind, nor have typical recurrent/opportunistic infections been reported.
  - Symptoms attributed to 'Aerotoxic Syndrome' are not consistent with known immunopathological mechanisms.
- Winder has listed "immune system effects" and "signs of immunosuppression" as long-term features of 'Aerotoxic Syndrome' but supporting laboratory evidence was not provided (British Airline Pilots Association, 2005):

Short term exposure	*Long- term exposure*
• ***Neurotoxic symptoms:*** *blurred or tunnel vision, nystagmus, disorientation, shaking and tremors, loss of balance and vertigo, seizures, loss of consciousness, parathesias;* • ***Neuropsychological or Psychotoxic symptoms:*** *memory impairment, headache, light-headedness, dizziness, confusion and feeling intoxicated;* • ***Gastro-intestinal symptoms:*** *nausea, vomiting;* • ***Respiratory symptoms:*** *cough, breathing difficulties (shortness of breath), tightness in chest, respiratory failure requiring oxygen;* • ***Cardiovascular symptoms:*** *increased heart rate and palpitations;* • ***Irritation*** *of eyes, nose and upper airways*	• ***Neurotoxic symptoms:*** *numbness (fingers, lips, limbs), parathesias;* • ***Neuropsychological or Psychotoxic symptoms:*** *memory impairment, forgetfulness, lack of coordination, severe headaches, dizziness, sleep disorders;* • ***Gastro-intestinal symptoms:*** *salivation, nausea, vomiting, diarrhoea;* • ***Respiratory symptoms:*** *breathing difficulties (shortness of breath), tightness in chest, respiratory failure, susceptibility to upper respiratory tract infections;* • ***Cardiovascular symptoms:*** *chest pain, increased heart rate and palpitations;* • ***Irritation*** *of eyes, nose and upper airways* • ***Sensitivity:*** *signs of immunosuppression, chemical sensitivity leading to acquired or multiple chemical sensitivity;* • ***General:*** *weakness and fatigue (leading to chronic fatigue), exhaustion, hot flashes, joint pain, muscle weakness and pain.*

Table 20: "Aerotoxic Syndrome: Short and Long Term Symptoms" from Winder, (British Airline Pilots Association, 2005).

- It has been claimed that certain non-mainstream investigations may be of value for assessment of patients with 'Aerotoxic Syndrome' (AS):

> "Investigations on AS sufferers were mostly reported as normal when investigated using NHS facilities (Myhill, 2007) and, unless chemical poisoning was suspected, toxicology procedures were not usually requested. Some patients with suspected AS had been investigated using diagnostic procedures not routinely available to the NHS. Such tests were more sensitive, and positive results had been obtained…"
>
> (M. Hale & Al-Seffar, 2008)

- One such non-NHS facility that offers immunological investigations for 'Aerotoxic Syndrome' is the Breakspear Hospital:

> "It may also be beneficial to measure antibodies to neuronal components, which provide an evaluation of the immunological problems that may have occurred and may be reversed with targeted treatment. A lymphocyte sensitivity test can evaluate whether or not there is a sensitivity (a negative immunological reaction), which has occurred in relation to organophosphates. This blood test assesses responses of cells, through measurement of calcium influx into the cell when it is being observed under confocal microscopy, and this can be assessed in relation to organophosphates in particular. If more calcium gets into the cell, it indicates that the cell membrane has become more permeable and is thereby responding adversely to organophosphates put in proximity to the cell.

> Following these evaluations, together with any others that may be specific to the crew member, a personal detoxification programme can be undertaken for clearing pollutants from the body."
>
> (Breakspear Medical Group Ltd, 2009)

- Antibodies to various "neuronal components" have been studied in patients with recognised neurological conditions (e.g. multiple sclerosis, inflammatory polyneuropathy, cerebral lupus, limbic encephalitis, epilepsy, paraneoplastic neurological disorders). However, their diagnostic value in patients considered to have 'Aerotoxic Syndrome' has not been validated.
- The "lymphocyte sensitivity" test described in the Breakspear newsletter is not a recognised or validated method for evaluating antigen-specific responses.
- The Breakspear laboratory also claims that:

> "Chemicals may also destroy or paralyze different enzymes involved in our natural detoxification systems, hence triggering hypersensitivity to minute amounts of chemical exposures…
>
> The clinician can be certain of the following diagnostic values by utilising a Comprehensive Immunotoxicology Panel:
>
> 1. The toxic chemicals or chemical groups that have evoked an immunotoxic response.
> 2. The specific amount of chemical antibodies detected.
> 3. Whether the resulting immunotoxic effects are primarily being expressed as immunosuppression or immuno-activation.
> 4. The degree of toxicity or immuno-injury sustained by the patient.
> 5. Recommendations for additional lab tests in order to rule out or clarify the patient's full immunotoxic condition or immunologic susceptibilities." (Breakspear Medical Group Ltd, 2010)

- These claims are not supported by evidence.

8.6 Appendix 6: Epidemiology Report: *A review of the epidemiological evidence for an Aerotoxic Syndrome related to aircraft cabin air contamination* (McLean, 2009).

- The Panel commissioned Dr David McLean of Massey University New Zealand to provide the following independent epidemiological report on the evidence for an aerotoxic syndrome related to aircraft cabin contamination.

8.6.1 Background

- Epidemiology is commonly defined as the study of the distribution and determinants of health-related states or events in specified populations, and the application of this study to the control of health problems (Last, 1995). Occupational epidemiology is the branch of epidemiology concerned with the study of human health risks related to exposures in the occupational environment. It is an exposure-oriented discipline in that in order to make any valid inferences about causality it is necessary to differentiate between exposed and non-exposed groups, and to conduct exposure-response analyses using the data generated from comparing disease rates in these groups. For this reason the standard of exposure assessment is central to the validity and informativeness of any occupational epidemiological research (Checkoway, Pearce, & Kriebel, 2004).
- Historically many occupational diseases have been identified first in case reports and case-series reviews by astute physicians, or by workers themselves, who associated illness with a particular exposure situation. In cases where the health outcome is rare (e.g. hepatic angiosarcoma or mesothelioma), or almost always arises from occupational exposure (e.g. pneumoconiosis), these types of studies have led to the confirmation of the relationship between workplace exposures and disease. However, most occupational diseases are not rare conditions confined only to the workplace, so determining the relative contributions of occupational and non-occupational risk factors becomes more of a challenge.
- Case reports and case-series reviews alone, therefore, are generally inadequate to confirm the relationship between workplace exposures and disease in those situations. In these circumstances more complete epidemiologic study designs that include definition or enumeration of the population at risk, complete ascertainment of cases in that population, estimation of the expected number of cases in the absence of exposure, comparison groups, and exposure assessments are required often complemented with findings from toxicological and/or animal experiments.
- In an ideal world an epidemiological investigation of possible hazards of work would begin with descriptive accounts of the distributions of exposures and various health outcomes in worker populations. This would involve determining the size and demographic features of the population at risk and the prevalence of the specific health outcomes in that population, comparing rates of

disease with those in unexposed reference populations, identifying the temporal sequence of case occurrence, and ultimately investigating formal hypotheses about potential causes using internal analyses comparing groups with different levels of exposure.

- In practice, however, perfect epidemiological studies do not exist and decisions often need to be made on the basis of the information that is available. Individual studies need to be assessed for the strength and precision of the effect estimates observed, and the strength and direction of possible biases including confounding, selection bias or information bias. In circumstances where the evidence is less than adequate, however, judgements still need to be made about the plausibility of the hypothesis and the evidence for the existence of the relevant exposures so that informed decisions can be made about the need for preventive efforts.

8.6.2 Review process

- A total of twelve published reports on various health conditions attributed to occupational exposure to smoke/fume incidents in airline staff were provided by Rumball Souter Floyd and Associates for this review. These included six case-series reviews (J. Burdon & A. Glanville, 2005; Coxon, 2002; A. Harper, 2005a, 2005b; Heuser, et al., 2005; Sarah MacKenzie Ross, 2008; Somers, 2005) and four cross-sectional questionnaire surveys, of which two were essentially duplicates (Cox & Michaelis, 2002; Michaelis, 2003; Whelan, et al., 2003; Winder, et al., 2002). We were also subsequently asked to include in this review the results of cohort studies of mortality and cancer incidence in aircrew, and were provided with three papers (Blettner, et al., 2003; Hammer, et al., 2009; Zeeb, et al., 2003).
- To complement the information provided in these studies a search was conducted on PubMed using search terms including “Aerotoxic Syndrome”, “aviation air quality”, “cabin air quality”, “tricresyl phosphate”, “jet engine oils”, “flight attendants”, “pilots”, “aircrew”, “exposure assessment” and “organophosphate-induced delayed polyneuropathy” to identify additional papers on either potential exposures occurring during smoke/fume incidents or health effects in aircrew. In addition, information was retrieved from websites including www.nap.edu/catalog/10238.html, www.ohrca.org, www.acer-coe.org and http://cot.food.gov.uk/pdfs/cotstatementbalpa200706. These searches identified a number of additional papers or reports on aircrew health and/or exposures in aircraft, and the total numbers of papers identified and included in this review is shown in Table 21 below:

Study type	***Number of references***
Health outcomes:	
Case-series reports	*6*
Questionnaire surveys	*3*
Cross-sectional surveys	*6*
Cohort studies	*7*
Case-control studies	*1*
Reviews	*6*
Exposures:	
Toxicological reviews	*5*
Laboratory simulations of pyrolysis	*2*
Sampling and analytical methodology	*3*
Reviews	2

Table 21: Publications and reports on health outcomes and exposures associated with cabin air quality incidents considered in this review.

- For this review I have evaluated the information available on exposures experienced by aircrew, the available epidemiological evidence on the overall health status of aircrew, and the specific epidemiological evidence for the existence of an aerotoxic syndrome. With regards to the evaluation of the epidemiological evidence I have used a standard set of categories (Institute of Medicine, 2004) to summarise my conclusions about the association between cabin air quality and aerotoxic syndrome, as outlined below:

Categories of Evidence Used in This Report

Sufficient evidence of a causal relationship
Evidence is sufficient to conclude that a causal relationship exists between the agent and the outcome. That is, the evidence fulfils the criteria for "sufficient evidence of an association" and, in addition, satisfies the following criteria: strength of association, biologic gradient, consistency of association, biologic plausibility and coherence, and temporally correct association.

Sufficient evidence of an association
Evidence is sufficient to conclude that there is an association. That is, an association between the agent and outcome has been observed in studies in which chance, bias, and confounding can be ruled out with reasonable confidence.

Limited or suggestive evidence of an association
Evidence is suggestive of an association between the agent and the outcome but is limited because chance, bias, and confounding cannot be ruled out with confidence.

Inadequate or insufficient evidence to determine whether an association exists
The available studies are of insufficient quality, consistency, or statistical power to permit a conclusion regarding the presence of an association. Alternatively, no studies exist that examine the relationship.

Table 22: Levels of evidence used in the epidemiological report.

8.6.3 Potential exposures

- It is well recognised that aircrew experience a number of potentially hazardous occupational exposures. There are a range of physiological stressors that affect both cabin crew and passengers, including fatigue, cramped space and disrupted circadian rhythms, as well as physical hazards including noise, cosmic radiation and electromagnetic fields. There are also a number of potentially significant chemical exposures that occur routinely during normal flight operations or less frequently under abnormal operating conditions, and these have been presented in tabular form, as reproduced in Table 23 below (J.D. Spengler & Wilson, 2003).

Exposures related to normal operations	Exposures related to incidents
Ozone	Carbon monoxide
Carbon dioxide	Smoke, fumes, mists, vapours from leaks of engine oils, hydraulic fluids, and de-icing fluids and their combustion products
Temperature	
Relative humidity	
Off-gassing from interior material and cleaning agents	
Bioeffluents	
Personal-care products	
Allergens	
Infectious or inflammatory agents	
Ambient airport air	
Cabin pressure/partial pressure of oxygen	
Pesticides	
Jet exhaust fumes (runway)	
Alcohol	

Table 23: Exposure sources relevant to aircraft cabin air quality (J.D. Spengler & Wilson, 2003)

- Of particular relevance to this review are the potential exposures from smoke/fume incidents that occur during abnormal operating conditions when bleed air taken from the engines or an auxiliary power unit for the aircraft's environmental control system is contaminated with hydraulic fluids, synthetic jet oils, de-icing fluids and/or their thermal degradation products. Such incidents are thought to occur primarily due to oil seal failures, but also possibly from oil pooled in compressor housings (J.D. Spengler & Wilson, 2003). The volatile or semi-volatile organic compounds produced in these incidents are also thought to condense inside cabin air supply ducts (van Netten & Leung, 2001). Although there is disagreement about the frequency of these events, and the suggestion that some aircraft and engine types are more susceptible to smoke/fume incidents, they are generally considered to be relatively rare events with the UK Committee on Toxicity report (Committee on toxicity of chemicals in food consumer products and the environment, 2007k) estimating they occur in 0.05% of flights (sectors).
- Although there are no published reports characterising the precise exposures occurring during abnormal smoke/fume incidents, there are many compounds considered likely to be present. For example, the jet engine oils and other fluids used may themselves enter the aircraft cabin air, and

these are known to contain a variety of potentially toxic constituents including triaryl phosphates present in jet oils as anti- wear additives. The thermal degradation of jet engine oils and the other fluids is known to form a range of volatile and semi-volatile organic compounds including formaldehyde and TCP isomers, in addition to CO, CO_2 and ozone (Committee on toxicity of chemicals in food consumer products and the environment, 2007k).

- Among the known toxic effects of exposure to triaryl phosphates is a condition known as organophosphate-induced delayed polyneuropathy (OPIDP), in which there is distal degeneration of some axons of both the peripheral and central nervous systems, and epidemics of this neuropathy have occurred in the past due to accidental ingestion of tri-*o*-cresyl phosphate (Lotti & Moretto, 2005). The delayed neurotoxic potential of various triaryl phosphates has been tested in vitro, and it has been shown that the potency of the different ortho-isomers of TCP varies significantly with the mono-*o*-cresyl isomers being at least twice that of the tri-*o*-cresyl monomer (Sprague & Castles, 1985). The manufacturers of jet engine lubricants have published reports indicating that TCP is present at concentrations below 3% in their products, and that their modern manufacturing practices have also produced "low toxicity" TCPs with limited neurotoxic potential (Daughtrey, et al., 1996); (Craig & Barth, 1999; Mackerer, et al., 1999; Weiner & Jortner, 1999) when compared with the more toxic "conventional" TCPs.
- In a recent study of jet engine oils the tri-*o*-cresyl phosphate isomer was found to be present in insignificant quantities, while the mono-*o*-cresyl isomers were found to be the predominant ortho isomers present (De Nola, et al., 2008). Airborne TCP from jet engine oil has been identified in a mechanical workshop from aircraft components operating on a test bench (Solbu, et al., 2007), and in an experiment investigating pyrolysis products at 525 degrees C (van Netten & Leung, 2000). It has also been hypothesised that thermal degradation could result in the formation of another neurotoxin, TMPP, from the trimethylpropane esters and TCPs contained in jet engine oils, however this was not observed under experimental conditions (van Netten & Leung, 2001). Unpublished reports have confirmed the presence of quantifiable levels of unidentified TCP isomers in cockpit/cabin air in Australian Defence Force aircraft (De Nola, et al., 2008) and in air filters and wall swabs from B757 aircraft (Committee on toxicity of chemicals in food consumer products and the environment, 2007k), and the results of a survey conducted in the US for the FAA are due for release in the near future (Personal communication, Laurel Kincl, Center for Research in Environmental Epidemiology (CREAL) Barcelona, Spain).
- The UK Committee on Toxicity in its Statement on the review of the cabin air environment, ill health in aircraft crews and the possible relationship to smoke/fume events in aircraft concluded that, in the absence of clear exposure data, there had been an undue emphasis placed on the triaryl phosphates as possible causes of symptoms in aircraft cabin crew (Committee on toxicity of chemicals in food consumer products and the environment, 2007k). They noted that a number of the symptoms described could equally be attributed to other exposures such as CO. Similarly the US National Academy of Sciences considered exposure to ozone to be of higher concern, and CO exposure to be of a similar level of concern to the hydraulic fluids or engine oils or their thermal

decomposition products as contaminants of aircraft cabin air (The Airliner Cabin Environment Report Response Team, 2002).

8.6.4 Epidemiological investigations of health outcomes in aircraft crew

- Epidemiological investigations on health outcomes in flight attendants and cabin crew have evaluated risks associated with a number of different aspects of working in the airline industry. These can be divided into two distinct types of studies that examine different exposure scenarios; those examining risks associated with the exposures present during **routine operating conditions**, and others attempting to evaluate chronic effects associated with exposures present during the more infrequent **abnormal smoke/fume incidents**. While the studies of risks associated with the cumulative effects of normal operating conditions are outside the scope of this review, the conclusions reported in review articles or individual studies of good quality are pertinent to an appreciation of the overall health status of flight attendants and cabin crew.

8.6.4.1 General health and comfort

- The general health and comfort of Swedish flight attendants and cabin crew in relation to cabin air quality has been investigated in a series of studies, both before and after smoking on flights was banned (Lindgren, Andersson, & Norback, 2006; Lindgren & Norback, 2002, 2005; Lindgren, et al., 2000; Wieslander, Lindgren, Norback, & Venge, 2000). A review of relevant studies has also been conducted (N. L. Nagda & Koontz, 2003). Increased prevalence of symptoms including fatigue, dryness or irritation of eyes, face and hands, and nasal and throat symptoms were observed, with distinct differences in prevalence observed in comparisons with office workers and also between staff employed on different aircraft types. The exposure implicated in these studies was low air humidity and, in the earlier studies, environmental tobacco smoke.

8.6.4.2 Respiratory symptoms

- Self reported respiratory symptoms in flight attendants have also been investigated in a US study that had as its primary focus reproductive health (Whelan, et al., 2003). Female teachers were used as a comparison group in the respiratory health study, on the assumption that both groups share common workplace exposure characteristics with regards to occupant density and ventilation efficiency. Data from national surveys of other female occupational groups were also presented for comparison. Overall, both flight attendants and teachers reported a significantly higher prevalence of work-related eye, nose and throat symptoms, wheezing, chest illness during the past three years, and five or more episodes of cold or flu in the past year than other working women, although the prevalence of upper respiratory symptoms were comparable to those observed in workers in other indoor office environments. Teachers were significantly less likely than flight attendants to have had nose symptoms and chest illness during the past three years, but more likely to have ever been diagnosed with asthma.

- Respiratory infections are possible causes of some of these symptoms in both groups given occupant density in both environments, although there is little evidence of increased transmission of respiratory infections in aircraft cabins (Leder & Newman, 2005); (Mangili & Gendreau, 2005). The cabin environment and possible contaminants, including cabin pressure, low relative humidity, ozone, CO_2 and constituents of engine lubricating oils, hydraulic fluids and their thermal decomposition by-products, and physiological stressors such as fatigue and disrupted circadian rhythms, were all suggested as possible causes in this US study although no internal analyses comparing disease rates in groups categorised according to any exposure were conducted.

8.6.4.3 Mortality and cancer incidence

- Overall mortality and cancer mortality has been examined in pilots and other cockpit or cabin crew using standard cohort study designs, often with a particular focus on cumulative exposure to cosmic ionising radiation (Blettner, et al., 1998; Blettner, et al., 2003; Zeeb, et al., 2003). The epidemiological evidence on overall mortality and cancer mortality in aircrew has recently been reviewed (Hammer, et al., 2009). The most striking findings of these studies have been a strong "healthy worker effect" for both all-cause mortality and all-cancer mortality observed in most studies (although this is the norm when working cohorts are compared with the general population), and the observation of significantly increased risks of mortality from aircraft accidents and HIV/AIDS.
- Where cancer incidence has been studied, significantly elevated risk of melanoma (Grayson & Lyons, 1996); (Pukkala, et al., 1995), as well as consistently, albeit moderately, elevated risk of female breast cancer (Pukkala, et al., 1995), prostate cancer (Band, et al., 1996; Band, Spinelli, Ng, Moody, & Gallagher, 1990; Pukkala, et al., 2002(Band, et al., 1996) and cancers of the central nervous system (Band, et al., 1990; (Blettner, et al., 2003) have been observed. The melanoma risk has generally been attributed to non-occupational exposure to ultraviolet radiation during layovers and the cancers of the central nervous system have been linked to exposure to radiofrequency/microwave radiation and socioeconomic status in a nested case-control study, but there is no clear evidence of potential causes for the excess of prostate or female breast cancers (Grayson & Lyons, 1996).

8.6.4.4 Aerotoxic syndrome

- A total of ten papers (or 9 if the duplicate from Harper is excluded) are relevant to the symptoms reported to be associated with smoke/fume incidents in cabin air, for which the term 'Aerotoxic Syndrome' has been proposed (Winder, et al., 2002). The range of health outcomes included in this syndrome is broad, and involve numerous body systems as reproduced below from Winder and Balouet:

- Neurotoxic symptoms: blurred or tunnel vision, nystagmus, disorientation, shaking and tremors, loss of balance and vertigo, seizures, loss of consciousness, paraesthesias.
- Neuropsychological symptoms: memory impairment, light-headedness, dizziness, confusion and feeling intoxicated, forgetfulness, lack of co- ordination, severe headaches, sleep disorders.
- Gastro-intestinal symptoms: nausea, vomiting, salivation, and diarrhoea.
- Respiratory symptoms: cough, breathing difficulties (shortness of breath), tightness in chest, respiratory failure requiring oxygen, and susceptibility to upper respiratory tract infections.
- Skin symptoms: skin itching and rashes, skin blisters (on uncovered body parts), hair loss.
- Cardiovascular symptoms: chest pain, increased heart rate and palpitations.
- Irritation of eyes, nose and upper airways.
- Sensitivity: signs of immunosuppression, food and alcohol intolerances, chemical sensitivity leading to acquired or multiple chemical sensitivity.
- General: weakness and fatigue (leading to chronic fatigue), exhaustion, hot flashes, joint pain, muscle weakness and pain.

- As most of the studies were case-series reviews there has been no attempt to enumerate the population at risk, or to estimate the prevalence of the condition within that population. Three of the studies were cross-sectional questionnaire surveys in which response rates were generally low, and in one study (Winder, et al., 2002) there was no clear sampling frame. Where statistical analyses were performed they were largely descriptive, and only one study (Sarah MacKenzie Ross, 2008) included an external reference group for comparison. An attempt to evaluate the extent of exposure relevant to the health outcomes was also made in only one study (Sarah MacKenzie Ross, 2008), with lifetime flying hours used as a surrogate for the likely extent of exposure to smoke/fume incidents. In the other two cross-sectional studies (Cox & Michaelis, 2002) information on flying history was apparently recorded but not used for subsequent analyses to evaluate associations between dose and the prevalence of symptoms (Michaelis, 2003). The relevant studies are presented in Table 24 below, with the study type, outcome measures used, symptoms observed and the strengths and limitations of each study noted.
- One of the aerotoxic syndrome case-series review papers provided for this epidemiological review described respiratory function test abnormalities and neurocognitive symptoms in a sample of ten flight attendants and four pilots referred to respiratory physicians (J. Burdon & A. Glanville, 2005). Eight of the 14 subjects reported having high smoke/fume dose exposure episodes that provoked symptoms of breathlessness and cough, and all experienced a recurrence of symptoms when they returned to duties. Although follow-up spirometry was found to be normal in most subjects, all had evidence of permanent injury to the respiratory system as indicated by various respiratory function tests, chest X-rays, CT scans and lung biopsy. The authors acknowledged the limitations of their study with respect to small sample size and the time that had elapsed since exposure, but regarded their findings as sentinel events indicative of a strong association between smoke/fume event

exposures and serious respiratory effects. While this study presents strong data for respiratory effects in a sample of airline staff, as a case-series review it is unable to provide strong evidence for an association between smoke/fume events and these effects for the reasons discussed previously that are inherent in this type of study.

- Similarly, three of the studies described neuropsychological test abnormalities in aircrew, with all finding deficits (Coxon, 2002; Heuser, et al., 2005; Sarah MacKenzie Ross, 2008). As in the study of respiratory symptoms these studies were all conducted in small samples, and only the study by Ross included an unexposed control group plus proxy measures of exposure. While these studies show deficits in the study participants, for all the study limitations mentioned previously they together provide insufficient evidence to determine whether a relationship exists.

Authors and Year	***Title***	***Study type***	***Outcome measurement***	***Symptoms observed***	***Study Strengths/Weaknesses***
Ross SM, 2008.	*Cognitive function following exposure to contaminated air on commercial aircraft: a case series of 27 pilots seen for clinical purposes.*	*Case-series.*	*Neuropsychological tests, clinical interview, psychometric assessment.*	*Significant correlations between total number of years flying and lowered scores on picture arrangement, Stroop test of mental flexibility, the trails B test of mental flexibility and test of verbal memory. Significant correlations between total number of hours flying and lowered scores on picture arrangement, semantic fluency, the trails B test of mental flexibility and three different tests of verbal memory.*	*Sample size 27 pilots. No exposure data, but lifetime flying hours used as proxy for exposure, as was time on specific aircraft BAe146 and Boeing 757. All participants asked about, and reported, "fume" incidents. Group from another study used as control group, matched well on age, gender and years of education, but level of intelligence higher in pilots.*
Winder C, Fonteyn P, Balouet J-C, 2002.	*Aerotoxic syndrome: a descriptive epidemiological survey of aircrew exposed to in-cabin airborne contaminants.*	*Cross-sectional questionnaire survey.*	*Self-reported symptoms.*	*Eye, skin and respiratory system irritation. Gastrointestinal symptoms. Neuropsychological symptoms.*	*No clear sampling frame, and no advertising of survey was done. All respondents were volunteers. Sample size 50 in total, 70% cabin crew and 30% flight crew. No exposure estimates. Respondents (88%) reported that symptoms occurred after fume events.*
Michaelis S, 2003.	*A survey of health symptoms in BALPA Boeing 757 pilots.*	*Cross-sectional questionnaire survey.*	*Health survey seeking answer to question "have you experienced any of the following symptoms during your work pattern" for 19 symptoms.*	*Irritation of eyes, nose throat (37%). Headaches, lightheadedness, dizziness (33%). Fatigue, weakness, decreased performance (30%). General increase in feeling unwell (27%). Concentration difficulties, confusion (21%). Diarrhoea (16%). Nausea, vomiting, gastrointestinal problems (15%). numbness (head, limbs, lips, fingers) (12%). short term memory impairment (11%). Joint pain, muscle weakness (9%).*	*Low response rate given sample size of 106, out of a survey population of 600 members of British Airline Pilots Association flying Boeing 737, 757 and Airbus A320 from one airline. From questionnaire responses flying history was recorded, as were numbers of smoke or fume events experienced. No internal analyses relating dose to prevalence of symptoms. No reference group.*
Harper A, 2005.	*Illness related to cabin air: A survey of symptoms and treatment among commercial pilots and cabin crew.*	*Case series.*	*Descriptive statements made by respondents, and reported comments from their doctors?*	*Diverse diagnoses reported.*	*Sample size 60, 39 pilots and 19 flight attendants. No information on response rate given. No standard survey instrument reported. Participants asked to identify fume events, when during flights they occurred, and year of occurrence. No internal analyses relating dose to prevalence of symptoms. No reference group.*

Authors and Year	*Title*	*Study type*	*Outcome measurement*	*Symptoms observed*	*Study Strengths/Weaknesses*
Heuser G, Aguilera O, Heuser S, Gordon R, 2005.	*Clinical evaluation of flight attendants after exposure to fumes in cabin air.*	*Case-series.*	*Physical examination, neuropsychological examination, Positron Emission Tomography (PET) functional brain scan.*	*Toxic encephalopathy, learning difficulties (general and in mathematics), reading disorders, disturbances in smell and taste.*	*Sample size 26 flight attendants. No exposure data. No internal analyses relating dose to prevalence of symptoms. No reference group.*
Cox L, Michaelis S, 2002.	*A survey of health symptoms in BAe146 aircrew.*	*Cross-sectional questionnaire survey.*	*Questionnaire asking - "do you experience any of the following symptoms during your work pattern".*	*Similar to study by Michaelis S, 2003.*	*Sample size 21, 90% pilots, 10% flight attendants. Sampling base not known, response rate not calculated. Data on years spent flying BAe146 recorded, but not used in analyses. No internal analyses relating dose to prevalence of symptoms. No reference group.*
Burdon J, Glanville A, 2005.	*Lung injury following hydrocarbon inhalation in BAe146 aircrew.*	*Case-series.*	*Spirometry, pulmonary diffusing capacity, arterial blood gas analysis, chest X-rays and CT scans.*	*In all cases "Injury to the respiratory system had been sustained". Otherwise symptoms not described.*	*Sample size 10 Flight attendants, 4 pilots, referred to respiratory physicians. No exposure data, but 8 of the 14 recalled discrete high dose fume exposure episodes. No internal analyses relating dose to prevalence of symptoms. No reference group.*
Coxon L, 2002.	*Neuropsychological assessment of a group of BAe146 aircraft crew members exposed to jet engine oil emissions.*	*Case-series.*	*Neuropsychological test batteries.*	*Deficits in a range of neuropsychological tests observed.*	*Sample size 8 aircrew referred by GPs. No exposure data. No internal analyses relating dose to prevalence of symptoms. No reference group.*
Somers M, 2005.	*Assessing over thirty flight crew who have presented as a result of being unwell after exposure to fumes in the BAe146 jets.*	*Case-series.*	*23 symptoms reported, and 2 questions re improvement away from work and length of recovery period.*	*Self-reported symptoms.*	*Sample size 38 patients. No exposure data. No internal analyses relating dose to prevalence of symptoms. No reference group.*

Table 24: Studies of symptoms in aircraft cockpit and cabin crew associated with aircraft smoke/fume incidents.

8.6.5 Evaluation of the epidemiological evidence

- From the studies of aircrew that have that have used more complete epidemiological study design, including cross-sectional surveys using reference populations, and historical cohort and case-control studies, it is clear that aircrew do experience an elevated prevalence of various symptoms related to some aspect of routine flight operations. These include symptoms such as fatigue, dryness or irritation of eyes, face and hands, and nasal and throat symptoms, and a significantly higher prevalence of work-related eye, nose and throat symptoms, wheezing, chest illness during the past three years, and five or more episodes of cold or flu in the past year. The cabin environment and possible contaminants, including cabin pressure, low relative humidity, ozone, carbon dioxide and constituents of engine lubricating oils, hydraulic fluids and their thermal decomposition by-products, and physiological stressors such as fatigue and disrupted circadian rhythms, are all plausible causes of this increased risk but no objective measures of exposure were included in these studies.
- In the mortality and cancer incidence studies, while a strong "healthy worker effect" has been observed where comparisons were made with the general population, there is clearly increased risk of mortality from aircraft accidents and HIV/AIDS, significantly elevated risk of melanoma, and significantly albeit moderately increased risk of female breast, prostate and central nervous system cancers. The elevated risks of HIV/AIDS and melanoma have both been attributed to lifestyle exposures, while the causes of the other cancers have not been confirmed. Although exposures such as cosmic radiation and electromagnetic radiation have been evaluated as possible causes of these cancers, internal analyses have largely been based on proxy measures of exposure such as "block hours" or annual radiation doses calculated from information on factors such as flight hours, aircraft types, and flight routes and schedules.
- The epidemiological evidence for an aerotoxic syndrome remains limited for several reasons. The condition itself is as yet poorly defined with a broad and non-specific range of symptoms reported, each of which could have a number of causes, and the evidence of exposure is limited. Most of the reports are from case-series reviews or limited cross-sectional studies, and chance, bias, and confounding cannot be ruled out with any confidence.

8.6.6 Conclusions

- Although the potential for the contamination of aircraft cabin air during routine operation is recognised, there has been relatively limited study of cabin air quality reported in the literature. There remains a complete lack of comprehensive exposure data and characterisation of the environment in aircraft during smoke/fume incidents. There is clear evidence of increased levels of a range of potentially hazardous contaminants during routine operating conditions, including ozone when flying at high altitude, a range of volatile and semi-volatile organic compounds and carbon dioxide. There are reports of the presence of traces of jet engine oil, hydraulic fluid and triaryl phosphates in aircraft tested during routine operating conditions or after smoke/fume incidents, but

no published studies of environmental measurements conducted during smoke/fume incidents. Laboratory simulations and tests at ground level have, however, shown that contaminants generated during these conditions include traces of the jet engine oils and hydraulic fluids themselves and the products of their thermal degradation including CO2 and CO, volatile and semi-volatile organic compounds and TCP isomers. No evidence is available on the levels of personal exposure of aircrew during smoke/fume incidents.

- There is consistent evidence that aircrew experience a variety of health effects, both acute and chronic, that are associated with work in the airline industry. This evidence has come from well-designed cohort studies or cross-sectional studies with good response rates and comparison groups, although at best surrogate measures of exposure, and using our review categories this evidence would be categorised as **Sufficient Evidence of an Association**. The evidence for the existence of an aerotoxic syndrome related to smoke/fume events is, however, still based almost entirely on case-series reviews and remains anecdotal, and is categorised as **Inadequate or Insufficient Evidence to Determine Whether an Association Exists**. It should be noted that this is based on the lack of adequately designed studies rather than on the presence of evidence to the contrary.

- The existence of an aerotoxic syndrome associated with cabin air quality during relatively rare smoke/fume incidents is likely to prove difficult to confirm using standard observational epidemiological methods. Proxy measures of exposure such as duration of employment in the airline industry, or even more refined estimates of contact time such as block hours, are useful for studying the effects of routine exposures in the industry but provide poor measures of exposure to what are infrequent and apparently random episodes of smoke/fume incidents. Research with an extended follow-up, and using either a biomarker of past exposure or extensive sampling of the levels of exposure to the contaminants of interest from smoke/fume incidents, would be required to discern any chronic effects associated with these exposures. It would also be possible to conduct cross-sectional studies for acute effects, provided that the appropriate tests such as spirometry and neurological testing could be performed on affected staff immediately after a smoke/fume event. This would allow for comparisons of results from groups without exposure, and for subsequent measurements to determine whether the effects are reversible.
- Circumstances such as this in which there is suggestive evidence of the potential for serious harm to result from an occupational exposure always generate debate about whether, how, and when to intervene. In the case of cabin air smoke/fume incidents there is the added imperative of the safety of passenger aircraft where pilots and other cockpit crew may be impaired. Even in the absence of definitive data on the exposures that occur during smoke/fume incidents, the prudent approach would be to take whatever action is necessary to prevent these incidents through engineering means. The products of thermal degradation of engine oils and hydraulic and de-icing fluids such as CO and VOCs that are known to be generated when bleed air is contaminated are sufficient to cause concern, and assurances about “low toxicity” TCP in jet engine oils are not reassuring. An extensive environmental monitoring programme conducted during smoke/fume events to clarify whether the exposures of concern exist is necessary.

8.7 Appendix 7: Table of defects reported to CASA 27 September 2002 to 5 October 2006

Item Number	Date Report Lodged	Corrective Action By Airline
Reports lodged between 27 Sep and 31 Dec 2002		
1	05 November 2002	Engine changed
2	05 November 2002	Maintenance action carried out
3	25 November 2002	Engine changed
4	25 November 2002	APU Cooling fan replaced
5	27 November 2002	*MEL applied
6	27 November 2002	Engine changed
7	27 November 2002	Engine changed
8	27 November 2002	APU replaced
9	03 December 2002	Engine changed
10	03 December 2002	Seal changed
11	03 December 2002	Maintenance action carried out
12	03 December 2002	APU replaced
13	03 December 2002	APU replaced
14	03 December 2002	Maintenance action carried out
15	03 December 2002	Engine changed
16	03 December 2002	Engine changed
17	04 December 2002	Seal and face plate replaced
18	04 December 2002	Seal and face plate replaced
19	04 December 2002	Engine changed
20	04 December 2002	Inspected
21	04 December 2002	Engine changed
22	04 December 2002	Maintenance action carried out
23	04 December 2002	Maintenance action carried out
24	04 December 2002	Engine changed
25	05 December 2002	Engine changed
26	06 December 2002	Engine changed
27	06 December 2002	APU Cooling fan replaced
28	16 December 2002	APU Cooling fan replaced
29	16 December 2002	APU oil cooler changed
30	16 December 2002	APU Cooling fan replaced
31	16 December 2002	APU Seal changed
32	16 December 2002	Engine changed

Item Number	Date Report Lodged	Corrective Action By Airline
33	16 December 2002	Maintenance action carried out
34	16 December 2002	APU Starter motor replaced
35	17 December 2002	Inspected
36	17 December 2002	Engine changed
37	17 December 2002	Engine changed
38	17 December 2002	Engine changed
39	17 December 2002	*MEL applied
40	17 December 2002	Inspected
41	17 December 2002	APU Cooling fan replaced
42	17 December 2002	Engine changed
43	17 December 2002	Inspected
44	17 December 2002	Engine changed
Year 2003 – Reports Lodged		
1	22 January 2003	APU Cooling fan replaced
2	23 January 2003	Engine changed
3	23 January 2003	Engine changed
4	23 January 2003	APU Cooling fan replaced
5	03 January 2003	Inspected
6	04 January 2003	Engine changed
7	08 April 2003	Engine changed
8	01 May 2003	Engine changed
9	01 May 2003	Engine changed
10	08 May 2003	*MEL applied
11	26 May 2003	Engine changed
12	27 May 2003	Inspected
13	04 June 2003	Engine Seal replaced
14	11 June 2003	Engine changed
15	23 June 2003	Engine changed
16	24 June 2003	Seal and face plate replaced
17	25 August 2003	Maintenance action carried out
18	26 August 2003	Engine changed
19	29 August 2003	*MEL applied
20	12 September 2003	Seal changed
21	09 October 2003	APU Cooling fan replaced
22	31 October 2003	Engine changed
23	20 November 2003	Seal changed
24	29 December 2003	APU replaced

Item Number	Date Report Lodged	Corrective Action By Airline
Year 2004 – Reports Lodged		
1	20 January 2004	Engine changed
2	30 January 2004	Engine changed
3	18 February 2004	APU replaced
4	24 May 2004	Engine changed
5	25 November 2004	APU replaced
Year 2005 – Reports Lodged		
1	14 March 2005	Engine replaced
2	12 April 2005	APU replaced
3	12 May 2005	Seal and face plate replaced
4	18 May 2005	Seal changed
5	16 November 2005	APU replaced
Year 2006 – Reports Lodged up to 5 October 2006		
1	03 October 2006	Inspection carried out but defect not confirmed
2	03 October 2006	Inspection carried out but defect not confirmed
3	03 October 2006	Inspection carried out but defect not confirmed
4	03 October 2006	Seal changed
5	03 October 2006	Engine replaced
6	03 October 2006	Maintenance action carried out
7	03 October 2006	Seal and face plate replaced
8	03 October 2006	Inspection carried out but defect not confirmed
9	03 October 2006	Inspection carried out but defect not confirmed
10	03 October 2006	Inspection carried out but defect not confirmed
11	03 October 2006	APU replaced
12	03 October 2006	Maintenance action carried out

"* MEL" refers to action allowed per CASA Airworthiness Directive AD/BAe146/86 to continue operations for a limited period with the problematic component isolated.

Table 25 Reports relating to air contamination in BAe146 aircraft lodged with CASA between 27 September 2002 to 5 October 2006 – adapted from (O'Brien & Campbell, 2007). Data supplied in answer to a Senate question posed by Senator O'Brien. Answered by Senator Ian Campbell, Minister for Transport and Regional Services.

8.8 Appendix 8: Recommended solutions made by former pilot Susan Michaelis in her submission to the Panel

"Solutions: I believe that the CASA EPAAQ must recommend the following and must ensure the aviation industry, regulators and Governments do not just ignore these as they have done in all cases in the past or paid lip service to them and established more research that goes on forever almost, and gives the answers the industry wants. This is no longer acceptable.

Recommendations include but are not limited to:

- Full scale epidemiological survey with aviation regulator providing required contact details;
- Recognition that there is a pattern of ill health more than likely caused by exposure to oil fumes and hydraulic fluids.
- Research into inhalation toxicity of heated engine oils, TCP including the MOCP & DOCP isomers & synergistic effects.
- Recognition that airworthiness regulation 25.831b is not met as long as permanent monitoring equipment is not mandated to be fitted
- Requirement to research and fit bleed air filtration and air cleaning technology
- Development and use of less toxic oils
- Bleed free technology is preferred
- Enhancement of engine oil seals so as to vastly reduce leakage of engine oil into the air supply
- Adhere to the EU precautionary principle
- Undertake a review of failed or delayed legal, insurance claims or chronic ill health with loss of career/pilot licence;
- Establish a compensation fund for those who demonstrate chronic ill health (or those that have passed away) related to contaminated air based on the balance of probabilities
- Ensure all aviation legislation related to cabin air contamination is adhered to including reporting, investigation of defects, airworthiness….
- Educate crews on the possible effects of contaminated air and the need to report these events"

(Michaelis, 2009a)

8.9 Appendix 9 FAA/ASHRAE aircraft cabin air monitoring programme – list of proposed analytes

CONTINUOUS MEASUREMENTS

Ozone
Carbon monoxide
Respirable particles
Relative humidity
Temperature
Pressure
Sound level
Motion

INTEGRATED AIR SAMPLE ANALYTES

Volatile Organic Compounds
Acetaldehyde (DNPH)
Acetone (DNPH)
Formaldehyde (DNPH)
1,1,1-Trichloroethane
1,3-Dichloropropane (cis+trans)
1,4-Dichlorobenzene
Carbon Tetrachloride
Chloroform
Methylene Chloride
Tetrachloroethen
Trichloroethene
2,2,4-Trimethylpentane
2,3-Dimethylpentane
2-Methylhexane
2-Methylpentane
3-Methylhexane
1,3-Butadiene
Benzene
Ethylbenzene
Toluene
M&p-Xylene
o-Xylene
Methycyclohexane
Methy tert-Butyl Ether
Styrene

Phthalates
Diethyl phthalate
Dibutyl phthalate
Butyl benzyl phthalate
di-2-ehtylhexyl phthalate

Tri-cresyl Phosphates (TCPs)
T-o-CP
T-m-CP
T-p-CP

Flame retardants
Brominated diphenyl ether (BDE) 47
BDE 99
BDE 100
BDE 183
BDE 209
Tris(1,3-diCl-isopropyl)phosphate (TDCPP)
Tris(2-Cl-ethyl)phosphate
Tris(2,3-diBr-propyl) phosphate
tetraBromo bisphenol A (TBBPA)
Hexabromocyclododecane (HBCD)
2-ehtylhexyl-tetraBr-benzoate (EHTBB, TBB)
Bis-(2-ehtylhexyl)-tetraBr-phthalate (BEHTBP, TBPH)
Triphenyl phosphate (TPP)

Other Semi-VOCs
Naphthalaene
Biphenyl
Acenaphthalene
Acenaphthylene
Fluorene
Phenanthrene
Anthracene
Fluoranthene
Pyrene
Benz(a)anthracene
Chrysene
Benzo(b)fluoranthene
Benzo(k)fluoranthene
Benzo(e)pyrene
Benzo(a)pyrene
Indo(1,2,3-cd_pyrene
Dibenz(ah)anthracene
Benzo(ghi)perylene
Sumithrin
Cis-permethrine
Trans-permethrine
2-butoxy ethanol
Limonene
Phenethylalcohol
Benzyl acetate
Hexyl cinnemal
1,3,4,6,7,8-hexahydro-4,6,6,7,8,8-Hexamethylcyclopenta-γ-2-benzopyran and related isomers) HHCB
6-acetyl-1,1,2,4,4,7-Hexamethyltetraline (AHTN)
Tris (2-chloroethyl)phosphate
Tris (dichloropropyl)phosphate
PCB 52
4,4-methylene-2-chloroaniline
Carvone
Limonene oxide

Figure 2 Analytes (FAA/AHSRAE project)

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