THE UNIVERSITY OF
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# Aerotoxic Syndrome

by

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A thesis submitted in fulfilment of the requirements for the degree of Master of Public Health (by Research)
The Faculty of Medicine
The University of New South Wales

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### 0.1.1 Thesis Cover Sheet

**PLEASE TYPE** **THE UNIVERSITY OF NEW SOUTH WALES**
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Surname or Family name: **Winder** First name: **Chris** Other name/s: -
Abbreviation for degree as given in the University calendar: **Master of Public Health (by research)**
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Title: **Aerotoxic Syndrome**

**Abstract**

From 1992, adverse health symptoms were reported in Australian pilots and flight attendants following "fume events" or "exposure events" of jet oil leaking from the airplane engines into the bleed air system, environmental control system, auxiliary power unit and thence the flight deck and passenger cabin. Examination of various documents circulating within the Australian industry indicates that there was considerable effort expended to minimise this issue, with a formulaic approach of denial, bluster and misinformation. There are a variety of reasons for this, including commercial pressures, fatalism about long standing and apparently insurmountable engineering problems, operational procedures that focus keeping aircraft flying and a culture within the industry to minimise health and safety risks. It is concluded that these actions breach the general duty of care mandated in OHS legislation. Reporting of such incidents appears low, with an escalating chain of underreporting, from exposed personnel to airline operators and to regulators. Further, few events reported to regulators are investigated. This project uses a mixed methods approach to study this problem. In 1999, an initial analysis of seven case studies from flight crew and flight attendants in four airlines operating in four countries and in three airplane models, noted that the reported symptoms had a degree of consistency. At the time, these symptoms were given the descriptive name "Aerotoxic syndrome". From review of the ingredients in aviation oils and hydraulics, it is apparent that some contain toxic ingredients. A detailed study of the ingredients in one proprietary jet oil in widespread use indicated that it contained at least two toxic ingredients, one neurotoxic and the other a sensitiser. Manufacturer product information such as the Material Safety Data Base (MSDS) understated the risk of the product. Monitoring studies of air quality on airplanes are generally favourable, although most are sufficiently flawed on methodological inadequacies to render their conclusions invalid, few monitor for the hazardous chemicals of concern, and none have been conducted during a fume event. The initial study of seven cases was followed up by a second study in 2001, of fifty pilots and flight attendants. A range of general, neurological, neuropsychological, respiratory, gastrointestinal, reproductive and irritancy symptoms were reported. There was sufficient commonality in reported symptoms to conclude a symptom basis for Aerotoxic syndrome. This is further supported by application of the Bradford Hill criteria for causation to the effects reported in this survey, and by later studies published in the literature. Whether or not Aerotoxic syndrome exists as a real condition remains controversial. The term certainly polarises opinion and this may not be helpful for those affected individuals seeking assistance. At best, the condition can be considered a form of Multiple Chemical Sensitivity (MCS) associated with fume events when exposed by working in the aviation industry.



Chris Winder

**30 October 2010**

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## 0.3 Acknowledgements

I would like to acknowledge the contributions from a number of organisations and individuals in the conduct of this research project, including:

- My supervisor, Prof Debbie Black, Faculty of Health Sciences, the University of Sydney; and my co-supervisor, Prof Ann Williamson, of the UNSW School of Aviation, and research support staff of the UNSW School of Public Health and Community Medicine.
- My friends and colleagues in the UNSW School of Risk and Safety Sciences, including Dr Anne-Marie Makin, Dr Christian Khalil, Dr Amanda Hayes, Prof John Wilson, Dr John Frith, Mr Michael Tooma, and others.
- In 1999, the then UNSW Faculty of Science and Technology provided a grant of $10,000 to assist in the conduct of the descriptive epidemiology study outlined in Chapter 6.
- My friend and colleague, Dr Jean-Christophe Balouet of Environment International, in France.
- My friends and colleagues working tirelessly in this area, including Dr Andrew Harper, Prof Christiaan van Netten, Prof Clem Furlong, Dr Moira Somers, former Australian Senator the Reverend John Woodley, Dr Mark Donohoe, Captain Tristain Lorraine, Captain Susan Michaelis, Ms Judy Cullinane, Ms Alysia Chew, Ms Joanne Turner, Ms Petra Stanley, Ms Julia Tobin and others.
- All the flying crew and cabin crew who gave freely of their time in the two surveys that have been conducted.
- My son Adam.

Thank you again.

Chris Winder

Chris Winder

August 2010

## 0.4 A Personal Note

I am a toxicologist and occupational health and safety professional with a PhD in toxicology and pathology and a Graduate Certificate in OHS Management who is Professor in Applied Toxicology, School of Risk and Safety Sciences at the University of New South Wales. I am not medically qualified, but as part of my professional and consulting activities, can comment on (among other things) occupational health and/or toxicological aspects of medical and OHS reports.

In 1997, I was visited by three aircrew (one flight attendant, two pilots) who came to see me about health problems they were having after being exposed to contaminated air while flying on a model of airplane called the BAe 146. It became apparent that the engines of this plane had a tendency to leak engine oil into the bleed air system, which was used in supplying air to the pressurised flight deck and passenger cabin.

As I began investigating this issue, I was contacted an ever increasing number of pilots and flight attendants. Three became five, six, eight, ten, fourteen, twenty. Most were working for Ansett Australia or National Jet Systems, the two airlines operating the BAe 146 aircraft in Australia.

A number of questions arose out of this early work:

- Was there something peculiar about the engine oil used on this particular model of airplane?
- Was there something peculiar about oil leaks on this particular model of airplane?
- Were these exposures associated with the symptoms and signs being reported by these individuals?
- Were the symptoms and signs due to some other factor (for example, lifestyle, medical, environmental)?
- Were the symptoms and signs related to nonspecific toxicity, for example, irritation or discomfort?
- Were the symptoms part of a specific toxicity to a specific chemical or chemicals?

Then, in 1998, I was contacted by another scientist, Dr Jean Christophe Balouet from Environment Internationale in France, working on apparently similar cases in Europe and the USA. We pooled information, and shared knowledge about the apparent lack of response by the airlines, who mainly seemed to be in denial about this issue.

Dr Balouet's cases were on different models of airplanes, on different airlines. But many of the symptoms and signs he was collecting from affected individuals were similar the symptoms and signs that I was collecting.

On a trip to Paris in August 1999, we collaborated on this issue, developing a list of symptoms that could be used by medical practitioners to help air crew who had been exposed. We coined the term "aerotoxic syndrome" as a means of focussing attention on the issue by the industry and its regulators.

We also recognised that there was a need for better knowledge about this issue, including, whether there were any toxic chemicals in use, if exposures were occurring on the apparent scale being reported, if any monitoring studies had been conducted, and if aviation legislation was being followed. We also considered that an epidemiological study of exposed workers should be conducted to better describe the condition, as no such study was being considered by the aviation industry itself.

## 0.5 For the Record: FAR/JAR Airworthiness Standard Section 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 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. 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 in excess of three percent by volume (sea level equivalent) is considered hazardous in the case of crewmembers. Higher concentrations of carbon dioxide may be allowed in crew compartments if appropriate protective breathing equipment is available.

(c) There must be provisions made to ensure that the conditions prescribed in paragraph (b) of this section are met after reasonably probable failures or malfunctioning of the ventilating, heating, pressurization, or other systems and equipment.

(d) If accumulation of hazardous quantities of smoke in the cockpit area is reasonably probable, smoke evacuation must be readily accomplished, starting with full pressurization and without depressurizing beyond safe limits.

(e) There must be a means to enable the crew to control the temperature and quantity of ventilating air supplied to the crew compartment, independently of the temperature and quantity of ventilating air supplied to other compartments.

## 0.6 Abbreviations Used in this Thesis

| | |
|---|---|
| AAFA | Australian Association of Flight Attendants |
| AAIB | Air Accidents Investigation Bureau, UK |
| ACARS | Aircraft Communications and Reporting System |
| ACGIH | American Conference of Governmental Industrial Hygienists |
| AD | Airworthiness Directive |
| AFA | Association of Flight Attendants (USA) |
| AFAP | Australian Federation of Airline Pilots |
| AIPA | Australian and International Pilots Association |
| ALAEA | Australian Licenced Aircraft Engineers Association |
| AOM | All Operator Message |
| APU | Auxiliary Power Unit |
| ASCC | Australian Safety and Compensation Council (formerly NOHSC) |
| ASHRAE | American Society of Heating, Refrigerating and Air Conditioning Engineers |
| ASR | Air Safety Report (UK) |
| ATA | Air Transport Association |
| ATSB | Australian Transport Safety Bureau |
| ATSM | American Society for Testing and Materials |
| BAe | British Aerospace Systems |
| BALPA | British Airline Pilot's Association |
| BASI | Bureau of Air Safety Investigation (Australia, now ATSB) |
| CAA | Civil Aviation Authority (United Kingdom) |
| CAIR | Confidential Aviation Incident Reporting system (Australia) |
| CAR | Civil Aviation Regulation |
| CASA | Civil Aviation Safety Authority (Australia) |
| cfm | cubic feet per minute |
| CFR | Code of Federal Regulations (USA) |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| COPIND | Chronic organophosphate neuropsychological disorder |
| COT | Committee on Toxicity (United Kingdom) |

| | |
|---|---|
| DfT | Department for Transport (United Kingdom) |
| DOCP | Di-ortho-cresyl phosphate |
| EASA | European Aviation Safety Agency |
| ECS | Environmental Control System |
| EPA | Environmental Protection Agency (USA) |
| FA | Flight Attendant |
| FAA | Federal Aviation Authority (USA) |
| FAR | Federal Aviation Regulations |
| FID | Flame Ionisation Detection |
| FODCOM | Flight Operations Department Communication (UK CAA) |
| GC | Gas chromatography |
| GC/MS | Gas Chromatography separation followed by Mass Spectrometry |
| HEPA | High efficiency particulate air (filter) |
| HPLC | High pressure liquid chromatography |
| HSE | Health and Safety Executive (UK) |
| HVAC | Heating, ventilation and air-conditioning |
| ICAO | International Civil Aviation Organisation |
| IFALPA | International Federation of Airline Pilots |
| ITF | International Transportworkers Union |
| JAA | Joint Aviation Arrangements |
| JAR | Joint Aviation Requirements |
| LAME | Licenced Aircraft Maintenance Engineer |
| MD | Major Defect |
| MEL | Minimum Equipment List |
| MOCP | Mono-ortho-cresyl phosphate |
| MOR | Mandatory Occurrence Report or Reporting |
| MS | Mass Spectrometry |
| MSDB | Material Safety Data Bulletin |
| MSDS | Material Safety Data Sheet |
| NASA | National Aeronautics and Space Administration (USA) |
| NES | National exposure standard (Australia) |
| NICNAS | National Industrial Chemicals Notification and Assessment Scheme (Australia) |
| NIOSH | National Institute of Occupational Safety and Health (USA) |

| | |
|---|---|
| NJS | National Jet Systems (Australia) |
| $NO_2$ | Nitrogen dioxide |
| NOHSC | National Occupational Health and Safety Commission (Australia, now ASCC) |
| $NO_x$ | Oxides of nitrogen |
| NTSB | National Transport Safety Board (USA) |
| $O_3$ | Ozone |
| OEL | Occupational Exposure Limit (UK) |
| OHS | Occupational health and safety |
| OP | Organophosphorus or Organophosphate |
| OPICN | Organophosphate Induced Chronic Neurotoxicity |
| OPIDN | Organophosphate induced delayed neuropathy |
| OSHA | Occupational Health and Safety Administration (USA) |
| PAN | Phenyl-alpha-naphthylamine |
| PEL | Permissible Exposure Limit (USA) |
| ppb | parts per billion |
| ppm | parts per million |
| SAE | Society of Automotive Engineers |
| SB | Service Bulletins |
| SDRS | Service Difficulty Reports Search (US FAA) |
| SHE | Safety, Health and Environment |
| SIL | Service Information Leaflets |
| SMAC | Spacecraft maximum Allowable Concentrations |
| SMACS | Spacecraft Maximum Allowable Concentration |
| STEL | Short Term Exposure Limit (ACGIH) |
| TCP | Tricresyl phosphate |
| TLV | Threshold Limit Value (ACGIH) |
| TMPP | Trimethyl propane phosphate |
| TOCP | Tri-ortho-cresyl phosphate |
| TWA | Time weighted Average |
| VOC | Volatile organic compound |
| WHO | World Health Organisation |

# 0.7 Abstract

From 1992, adverse health symptoms were reported in Australian pilots and flight attendants following "fume events" or "exposure events" of jet oil leaking from the airplane engines into the bleed air system, environmental control system, auxiliary power unit and thence the flight deck and passenger cabin. Examination of various documents circulating within the Australian industry indicates that there was considerable effort expended to minimise this issue, with a formulaic approach of denial, bluster and misinformation. There are a variety of reasons for this, including commercial pressures, fatalism about long standing and apparently insurmountable engineering problems, operational procedures that focus keeping aircraft flying and a culture within the industry to minimise health and safety risks. It is concluded that these actions breach the general duty of care mandated in OHS legislation. Reporting of such incidents appears low, with an escalating chain of underreporting, from exposed personnel to airline operators and to regulators. Further, few events reported to regulators are investigated.

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In 1999, an initial analysis of seven case studies from flight crew and flight attendants in four airlines operating in four countries and in three airplane models, noted that the reported symptoms had a degree of consistency. At the time, these symptoms were given the descriptive name "Aerotoxic syndrome".

From review of the ingredients in aviation oils and hydraulics, it is apparent that some contain toxic ingredients. A detailed study of the ingredients in one proprietary jet oil in widespread use indicated that it contained at least two toxic ingredients, one neurotoxic and the other a sensitiser. Manufacturer product information such as the Material Safety Data Base (MSDS) understated the risk of the product.

Monitoring studies of air quality on airplanes are generally favourable, although most are sufficiently flawed on methodological inadequacies to render their conclusions invalid, few monitor for the hazardous chemicals of concern, and none have been conducted during a fume event.

The initial study of seven cases was followed up by a second study in 2001, of fifty pilots and flight attendants. A range of general, neurological, neuropsychological, respiratory, gastrointestinal, reproductive and irritancy symptoms were reported. There was sufficient commonality in reported symptoms to conclude a symptom basis for Aerotoxic syndrome. This is further supported by application of the Bradford Hill criteria for causation to the effects

reported in this survey, and by later studies published in the literature.

Whether or not Aerotoxic syndrome exists as a real condition remains controversial. The term certainly polarises opinion and this may not be helpful for those affected individuals seeking assistance. At best, the condition can be considered a form of Multiple Chemical Sensitivity (MCS) associated with fume events when exposed by working in the aviation industry.

# Chapter 1

# Chemical Exposures at Altitude

The Aviation industry prides itself on being a safe industry. It has a range of engineering and administrative procedures in place to ensure that non-airworthy airplanes do not enter service. However, this does not always mean they are safe. This chapter introduces the concept of air safety, and discusses how this concept is different form other forms of safety, such as public safety or OHS. Further, in the case of poor air quality through contaminated air, the requirements of FAR/JAR Airworthiness Standard Section 25.831: Ventilation is likely to be interpreted by erring on the side of convenience or self interest.

# 1 Chemical Exposures at Altitude

## 1.1 Air Safety is Important

There is no question that air safety is an important issue. Unlike many other types of transportation accidents, the loss of a passenger airplane in flight is a catastrophe. There are a range of factors that can lead to airplane accidents, including problems of language,[1] problems of communication,[2] problems with technology,[3] and problems with attitudes to safety.[4,5] A major aircraft manufacturer recently stated (in an Australian Senate Inquiry) that its definition of aircraft safety was based upon the aircraft not having had a fatality due to a technical problem.[6]

The term air safety means safety in the air. However, government agencies charged with the responsibility for air safety tend to focus on the engineering systems that keep airplanes flying. They look at engines, and airplanes and airworthiness and flight control. However, they don't necessarily seem to recognise that human beings are flying planes and are providing services to passengers and crew.[7]

## 1.2 Air Safety, not Public Safety

In commercial air transport, it seems obvious that the safety and well being of passengers is important. Passenger safety, particularly with exposure to some hazards of aviation (such as sitting for long periods, cosmic radiation, ozone, cognitive problems of jet lag), would seem to be a priority issue. Further, a range of factors can affect the objective or subjective perceptions of passengers travelling on airplanes, as shown in Table 1-1.[8]

***Table 1-1: Risk Factors for Air Travel***

| Intrinsic | Extrinsic |
|---|---|
| o Age | o Temperature |
| o Gender | o Humidity |
| o Health status | o Air ventilation rate |
| o Genetic predisposition (atopy) | o Radiant heat |
| o Body mass | o Turbulence |
| o Level of mental cognition | o Noise |
| o Insulation (clothing) | o Vibration |
| o Anxiousness | o Lighting |
| o Level of fatigue | o Ergonomics |
| o Level of jet lag | o Long periods of confinement |
| | o Presence of air contaminants |
| | o Exposure to cosmic radiation |

A recent focus on deep vein thrombosis in passengers emerging from long haul flights suggests that health issues are becoming an issue with passengers.

Another issue is air quality. Airborne contaminants are found in airplane air. Contaminants such as ethyl alcohol and acetone may be produced by human metabolic processes. Others may arise from such processes as maintenance or cleaning. But levels of these or other contaminants cannot be dismissed on this basis. Levels must be characterised and evaluated in a proper context.

## 1.3 Air Safety, not Occupational Health and Safety

It has become apparent that regulatory agencies such as the US Federal Aviation Administration and the Australian Civil Aviation Safety Authority do not consider that worker health and safety is part of its responsibility. This begs the obvious question, just who is responsible for the safety of workers in the airlines?

Certainly, there are problems with transjurisdictional application of occupational health and safety and workers compensation legislation in work that traverses nations, states and territories. Further, occupational health and safety authorities appear reluctant to become involved in an industry where they see a potential jurisdictional conflict with an industry specific safety authority.

There are a number of occupational health and safety issues of central importance in the cabin of airplanes, such as: flight and duty times, protection from physical injury (which, in particular means turbulence and cabin baggage policies, unruly passengers/crewmember interference), cabin air quality, standard of rest facilities on board, and minimum training requirements. Occurrence/Incident/Injury reporting systems and data collection is also a key issue.

This is not an exclusive list, and one such problem is that of exposure to airborne contaminants while in flight. Some models of aircraft, such as the BAe 146 appear to be especially prone to engine oil leaks. While the performance of airplane engines is a responsibility of engineering services in the airlines, all crew have a legitimate interest in and contribution to make towards operational safety issues (such as evacuation, fire protection, use of personal protective equipment) which by definition are also occupational safety issues for them as employees.

It is important that the regulatory authorities recognise that these issues, which have only been subject to regulation so far where there is an operational safety dimension, require regulation for occupational health and safety reasons if the issue of airline safety is to be addressed properly.

This would requires the regulatory authorities to acknowledge and give due regard to the occupational safety dimensions of their regulatory activities - something that they have singularly failed to do so far, and that operators and manufacturers have strenuously resisted.

With regard to air quality, studies indicate[9] that it is common that all modes of transport have ventilation rates less than current ASHRAE 62 guidelines for commercial buildings.[10] This finding, of itself, does not imply poor air quality. However, it suggests that initiatives to reduce air quality should be resisted and indicates that opportunities to improve air quality should be encouraged. For example, a Canadian study of one aircraft type and airline found that 24 of 33 commercial flights did not satisfy the ASHRAE air ventilation criteria of fifteen cubic feet/occupant, and that 18 of 33 flights had less than ten cubic feet/occupant.[11]

## 1.4 Bleed Air

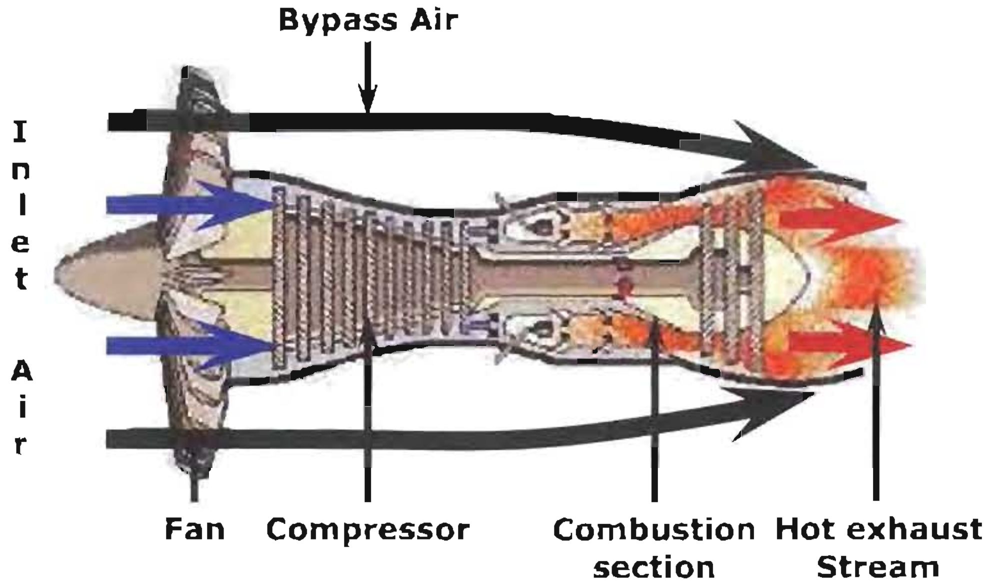
### 1.4.1 The Concept of Bleed Air

The problem of flight deck and altitude hypoxia was identified in the early days of aviation. Early open cabin aircraft were uncomfortable and not conducive to passenger travel; therefore the concept of the pressurised aircraft emerged. The pressurisation altitude for aircraft was established at 8,000 ft (about 2400 m) through tests on healthy male volunteers, and various sources of pressurisation attempted, such as turbo compressors or ram air systems.

"Bleed air" was one such source. Basically, air outside the aircraft (at low pressure when flying at altitude) is compressed in the aircraft engines or auxiliary power unit to the pressurisation altitude, conditioned to physiological temperatures and pressures, and passed through ducting to the environmental control system (ECS) and then to the cabin.[12]

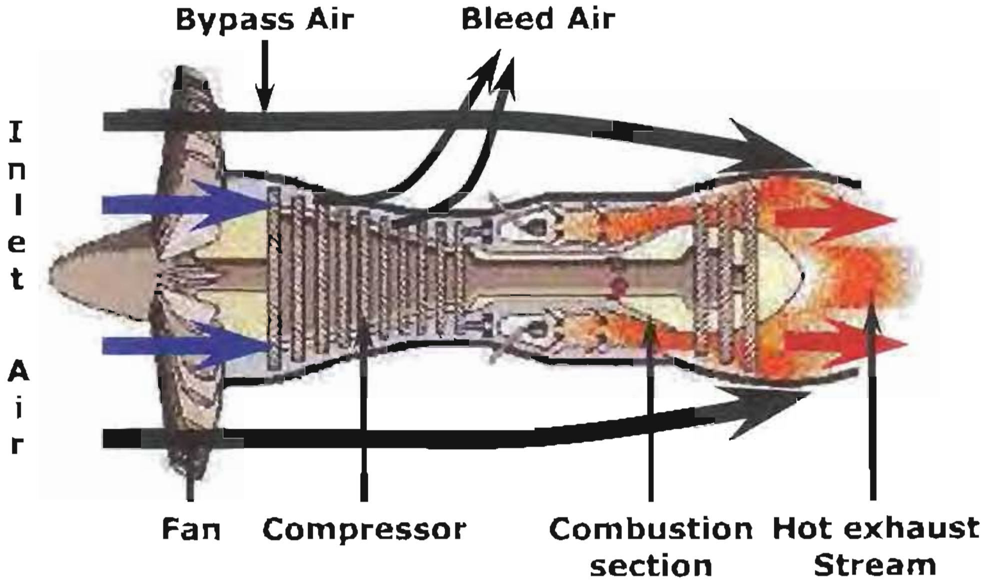
To make bleed air viable, engine air compressors are separated into the side that supplies bleed air and the side that supplies oils to the engine. Each side is separated from each other by engine oil seals (see Figure 1-1).[13] Air leaving the engine at the beginning of the bleed air system is at high temperature (up to 500°C) and pressure (approximately 3800 mm Hg). It is a requirement of the bleed air system and environmental control system that this temperature is reduced to physiologically comfortable conditions.

***Figure 1-1: Schematic of the Air Flow in the Aircraft Bleed Air System***




Shortly after the introduction of oils seals for the bleed air system, in a 1953 book on Aviation Toxicology on the Committee on Aviation Toxicology of the Aeromedical Association noted that toxic substances such as pyrolised engine oil could leak from the engine into the bleed air system, contaminating the ductwork, air conditioning system and fight deck/passenger cabin (see Figure 1-2).[14]

***Figure 1-2: Schematic of the Bleed Air Flow in the Aircraft Bleed Air System***




Further, a paper presented to the Society of Automotive Engineers in 1955 highlighed the problem of bleed air contamination "because of internal engine oil leakage into compressor air".[15] Despite these concerns, bleed air was introduced on the Caravelle in the early 1950s and the Boeing 727 in 1963, and became the preferred method of pressurisation and air supply on most aircraft models from that time.

Safety systems within the bleed air system allow the air flow to be shut if hazardous situations, such as excess heat or pressure, leaks (contaminants) or fires (smoke) arise. Shut-off valves can stop the flow of bleed air from entering the airplane when flight crew detect something untoward.

While the engines on airplanes provide power for flight, they also provide power for all other systems. This can be a problem when airplanes are on the ground and the engines are not running. Airplanes can access power from ground-based sources, but a second source of power, a small turbine engine called the auxiliary power unit (APU) is usually available. The APU can be used for power, engine start, and operation of aircraft systems. The APU can also be used to run the air conditioning system when air cannot be spared from the engines, for example at times of maximum power demand, such as during take off.[16]

Notwithstanding such systems, toxic exposures in aircraft still occur. In 1953, The US Aeromedical Association first expressed their concerns about the toxicity risks of cabin air contamination by hydraulics and lubricants.[14] Other risks have been identified more recently, either as part of the chemicals routinely used in maintaining airplanes,[17] or as toxicological factors in aviation accidents.[18] Passenger protective breathing equipment tests conducted by the UK Air Accidents Investigation Branch identify contaminants such as carbon monoxide, hydrogen cyanide, hydrogen fluoride, hydrogen chloride, nitrogen oxides, sulphur dioxide, ammonia, acrolein, and other hydrocarbon compounds in combustion situations.[19]

As well as emergency situations, there are a range of other situations that can arise whereby airplane cabin air can be contaminated.[20] These include:

- ingestion of exhaust from other aircraft or on ground contamination sources,
- application of de-icing fluids,
- hydraulic fluid leaks from landing gear and other hydraulic systems,
- excessive use of lubricants and preservative compounds in the cargo hold,
- preservatives on the inside of aircraft skin;
- large accumulations of dirt and brake dust may build up on inlet ducts where auxillary power units extract air from near the aircraft belly;
- ingestion of oil and hydraulic fluid at sealing interfaces, around oil cooling fan gaskets and in worn transitions;
- oil contamination from synthetic turbine oil;
- engine combustion products (for example, defective fuel manifolds, seal failures, engine leaks).

Aircraft materials including as jet-fuel, de-icing fluids, engine oil, hydraulic fluids, contain a range of ingredients, some of which are toxic.[21,22,23,24] The aviation industry has used engine oil, hydraulic fluids and other materials that can contain a range of toxic ingredients, for example:

- organophosphate compounds, including Tricresyl phosphates (TCP), Tributyl phosphates (TBP), Triphenyl phosphates (TPP) and their derivatives, from 3 to 25% in content;
- other toxic inorganic molecules, such as naphthylamines, amines and esters;

- organometallic additives (zinc dialkyl dithiophosphates, calcium alkyl phenates, magnesium sulphonates, molybdenum and barium containing additives).

Concerns of the contamination problems of bleed air continued to be reported.[25,26,27]

### 1.4.2 The Problem of Bleed Air

Some bleed air contamination problems can persist for decades. For example, a problem of oil contamination of the air conditioning system of the BAe 146 was first noted by the aircraft manufacturer in 1984,[28] but was the only subject of a specific term of reference to an Australian Senate Aviation Inquiry held 1999-2000, over fifteen years later.[29]

While changes in product formulations have attempted to make less toxic products,[30] concern still exists as to the potential toxicity that exposure to these materials may cause.[31]

Although these chemicals are usually retained in the engines and equipment into which they have been added (such as auxiliary pack units or APUs), they can sometimes find their way into cabin air where crew and passengers are located, through incidents such as engine oil leaks, seal failures and fluid ingestion by APU/engines.

Environmental control for airplanes encompasses more than the provision of acceptable temperatures and ventilation for air crew and passengers – it provides for the support of life in an environment where human survival would not normally be possible, and provides cooling for avionics and other functions (such as de-icing). This role is performed by the Environmental Control System (ECS). The ECS can be configured in many ways, and some systems are more efficient than others.[32]

Further, operational activities, such as APU "pack" burnouts or use of re-circulated air during take off and landing, can give rise to significant contamination.

In some cases, this contamination may be to the materials used in aircraft such as jet fuel or other materials in vapour, fume or mist forms.[33] However, effects are also possible from exposure to combustion or pyrolysis products such as smoke.

Hundreds of in-cabin leak/smoke events are documented each year and are often correlated to aircraft fluid leak events. There is a spectrum of defects and malfunctions in an airplane engine ranging from the trivial, to the serious, to the catastrophic. Fume events are much more frequent, correlated to less important aircraft fluid leaks (in the order of hundreds a year). However, as trivial malfunctions can escalate into serious events, it is necessary to ensure that all types of malfunctions are identified, investigated and rectified.

For the purposes of discussion below, events leading to leak, smoke or fume incidents will be combined as "leak/smoke/fume events" or "exposure events".

The aviation industry itself acknowledges that air quality exposure events are primarily due to oil leaking into the air supply. All parties acknowledge that a problem exists, and has existed for a long time.[34,35] However, they then paradoxically deny that leaks are a serious matter, suggesting that it is not it is an air safety issue, rather an OHS, general health or comfort issue.[36] Regulatory agencies indicate that "serious impairment" includes the loss of crew's ability to see flight deck instrumentation or perform expected flight duties. However, they also suggest this excludes purely psychological aspects of the concern of odours, and concerns about long-term exposure.

When a leak occurs, it may be dismissed by the pilot as being a nuisance, in that it appears to have no apparent effect. Or it may be considered minor and reported within the company and fixed without record (anecdotally, some pilots report leak events to ground crew verbally or unofficially, for example, on scrap paper or even cocktail napkins). In this, there is inappropriate subjective interpretation of the terms "undue discomfort" and "harmful or hazardous levels of gases or vapours" specified in aviation regulations, and this interpretation errs on the side of convenience. Or a record may be made, but not considered sufficiently serious to report to aviation regulators, either voluntarily or as part of mandatory requirements. Lastly, as aviation regulations impose strict guidelines on how aircraft defects are defined, must be reported, investigated and dealt with, some leaks may actually be reported to aviation regulators. These reports tend to cover the serious problems, but not always so. However, with substantial under-reporting and a culture of complacency exists between operators and regulators, no aviation regulatory authority can honestly consider that the reports they receive from the industry represent anything other than a very small tip of a very large iceberg of leak events.

From review of available sources and reported and accessible information, it is apparent that only a small fraction of the known incidents are reported. Evidence suggests that there are a substantial number of leak incidents on airplanes, especially on certain models of aircraft. Many of these leaks go unreported to aircraft operators. Of those leak incidents that are reported to aircraft operators, many are not reported to regulatory authorities. Of those leak incidents that are reported to regulatory authorities, not all are added to relevant databases. Ultimately, only a very small number of leak incidents are investigated fully.

The range of bleed air contaminants and their concentrations that may be found during in-cabin exposure events during flight can be extensive. Significant contaminants include: aldehydes; aromatic hydrocarbons; aliphatic hydrocarbons; chlorinated, fluorinated, methylated, phosphate, nitrogen compounds; esters; and oxides.

## 1.5 Industry based information

The aviation is a high technology industry and over the years has developed sophisticated documentation systems for recording matters relating to its activities. Some of this documentation relates to the problems the industry has with oil leaks in airplanes and concerns of staff about the consequences of such exposures. But much of this documentation is commercially confidential or inaccessible. However, with regard to the issue of oil leaks on the BAe 146 at Ansett Australia from about 1992, substantial documentation has become available, either by being made available from workers in this industry, or as part of workers compensation litigation. While such documentation is not peer-reviewed it serves to illustrate what was happening in this industry.

Information about the design of poor exhaust systems on aircraft has been known for over thirty years. Some of this is in the public domain. This section covers issues relating to the design and operation of the BAe 146; a description of the airframe, engines, APU and ECS is provided in Section 1.7.

In a Handbook published by the Garrett Corporation (the original manufacturer of the APU on the BAe 146) in 1974 it is noted that the least favourable location of an exhaust inlet "*is an inlet located well aft at the bottom surface of the fuselage. Fluids likely to be ingested with this type of inlet include those that may be spilled within the aircraft fuselage, fuel-tank-leakage and vent-system discharge, leakage from the hydraulic system etc*".[37] This is precisely where the exhaust inlet was located by the designers of the BAe 146.

In 1976, the UK Civil Aviation Authority issued the document: *British Civil Airworthiness Requirements*. Chapter D6-11 covers ventilation and pressurisation of crew and passenger compartments.[38] In 1997 correspondence between Ansett's Medical Director (Dr Dai Lewis) and the General Operations Manager (Captain Trevor Jensen), it was noted that the BAe 146 failed requirements for ventilation (section 3.2.2), noxious vapours (section 3.3.10(d)), contamination (section 3.3.10(e)), and failure of components (section 6.3).[39]

The issue of the introduction of bleed air in the 1960s was discussed in Section 1.4. Problems with this system on a number of airplane models began to emerge afterwards.

In general, the aviation industry would have known about the possible effects of exposure to jet oils leaking into the bleed air system for many years. The earliest case found in the literature of toxicity following jet oil exposure and adverse health problems in air crew was reported in 1977. A previously healthy member of an aircraft flight crew was acutely incapacitated during flight with neurological impairment and gastrointestinal distress. His clinical status returned to normal within a day. The aetiology of his symptoms was related to an inhalation exposure to aerosolised or vapourised synthetic lubricating oil arising from a jet engine of his aircraft.[40]

In 1981, the Society of Automotive Engineers (SAE) noted in an Aerospace Information Report "*Engine compressor bearings upstream of the bleed ports are the most likely sources of lube oil entry in the engine air system and thence into the bleed system contaminating the cabin/cockpit air conditioning system.*"[41]

By the late 1980's and early 1990's, airline operators began noting problems. Air UK reported problems on the BAe 146: "Our problem stemmed from contamination of air conditioning ducts. APU oil smells in cabin and fungi in galley/toilet areas (1989-90)."[42] A 1992 BAe Aerospace letter to Allied Signal notes that two operators of the BAe 146-300 aircraft (Dan Air and Ansett) were experiencing unpleasant cabin odours from "your Auxiliary Power Unit". This problem was "first raised to Garrett at the Operators Conference in Perth in 1989."[43]

In 1989, the Garrett APU Division of Allied Signal issued a Service Bulletin regarding the compressor seal assembly, noting that "*the current compressor seal has shown an unacceptable rate of failure which can result in smoke in the cabin*" and "*The failure of the compressor seal assembly allows gearbox oil to* *leak into the compressor inlet resulting in smoke in the cabin. The new seal has been redesigned to improve sealing characteristics and reliability.*"[44] However Service Bulletins are not mandatory. All Allied Signal could recommend was for airplane operators make replacements at their convenience.

Further published studies of exposures in aircraft included a 1983 study of eighty nine cases of smoke/fumes in the cockpit in the US Air Force,[45] a 1983 study of Boeing 747 flight attendants in the USA (this paper linked symptoms to ozone),[46] a 1990 study of aerospace workers.[47]

Risks to health from exposure to jet oil emissions specifically on the BAe 146 were reported in a 1998 study of BAe 146 flight crews in Canada over a four-month period.[48] A 2002 survey of predominantly BAe 146 aircrew reported similar findings in a group of fifty aircrew respondents (outlined in Chapter 6),[49] and a union based study of pilots on the BAe 146 provide additional data.[50]

### 1.5.1 Evidence of Leaks before 1992

#### 1.5.1.1 Evidence from the Industry

Whether aircraft manufacturers such as BAe Aerospace, or engine manufacturers such as Avco Lycoming, or auxiliary power unit manufacturers such as Garrett (taken over by Allied Signal, who in turn was taken over by Honeywell) or airline operators such as Ansett and East West knew about the possible health problems from the leaks could be questioned. But they certainly knew about the leaks on the BAe 146.

BAe documentation includes:

- In December 1984, British Aerospace (the manufacturer of the BAe 146) issued the 146 Service Information Leaflet (SIL) "Oil Contamination of Air Conditioning System" that acknowledged that oil contamination of ducting was a problem, suggesting ways in which such problems might be resolved.[51] Among other things, this leaflet recommended the development of an operational procedure called an Air conditioning Pack Burnout Procedure, "Operating the system, before the first revenue flight of the day, in hot mode for five minutes (manually controlling the duct temperature at 70°C. This will help purge residual oil from the packs and ducting." While pack burn outs were supposed to be carried out without airline staff on the airplane, for example, making pre-flight checks (engineers) of getting the airplane ready for flight (flight attendants), at Ansett it was common that personnel were present during this procedure.

- Dan Air and AirUK complained of problems of smells and oil leaks in about 1989. By 1991, Dan Air was seeking information: "Can Hatfield (British Aerospace) provide a definitive statement on the medical implications of fumes/smells in the cabin (Dan Air cabin crew have complained of headaches and nausea) (February 1991).[42,43,52]

- A 1992 BAe Aerospace letter to Allied Signal notes that two operators of the BAe 146-300 aircraft (Dan Air and Ansett) were experiencing unpleasant cabin odours from "your Auxiliary Power Unit". This problem was "first raised to Garrett at the Operators Conference in Perth in 1989."[53]

- *A 1992 146 Aircraft Modification Service Bulletin that notes* "It has been found that there is a possibility of ingestion of APU bay contamination with the existing design of APU inlet plenum bellows. This can result in fumes entering the passenger compartment."[54]

- Minutes of a June 1992 meeting between BAe and the French filtration company Le Bozec to discuss the cabin smell problem and finding an acceptable solution for Ansett, noting that the problem had "spanned the previous eighteen months".[55]

- In September 1997, an email was sent to Captain Trevor Jensen, Chief Pilot at Ansett, reporting that Air British Columbia were experiencing cabin crew complaints on their BAe 146s, including oil fumes and bad odours, cabin crew feeling such with nausea, sore throat, burning eyes, rapid heart rate and trembling hands.[56]

Mobil (manufacturer of jet oils) documentation includes:

- A 1985 letter noting problems of cabin odour on the BAe 146/ALF502.[57]

Avco Lycoming (manufacture of the ALF502R jet engine used on the BAe 146) documentation includes:

- *A 1992 letter to Ansett suggesting that Mobil Jet Oil 254* "reduces carbon build up and as an added benefit to reduce cabin odors caused by seal leakage."[58]

- The impact of physical properties of oil.
- Evidence from the Industry.

### 1.5.1.2 Evidence from Ansett Australia

Because of potential litigation from employees and possibly passengers, Ansett were very worried about the issue of cabin contamination. They absorbed the East-West fleet of BAe 146s into the company and began the process of taking over engineering responsibilities of these aircraft at the end of 1991. At that time, the cabin smell was well known, and it was well known that the contamination was from the APU.[59]

As an airline operator, Ansett was at the forefront of this problem. They had a significant number of BAe 146-200 and 146-300 airplanes (see Table 1-2, sourced from Internet sources).

***Table 1-2*: *The Ansett Australia BAe 146 Fleet***

| Reg No | Model | Operator | Delivery | To Ansett |
|---|---|---|---|---|
| VH-JJP | BAe 146 200A | Ansett WA | Apr 1985 | Jan 1993 |
| VH-JJQ | BAe 146 200A | Ansett WA | Jun 1985 | Jul 1993 |
| VH-JJS | BAe 146 200 | Ansett WA | Oct 1988 | Jul 1993 |
| VH-JJT | BAe 146 200 | Ansett WA | Nov 1988 | Jul 1993 |
| VH-JJW | BAe 146 200 | Ansett WA | Mar 1989 | Jul 1993 |
| VH-JJY | BAe 146 200QT† | Ansett | May 1989 | |
| VH-JJZ | BAe 146 200QT† | Ansett | May 1989 | |
| VH-JJU | BAe 146 200 | Ansett NZ | Jul 1989 | Jul 1993 |
| VH-JJX | BAe 146 200 | Ansett NZ | Jul 1989 | Jul 1993 |
| VH-EWI | BAe 146 300A | East-West | Aug 1990 | Oct 1993 |
| VH-EWJ | BAe 146 300A | East-West | Aug 1990 | Oct 1993 |
| VH-EWK | BAe 146 300A | East-West | Sep 1990 | Status uncertain |
| VH-EWL | BAe 146 300A | East-West | Oct 1990 | Oct 1993 |
| VH-EWM | BAe 146 300A | East-West | Dec 1990 | Jul 1993 |
| VH-EWN | BAe 146 300 | East-West | Apr 1991 | Status uncertain |
| VH-EWR | BAe 146 300 | East-West | Jun 1991 | Jul 1993 |
| VH-EWS | BAe 146 300 | East-West | Jun 1991 | Jan 1993 |

† The QT (quiet trader) airplanes were cargo freighters

At that time, two different Allied Signal APU's were being used: the 150M APU was used on the BAe 146-300 airplanes, and the 100M APU was used on the BAe 146-200 airplanes.

The BAe 146 is configured to carry about 70 passengers with a normal crew of two pilots and three flight attendants.

1991-92 was a significant watershed period with this issue, with documentation including:

- An Ansett Engineering release dated 12 December 1991 describes introduction of a Flexiwrap gasket "to prevent oil fumes from entering duct and consequently into the cabin", works to be completed "not later than 28 February."[60]

- A summary document called a Component Condition History Record lists sixty entries from December 1991 to September 1992 finding that air conditioning packs on the BAe 146 were dirty *(from December 1991)* and contaminated with oil *(from February 1992)*.[61]

- Ansett In-flight Health Surveys, completed by flight attendants. There are many forms *(a sample is shown in* Figure *1-3)* and a significant proportion indicate problems, such as (in June to August 1992):[62]

***Figure 1-3: The Ansett In-Flight Health Survey***

**IN-FLIGHT HEALTH SURVEY**

RECEIVED 20 JUL 1992 FLIGHT ATTENDANTS DEPT.

DATE: 19-7-92

TIME: 0610

AIRCRAFT REGO: I J K L M R S EWM

FLIGHT NO: 352-353 SYD-BNE-HTI-BNE

PURSER: [redacted]

NAMES OF FLIGHT ATTENDANTS: [redacted]

1. Odour Detected — Yes ✓ / No — If Yes by how many: 2 F/As + pilots (1 F/A has no sense of smell)

2. Duration of Odour during Flight — Foul / Stale / Oil ✓ / Pungent ✓

Please describe: Oil fumes detected on initial boarding of a/c at SYD. Pilots had been burning off airconditioning packs — strong oil fumes at row 1 at all times (on ground, ascent, cruise, descent) — especially noticed throughout a/c when landing + on the ground at all ports — oil odour around engine area during cruise. Pilots could smell oil fumes in cockpit — they found oil to be leaking from an engine.

3. F/A Reactions to Odour Symptoms — None / Nausea / Lightheaded ✓ / Dizzy

Sore Throat ✓ (Dry throat from first sector onwards) / Shortness of Breath ✓ / Requiring Oxygen ✓ / Other: very dry, stinging, red eyes

4. Number of F/A's with Symptoms: 2

5. Passenger Reaction — Yes / No ✓ — If Yes, how many?

Comments: After noticing oil fumes on initial boarding of a/c at SYD, F/S Ferguson started to have a very dry throat + slight breathlessness during the first + 2nd sectors to BNE & HTI. Noticed at all times throughout duty, oil fumes were strong around row 1, close to my own area.

Upon closing a/c door at HTI, I found it difficult to breath. F/A Paine noticed I was having a problem breathing, which continued throughout the entire flight + the next few hours after signing off at BNE. I found it necessary to use supplementary oxygen throughout the entire flight, except when I tried to do the cabin service + still could not breath properly. I felt lightheaded as well. Please note that I did not have any breathing problems before boarding the a/c today.

- "*Fog in cabin when purging AC – really bad smell*"- this shows that pack burn outs were carried out when flight attendants were on the airplane getting ready for the days flights. Indeed, in April 1997, Ansett Engineering installed an air purifying respirator and filters in the coat cupboard of each aircraft for use by crew as required. This was "*an interim measure to reduce the possibility of* *an industrial issue regarding carrying out pack burn outs as part of our "smell" management policy";*[63]

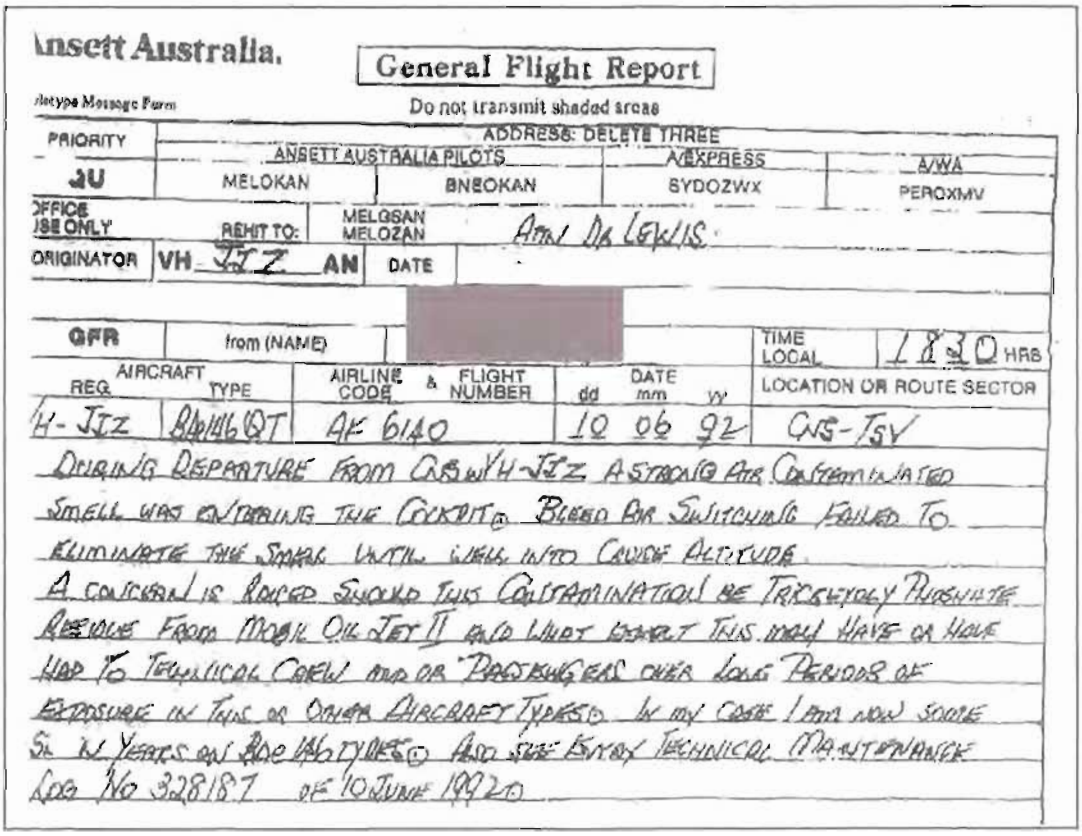
- "Smoke in cabin and cockpit as pre flight checks were carried out", "burning red eyes, nose and throat. Skin red and itchy";

- "*Xxxx Xxxxx* (a flight attendant) *felt quite sick on one sector and had to sit down with $O_2$*" - this demonstrates that on occasion, oxygen was used by flight attendants;

- *A pax (passenger) commented that she* "could smell fumes on this flight and was on EW 146 so many months ago (I think 11) from HBA *(Hobart)* to CNS *(Cairns)* and fumes were quite strong, sitting near engines. 10 mins after disembarking in CNS she became violently ill, vomiting and had stomach cramps. She said she didn't eat anything to cause food poisoning" - *this demonstrates that passengers could also be affected.*

- Pilots were also reporting problems: A General Flight Report completed in June 1992 actually mentions "a concern is raised should the contamination be tricreyoly (sic) phosphate residue from Mobil Jet Oil II" (see Figure 1-4).[64]

***Figure 1-4: The Bleed Air System in the BAe 146***



Ansett Australia.

General Flight Report

Teletype Message Form

Do not transmit shaded areas

| PRIORITY | ADDRESS: DELETE THREE | | | |
|---|---|---|---|---|
| | ANSETT AUSTRALIA PILOTS | | A/EXPRESS | A/WA |
| QU | MELOKAN | BNEOKAN | SYDOZWX | PEROXMV |

OFFICE USE ONLY — REHIT TO: MELOSAN MELOZAN — Attn Dr Lewis

ORIGINATOR VH JIZ AN DATE

GFR from (NAME) [redacted] TIME LOCAL 1830 HRS

| AIRCRAFT REG | AIRCRAFT TYPE | AIRLINE CODE & FLIGHT NUMBER | DATE dd | mm | yy | LOCATION OR ROUTE SECTOR |
|---|---|---|---|---|---|---|
| H-JIZ | BAe146QT | AF 6140 | 10 | 06 | 92 | CNS-TSV |

During departure from CNS VH-JIZ a strong air contaminated smell was entering the cockpit. Bleed air switching failed to eliminate the smell until well into cruise altitude.
A concern is raised should this contamination be tricreyoly phosphate residue from Mobil Oil Jet II and what effect this may have or have had to technical crew and or passengers over long periods of exposure in this or other aircraft types. In my case I am now some six years on BAe146 types. Also see entry technical maintenance Log No 328187 of 10 June 1992.

- East West formed an odour committee from about 1991, and instigated a non-mandatory odour occurrence reporting system (by flight attendants) from about this time (this continued after the Ansett takeover of East West in 1992). Reports from this scheme indicate an exceptionally high rate of incidents, peaking at one in every sixty six flights in 1992. As an example, analysis of Ansett odour incidents occurrences for the period 4 June 1992 to 15 June 1992 lists 53 incidents over seven different BAe 146 aircraft (see Figure 1-5).[65]

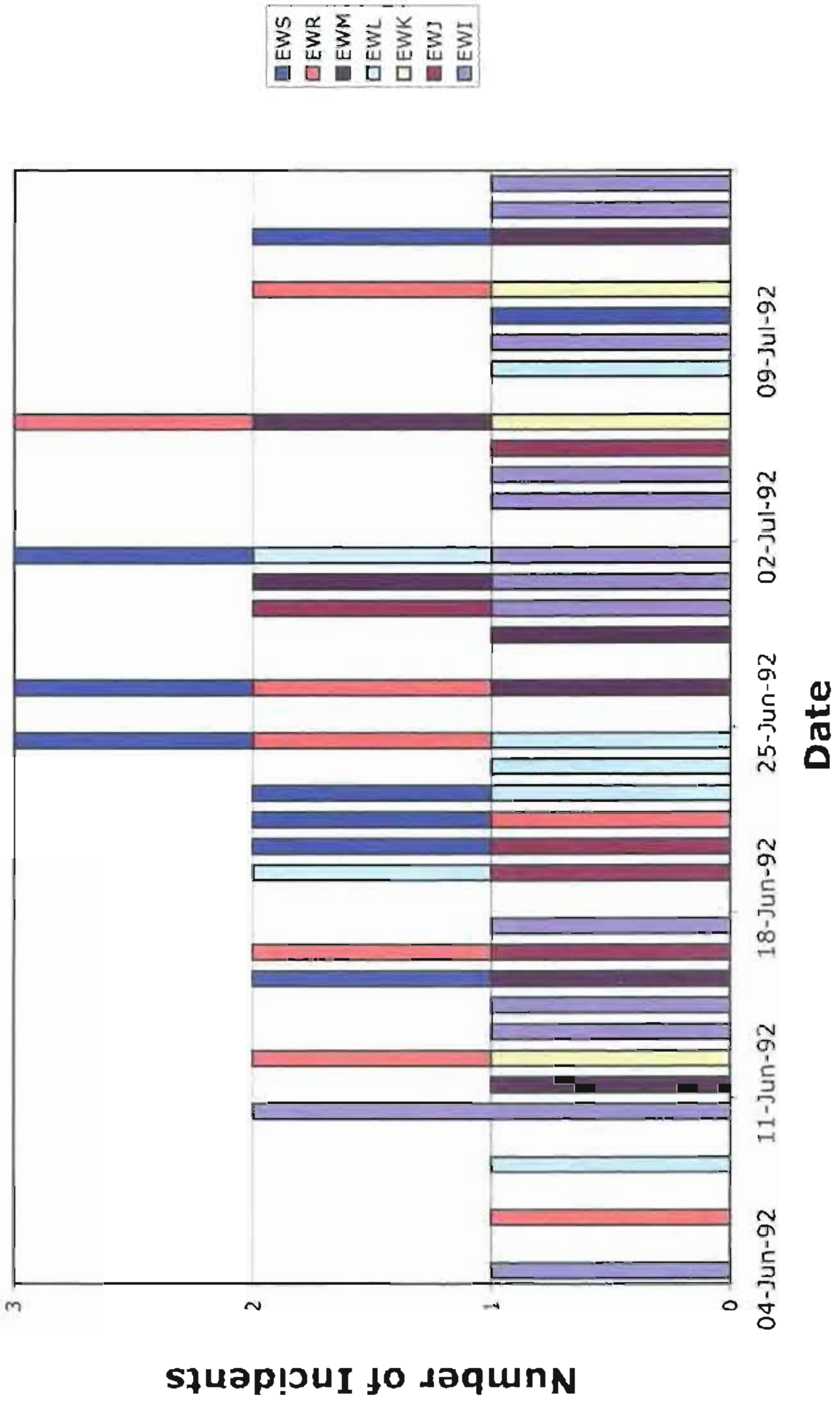



***Figure 1-5: Incident Reporting from the Ansett Non-mandatory Scheme***

While it is difficult to establish a benchmark for the incidence of incidents involving jet oil leaking into aircraft bleed air systems, and agencies such as the Australian Civil Aviation Safety Authority note that *"All engines and APUs leak oil and suffer fumes as a feature of the design of air conditioning systems using bleed air",*[66] data from the UK CAA state that smoke, gas or leak incidents occur once every 22,265 flights (128 events from 1989 to 1999).[67]

Ansett knew that oil leaks on the BAe 146 were a common enough problem and took them sufficiently seriously enough to reform the Odour Enquiry Committee from at least 1996.

- A 3 July 1992 circular to all licenced aircraft maintenance engineers employed at Ansett written by Chris Ryan of the Australian Licenced Aircraft Engineers Association made a number of important points: "The Association is concerned at the potential health and safety risks involved in carrying out pack burnouts on the air conditioning systems on the BAe 146 aircraft"; and the circular advised that members should utilise on board oxygen "during the phases of the pack burn outs when vapor/mist is produced."

- A 7 August 1992 circular written by Mr Ken Crawford, Assistant General Manager, East West Airlines makes a number of important points: i) "The issue of odour on the BAe 146-300 series is of course a worldwide problem with similar occurrence in other airlines operating this type and series aircraft," a clear admission that East West knew about this problem from at least that time; ii) "the results of four independent overseas research reports into cabin odours and our own air sampling conducted on East West aircraft by Dr Vasak" indicates significant activity investigating this problem; iii) "major equipment modification and operating procedural changes have been made to the APUs and air conditioning systems, and the availability in November [1992] of totally new prototype air filtration units" indicate that changes in the planes were made in an attempt to deal with this problem; iv) "an intense occurrence of odour in a flight from Sydney resulted from a seal failure." This letter is also remarkable as it attempts to stifle flight attendant discussions with the comment "it is essential that the reporting of any odour is conducted through the proper channels and not the subject of discussion outside of East West."[68]

- Ansett completed an Engine Defect Report each time an airplane was reported. There are many such reports throughout 1992, most noting oil contamination and listing the steps taken for rectification.[69] Under an entry for "Recommendations to prevent recurrence" are entries such as:

RECOMMENDATIONS TO PREVENT RECURRENCE: This is an ongoing problem and BAe, Garrett and Ansett Tech Services are conducting extensive investigation to locate the cause of this defect. To-date no definite cause has been established.

or

RECOMMENDATIONS TO PREVENT RECURRENCE: This is an ongoing defect and extensive inspection by Garrett Rep's during APU dismantle have highlighted some defects in the bellows type seal, as yet no conclusive recommendations have been made by Garrett.

Other evidence on oil leaks at Ansett was their "discrepancy reports". These are reports to Ansett engineering about problems with airplanes (see Figure 1-6, with some columns being: A/C - Aircraft Registration, ATA - Aviation Transport Association Code for Equipment, STA - Base/Port).

***Figure 1-6: Sample Ansett Discrepancy Reports***

```
MC380PDP                                         DISCREPANCY HISTORY REPORT
TIME: 13:36:10                                   FROM  01/03/92  TO  30/05/92
                                                 ----------------------------
INPUT PARAMETERS :  AIRCRAFT= ***  FLT= 01  AIRLINE= AN  ATA= SMELL DISC= ***
                    DISC TYPES= MDIS  PDIS  MTSI

 A/C   ATA   D-NO    DATE    STA  TYPE  LOG NUMBER  DISCREPANCY  TEXT
 ---   ----  ----  --------  ---  ----  ----------  -----------------
                                                    AT MAJOR PORT.

                   20MAY92        FACT              REFER 77-10/40f.

 EWR  76 40  674   31MAR92   SYD  MDIS  L 340186/1  31 DUCT O/HEAT DOLLS EYE INDICATION
                   31MAR92        FACT  L 340186/1  DOLLS EYE RESET
                                                    ENGINE GROUND RUN CARRIED OUT NIL ABNORMAL INDICATIO
                                                    NS EVIDENT
-------------------------------------------------------------------------------------------------
 EWS  21 10  674   04MAR92   BNE  PDIS  L 337630/1  BAD ODOER EVIDENT IN CABIN AFTER APU SELECTED ON AND
                                                    CABIN AIR RECIRC. AFTER LOG SMOKE AND EXTRA STRONG
                                                    SMELL FROM FLOOR VENT IN REAR GALLEY.
                   04MAR92        FACT  L 337630/1  NEW APU AND AIRCOND PACKS FITTED.
                                                    A/C DECONTAMINATED.
-------------------------------------------------------------------------------------------------
 EWS  21 20  682   02MAR92   HBA  PDIS  L 337624/1  RETURN TO TARMAC DUE OILY VAPOUR IN CABIN WITH BURNI
                                                    NG SMELL ON TAXI PRIOR TO T/O VAPOUR CLEARED WHEN
                                                    PACK #2 SWITCHED OFF [illegible] ON. REFER HISTORY
                                                    AFTER SUBSEQUENT RESELECTION ON VAPOUR DID NOT
                                                    REAPPEAR ON ADVISE FROM RAY CAIN MEL. SYSTEM RUN ON
                                                    FULL HOT FOR SEVERAL MINUTES TO BURN OUT RESIDUAL
                                                    SMELL WHICH HAS SEEMED TO HELP
                   02MAR92        MFNL  L 337626/1  SATISFACTORY FOR FLIGHT PROBLEM UNDER INVESTIGATION
                   07MAR92        FACT  W 040392/0  DECONTAMINATION CARRIED OUT.
-------------------------------------------------------------------------------------------------
 EWS  21 20  119   10APR92   SYD  PDIS  L 339127/1  OILY SMELL IS APPARENT FROM BOTH APU & ENG OPS.
                                                    IS MOST NOTICEABLE AFTER AIR HAS NOT BEEN USED
                                                    FOR SHORT TIME, THEN TURNED ON.
                                  TSI               ****************************************************
                                  TSI               15-4-92
                                  TSI                    ON ENGINES #2, #3 & #4:
                                  TSI               .
                                  TSI               1. CHECK FOR EVIDENCE OD OIL LEAKING FROM FAN EXIT
                                  TSI                  GUIDE VANE WEEP HOLE AND/OR AN OIL PUDDLE AT
                                  TSI                  6 O'CLOCK SUPERCHARGER AIR SEAL TO VERIFY OIL
                                  TSI                  LEAKAGE FROM #9 SEAL AREA.
                                  TSI               .
                                  TSI               2. REMOVE FORWARD COMBUSTOR DRAIN AND INSPECT WITH
                                  TSI                  BORESCOPE COMBUSTOR LINING HOUSING FOR EVIDENCE
                                  TSI                  OF OIL WETNESS.
                                  TSI               .
                                  TSI               *******************************************THE*RG***
```

Over the period 1992-94, there were 339 pages of discrepancy reports for the Ansett BAe 146 fleet.

These pages were analysed to see how many reports included information about odours or oil leaks. Sample reports include:

- Strong smell from aircon system noticed by aircrew and flight attendants on last part of descent and on & after landing. Nil operational impact. RH pack burn out carried out. Nil evidence of oil smell.

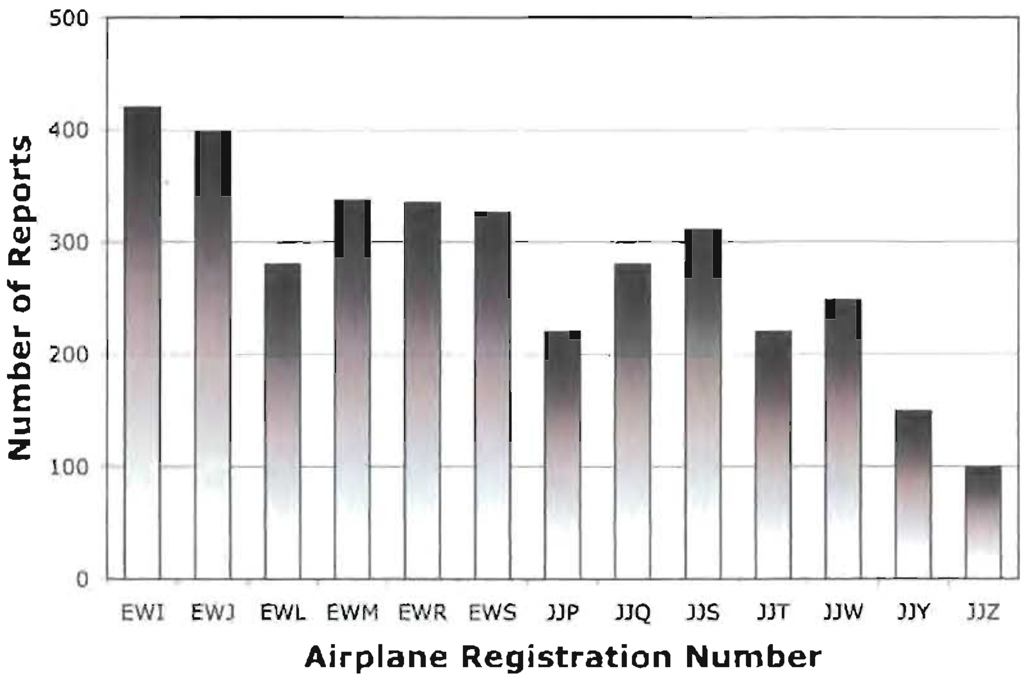
- For info: oily smell from APU air whenever used. Noted. APU air not to be used. To be investigated at comp conv. Checked for leaks, nil found. Extensive ground run carried out. Nil smells evident.

- Oily smell in cockpit from APU air, only very slight smell in cabin. Pack burn out carried out. APU cooling fan inspected nil oil evident. Report further if necessary.

In all, there were 3828 discrepancy reports; 1660 in 1992, 1093 in 1993, and 1075 in 1994;, with no apparent effect of month or season (a minimum of 271 reports in September; a maximum of 391 in May)

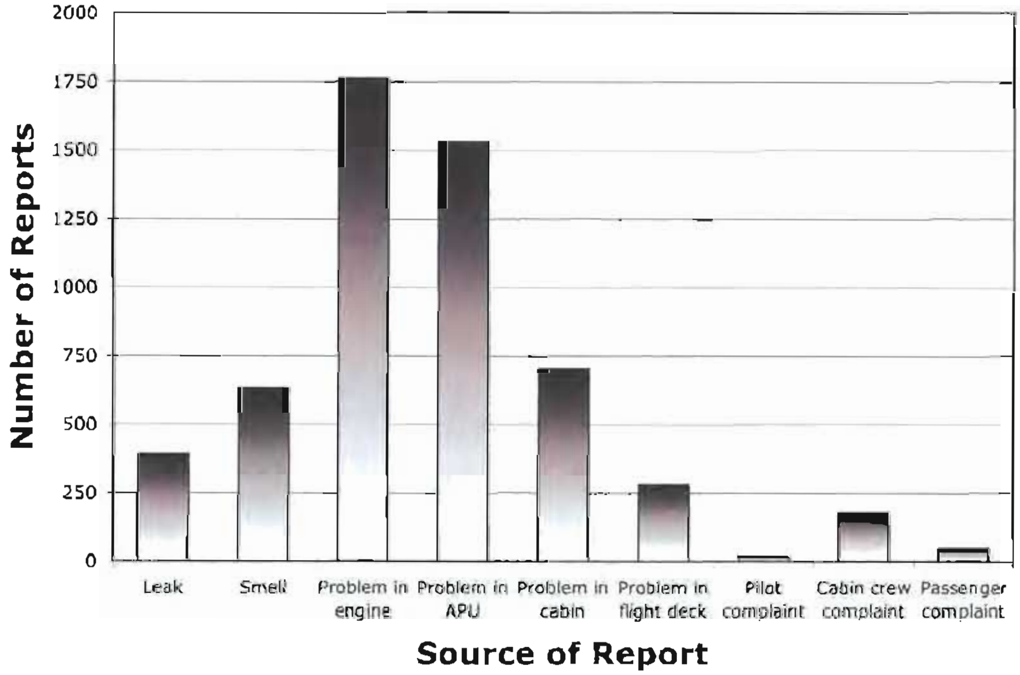
There was a perception with Ansett that the oil leak problem was only in one type of airplane (initially thought to be the BAe 146-300 series).[70] However, further analysis of this data suggests that all airplanes in the Ansett BAe 146 fleet were affected to some degree (see Figure 1-7).

***Figure 1-7: 1992-94 Discrepancy Reports, by Airplane***



Also, the source of the problem varied. Sometimes the problem was a leak; sometimes it was a smell (see Figure 1-8, where data may arise from more than one source). Most often the source was the engine (1792 reports), followed closely by the APU (1530 reports).

***Figure 1-8: 1992-94 Discrepancy Reports, by Source of Problem (Reported by Crew)***



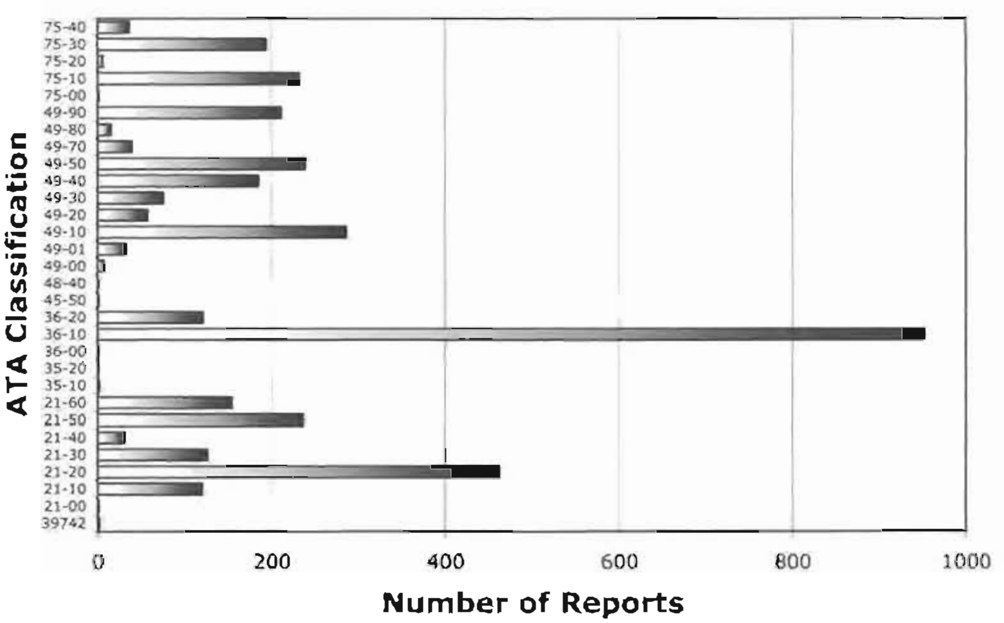

ATA Chapters mentioned in this analysis and the number of reports selected in this analysis are shown in Table 1-3 and Figure 1-9.

***Table 1-3*: *ATA Codes, Chapters and Subsections***

| Code | Chapter Heading | Chapter Subsection | No |
|---|---|---|---|
| 21-00 | Air Conditioning | General | 1 |
| 21-10 | | Compression | 120 |
| 21-20 | | Distribution | 462 |
| 21-30 | | Pressurisation control | 126 |
| 21-40 | | Heating | 30 |
| 21-50 | | Cooling | 237 |
| 21-60 | | Temperature Control | 154 |
| 35-10 | Oxygen | Crew | 2 |
| 35-20 | | Passenger | 1 |
| 36-00 | Pneumatic | General | 1 |
| 36-10 | | Crew | 952 |
| 36-20 | | Passenger | 121 |
| 45-50 | Information Systems | Miscellaneous | 2 |
| 49-00 | Airborne Auxiliary Power | General | 39 |
| 49-10 | | Power plant | 287 |
| 49-20 | | Engine | 57 |
| 49-30 | | Engine Fuel and Control | 75 |

| Code | Chapter Heading | Chapter Subsection | No |
|---|---|---|---|
| 49-40 | | Ignition/Starting | 186 |
| 49-50 | | Air | 239 |
| 49-70 | | Indicating | 39 |
| 49-80 | | Exhaust | 15 |
| 49-90 | | Oil | 211 |
| 75-00 | Air | General | 1 |
| 75-10 | | Engine Anti-Icing | 232 |
| 75-20 | | Cooling | 6 |
| 75-30 | | Compressor Control | 194 |
| 75-40 | | Indicating | 36 |

***Figure 1-9: Frequency of Discrepancy Reports, by ATA Category***




Both Table 1-3 and Figure 1-9 show that the highest number of ATA category equipment were from Air conditioning (1130 reports), Pneumatic systems (1074 reports, and Airborne auxiliary power (1138 reports).

### 1.5.2 Early Documentation about Health Problems

Mobil (manufacturer of jet oils) documentation includes:

- *In 1983, Mobil Oil (manufacturer of Mobil Jet Oil II) noted in correspondence to a customer that* "If cabin air becomes contaminated with any lubricant and/or its decomposition products, in sufficient quantities, some degree of discomfort due to eye, nose and throat irritation could be experienced. Problems like these can be generally traced to improper design, improper maintenance or malfunctioning of the aircraft."[71]

However, in a 1993 inter-Office Memo between Dr Dai Lewis and Kevin Sullivan (Ansett Air Freight), Dr Lewis noted: "*This is a worldwide problem with BAe 146 aircraft*" and "*The contaminant is known to be pyrolytic products of Mobil Jet Oil III having leaked into the air conditioning packs.*"[72]

Other documentation held by Ansett from physicians or passengers included:

- In August 1992, a letter from a Dr Joseph Waks notes he had seen four flight attendants reported dryness and irritation of the eyes and upper respiratory tract; two required in flight oxygen. These symptoms were consistent with operation of the APU. This is the earliest notification found of medical problems.[73]
- In August 1995, a letter from A and M Nasato notes "I regularly feel nauseous during and particularly after aircraft travel. Other symptoms also include frequent headaches, tiredness, I become irritated and feel uncomfortable, once again after air travel."
- In November 1995, a Dr Shaughan Terry wrote to Ansett's Medical Director responding to a reply about a flight attendant he was treating, suggesting: "*Most of the investigation that you have sent me were done by British Aerospace themselves and I wonder whether these investigations are useful from a scientific point of view as they must inevitably be biased*" and "*there is a consistent complaint from crew in many different airlines and from different countries that there is a problem with this particular aircraft*".[74]

### 1.5.3 The August 1992 Meeting at BAe, Hatfield

#### 1.5.3.1 Background to the meeting

The issue of jet engine oil leaks at Ansett/East West grew through 1992. As noted below in Section 1.6, engine oil leaks were occurring on the BAe 146 at a high rate. The problem was mainly on the BAe 146-300 series airplanes, and appeared to be due to seal failures on engines and particularly, APUs.

The documentation indirectly mentions an incident on the BAe 146 airplane VH-EWJ, where a massive oil leak occurred on a flight from Sydney to Coolangatta. Specific documentation on this incident is not available. However, the incident is sufficiently serious enough that the Flight Attendants Association of Australia (FAAA) considered a recommendation to not crew these airplanes, thereby causing them to be grounded. This was not well regarded by other sectors of the industry.

In August 1992, Ansett learned from BAe that they were having a meeting with Garrett in the UK. Alan Harrison, Ansett Aircraft Maintenance and Overhaul Director attended this meeting.[75] John Playford, industrial Officer of the FAAA was also invited to attend as an observer to allow "*BAe to suitably impress the representative with the work being done by BAe on the problem*".

### 1.5.3.2 The Meeting

A meeting was held between the parties (BAe, Garrett, Ansett and the FAAA). Documents from these meetings (no minutes are available) are illuminating as they offer a window into how this industry operates. Alan Harrison, Aircraft Maintenance and Overhaul Director from Ansett attended. His memos from the meetings offer a unique inside perspective:[76,77,78,79]

- "it would be an understatement to say that there is considerable friction between both parties (Garrett/BAe) over the subject of cabin smells."
- "Garrett still claims that the build of the APU fitted to EWJ is a contributing factor to the failure of the seal."
- "It would appear that the seal which we believed was designed for the job is in fact an existing seal used within a military application."
- "However you wish to look at it, Garret claim the seal height was excessive and thus seal face pressures were above design limits."
- "after almost 3 hours of bickering between BAe and Garrett with AN (Ansett) principally looking on, ..."
- "The last few days have been extremely hectic, and sometimes very emotional, between BAe and Garrett. For the most part our role as the customer of BAe has been one of sitting on the sidelines and watching."

### 1.5.3.3 Outcomes from the meeting

There are no minutes of this meeting available, although it became apparent that there was a problem with the specification of seals in the Garrett APU (that the wrong seal had been specified), that engineering maintenance by Ansett was probably contributing to the problem and there was a growing realisation that this was a problem for all BAe 146s with such APUs. It must have been a sobering moment when all parties considered the potential litigation that might arise.

Initially, Alan Harrison from Ansett was able to obtain agreement:[77]

- "Garrett have been asked, and have agreed, to provide a new factory built APU with the seal bellows installed for installation in an Ansett BAe 146-300 FOC" *(free of charge).*

- "Garrett will provide FOC a mechanic from their APU build area to work beside AED *(Ansett Engineering Department)* to turn around all the 150M APUs, complete with Seal Bellows, to the Garrett tolerance. The mechanic will stay as long as it takes and will have his fingerprints in every build."

- "In a nutshell Garrett will have ownership of the work performed on every APU installed within the -300 fleet. If a failure occurs they will have no-one to flick pass the problem."

- "In the meantime until the APU's are returned to service meeting the Garrett specification it is essential we operate the APU with the Bleed Air off (MEL)."[1]

- "The proposed filtration system looks good and six shipsets (Masefield) will be delivered by the end of October."

- "What we must collectively do now is apply pressure to Avco Lycoming such that they also develop engine seals to keep the bleed air system free of oil contamination."

So the main outcomes of the August 1992 Hatfield meeting were that a seal system that met the engine specification would be installed in the APU and a new filtration system would be installed on all Ansett BAe 146-300s.

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[1] The MEL is the minimal equipment list, a procedure where minimum airworthiness requirements can be met, but should be fixed in a specified period of time (normally not more than ten days).

### 1.5.3.4 The Confidential Agreements

To confirm the arrangements for dealing with the BAe 146 problem, three 1993 agreements were made, between Ansett and East West on one part, and BAe, Avco Lycoming and Allied Signal (who had taken over Garrett) on the other. These agreements follow a similar pattern with a qualifying preamble, the tem of the agreement and signatures.

**The Preamble to the Ansett/East West – BAe Agreement**

WHEREAS:

(A) Pursuant to various aircraft purchase agreements ("the Aircraft Purchase Agreements") between BAe and Ansett and BAe and EWA, BAe agreed to sell and Ansett and EWA agreed to purchase a number of British Aerospace 146 Series 200 and 300 passenger transport aircraft ("the Aircraft") upon and subject to the terms and conditions therein contained.

(B) Pursuant to the Aircraft Purchase Agreements, BAe warranted that relevant parts of the Aircraft (as therein defined) would conform to applicable specifications supplied by BAe and would be free from defects due to defective material or defective workmanship or defective design on the part of BAe all in accordance with and subject to the terms, conditions and limitations contained in the Aircraft Purchase Agreements.

(C) Ansett and EWA have made certain written claims against BAe alleging defective design of the Aircraft resulting in the production of obnoxious oil and other (the "cabin environment problem")fumes affecting the passenger cabins of some or all of the Aircraft.

(D) Following certain discussions and negotiations the parties hereto have agreed to settle such claims upon and subject to the terms and conditions hereinafter contained.

**The Preamble to the Ansett/East West – Allied Signal Agreement**

WHEREAS:

A. EWA and Ansett are the operators of certain BAe146 Aircraft incorporating Allied Signal Auxiliary Power Units ("APUs").

B. Soon after delivery of the aircraft, it became apparent that the bleed air system in the aircraft periodically circulated an unpleasant smell throughout the cabin.

C. After detailed and protracted investigations, it was determined that a source of the smell was oil leakage from Allied Signal APUs which entered the bleed air system through the air conditioning packs.

D. Over the course of several years of investigation and combating the cabin smells, significant costs were incurred by EWA and Ansett (the "Loss").

E. Allied Signal has denied that there exist any deficiencies or inadequacies in the APUs or that it has in any way contributed towards the Loss.

F. Allied Signal and EWA and Ansett seek to settle and terminate immediately all disputes, differences and claims between them in relation to the Loss and to avoid future controversy and expense with respect to the foregoing.

**The Preamble to the Ansett/East West – AVCO Agreement**

WHEREAS, Ansett and EWA are the operators of certain BAe 146 Aircraft powered by ALF502 gas turbine engines manufactured by Textron Lycoming (the "Engines"); and

WHEREAS, Ansett and EWA have alleged that they experienced engine bleed air problems between the date of purchase of the aircraft in 1989 and early 1993 (the "incidents") and that their experience with the Engines has shown that various deficiencies and inadequacies exist in the Engines, and that such deficiencies and inadequacies have resulted in economic loss to Ansett and EWA, (the "Loss"); and

WHEREAS, Textron Lycoming has denied that there exist any such deficiencies or inadequacies in the Engines, or that Ansett and EWA or either of them have suffered economic loss due thereto, and

WHEREAS, Textron Lycoming and Ansett and EWA desire to settle and terminate immediately all disputes, differences and claims between them in relation to the Loss and to avoid future controversy and expense with respect to the foregoing

The excessively legal nature of the documents is careful to deny what had actually happened, that is, that a substandard airplane containing substandard equipment had been supplied, and the airlines had suffered loss.

The services rendered in these agreements were:

- **BAe Aerospace:** Aus$750,000 being paid in two parts: Aus$300,000 by 31 August 1993 and the balance of Aus$450,000 by 31 January 1994.

- **Avco Lycoming:** US$150,000 in cash within 30 days of the signing of the agreement; and credit of US$100,000 against accounts relating to purchase of spare parts.

- **Allied Signal:** A credit of US$1,235,000, being paid in three instalments of $200,000 on signing of the agreement, US$400,000 on 1 January 1994 and US$635,000 on 1 January 1995. The credit relates to purchase of APUs and APU parts including labour and conversion kits.

While these agreements may be considered a normal part of the operational activities of commercial organisations, their content goes beyond what might be considered acceptable or reasonable behaviour, because all three contain secrecy provisions:

- **BAe Aerospace:** "The existence and terms of this agreement are confidential between the parties hereto and shall not be disclosed by any party in whole or in part to any other person or body without prior written consent of the other parties."

- **Avco Lycoming:** "Except as specifically agreed to otherwise in writing in advance by Textron Lycoming and Ansett and EWA and both of them agree to maintain the existence and all terms of this Settlement Agreement in strictest confidence and to disclose any terms hereof or information relating hereto only its employees and legal or other professional advisors. Disclosure to such advisors however may be made if they agree to be bound to the confidentiality requirement set forth on a "need-to-know" basis."

- **Allied Signal:** "EWA and Ansett and Allied Signals agree to maintain the existence and all terms of this Settlement Agreement in strict confidence and not to disclose any terms hereof or information relating hereto save as to the extent required by law."

The secret provisions in these agreements may help to explain the continuing denial by all sectors of the aviation industry that oil leaks were not a significant issue. As such, pilots and flight attendants of the airlines who had been affected by oil leaks have been denied natural justice. These Agreements constitute a mendacious and contumelious disregard for the safety of flight crew, flight attendants and passengers and represent corporate corruption of the basest type.

In a 1999 letter to Ansett from the Chairman of the Australian Senate Inquiry into Cabin Air Quality in the BAe 146, the question was put: "*I would be grateful if you could inform me about any legal action undertaken by Ansett Australia with British Aerospace as a respondent, the disclosable outcomes of such outcomes, and the current status of such outcomes.*"[80] Ansett's reply, from Captain Trevor Jensen, Executive General Manager Operations and In-flight Services was a carefully worded denial: "*Ansett Australia did not in 1992 or at any other time initiate any legal proceedings against the aircraft manufacturer British Aerospace, in respect of the BAe 146 aircraft*".[81]

Eventually, these agreements were disclosed by the Tasmanian Senator Kerry O'Brien in the Australian Senate in August 2007,[82] fourteen years after they had been signed, and eight years after Ansett had gone into receivership. Letters requesting information about this issue to Aviation regulators about the significance of these revelations were somewhat muted:

- A spokesperson for the UK Department for Transport noted: "in relation to agreements between commercial parties, these are matters for the parties concerned";[83]

- A spokesperson for the US FAA noted: "The FAA does not usually become involved in contractual agreements between manufacturers, operators, or other companies. Such agreements are outside of the scope of our regulatory authority. Therefore, it is inappropriate for me to comment further on these documents."[84]

A reply to a 2007 letter to the then Australian Prime Minister noted that it had been forwarded to the Minister for Transport and Regional Services,[85] although no reply from the minister was received.

### 1.5.4 Later Actions

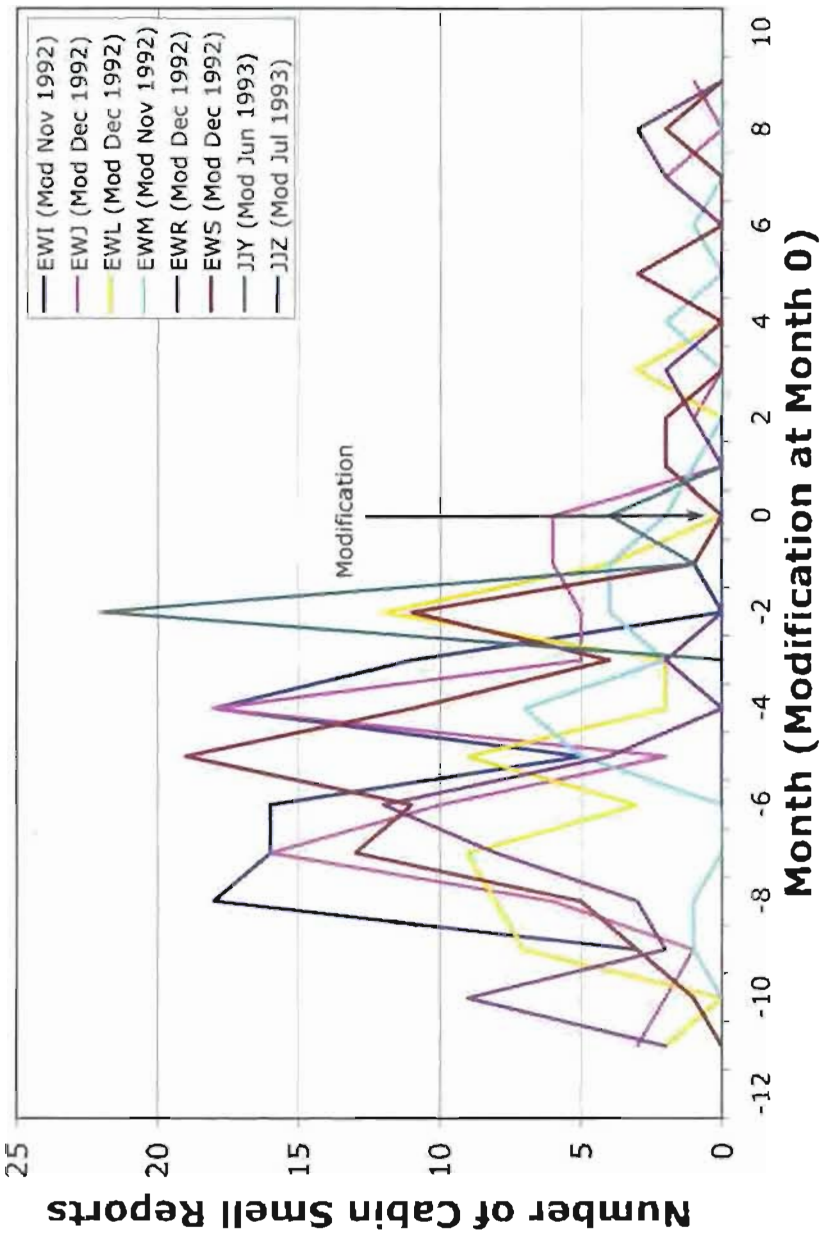
#### 1.5.4.1 Engineering Activities

Ansett were also aware that new filtration systems which could reduce odours were available in 1992, however, the urgency in which Ansett Australia gave to this matter could hardly be considered speedy. Towards the end of 1992, Mr John Bibo, Assistant General Manager - Technical of Ansett wrote to British Aerospace, "concerned at the progressive slippage of the filter program".[86] Progress was slow. An Ansett engineering release in July 1993 which followed BA Service Bulletin SB 21-70-

01316A indicated the process to be followed for the BAe 146-300 airplanes: catalytic converters were to be removed, ECS ducts were to be replaced, coalescers were to be installed, cockpit and cabin filters were to be installed, and the pack valve to duct seal was to be replaced.[87]

In a review of how successful engine modifications had been in October 1993, Mr Brian Girdwood, Engineering Fleet Manager, noted that "installation of the new filtration system had been successful and has had a significant effect on reducing the number of reports of this problem" (see Figure 1-10).[88]

*Figure 1-10: Impact of Engine Modifications on Cabin Odour Reports Jan 1992-October 1993*




However, the installation of coalescers and filters only contained the problem. The sources of the leaks had not been addressed. In November 1994, Avro International contacted

Ansett and suggested that the primary source of leaks was the carbon seal on the APU (and an ejector modification to the APU had reduced the possibility of oil contamination) and engine seals 1, 2 and 9 (the seals had been modified and an air diffuser had been re-designed).[89,90]

Modifications were not installed across the entire Ansett BAe 146 fleet. A 14 July 1995 circular from Ms Jennifer Shepperd, National Manager Flight Attendants, Ansett Australia to Cairns and Perth Crews notes "JJJ is at present in the hanger having major work on the engines and will be back on line with new filtration units." This was nearly three years after the initial circular, and two and a half years when the filtration units were said to be available. Further, some Ansett BAe 146 airplanes were not fitted with coalescers.[91]

By 1996, problems were still occurring largely because on continuing complaints by (mainly) flight attendants about the BAe 146 cabin smells. Alan Harrison, Ansett's General Manager Technical, wrote to Avro International, noting *"However, we must find ways to keep Mobil II out of the packs or we fear it is only a matter of time before every 146 in Australia is against the fence"*. Further, Ansett's continuing frustration is illustrated by the somewhat drastic suggestion *"Unless we can find a meaningful solution I will have no other choice but to suggest to Ansett that we phase out the type"*.[92]

#### 1.5.4.2 Occupational Health and Safety Activities

In April 1995, Queensland Workers compensation began denying WorkCover claims by Ansett flight attendants.[93,94]

From October 1995, in a memo to Ms Jennifer Shepperd, National Manager Flight Attendants, Dr Dai Lewis, Ansett's Medical Director, concluded that there was no toxicological hazard in BAe 146 duties, and it was his view that doctors providing illness certificates needed to be reversed.[95] Dr Lewis began attempting to advise the medical practitioners contacting him with a view to suggesting that the problem was somehow not related to oil leaks on the BAe 146.[96,97] Internal meetings at Ansett considered the issue, with a focus on minimising costs *"This problem ... is now emerging as a likely very costly workers comp and litigation problem"* and a need to keep the issue within Ansett *"Everyone is hoping this will not go outside the company"*.[98] This indicates that health problems from the oil leaks were acknowledged as a problem.

A 26 March 1996 circular from Ms Jennifer Shepperd, National Manager Flight Attendants, Ansett Australia notes "extensive air sampling, testing and analysis were undertaken over a long period of time by an independent consultant and the NSW

WorkCover Authority." This was a misrepresentation of the facts: a 12 January 1998 letter from Mr Graham Saunders, Coordinator Chemical Safety Unit, NSW WorkCover to Mr Laurie Cox of the Australian Federation of Aviation Pilots notes "A number of years ago we carried out sampling for oil mist in this model aircraft but found only a low levels of contamination. The testing was not carried out in flight and the comment was made at the time that the contamination is spasmodic so the results of our testing may not necessarily be representative of actual situations." This suggests that Ms Shepperd's belief in the results of such monitoring were not shared by its authors.

In March 1996, Dr Lewis decided it was time to be more confrontational. In an inter-office memo to Alan Harrison, General Manager -Technical Dr Lewis noted:

*"1. We are unlikely to ever fix the engineering problem to the Flight Attendants satisfaction.*

*2. They are repeatedly and inadequately briefing external agencies who then make their recommendations on ultra-poor data.*

*3. There are plenty of new age doctors out there prepared to make non-evidential medical diagnoses such as "Multiple Chemical Allergies.*

*4. The Flight Attendant Association continue to run us ragged."*[99]

This memo crystallises the approach subsequently taken by Ansett from that time, which was to challenge any external medical reports, and formulate an official Ansett position using external authorities and panels of experts. To this end, a standard letter to medical practitioners attending Ansett Crew after odour exposure was formulated, which suggested a range of transient symptoms, and that contained a denial that there were any useful diagnostic or clinical tests that could be used.[100]

The Ansett BAe 146 Air Contamination Investigative Committee had its first meeting in Brisbane on 16 May 1996.[101] A plan of action from this meeting included sampling of air, better reporting, consultation with the FAAA, and pack burns to continue. Improved procedures for dealing with fume incidents were issued in April 1997.[102]

As part of the more aggressive approach taken by Dr Lewis, a meeting was held on 27 March 1996 between Dr Lewis, Ms Jennifer Shepherd and a Medical Practitioner, Dr Mark Donohoe, who had been cited in an adverse article published in the newspaper, the Sun Herald. Even though carefully worded, the summary of this meeting indicates a certain amount of tension during the discussion. Dr Lewis: "*I thought we had this under control until the story broke in the Sun Herald*" and that "*he had been given the job of sorting this mess out before it gets* *out of hand."* Among other matters discussed, Dr Lewis' views were that the terms chronic fatigue syndrome and mult ple chemical sensitivities did not have a scientific basis. Dr Donohoe disagreed, prompting Dr Lewis to assert *"The multiple chemical sensitivities patients are neurotic, aren't they?"* Again, Dr Donohoe disagreed. Dr Lewis then suggested that Dr Donohoe did not understand the commercial implications of this issue, *"which could threaten Ansett's very existence"*. Dr Donohoe noted the issue was one of health and safety. Dr Lewis then suggested Ansett might consider legal action against the Sun Herald.[103] This was an extraordinary meeting from the perspective of how it illustrated the strong stance Dr Lewis was taking.

From about that time, air crew that had medical certificates to be excluded from flying on the BAe 146 were rostered back onto the aircraft. Complaints were received by Ansett's medical staff from flight attendants, accompanied by increased reporting of incidents.[104] By November 1996, the FAAA sought advice from Ansett about the issue.[105]

An April 1997 Ansett Aviation Medicine Advisory Circular (No 47), prepared by Dr Dai Lewis, Medical Director, Occupational Health Department, Ansett Australia also discusses BAe 146 Cockpit Odours. This circular notes that the symptom of vertigo has been experienced by two, possibly three, BAe 146 Technical Crew. This symptom had been reported by at least one pilot flying an air freighter after an oil leak flying into Melbourne n 1997 (the Kolver incident). The loss of ability to fly an aeroplane because of symptoms which can influence ability during flying is a serious safety issue and an advisory of this nature seems appropriate. However, rather than explore the issue in some depth, the advisory discusses clinical causes of vertigo, and indicates that there is no known toxicological agent that produces vertigo. However, the circular ignores symptoms other than vertigo, and the possible safety implications of pilots affected by fumes. This was left to the then Bureau of Air Safety Investigations (BASI) to investigate more rigorously.

In this particular case, a pilot experienced difficulties (difficulty in concentration, vertigo and loss of situational awareness) following the presence of strong oily odours and fumes in the cockpit while landing a plane. The pilot was sufficiently incapacitated that he had to hand over the plane to the first officer. The BASI report[106] notes:

*At 3,000 ft on approach to Melbourne Airport, the pilot suffered vertigo and handed control of the aircraft to the co-pilot. At the same time a check pilot suffered from nausea. The incapacitation occurred after the crew smelt oil fumes in the cockpit air supply.*

The onboard maintenance record noted that an oil smell had been reported 23 days prior to this incident, and that the repair had been noted for repair at company convenience, indicating even in 1997, the lack of priority that the airlines gave to oil fume problems. The consequences of what might have occurred if oil fumes had affected two of two pilots, rather than two of three pilots are unthinkable.

In April 1997, Dr Lewis began considering an active defence to hold in reserve. In a memo to the General Manager Operations, he suggested that flight attendants be transferred to ground duties where they have to work longer hours or overtime to retain similar incomes. He noted that "a threat of loss of flying duties worked well before East West were absorbed."[107] This became part of Dr Lewis' standard letter to requests for advice from medical practitioners treating flight attendants: "*We would attempt to find ground duties for your patient should you require the degree of her reaction justifies such a recommendation*".[108]

In March 1998, a "Expert Panel of Specialists for the BAe 146 Odour Occurrences" convened by Ansett meeting in Brisbane agreed that"

*"The source of the odours has been identified as primarily Mobil Jet Oil II leaking past oil seals in the engines and or APU unit into the air conditioning system."* and *"The short-term symptoms associated with odours that have been reported on the BAe 146 and other types are substantiated. These odours have been generally linked with inadequate ventilation together with aircraft system defects."*[109]

Ansett had previously admitted that oil leak problems were occurring on the BAe 146 (see above). However, here is Ansett's first public admission that exposures were associated with health problems (albeit short term symptoms).

Aviation medical staff at Ansett would have known about the occupational causes of RADS (reported in some exposed crew) from about 1985 and dermatitis from even earlier as part of their general medical knowledge. They should have been aware of the debate in the medical community about multiple chemical sensitivity, for which a definition was given in which 1987 and consensus criteria for diagnosis in 1999. However, the hard line adopted by Ansett's medical group was not conducive to a balanced debate.

Again, whether such individuals would be willing to diagnose such conditions and to associate such exposures with occupational factors may also be questioned. Certainly, in a number of court cases brought against airline employers by injured aircrew over since 1997, airlines such as Ansett and National Jet Systems have been reluctant to admit anything.

The BAe 146 has four wing mounted engines. Common to many jet engines, these comprise a high pressure compressor, the burners/combustion chamber and the turbine section. The engine on the BAe 146 also has a high pressure compressed air bleed from the engine section which is used for pressurisation and air conditioning. This air bleed is ducted to the rear of the plane, where it is passed through the auxiliary power unit (APU) and two air conditioning packs. The engines on the left wing of the BAe 146 service air conditioning Pack 1 (provides air to the cockpit and passenger cabin) and the engines on the right wing service air conditioning Pack 2 (provides air to the passenger cabin only). The APU primarily supplies compressed air for ground operation of the air conditioning system and is also used during take off and landing.

The compressor section of the engine contains lubricating oils (Mobil Jet Oil II). Engine maintenance manuals note "*Do not keep the oil on the skin for a long time. If you do not clean the oil off, the oil can cause injury*" and "*Do not let the oil stay on your skin. You can absorb poisonous materials from the oil through your skin*". This suggests that oil is hazardous. This information is obviously aimed at maintenance personnel, and presumably envisages that nobody else will come into contact with the oil.

The 1992 Australian Material Safety Data Sheet (MSDS) for Mobil Jet Oil II, states:[110]

*"Health Effects*

*This product contains Tricresyl phosphate. Overexposure by ingestion may produce nervous system disorders including gastrointestinal disturbances, numbness, muscular cramps and weakness. The effects may be delayed. ... Prolonged or repeated skin contact has produced inhibition of cholinesterases in animals"*

Ansett would have known about controls and preventive measures for using and handling Jet Oils, because their aircraft engine service engineers would have had access to manuals provided by the aircraft and/or engine manufacturer and product labels and material safety data sheets provided by the engine oil supplier. These materials are, however, deficient in providing information about oils materials that have undergone heat and pressure and possible combustive or pyrolytic degradation after leaking from an engine in flight and being present in air as vapours, mists or smoke. Further, prior to 1998, such information was not made available to aircrew who may have been possibly exposed through oil leaks.

Leaking oil seals in the compressor section suggest that oil would enter the high pressure bleed to the air conditioning packs and APU, and therefore, into the passenger cabin itself.

Leaking oil seals leak at different rates and therefore different planes will have different levels of contamination. The APU also can suffer from the same problem of leaking compressor bearing oil seals. Filters were introduced between the air conditioning packs and the cabin distribution outlets some time after 1992 (and not by Ansett until later), but are of unknown effectiveness if not regularly serviced.

A 10 July 1991 letter written by Mr RW Sands, Services Support Manager, British Aerospace, to Mr J Nicholson, Engineering Manager, East West Airlines, provides an update on the BAe 146 APU smell problem. This letter also notes that problems are reported in another airline flying the BAe 146, DanAir.

A 22 July 1991 report prepared by Richard Fox of Allied Signal Aerospace reports the results of air quality testing for DanAir London. This report notes that "*several BAe 146 aircraft are having reports of objectionable odours described as 'dirty socks or musty'.*" The report also notes that "*no contaminant appeared to be that great, but they do act in synergism and their combined effect could be enough to trigger the odour complaints.*" Here is the report of odour problems of another airline flying the BAe 146.

While pack burn outs from seal failures were supposed to be conducted while the aircraft was empty, it was common practice for such burnouts to be carried first thing in the morning, while cabin crew were getting the aircraft ready for its first flight. In April 1997, Ansett Engineering revised the instructions for air conditioning pack burn outs, including stricter attention to the absence of staff on the aircraft. Pack burn outs: i) had to be carried out after the last flight of the day or at least one and a half hours before crews attended aircraft for the first flight of the day; ii) had to be carried out every day; iii) no person was allowed to be on board during the procedure except the person carrying out the task (usually the pilot); iv) all doors and cockpit windows were to be kept open (except the front passenger door leading to the air terminal if the plane was parked at an aerobridge); v) the procedure was to be continued if an oil smell was detected; vi) the procedure had to be recorded in the maintenance log; Viii) signoff time was fifteen minutes after completion of pack burnout. This suggests that previous pack burn out procedures (going back to the procedure outlined in the 1984 SIL) were now considered problematic.

In November 1997, an Ansett "BAe 146 Update" noted that "*the procedure of a daily pack burn will cease from Wednesday 24 December 1997.*"

A 16 April 1998 operational notice written by Kingsley Hughes, Chief Pilot BAe 146, Ansett Australia, outlined recommended practices for engine/APU selection during flights and suggested that if there was an incident of odour or fumes, that pilots experiment with engine/APU configuration not to reduce the intensity of exposure, but to find the source of contamination – *"should an aircraft develop a Cabin Odour or Fumes incidence, endeavour to vary the switching order in an endeavour to localise the source."*

In May 1998, Ansett re-constituted its external panel of experts and held a meeting in Brisbane. A "consensus document" was released after this meeting, with the panel noting:

*1. The panel ... is of the opinion that the air conditioning contaminants at the levels detected for both in-flight, and worst case scenario of 'pack burnoffs', will not cause long term health effects.*

*2. The panel accepts that the short term symptoms associated with odours that have been reported on the BAe 146 and other types are substantiated.*

*3. These have been generally linked with inadequate ventilation together with aircraft system defects."*[109]

This meeting represents a watershed in Ansett's position, as here, for the first time, Ansett admitted that some health effects were occurring (albeit short term) and agreed on the source of those symptoms.

What is also acknowledged implicitly here (although not appreciated at the time) was that if contaminants were present in the airplane sufficient to cause short term health problems (that is: "crew and passenger compartment air must be free from harmful or hazardous concentrations of gases or vapors" sufficient to "to enable crewmembers to perform their duties without undue discomfort or fatigue"), then this was a breach of FAR/JAR Airworthiness Standard Section 25.831.

### 1.5.5 The Australian Senate Inquiry

The Senate of Australia had a Rural and Regional Affairs and Transport References Committee, chaired by Senator John Woodley. In March 1999, this Committee began conducting an inquiry into a range of airspace and air safety issues. One of the matters referred for inquiry was *"the evaluation of air safety, with particular reference to cabin air quality on BAe 146 aircraft"*. A large number of submissions received by the Committee secretariat (31 public and 22 private) that were concerned with the BAe 146 issue, so the committee decided to treat this item as a separate inquiry.

Nine public hearings were held in Canberra, Sydney and Brisbane from November 1999 to August 2000, where oral evidence was heard. The Committee also heard private submissions *in camera*. Although there were differences of opinion on some issues, all parties agreed that:

*"occasionally, fumes enter all jet aircraft through the air conditioning system*

*these fumes may cause temporary discomfort*

*a number of air crew had experience short term health problems*

*occasionally, oil leaks in the engines and hydraulics were the source of discomfort and maybe health problems."*[111]

The Committee's report, published in October 2000, contained eight recommendations covering accident reports, air conditioning system modifications, development of a suitable fume monitoring test, review of the toxicity of the oil, health monitoring of crew and passengers, review of workers compensation cases and cabin air filtration.[112] The Australian Federal Government's response to the Report of the Inquiry was for the Civil Aviation Safety Authority (CASA) to establish an internal Cabin Air Quality Reference Group to monitor developments in this area, which met twice in 2002-03, but thereafter did very little. Certainly, none of the report's eight recommendations have ever been actioned.

### 1.5.6 Discussion: Industry Based Information

It can be seen that there was a great deal of knowledge within the aviation industry before 1992 (and even more afterwards) that there were problems with operation of the BAe 146. It is unlikely that a responsible airline would not have been aware of such information. Other information emerged during the 1990s that attempted to deal with continuing oil leaks into the bleed air system, but these were reactive in approach, and none tried to resolve the underlying causes. At Ansett Australia, the BAe 146 continued to operate, and leaks continued to occur.

Ansett Engineering were faced with a problem that required an engineering solution, and they tried to solve this firstly within the company as the BAe 146 fleet were transferred to Ansett at the end of 1991, then with the manufacturers of the airplane, engines and APU. By mid-1992 the problem was well established and a number of options were being evaluated, including new seals, coalescers, filters, and maintenance options. Some of these began reducing the numbers of leak incidents, but none completely abolished the problem. The main issue with these solutions was the way in which all parties deliberately kept their activities confidential, through secret agreements.

The sections at Ansett responsible for health and safety of employees were also faced with the problem of their employees persistently complaining about exposures and health problems. Ultimately, the solution to this problem was to deny the problem existed, and to resist any suggestions otherwise. A number of workers compensation cases were made and some were successful.

Individuals who have experience and knowledge within any industry are sometimes more contemptuous of the knowledge of the outsider. Usually, they consider that their industry is a special case, with special needs and singular solutions for the problems they have. This "island industry" belief system is found in many industries, such as mining, construction, agriculture, defence and in this case, the aviation sector. Such individuals believe they set the agenda with regard to culture, policy and acceptable practices, and are often dismissive of any attempts to provide an alternative view. Yet sometimes, with the support of those industry professionals around them, they can make ludicrous and presumptive decisions about their actions and activities.

This was very much the position taken by Dr Dai Lewis, and hence, the rest of Ansett management. What becomes apparent in this review documentation internal to Ansett and external, is that the option of grounding the BAe 146 was never given any responsible consideration. As such, management at Ansett placed the commercial imperative above the health and safety of its employees. In this, it is clear that notwithstanding considerable activity in engineering modifications, with secret agreements and aggressive case management, they breached their obligations under Australian occupational health and safety legislation.

## 1.6 Oil Leak Incidents

As commercial imperatives drive any business, the need to keep aircraft flying is critical and malfunctions in aircraft could be seen as a threat to business activities. A system needs to be developed that identifies such malfunctions, assesses their significance and efficiently resolves the problems they create. One such problem, discussed below, deals with malfunctions in the engine or hydraulic system, that leads to flight deck and passenger cabin air quality problems.

Studies indicate[113, 114] that it is common that all modes of transport have ventilation rates less than current ASHRAE 62 guidelines for commercial buildings.[115] For example, a Canadian study of one aircraft type and airline found that 25 of 33 commercial flights did not satisfy the ASHRAE air ventilation criteria of fifteen cubic feet/occupant and that 18 of 33 flights had less than ten cubic feet/occupant.[116] This finding, of itself, does not imply poor air quality. However, it suggests that initiatives to reduce air quality should be resisted and indicates that opportunities to improve air quality should be encouraged.

The cabin of an airplane is a specialised working environment and should be considered as such. Recommendations for pressurisation of airplane cabins (to an equivalent of 8000 feet) were established in the 1960s using healthy male volunteers from the military.[117] This is sufficient to lower the partial pressure of oxygen (from 159 mm Hg at sea level to 118 mm Hg), that is, a level that may have an impact on physiological function (itself dependent on blood $O_2$ saturation) of some individuals and an impact on physiological function is more likely where individuals are undertaking effort.

The oils and hydraulics used in airplane engines are toxic, and specific ingredients of oils are irritating, sensitising and neurotoxic.[118] When oil or hydraulic fluids leak out of the engines, this contamination may be in the form of unchanged oil/fluid, degraded oil/fluid from long use in the engine, combusted oil/fluid or pyrolised oil/fluid. A leak may be in the form of gases, vapours, mists and particulate matter. If leak incidents occur and the oil/fluid is ingested into the air being used for the cabin (bleed air) and passed to the flight deck and passenger cabin, exposed staff and passengers may be exposed to contaminants that can affect their health and safety and do they not have access to appropriate information that can advise them as to hazard, risk or control of exposure. Where leak incidents are known to be mixed forms of contaminants, an additional component of toxicity exists whereby irritant or toxic vapours or gases may be adsorbed onto the surface of mists or particulates. Under such circumstances, the dose response characteristics of the gas or vapour may be altered. Therefore, the use of risk acceptability criteria for chemical exposures such as exposure standards or threshold limit values (TLVs) to conclude that exposures are acceptable is inapplicable in certain situations in the aviation industry.[118,119] Such standards should not be applied at altitude, or in other situations where the possibility of escape to fresh air is lacking. Acceptability criteria for chemical exposures at altitude must consider the interaction of reduced oxygen, skin exposure to mists, and interactions with other contaminant exposures.

*"Contaminants may be well below current recommended safety standards, yet generate complaints due to the synergistic effect. Some standards are outdated having not incorporated more recent medical and scientific evidence. Additionally, extenuating factors onboard aircraft including humidity and cabin pressure have not been studied to the extent that new standards can be proposed incorporating these factors or interactions between them."*[120,121]

There is currently no agreement amongst aviation toxicologists on whether the Threshold Limit Values (TLV's) or NASA Spacecraft Maximum Allowable Concentrations for Airborne Contaminants (SMACS) are the most appropriate toxicological standard.[122] Symptoms of immediate nature and reported by exposed staff in single or few leak incidents are consistent with the development of irritation and discomfort. Symptoms of a short term nature (that is, continuing symptoms for up to six months) reported by some exposed staff following small numbers of leak incidents are consistent with the development of initially temporary but eventually irreversible health problems in a number of body systems. Additionally, symptoms of a long term nature (that is, sustained symptoms for at least six months) reported by some exposed staff following small to moderate numbers of leak incidents are consistent with the development of an irreversible discrete occupational health condition, termed aerotoxic syndrome.[121,123] When the level of contamination of air in flight deck and passenger cabin is sufficient to cause symptoms of discomfort, fatigue, irritation or toxicity, this contravenes air quality provisions of the Federal Aviation Regulations (FAR) or most notably FAR 25.831a/b.[124]

This is a significant aviation safety matter to pilots, cabin crew and passengers where leak incidents affect the ability of pilots to fly planes safely or the ability of cabin crew to perform their duties as expected in either normal or in emergency conditions. Also, there is a significant health and safety matter to airline staff and passengers where leak incidents affect their health.

Information provided by oil manufacturers to airplane manufacturers understates the toxicity of their oil products.[118] This has been accepted uncritically by aircraft manufacturers and airline operators and is used by them in a manner that misleadingly understates risk. Additionally, all studies that have been carried out to measure atmospheric contamination in airplanes from leak events are sufficiently flawed on methodological inadequacies as to render their conclusions invalid.[118]

Evidence is available that suggests that there are a substantial number of leak incidents on airplanes, especially on certain models of aircraft. Many of these leaks go unreported to aircraft operators. Of those leak incidents that are reported to aircraft operators, many are not reported to regulatory authorities and those leak incidents that are reported to regulatory authorities, not all are added to relevant databases. Additionally, only a very small number of leak incidents are investigated fully and available for review, however most of these investigations have been found to be inadequate.

### 1.6.1 Engine Lubricating Oil and Hydraulic System Malfunctions: Sources of the Problem

The aviation industry itself acknowledges that air quality exposure events are primarily due to oil leaking into the air supply. For example, company memoranda, industry and government submissions to previous Government Inquiries, and other documentation indicate:

- Society of Automotive Engineers (SAE) Aerospace Information Report[125]

  *"Engine compressor bearings upstream of the bleed ports are the most likely sources of lube oil entry in the engine air system and thence into the bleed system contaminating the cabin/cockpit air conditioning systems."*

- Mobil Oil (manufacturer of Mobil Jet Oil II)[126]

  *"If cabin air becomes contaminated with any lubricant and/or its decomposition products, in sufficient quantities, some degree of discomfort due to eye, nose and throat irritation could be experienced. Problems like these can be generally traced to improper design, improper maintenance or malfunctioning of the aircraft."*

- Allied Signal (Manufacturer of Airplane Auxiliary Power Units, or APU)[127]

  *"Several BAe 146 aircraft are having reports of objectionable odours described as "dirty socks" or musty smells. Very little work has been done in the aviation industry to pinpoint the chemical compounds causing such odours ... the odour appears to be coming from breakdown products of the oil, either through incomplete combustion on the catalytic converter, or by chemical or biological reaction occurring in the environmental control system of the aircraft."*

- British Aerospace (BAe, Manufacturer of airplanes)

  *"Every engine leaks oil from its seals and bearings."*6

  *"The air supply is protected from contamination by seals, which achieve maximum efficiency during steady state operation. However, they may be less efficient during transients (engine acceleration or deceleration) or whilst engine is still achieving an optimum operating temperature. Improvements in seal design continue to increase efficiency, and when available, modifications are provided for the engines and APU".*[128]

  *"Reports of cabin air odours have been received from time to time and have predominantly been determined to be due to minor systems failures such as leaks from oil seals on the aircraft engines or APU"*[6]. *BAe Service Information Leaflet (SIL) 21-45 Troubleshooting - Operator experience of oil contamination of the engine/APU bleed air."*[129]

- Ansett Australia (former Airline)

*"The source of the odours has been identified as primarily Mobil Jet Oil II leaking past oil seals in the engines and or APU unit into the air conditioning system"*[130]. *" the short-term symptoms associated with odours that have been reported on the BAe 146 and other types are substantiated. These odours have been generally linked with inadequate ventilation together with aircraft system defects".*[131]

- The Civil Aviation Safety Authority of Australia (CASA)

  *"All engines and APUs leak oil and suffer fumes as a feature of the design of air conditioning systems using bleed air."*[132]

- The Civil Aviation Authority of the United Kingdom (CAA)

  *"Although the exact cause of crew incapacitation is not yet known, the most probable source is oil leaking from the engines or APU and contaminating the air supply to the cabin and cockpit through the air conditioning system."*[133]

  *"Although the immediate investigations were not able to find a definitive cause of the symptoms experienced, circumstantial evidence suggested potential contamination of cabin air by abnormal concentrations of noxious gases or vapours."*[134]

  *"Evidence from these incidents indicated that contamination of the ventilation systems by engine oil fumes was the most likely cause."*[135]

There is a paradox that all parties acknowledge that a problem exists, but then deny that it is a serious matter. Many deny that it is an air safety issue, rather an occupational health and safety (OHS) general health issue or comfort issue.[6,130,131,132,136]

Dozens of in-cabin leak/smoke events are documented annually, often correlated to aircraft fluid leak events. However leak incidents are much more frequent, correlated to less obvious aircraft fluid leaks and residual contamination that are seen by many as a normal part of flying.[118,137]

### 1.6.2 Regulatory Requirements

National aviation safety regulations such as the FARs and JARs cover areas of airplane performance, and include ventilation airworthiness requirements that require a sufficient amount of uncontaminated air to be supplied that enables the crew to operate without undue discomfort or fatigue and that the cabin be free of harmful or hazardous levels of gases or vapours.[124]

While the term "undue discomfort" may be interpreted subjectively, the presence of contaminants in airplane air sufficient to impair flight crew capability or the ability of cabin crew to perform their duties effectively as expected under the legislation, would seem to be an apparent example of a breach of these regulations.

While the term "harmful or hazardous levels of gases or vapours" may also be subject to misinterpretation, especially in the use of measures of risk acceptability such as exposure standards, at least these offer the potential of clarifying minimum sea level equivalences of what constitutes "harmful" or "hazardous". Lack of or inadequate monitoring can not imply there are no harmful or hazardous contaminants present if reports are consistently being made.

The aviation industry refers to ozone, carbon monoxide and carbon dioxide when considering contaminants in terms of the airworthiness requirement,[138] and has until recently ignored all other contaminants.

### 1.6.3 Reporting Requirements

There is a spectrum of defects and malfunctions in an airplane engine ranging from the trivial, to the serious, to the catastrophic. As trivial malfunctions can escalate into serious events, it is necessary to ensure that all types of malfunctions are identified, investigated and rectified.

FAR/JAR regulations impose strict guidelines on how aircraft defects are defined, must be reported, investigated and dealt with. Of necessity, these are based upon those airworthiness standards taken from the FAR's and JAR's which cover the aircraft design and operation.

The regulations are clear on maintenance and reporting, for instance in the UK, the aircraft commander must report all technical defects in the aircraft technical log[139]. Reportable occurrences are incidents or defects which if not corrected would endanger the aircraft, its occupants or any other persons and are to be made to the aviation regulator under the Mandatory Occurrence Reporting (MOR) scheme. These must be filed by the Captain as an MOR with the CAA within 96 hours so as to advise of hazardous or potentially hazardous incidents and defects.[140,141] A few examples include fire, explosion, smoke or toxic or noxious fumes which resulted in the use of emergency equipment or procedures, incapacitation of any member of the flight crew or incapacitation of any member of the cabin crew which renders them unable to perform essential emergency duties, leakage of hydraulic fluids, fuel or oil which resulted in possible hazardous contamination of the aircraft structure, systems or equipment or risk to occupants.

In Australia, reports required include reports of "major defects" and "defects". A major defect is "*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*",[142] or "*smoke, toxic or noxious fumes inside the aircraft*".[143] All defects must be reported in the aircraft technical log by the pilot by the termination of the flight,[144] with a defect being seen as an "*imperfection that impairs the structure, composition or* *function of an object or system"*.[36] Reports on major defects such as oil contamination must be made and investigated in a variety of ways and reported to CASA within two days[144,145] as well as the "accumulation or circulation of toxic or noxious gases in the crew compartment or passenger cabin".[146] Air safety reports must be made to the Australian Transport Safety Bureau (ATSB) within 72 hours for any occurrence that could affect the safety of the operation of the aircraft.[147]

### 1.6.4 Evidence of Reporting of Defects

The reporting systems documented under the International Civil Aviation Organization (ICAO) protocols and legislated by national aviation safety regulations are established so that information arising from incident events passes from the aircraft operator, to the regulator and manufacturer, such that modifications can be made where necessary and so that the information is shared by all parties. These must be adhered to for the information to be utilised effectively.

However, there are many different types of mandatory and non-mandatory report formats available with some of the mandatory reports including: defect reports in the aircraft technical log, defects and major defects sent to the aviation regulator and air safety incident reports. Some of the non-mandatory ones include: airline and crew internal reports/information, reports sent between the manufacturer, regulator and operator, confidential reports to the regulators or bureau of air safety, union reports, crew surveys, medical/legal reports, passenger reports and so on.

In fact, for such a heavily regulated industry, there is a surprising lack of conformity in the ways in which malfunctions and defects can be reported in the various national systems.

Other possible sources of data that can be used to suggest that incidents are occurring include manufacturer's Service Bulletins (SB), Service Information Leaflets (SIL) and Airworthiness Directives (AD) that are issued to deal with problems identified in the operation of aircraft.

Despite the fact that there are over 240 Service bulletins and service information leaflets and other manufacturer and operator communications for two aircraft types relating to the specific issue of oil leaks and fume contamination from 1984-2003 which are advisory[148], the CAA and CASA have only issued three Airworthiness Directives (ADs) in support of fumes. An AD is issued by a regulator to compel the aircraft operator to comply with manufacturer's service bulletins in the case where a safety threat exists or could exist. Until recently oil fumes in Australia were not seen by CASA as a major defect and were not forwarded to CASA, despite the regulations necessitating this.[149,150]

A small fraction of the known reported incidents has been collected together and is based on reported and accessible information. This information must be looked at whilst bearing in mind the scale of under reporting, which is examined below. The information available clearly varies greatly dependent on the source. It can be seen that there are a substantial number of reports on particular types of aircraft. Some of the more significant ones are:

Despite even the very limited numbers of incidents reported (which are quite high), particularly in the case of the Ansett Australia Airlines BAe 146, the aviation industry regulators report that fumes/oil contamination is a rare event.

Ansett Australia Airlines claimed fume events are a "very, very rare occurrence"[130] but at the same time encouraged its crew to report odour occurrence events (yet this was acknowledged as still widely under-reported[151,152]). The crews who worked on a fleet of 13-15 aircraft, operating an average number of 3-5 sectors per day, reported one fume related event every 66 flights in 1992, reducing to one every 131 flights in 1999.[130] The odour/fume reports were primarily associated with leaking oil.[130] Therefore, this "very, very rare occurrence" could amount to a fume/oil related defect report every day or two.

In the UK, the CAA state that smoke, gas or leak incidents occur once every 22,265 flights (128 events from 1989 to 1999)[153,154] and the CAA say they have 189 MOR reports on two aircraft types (162 from 1996 to 2004).[153] The UK Air Accidents Investigation Bureau (AAIB) had nineteen reports of smoke/fume incidents from 2000 to 2002 on the BAe 146 and B757.[155]

In the US, the FAA state there is one air quality incident every 3,590,000 departures (23 related to toxic contamination in ventilation systems) and the FAA AIDS database has 60 cases of ventilation toxic contaminant events from 1978 to 1999.[156]

In Australia, CASA states there have been 22 events in six years[157] (despite providing evidence showing defect reports occurring up to every 131 flights on BAe 146 fleet, being almost every day). Fume events are also thought to be 50% greater than reported,[158] with others suggesting a 90% under-reporting rate with fumes seen as a normal part of flight[137]. The Australian Bureau of Air Safety (ATSB) had 32 BAe 146 incident reports of oil or hydraulic fumes/smoke or odour incidents from 1991 to 2002.[159,160]

Some data are known to have been reported fails for various reasons to actually be present on regulator databases. BALPA has 47 Boeing 757 reports sent direct from crews via email or submitted to airlines which did not get entered into UK CAA database along with 22 BAe 146 airline reports all from one airline which are not on UK CAA database.[161]

Another example of how many regulator databases lack accuracy in relation to fume events is that there are 775 mandatory Australian BAe 146 aircraft log reports[130] and 791 optional "BAe 146 odour occurrence reports" [162] which reported to Ansett Australia, yet only 32 were received by the Australian Transport Safety Bureau (ATSB),[159] and a very small number appear on the Australian CASA database.[157]

Use of information from within one source is often inconsistent and can vary greatly. An example is the UK CAA data bases which list 56 fume events from 1996-2003, 66 cases where crew and passengers suffered symptoms of discomfort while the MOR data base shows 162 reports during this period. This does not even take into account the incomplete database and under-reporting factors.[133,160,163]

The differing databases and lack of real understanding of the scale of the problem led one BAe 146 operator to state that events were increasing over a period of time while the regulator stated there was a decrease in reports.[164,165]

Other examples of how defects and fumes are reported include:

- *BAe Complaint of difficulty report: Report 27803. BAe 146 reported by B Rogers of BAe regarding Dan Air:* "Can Hatfield (British Aerospace) provide a definitive statement on the medical implications of fumes/smells in the cabin ... Dan Air cabin crew have complained of headaches and nausea ... Here we have a reported case of fumes and nausea and despite a two year wait we still have not statement on health and safety. Can you please hasten an answer at this point" *(February 1991).*[166]

- *Ansett Australia BAe 146 odour Occurrence report:* "All three flight attendants had tightness in chest, sore throats, headaches, slurred speech from purser during P/A" *(May 1995.*[158]

- *UK Air Safety Report (ASR) - B757:* "Toxic fumes in flight deck. Aircraft had two previous flights with oil fumes in flight deck reported. Suggests air conditioning ducting needs to be cleaned before further flight. Captain felt giddy and ill, while First officer, ground staff and cabin crew all reported headaches and feeling unwell" *(1998). This ASR was not passed to the UK CAA, despite the MOR box being ticked requiring report to be forwarded to UK CAA.*[159]

- *UK CAA Mandatory Occurrence Report 200007913 - B757:* "Fumes on flight deck and in cabin. Recurring fault considered to be residual engine oil contamination in the bleed ducts. Reporter confirms that similar incident had been reported on previous sector and that the aircraft has a history of oil leaks ... although there were no written reports as such. After take-off thrust was set, a strong smell likened to "burning rotten socks" was apparent on flight deck ... during climb, smell was still evident on flight deck - each pilot in turn breathed 100% oxygen because they both felt light headed....on shut down both pilots still felt light headed and also shaky" *(October 2000).*[167]

- CASA Major Defect Database - BAe 146: "No 1 engine No 9 bearing seal leaking. Suspect fumes entering cabin and causing crew problems" (August 2001).[157]

A study conducted by the US Association of Flight Attendants over the period January 2006 to June 2007 collected a dataset of 470 air supply contamination events (an average of 0.86 events/day). The authors of this paper still consider their data are an underestimate.[168]

Indeed, the difference between statistics due to under-reporting, varying data on internal databases, reporting to operators and "official" reporting to regulators allows all parties to use flawed data to perpetuate well entrenched positions with important health and safety trends ignored.

### 1.6.5 Under-Reporting

The Australian Senate inquiry into the BAe 146 cabin air quality recognised that under-reporting was a major problem.[169] The 2001 BALPA Boeing 757 survey reported 1667 fume/smoke incidents, while the UK CAA database shows only 104 Boeing 757 reports[160] highlighting the problem of relying on regulator databases for accuracy of the scale of the problem whilst under reporting continues to occur.

The reasons for under-reporting are complex. There is a long standing culture existing in some airlines of crews not reporting fumes or reporting leak incidents verbally[170] and some crews may be discouraged from writing reports in the aircraft log.[171] It must also be remembered that fumes and their effects are poorly understood by crews and dismissed by many in the aviation industry as not being an aircraft safety issue but a health problem.[6,130,132] Crews are advised that inhalation of aircraft oil/fluids is not harmful to their health and that their symptoms are not related to aircraft air.[157] Crews may be fearful of reporting fumes due to awareness that some crews have been harassed, stood down and or terminated after reporting fumes,[164,172] and that others have lost their medical licences.[173] Others have continued their rostered duty after fume events as the effects are poorly understood or they have been advised or felt the pressure to continue flying.[150,158,160,169] Others report fear of being branded as troublemakers as they would be reporting fumes too often if all cases of fumes were to be reported in the aircraft defect.[150] Additionally leak incidents that do not affect all crew members equally are not viewed by some as an aircraft defect.[174]

Oil seals are not as efficient in certain stages of flight and therefore the problem may be seen as being intermittent and part of normal operations.[128] Failure of some airline engineers to rectify leak problems or to comply with ventilation regulations such as FAR/JAR 25.831 does not encourage crews to report fumes, especially when leak incidents are often reported to be rectified at "company convenience",[175] "not safety of flight", "for information only", "no fault found", "report further" or similar.[137,160]

Leak incidents may occur over numerous sectors and are often ongoing over days, sometimes months[160,164] with residual contamination being an important problem on some aircraft[118,176] which also fails to generate reports. Additionally there is an accepted practice in the industry of only reporting non vital defects at the end of the day or duty.

Engineers may have difficulties in tracing and isolating the source which may result in the aircraft being returned to service with "no fault found" and the leak unresolved.[136,160,176]

### 1.6.6 Discussion: Number of Incidents

It can be seen that there are engine oil and hydraulic fluid leaks occurring on aircraft due to reasons which include the design issue that some engine seals not as efficient in transient operations, residual contamination events and more major contamination events due to part or full system malfunctions. This combined with the fact that fume events have been under recognized and under-reported and seen as more of a nuisance, raises a number of significant concerns.

It is clear that these fume events and the medical effects experienced by crews and passengers, occur a lot more frequently than the industry and regulators are prepared to publicly accept. In some cases the regulator actually denies that pilots could conceivably fail to report all fume events, yet this is factually known to be occurring.[150,157,170,177]

Even if collated fully, the documentation will not collect together the majority of incidents actually occurring because of the under-reporting problem, but it could at least show important trends. Despite fume events relating to oil contamination being dismissed by the CAA as being of "no risk to health or safety"[178] the lack of accurate data is of concern due to the health and safety ramifications from the medical effects of crew breathing contaminated air. Crew symptoms of feeling unwell and irritation are not seen as a regulator responsibility unless classified as partial impairment or greater such that the safety of flight and landing is effected.[163,177] Regulatory agencies and manufacturers usually claim the issue is one of OHS importance and not one of flight safety132, despite acknowledging this is outside their field of expertise.[6,132] Conversely, the OHS authorities claim the problem is not within their responsibility as it is a regulator problem.[174] Airlines not surprisingly usually claim it is neither a health or safety issue.

While fumes have generally been dismissed as a "non event",[179] one manufacturer has acknowledged that fumes were previously seen as a "nuisance" rather than a potential threat to flight safety.[180, 181] Aviation safety notes that use of oxygen is a "serious incident", [182] but crews are generally not using oxygen even though advised it is required when fume events are suspected.[133]

The true extent of the problem remains largely unknown. For the full scale of the problem to be better understood the regulators need to enforce regulations that require leak incidents to be reported and the reports that are made need to be forwarded to the regulators as required by the legislation.

In general, the regulations surrounding contaminated air defects on aircraft are not being followed. While low numbers of major incident leak reports get reported and investigated, this process is often inadequate.[135,155] Most others slip between the cracks and a lot of objective information is deemed anecdotal by industry. This allows an inaccurate picture of the real situation to develop, which is then accepted as reality, adopted as practice and defended with the rigor that only incorrect dogma can produce.

Whilst civil aviation has denied and continues to deny the scale and effect of these issues from both an under reporting and medical effect perspective for over thirty years, the military now accepts that "the occurrence of smoke and/or toxic fumes in the aircraft cockpit or cabin is more common than is generally realised" and "there is some evidence that continued exposure to small amounts of certain contaminants may produce chronic, long term, and irreversible damage to humans".[119]

Ultimately, the issue of aircraft air contamination due to oils and hydraulic fluids leaking into the aircraft air supply is a known problem in the aviation industry. There are a range of regulations that are in place to ensure all cases of fume contamination are reported and therefore investigated. However there is strong evidence that the reporting system to regulatory agencies is not working, and consequently, under-reporting is occurring and the fume events taking place are considerably higher than the aviation industry admits. There are a variety of reasons for this, including commercial pressures, fatalism about long standing and apparently insurmountable engineering problems, operational procedures that focus keeping aircraft flying and a culture to minimise health and safety risks. These have significant health and safety implications for crew and passengers.

## 1.7 Cabin Contamination of the BAe 146

This report concerns itself with the contamination of the cabin of the BAe 146 by toxic chemicals and the production of symptoms of toxicity in exposed airline personnel, both flight attendants and pilots. The relevant constituent components of the BAe 146, and the problem of cabin contamination of the flight deck and cabin by bleed are, are discussed below.

### 1.7.1 The BAe 146 Airplane

The BAe 146 was developed in 1973 by British Aerospace and is a medium sized non-jet airplane designed for short-range transport. It was first test flown in 1981, and was flying commercially by 1983 (Dan-Air was the first airlines that used this plane; Ansett Australia was the second).

By the end of 1993, a total of 217 BAe 146 aircraft were in use worldwide, of which 193 were being operated by 59 different airlines.

The BAe 146 airplane ceased production in 2002.

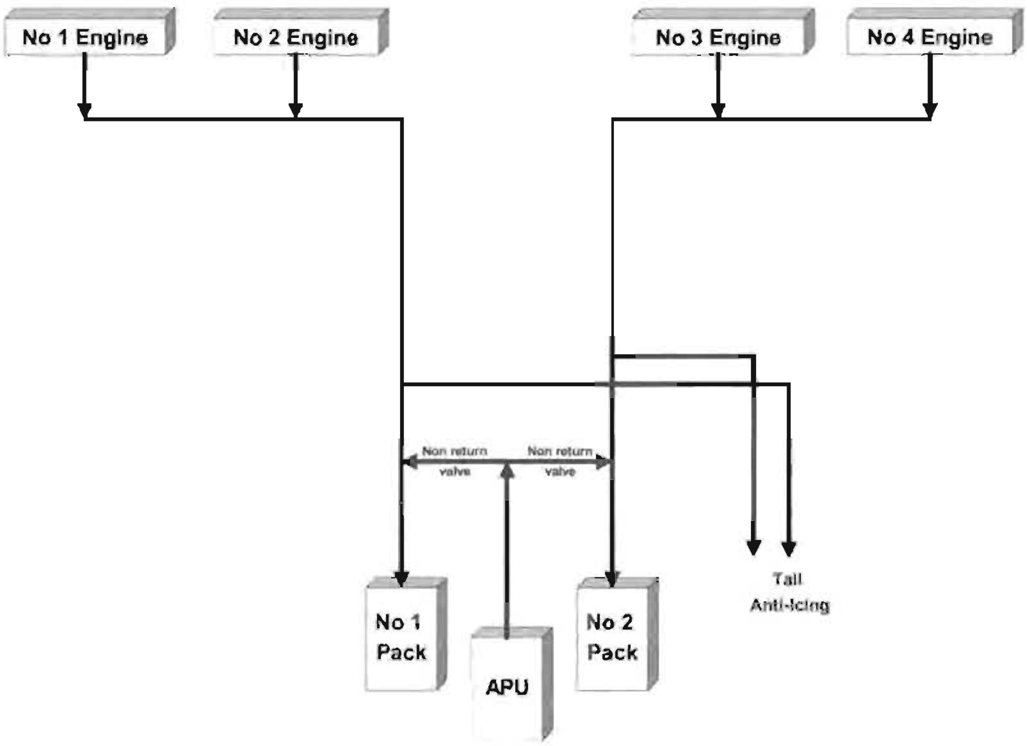
### 1.7.2 The BAe 146 Engines

Aircraft engines rely on mass inward airflow to produce forward thrust for the forward motion of aircraft.

The BAe 146 has four wing mounted Textron Lycoming turbojet engines (ALF502R5) engines; these engines are only used on this airplane. This engine was designed for heavy lift helicopter use by the US military in the Viet Nam war (that is, for vertical engine orientation), and not for commercial fixed wing airline transportation (which use a horizontal engine orientation). This means engines on the BAe 146 are of a smaller design/size, and have proportionally larger thermal/expansion stresses along with extreme high (15,000/20,000) revolutions a minute (rpm) to produce littlely forward thrust of approximately 6500 lbs/engine - at all power settings. For this reason, the BAe 146 requires four engines.

Common to many jet engines, the engines on the BAe 146 comprise a high-pressure compressor, the burners/combustion chamber and the turbine section. The engine also has a high-pressure compressed air bleed from the engine section, which is used for pressurisation and air conditioning. This air bleed is ducted to the rear of the plane, where it is passed through to two air conditioning packs. The engines on the left wing of the BAe 146 service air conditioning pack 1 (provides air to the cockpit and passenger cabin) and the engines on the right wing service air conditioning pack 2 (provides air to the passenger cabin only, see Figure 1-11).

***Figure 1-11: Schematic of Air System in the BAe 146***




The bearings in the high pressure engine compartment are separated from the compressors supplying the bleed air system by the use of carbon seals. These seals are delicate structures that rely on precise tolerances in order to maintain their ability to maintain an adequate seal. They stop the flow of oil from the "oil side" of the engine to the "bleed air side", but may leak when the engines are powering up (pressure from the engine side is required to bed the seals for normal operation), or when they are improperly installed, or when they become worn, cracked or distorted, or when the spring washers used to maintain pressure are not to specification.

The design features for the BAe 146 engine incorporated many changes to produce forward thrust, including the addition of a fan and nozzle bypass. Many modifications may have been incorporated that have been basically unsuccessful or have produced poor results. Other components of the engine (such as seals) have not been changed from the original design.

Further, engine operational conditions such as temperature and pressure are high and cause problems such as internal and external thermal stresses, thus contributing to the poor reliability of the engine.

The engines can ice up at high altitudes, and therefore the BAe 146 is not allowed to fly above 26,000 metres or be in the vicinity of cloud formations, or "roll back" can occur. This term describes the situation where all engines have failed and the analogue meters in the cockpit that show engine rpm "roll back" to zero - an example of risk understatement common in industries that attempt to normalise or minimise danger.

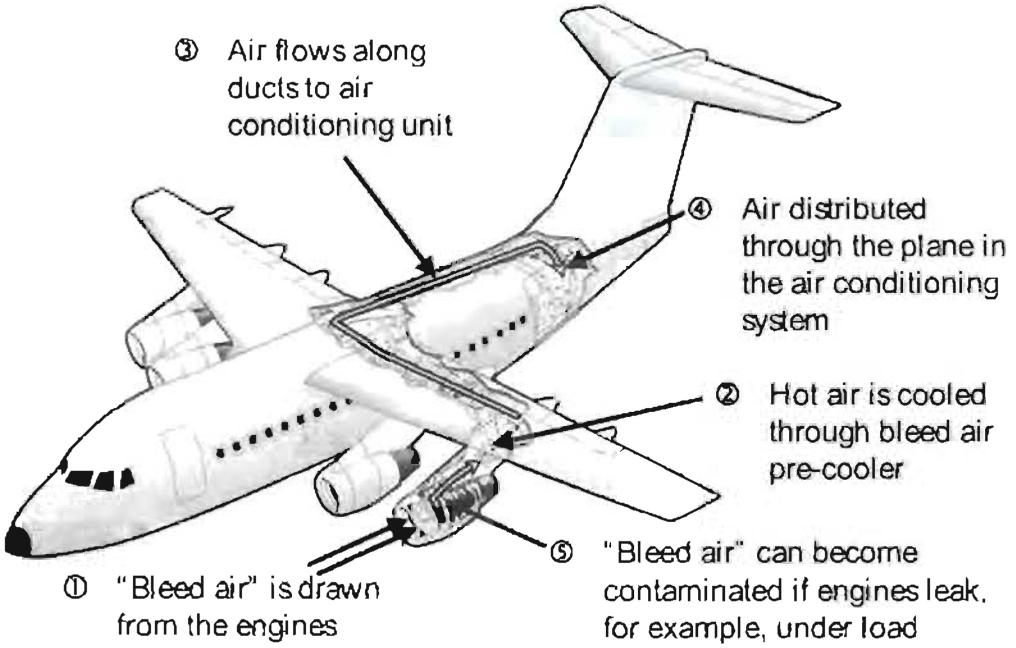
Air for cabin pressurisation derives air from engine compressors (bleed air). The demand for bleed air is high, thus causing further stresses as the volume of air to the engine is low while the pressures and temperatures in the engine are high. These physical properties are true in the sense that they comply with the first and second laws of thermodynamics.

Bleed air can operate in fresh air (all air to the cabin comes directly from the engines) or re-circulated mode (air in the cabin is passed back into the air conditioning system and re-used at rates up to 60%). Fresh (bleed) air has an extremely low humidity, and can produce dry eyes and upper airway dryness which in turn can lead to irritation. Recirculation of air through the cabin allows the humidity to be increased. This means that passengers are used as humidifiers. As also, as air filters, too.

The operational demand conditions of the engine indicates that at conditions of high demand (such as take off) and while in fresh air mode, insufficient airflow to the engine places additional loads upon mechanical seals and bearings, which become excessively out of operational specifications.

The mechanical carbon seals are a major concern (its backup spacer ring fails thus causing the bearing faces to misalign thus causing oil to enter the compressor air side of the engine). Bearings and mechanical seals tend to develop an eccentric shape due to the elastohydrodynamic characteristics of lubrication. This is a major contributor to passenger cabin/flight deck air contamination (see Figure 1-12).

***Figure 1-12: The Bleed Air System in the BAe 146***




One further feature is that the ducting for the latter part of the air conditioning system is partially made of fibre glass, probably used for weight purposes. However, oil leaking through the system will adsorb onto and into fibre glass materials, and even if removed from ducting, will continue to vapourise from such surfaces. This perhaps provides a reason for the "146 smell".

While the engine seal system meets relevant regulations and standards, it is, frankly, substandard. The mechanical seals that have failed on the BAe 146 (to keep the oil/air breather systems apart) were not designed rigorously enough to do the job. This has been shown many times due to the poor maintenance reliability of engine components that have failed in use.

In fact, the reliability of the components in this engine is and remains poor. This leads to engine failures with in flight engine shutdown due to either oil loss or contamination. In turn, this leads to further problems with operational and maintenance procedures, and with crew and passenger discomfort. So, when the engine seal system fails, it almost certainly fails relevant regulations and standards.

### 1.7.3 The BAe 146 Auxiliary Power Unit (APU)

The BAe 146 also contains a Garrett/Sunstream auxiliary power unit (APU) which primarily supplies compressed air for ground operation of the air conditioning system and is also used during take off and landing. The APU is secondary to the engines, and may be turned off without causing any problems (providing the engines are working).

The APU is a small turbine compressor that supplies the air conditioning system combined with a generator installed on the gearbox to provide electrical power. The APU also contains carbon seals with some of the same problems as those in the engine. That is, the APU seals are a known source of air contamination through the front compressor seal, cooling fan seal and APU plenum to gearbox seal.

A schematic of the engine, APU and air conditioning packs was shown in Figure 1-11.

Both the engines and APU have been implicated as sources of the fumes/mists that have entered the flight deck and cabin, although the engines are considered the main source of the problem.

### 1.7.4 The BAe 146 Environmental Control System (ECS)

The BAe 146 environmental control system (ECS) comprises a series of ducts, valves, air cycle machines, filters, coalescers and other components.

If the ECS became contaminated, a full removal and cleanout of the system would be required.

Prior to 1997, a procedure called a pack burnout was carried out if the ECS became contaminated with oil. This requires the engines to be run prior to flight and for the temperature in the ECS to be raised so that the hot air would force any oil in the system through to the cabin (and beyond). This procedure was suspended in 1997.

## 1.8 Sources of Exposure Events on the BAe 146

There is a range of ways in which exposure events can occur.

Leaking oil seals in the compressor section of the engine suggest that oil would enter the high-pressure bleed to the air conditioning packs and APU, and therefore, into the passenger cabin. Leaking oil seals leak at different rates and therefore different planes will have different levels of contamination. The

APU also can suffer from the same problem of leaking compressor bearing oil seals. There is some evidence that a low pressure occurs in the ECs when the system is on fresh air mode during times of high engine demand (for example, on take off), and this low pressure causes contamination to occur.

Filters were introduced between the air conditioning packs and the cabin distribution outlets in some airlines some time after 1992. The installation of filters into the Ansett fleet of BAe 146s is discussed below.

Therefore, one probable source of exposure events is engine oil leaks, which are re-circulated through the plane in its air conditioning system.

Another source of exposure events, fortunately rare, is an engine fire, leading to emission of smoke into the cabin. However, with high engine operating temperatures and leaks of engine materials into the air conditioning system, the possibility of leaks of partly combusted or pyrolised products into the cabin cannot be excluded. Exposure incidents that report smoke or black mist may indicate such events.

In a study of 89 incidents of smoke/fumes in the cockpit during the flight of USAF aircraft from 1970 to 1980, a broad spectrum of symptoms were reported, including: loss of consciousness, chest pain, heaviness, parathesias, irritated eyes and mucous membranes, alterations in visual acuity, cough, headache, dizzy, light headed, confusion, disorientation, performance decrement, nausea/vomiting (more than one symptom was reported in some instances).[27]

Further, an engineering procedure called a APU Pack Burnout Procedure, by which the air conditioning system is heated with hot air to remove (burn out) any oil contamination in the system was used routinely till 1998. This would have produced substantial exposure to exposed personnel.

Therefore sources of exposure events on BAe 146 planes may be due to:

- oil leaks to the air conditioning system;
- smoke from combustion/pyrolysis events;
- contamination following pack burn outs;
- exposures during times when contaminated engines/APU are being used;
- residual contamination.

Leaks of engine oil contaminants into the passenger cabin of an aircraft in flight appear to be a significant problem necessitating a prompt response. It is apparent that the airlines in Australia knew about the problem from at least 1992. However, attempts to deal with the situation, such as establishing an odour committee or "panel of experts" seem to be more about addressing industrial relations issues, rather than establishing genuine efforts to rectify the problem through design or engineering solutions.

### 1.8.1 The impact of physical properties of oil

Another critical factor is the vapour pressure of the oil. The vapour pressure for Tri-orthocresyl phosphate is very low, at 0.02 mm Hg at 150°C. It is unlikely to reach high concentrations in air as a vapour, and therefore unlikely to be toxic as a vapour. The development of inhalational toxicity is more likely to arise from exposure to mists and aerosols. As will be noted below, attempts at collecting aerosol samples that coalesce on collector surface, leaving a residual vapour that is extracted for analysis, severely underestimates exposure.

## 1.9 Control of Chemical Exposures: The Hierarchy of Controls

When confronted with any workplace risk, the control of such risks should use the "hierarchy of controls". This is a preferred series of risk control options which attempt to deal with a given risk situation. In order, the hierarchy is:

- elimination;
- substitution;
- control at source to abolish exposure;
- control to reduce exposure;
  - engineering controls,
  - administrative controls,
  - controls of a personal nature, such as respirators,
  - controls which deal with unusual/emergency situations;
- monitoring and health surveillance to ensure controls are working.

In any risk situation, some options are more possible or likely or valid than others.

Applying the hierarchy of controls to the problem of the risk of oil fumes in aircraft cabins seems to ignore this simple philosophy. Examples of this include:

- Elimination

  Why have toxic ingredients in the oil at all? Use of aircraft engine oils that contain toxic ingredients should be questioned as it is possible that they can be eliminated.

  Also, use of such oils is a risk to maintenance personnel as well.

- Substitution

  Use of aircraft engine oils that contain toxic ingredients should be questioned as it is possible that other less toxic ingredients exist, which may be able to carry out the same functions (fire retardants, and so on).

- Control at source

  Aircraft engine design is flawed if oil leaks occur too often. Aircraft should be designed so that oil leaks either do not occuror are rare.

- Controls to reduce exposure (engineering controls)

  While the first few options in the hierarchy of controls can remove all exposures, the use of this option (and those below it) implicitly assumes that there will be some exposure. At this stage it is assumed that such exposures will be below acceptable risks. The concept of acceptable risks (as indicated by exposure standards) must be challenged for mixed exposures and at altitude.

  Aircraft ventilation systems are flawed if such leaks are deliberately allowed (by bad design) to enter the air circulation system, where crew and passengers may be exposed.

  In some cases, certain flight circumstances use re-circulated air into cabins which has the potential to increase exposure.

  Retrofitting filter units is an example of an engineering control to reduce exposure.

- Controls to reduce exposure (administrative controls)

  These include training of personnel, job rotation, housekeeping, planned maintenance and so forth.

  An APU Pack burn out has administrative features, where all staff are removed and aircraft must be empty of all personnel and passengers (and the doorway to the airport closed).

- Controls to reduce exposure (personnel protection)

  Are maintenance personnel handling the oil made to wear gloves? It would seem a sensible option.

  The use of respiratory protection in air staff exposed to oil fumes is one option, although the concern it would generate in passengers would probably prohibit its use.

  The use of oxygen at critical times (for example, when landing) is an example of personal protection. Of course this particular example is also a major safety issue.

- Monitoring/Surveillance

  Monitoring and surveillance programs are useful because although they are not preventive, they establish whether the controls are working. However, they are not preventive. Emphasis on such programs at the expense of trying to control the risk will delay fixing the problem.

  It seems that the emphasis by some sectors of the industry (particularly airline operators) on engineering controls, administrative procedures and monitoring is in the wrong place. Perhaps attempts should also be made to fix the oil problem or the re-design of the airplane.

## 1.10 Discussion

This thesis considers the tensions between aviation professionals who focus on air safety as a priority, sometimes at the expense of the safety of the travelling public (passenger safety) or workers (occupational health and safety). This focus is commercial – it is a rubric in this industry that airplanes only make money when they are flying, so anything that might impact on this will be resisted.

By using cabin air quality as an example, the issues of how poor air quality may impact on worker and passenger health and safety will be examined, using the specific example of jet oils leaking into bleed air, and being passed through to the flight deck and passenger cabin of airplanes. There have been indications that the health problems associated with these exposures may be linked to such exposures, and a suggestion that they may cause a specific health condition.

The structure of the remainder of this thesis is:

- Chapter 2: Thesis aims;
- Chapter 3: Examination of the health problems reported by seven case studies of aviation workers exposed to contaminated air;
- Chapter 4: An assessment of the chemical products used in the aviation industry, with a close examination of jet oils;
- Chapter 5: Review of the various air monitoring studies, looking at the published studies that investigate air quality in airplanes;
- Chapter 6: A descriptive epidemiological study of fifty self-selected aviation workers reporting health problems following exposure to contaminated air;
- Chapter 7: A discussion of the existence of a discrete health condition called aerotoxic sydrome;
- Chapter 8: Dicussion, conclusions and recommendations.

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# Chapter 2

## Project Aims

# 2 The Aims of this Research Thesis

Chapter 1 has outlined the problem of bleed air, contamination of bleed air from jet engine oil leaks and the impacts such exposures may cause on exposed personnel and passengers. This chapter outlines the aims and the methodology used in the thesis.

## 2.1 Aim of this Research Thesis

The main aim of this thesis is to investigate aspects of aviation industry workers' response (mainly pilots and flight attendants) when exposed to contaminated air during their occupational activities while flying.

These aspects include health, toxicological, occupational hygiene (workplace monitoring), operational, and legal factors.

The thesis to integrate these aspects to allow a fuller understanding of this matter for the first time.

## 2.2 Research Objectives

The objectives of this thesis are:

- Critically review the literature about health problems from air quality problems while flying.
- Conduct a health survey of aviation workers who have been exposed to contaminated air while flying.
- Assess the chemical and toxic properties and hazards of relevant chemicals used in the aviation industry.
- Review information on the studies conducted to assess air quality of airplanes.
- Review information (largely sourced from within the aviation industry) about what was known about this issue.

## 2.3 Research Questions

The research questions of this thesis are:

- Are the chemical products used in aviation toxic?
- Has any monitoring of the airplane cabin environment been conducted, and if so, what did such monitoring find?
- Are exposure events where the airplane cabin environment has become contaminated with chemical contaminants been reported to airline operators or aviation safety regulators?

- What are the possible effects of exposure to chemical contaminants in exposure events to employees working in the airplane cabin?

## 2.4 Research Methodology

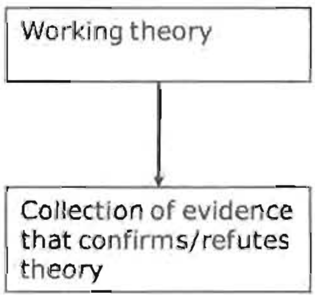
### 2.4.1 Introduction to Mixed Methods

In keeping with the methodologies of conventional research, this thesis is a research project that was conducted using a variety of methods and approaches. These various activities are useful because they generate findings that contribute to a larger picture than could be explained by a single study. Because of the nature of its research questions, it is difficult to separate out and prioritise the individual components of the project because they overlap and are ultimately, are inextricably intertwined. The various strands of scholarship, qualitative and quantitative approaches are like the strands that make up a cable, and can, when all bound around each other together, considered a better, amalgamated whole.

This research therefore uses mixed methods as a means of developing a fuller picture of the research topic. Mixed methods research is becoming more common in research and is defined as a procedure for collecting, analysing, and mixing both quantitative and qualitative data into a single tangible concept.[1]

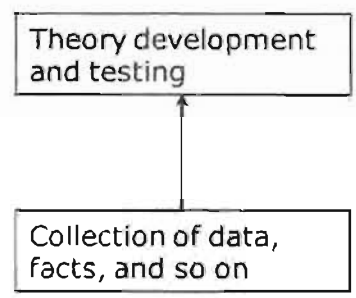
Qualitative research tries an open ended approach based on a working theory to obtain key answers from an non-random sample through the collection of non-numerical data or from explanation based on the attributes of a source of data.[2,3] Selection of such samples is purposive, rather than random, and is based on indicative, sentinel or otherwise significant sources. This process is deductive, in that it can confirm, or lead to modification, or refute research questions. It can also generate ideas that can be used to create further research questions for later study.[4]

Deductive Reasoning

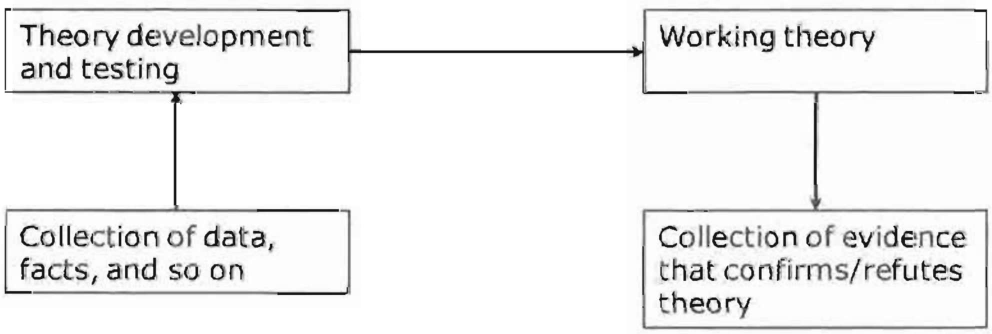


Quantitative research tries to obtain numerically based answers from a representative sample or samples. A reductionist, purely scientific approach is most applicable to research situations that can be controlled and are repeatable, and generate sufficient data from representative sample.[5] Such situations allow the collection of quantitative numerically based data that can be analysed using standard statistical methods.[6,7] As such, quantitative research is inductive, in that data is collected and analysed to see if any patterns emerge, from which it may be possible to generate generalisations, theories or models.

Inductive Reasoning




Therefore, mixed methods research combines these approaches. It is empirical research that involves the collection and analysis of both qualitative and quantitative data. This is research where more can be learned about the research topic by combining the strengths of qualitative research with the strengths of quantitative research, by applying different approaches at any or all of a number of stages through the research.[8]




There are advantages and disadvantages in doing this. Advantages include using different methods to examine different types of phenomena is often resource efficient. Some methods may not be ethical, useful, desirable or even possible, especially where data is difficult to obtain. Indeed, the mixing of methodologies within a broad quantitative or qualitative approach may raise almost as many issues as when working across approaches.[9]

The combination of methods used, and the availability of the different interpretations they can generate, amounts to conducting different studies in the hope that they generate findings that support and build the same final conclusion (providing that such a conclusion was not an artefact of method and each method had predictable and measurable sources of error). Mixed methods are useful because the different approaches will tend to cancel out any methodological differences and systematic errors, and any potential conclusion that might arise will do so in spite of such biases, not because of them.

One thing that mixed methods research can do that is not an end product of other research approaches is that at the end of the various activities that make up the research project, the end result is usually greater than the sum of its individual qualitative and quantitative parts.[10]

Mixed methods are used to enrich understanding of an experience or issue through by initiating new ways of thinking about the subject of the research, extension of knowledge or confirmation of conclusions.

Therefore, it becomes necessary, to clarify just *what* is being mixed - and *how* it is being mixed. The "mixing" may be nothing more than a side-by-side or sequential use of different methods, or it may be that different methods are being fully integrated in a single analysis.[11]

However, there are a range of mixed methods approaches, including, triangulation, convergence, embedded and accretion methods:

- Triangulation is the combination of at least two or more theoretical perspectives, methodological approaches, data sources, or data analysis methods. It is the commonest approach used in mixed methods research, and the purpose of this approach is to obtain but complimentary data regarding the same issue.[12] Triangulation strategies do not strengthen a flawed study, but are usually used to decrease or counterbalance the deficiency of a single strategy, thereby increasing the ability to interpret the findings.[13]
- Convergence is the availability of data complementarity, which avoids premature closure, allows the development of different interpretations, and helps assure proportionate weighting of findings from different approaches. In some cases, convergence across different perspectives or research methods, builds a better picture of the issue being studied.[14]

- Embedded methods are where one data set (of either the qualitative or quantitative type) provides a supportive role in a study of mainly the other type.[12] Such studies must be designed properly at the outset.
- Lastly, there is a combination of triangulation and convergence approaches, where the increase of findings by addition or accumulation (accretion) from studies looking at an issue from different perspectives and using different research methods, generates findings that provide a better quality understanding of the issue under study.[15]

### 2.4.2 The Mixed Methods used in this Thesis

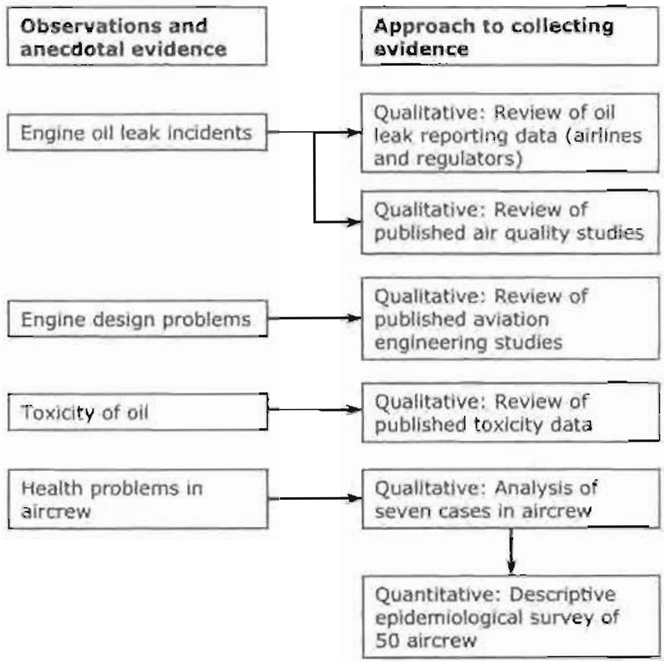
The main approaches that will be adopted in the research thesis are:

1. Critical analysis of published literature, especially health effects, air quality studies, and toxicology information.
2. Review and analysis of unpublished information, such as MSDS and labels, incident reports, engineering reports and company correspondence.
3. To conduct an epidemiological survey(ies) of affected workers. Because of the difficulty in obtaining information from workers in an industry that discourages such studies, these will be descriptive in nature.

Sometimes, the reason for choosing a mixed methods design is not made clear by the researcher at the outset, potentially leading to confusion in the design phase of the study.[16] Some of the purposes necessitating mixed methods may be initiation, expansion or corroboration.[17]

In this thesis, the mixed methods approach allowed specific aspects identified in earlier studies to be followed up, in some cases, using different methodological approaches. For example, the indicative findings of the case studies in Chapter 2 lead to the design of a fuller descriptive epidemiological study in Chapter 6. This initial survey also raised questions that lead to other studies, such as engine design factors, numbers of leak incidents, air quality studies, toxicity of the oils, action of airlines and so on. This triangulation allowed validation by corroboration (see Figure 2-1).[18,19]

*Figure 2-1: Mixed Methods, as Used in this Thesis*




# 2.5 Administrative Matters

## 2.5.1 OHS Awareness and Training

Training of all research students of the UNSW School of Public Health and Community Medicine is mandatory. As I hold a Graduate Certificate in OHS Management and have completed the WorkCover Authority OHS Committee Member four day training course, this was considered sufficient.

## 2.5.2 Risk Assessment

In accordance with the UNSW School of Risk and Safety Sciences One Plus One Risk Assessment System, this project does not require access to School resources and is rated as one of low risk that does not need a risk assessment.

## 2.5.3 Ethics approvals

In accordance with the UNSW Ethics approvals processes, applications were made for the epidemiological studies presented in this thesis, which were awarded and are detailed below.

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# Chapter 3

## The Case Study Paper

One, two or three cases do not make a new health condition or disease. However, in the early study of puzzling symptoms and signs that appear to have a consistent nature, there comes a point when an apparent trend needs exploring. By the end of 1997, I had seen about six fight attendants and pilots and had started looking at exposures, symptoms and causes. This was reinforced by being contacted by Dr Jean Christophe Balouet in France, working on apparently similar cases in Europe and the USA. We pooled information, and selected seven case studies for presentation at scientific meetings and publications.

Most of the material in this chapter was published in:

- Winder, C., Balouet, J.-C. Symptoms of irritation and toxicity in air crew as a result of exposure to airborne chemicals in aircraft. *Journal of Occupational Health and Safety - Australia and New Zealand* **17:** 471-483, 2001.

# 3 The Case Studies

## 3.1 Introduction

As introduced in the previous chapter, my work in this area grew out of increasing contacts I had with pilots and flight attendants flying on the BAe 146 in Australia.

Then, in 1998, I was contacted by another scientist, Dr Jean Christophe Balouet from Environment Internationale in France, working on apparently similar cases in Europe and the USA. We pooled information, and shared information about the apparent lack of response by the airlines, which seemed to be in denial.

Dr Balouet's cases were on different models of airplanes, on different airlines. But many of the symptoms and signs he was collecting from affected individuals were similar the symptoms and signs that I was collecting. On a trip to Paris in August 1999, we collaborated on this issue, developing a list of symptoms that could be used by medical practitioners to help air crew who had been exposed. We coined the term "aerotoxic syndrome" as a means of focussing attention on the issue by the industry and its regulators.

We also recognised that there was a need to carry out an epidemiological study to better describe the condition. In the interim, we decided to publish a short descriptive study of 5-7 cases, describing demographics, exposures, health problems, treatments, outcomes and company actions. These case studies are discussed below.

## 3.2 Seven Case Studies

To study some of the problems of exposure to flight crew and flight attendants exposed to in cabin contamination while flying, seven cases of symptom development from such exposure events were investigated. These case studies were taken from flight crew and flight attendants in four airlines operating in four countries and in three airplane models.

A wide range of symptoms is reported in these seven case studies, outlined in case reports below.

| **Case Study No 1** | | | |
|---|---|---|---|
| ***Demographic/occupational*** | | Country: | France |
| Aircraft type: | B-747 | Date of incident: | 1985 |
| Occupation: | Cabin crew | Years of experience: | 15-20 |
| Age at incident: | 35-40 | Gender: | Female |
| Medical: | Asthma, non-smoker, no alcohol, no recent illness. One first in-cabin smoke exposure eight years previously (no fire on board), with all crew reporting headache, nausea, vertigo, blurred vision. | | |
| **Incident:** Residual leak: | Symptoms occurred on three flights where complaints were reported. | | |
| **Symptoms:** Onset: | Symptoms including tight chest, difficulty in breathing, nausea and abdominal spasms, palpitations, disorientation, feeling intoxicated | | |
| In-flight treatment: | None | | |
| Longer term symptoms: | Alopecia, memory impairment, chronic fatigue, altered coordination, loss of balance, hypothyroidy (not existing prior to exposure), depression. | | |
| **Company actions**: | Incapacitation acknowledged by social security three years after exposure. Compensation for loss of licence (private insurance). | | |

| **Case Study No 2** | | | |
|---|---|---|---|
| ***Demographic/occupational*** | | Country: | Canada |
| Aircraft type: | Fokker 100 | Date of incident: | May 19, 1989 |
| Occupation: | Cabin crew | Years of experience: | more than 10 |
| Age at incident: | 35-40 | Gender: | Female |
| Medical: | No relevant medical precedent, non-smoker, no alcohol, no recent illness. | | |
| **Incident:** Odours: | One-hour flight. Odours detected and recorded on flight log. Evidence also available of mechanical problems on this flight and ongoing aircraft repairs.<br>Two other cabin crew had similar symptoms, though headaches less severe. Pilot without symptoms, co-pilot reported feeling "intoxicated" and legs very weak, generalised fatigue, inability to stand up and talk. | | |
| **Symptoms:** Onset: | Initiated during flight, worse during descent. Severe headache, vertigo, loss of balance, nausea, loss of sensation in leg, difficulties in keeping eyes open (probably narcosis). | | |
| In-flight treatment: | Oxygen supply, producing a slight improvement after some time, although difficulties with opening eyes persisted for a few days. | | |
| Post-flight: | A visit to emergency room, four hours after incident - same symptoms as in flight, plus: chest pain, tight chest, heart palpitations, exhaustion, problems in concentration, irritability, feeling intoxicated. Symptoms diagnosed as possible carbon monoxide intoxication, although clinical and biochemical examination normal (concluded that the $O_2$ intake during flight corrected the CO exposure) | | |
| Longer term symptoms: | Irritability, somnolence, generalised weakness, "grey out" (incapacity to stand up and talk), weakness, confusion, memory problems, nausea, concentration difficulties, paralysis events (whole body versus left haemiplegia, positively treated by Serax), depression. | | |
| Diagnostic tests: | Neuropsychological tests concluded in reduced visuo-spatial analysis and organisation, reduced visual information retention, altered verbal fluidity for phonologic tests while semantic within normal, reduced analytical reasoning, limited capacity for information evocation, cognitive disorders, depression. No structural anomaly evidenced. | | |
| Symptom persistence: | Symptoms (mainly neuropsychological) have been almost stable over a four year period post-exposure. She was not able to work for over four years after incident (follow-up was only for four years). | | |
| **Company actions:** | Occupational exposure acknowledged and compensation for deficit granted 3½ years after the incident. | | |

## CASE STUDY NO 3

| | | | |
|---|---|---|---|
| ***Demographic/occupational*** | | Country: | Australia |
| Aircraft type: | BAe 146 | Date of incident: | September 30 October 1993 |
| Occupation: | Cabin crew | Years of experience: | 2-4 |
| Age at incident: | 25-30 | Gender: | Female |

| | | |
|---|---|---|
| | Medical: | Non-smoker, low alcohol. Deteriorating health over previous two years while continuing to work. The following complaints commenced in January 1992: headaches, watery eyes, sinus problems, nausea, swollen glands, dizziness, sleep difficulties, brain fogginess and skin rashes. Oxygen was requested on a flight in June 1992. Blood was coughed up post-flight. Diagnosed with EBV (Epstein Barr Virus) nine months before major incident. |
| **Incident:** | Smoke | 1-2 hour flight. Black smoke emitted into the cabin from the air-conditioning ducts, sufficient for passengers to believe a fire had started. Captain vented the cabin but a haze remained sufficient to obscure the back of the plane for the flight. Event logged. Other cabin crew had symptoms of irritation. |
| **Symptoms:** | Onset: | Pre-existing symptoms from previous flights exacerbated: Fatigue, headaches, inability to concentrate, skin rash. |
| | In-flight treatment: | None. |
| | Post-flight: | Same symptoms as in flight, plus: headaches and head spasms, sinus problems, nausea, eye soreness and pain, exhaustion, problems in concentration, irritability, swollen glands, neuropsychological symptoms, such as giddiness, "brain fogginess", memory lapses, irritability, sleep difficulties, dyslexia. |
| | Longer term symptoms: | Chronic fatigue, headaches, weakness, confusion, memory problems, nausea, concentration difficulties, depression, multiple chemical sensitivity. |
| | Diagnostic tests: | Chemically sensitised. Neurological dysfunction in (AERP) auditory evoked response potential test. Metabolic imbalances. |
| | Symptom persistence: | Some symptoms abated, some declined but flared on chemical exposure, some remained. Symptom-free on holiday in 1997, but symptoms recur on return to city. Now working part time in an unrelated field. |
| **Company actions**: | | Formed an expert panel that acknowledged irritant effects but repudiated long term effects. Defended a workers compensation case, which was decided against the company in 1999 for exacerbation of pre-existing illness. |

| ***Case Study No 4*** | | | |
|---|---|---|---|
| ***Demographic/occupational*** | | Country: | USA |
| Aircraft type: | B-727 | Date of incident: | 1992 |
| Occupation: | Cabin crew | Years of experience: | 3-5 years |
| Age at incident: | 40-45 | Gender: | Female |
| Medical: | No relevant medical precedent, non-smoker, no alcohol, no recent illness. | | |
| **Incident:** Fumes: | One-hour flight. Blue haze and "sweet smell" in cabin ten minutes after take-off. Loss of hydraulic pressure detected before take-off and "repaired on tarmac". Aircraft grounded after landing at destination for hydraulic repair. All cabin crew intoxicated, although less severe symptomatology as compared to the present case study. Flight deck crew used oxygen masks and reported no symptoms. | | |
| **Symptoms:** Onset: | Initiated during flight, ten minutes after take off. Severe headache, dizziness, nausea, sweating, shaking, laboured painful breathing - tight chest and chest pain, incoherence, weakness, stumbling, disorientation, memory impairment, palpitations, tunnel vision, eye burns, loss of consciousness. | | |
| In-flight treatment: | None | | |
| Post-flight: | At emergency room on same day and visit the next day: further symptoms to those reported to the in-flight reported symptoms: abdominal pain and cramps, blurred vision and disorientation, altered coordination, blurred speech. Diagnosed as toxic encephalopathy. | | |
| Longer term symptoms: | Skin rash and blisters on uncovered body parts, tunnel vision, diarrhoea (for a week), loss of balance, neck/eye pain, alopecia ( for 2 months), no menses for 6 months, Impairment in cognitive and reasoning problems, altered memory, unstable body temperature, ataxia, muscle weakness, chronic fatigue, seizures. | | |
| **Company actions**: | Compensation for medical bills and partial compensation for loss of income (five years after). | | |

| **CASE STUDY NO 5** | | | |
|---|---|---|---|
| ***Demographic/occupational*** | | Country: | Australia |
| Aircraft type: | BAe 146 | Date of incident | 30 October 1997 (major exposure event hereunder described, further incapacitated on a flight three weeks later). |
| Occupation: | Flight crew | Years of experience | 15-20 |
| Age at incident: | 30-35 | Gender: | Female |
| Medical: | non-smoker, almost no alcohol. No recent illness, against a background of deteriorating health over previous six months. Six years flying BAe 146 with chronic exposure and numerous exposures under pack burnout procedures. | | |
| **Incident:** Residual leak: | One to two hour flight. Flying in plane with smell of engine contamination of air. Event logged. Eventually subject to (BASI) Bureau of Air Safety and Investigation report. Eye redness and lacrimation in flight crew. Cabin crew and passengers complaining of smell. | | |
| **Symptoms:** Onset: | Nausea, vestibular problems, tunnel vision, "grey out", headaches, sore eyes. | | |
| In-flight treatment: | None. Was not able to think clearly enough to use oxygen or hand over to first officer. | | |
| Post-flight: | Visit to general medical clinic immediately after landing. Same symptoms as in flight, plus: scalp numbness, perception displacement, feeling of intoxication, fatigue. Diagnosed as nystagmus/labyrinthitis. | | |
| Longer term symptoms: | Headaches, and head pressure, weakness, chronic fatigue, concentration and memory difficulties, loss of clarity of thoughts, slurred speech, eye problems including severe syntagms, accommodation and vision (fluorescent, bright lights, bright background lights) problems, sleep problems, weight loss, nausea and diarrhoea, reactive hypoglycaemia, tremors, food and alcohol intolerance, multiple chemical sensitivity, lack of coordination, loss of muscle control in face, head movement sideways or up or down, motion sickness. | | |
| Diagnostic tests: | CT scan normal. Chemically sensitised. Neurological dysfunction in auditory evoked response potential AERP test. Metabolic imbalances. | | |
| Symptom persistence: | Some symptoms abated, some declined but flared on chemical exposure, some remained. Unable to pass aviation medical test for flying licence. Not working since incident. | | |
| **Company actions**: | Suspended flying licence. formed expert panel that acknowledged irritant effects but repudiated long term effects | | |

| **CASE STUDY NO 6** | | | |
|---|---|---|---|
| **Demographic/occupational** | | Country: | Australia |
| Aircraft type: | BAe 146 | Date of incident: | November 1997 |
| Occupation: | Cabin crew | Years of experience: | 10-15 |
| Age at incident: | 30-35 | Gender: Female | |
| Medical: | non-smoker, low alcohol. No relevant medical precedent, but deteriorating health over previous twelve months, including headaches, nasal congestion, sinus problems, hyposmia. | | |
| **Incident:** Residual leak: | Three days of short and long haul flights up to eight hours/day with reported air quality problems and complaints. The situation of oil leaks/inoperative filters detailed in Engineers and Flight reports. All three cabin crew taken to hospital post-flight. | | |
| **Symptoms:** Onset: | Overcome by fumes. Exacerbation of fatigue, inability to concentrate, coordination and speech impairment, body paralysis lasting few minutes, swelling, nausea, pain in left temple, breathing difficulties, dilated pupils, bloodshot eyes. | | |
| In-flight treatment: | None. | | |
| Post-flight: | Same symptoms as in flight, plus: intense headaches, nausea, eye soreness and pain, exhaustion, problems in concentration, irritability, neuropsychological symptoms, skin rash, skin colour grey, impaired vision, bruising of legs. | | |
| Longer term symptoms: | disorientation, reactive hypoglycaemia, confusion, poor concentration, impaired memory, short term memory loss, grey in colour for 7 months, dilated pupils, constricted breathing (sometimes), chronic fatigue, nausea, gastrointestinal problems, food and alcohol intolerance, irritability, alopecia, dermatitis, conjunctivitis, pressure and sharp head pains, chemically sensitive, motion sickness. | | |
| Diagnostic tests: | Neurological dysfunction in AERP, metabolic imbalances. | | |
| Symptom persistence: | Many symptoms remain, two years after incident. | | |
| **Company actions**: | Established odour committee and collected samples. Formed expert panel that acknowledged irritant effects but repudiated long term effects. One cabin crew was granted workers compensation for 1 day. This crew member denied workers compensation but was granted leave to proceed for negligence/damages against airline/employer. | | |

| *Case Study No 7* | | | |
|---|---|---|---|
| **Demographic/occupational** | | Country: | Australia |
| Aircraft type: | BAe 146 | Date of incident: | Ongoing exposures 1994-97 |
| Occupation: | Flight crew | Years of experience: | 10-15 |
| Age at incident: | 30-35 | Gender: | Female |
| Medical: | non-smoker, low alcohol. No relevant medical precedent, but deteriorating health 1994-97, including headaches, nasal and throat problems, stridor, nausea, fatigue/lethargy, loss of concentration. | | |
| **Incident:** Residual leak: | Planes generally contained odours regularly throughout final three years of flying (worse on ground, takeoff, climb, descent). Exposures on occasion were intense enough to cause temporary incapacitation. | | |
| **Symptoms:** On exposure: | Upper airway irritation, hoarseness leading to loss of voice (eventually requiring surgery), headaches and head pressure, fatigue becoming worse over time, inability to concentrate, (all these symptoms would begin soon after switching on the air conditioning and abate quickly when leaving the plane). Later symptoms include nausea and development of sensitivity to chemicals in and around the airport environment. | | |
| In-flight treatment: | None. Hand over to other flight officer on occasion. | | |
| Last two days: | All symptoms as above, abating on the first day, and increasing on the second day. Symptoms continued, followed by massive increase in head pressure (sufficient to presuppose a stroke had occurred), fatigue, weakness, loss of voice within 24-48 hours. | | |
| Longer term symptoms: | Headache and head pressure, numbness, tingling, dizziness, reactive hypoglycaemia, confusion, poor concentration and information processing, impaired memory, short term memory loss, feeling as though not enough oxygen is getting to the body, chronic fatigue, nausea and vomiting, food and alcohol intolerance, skin rashes, chemically sensitive. | | |
| Diagnostic tests: | Neurological dysfunction in AERP, evidence of injury to CNS in neuropsychological tests, abnormality in lung diffusion test. | | |
| Symptom persistence: | Many symptoms remained, over three years after last exposure. Unable to pass aviation medical test for flying licence. Not working since last exposure. | | |

## 3.3 Analysis

A wide range of symptoms is reported in these seven case studies. Symptoms may be possible from single/short term or longer-term exposures.

A summary of the effects seen in these seven case studies is shown in Table 3-1.

***Table 3-1: Symptom Summary: Seven Case Studies***

| Symptom/Symptom cluster | Case Study No | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| Loss of consciousness, "grey out" | | ✓ | | ✓ | ✓ | | | 3 |
| Ataxia, seizures | | | | ✓ | | | | 1 |
| Narcosis, somnolence | | ✓ | ✓ | | | | | 2 |
| Vertigo | ✓ | ✓ | | | | | | 2 |
| Loss of balance | ✓ | ✓ | | | ✓ | ✓ | | 4 |
| Disorientation | ✓ | ✓ | ✓ | ✓ | | | | 4 |
| Shaking/tremors/tingling | | | | ✓ | ✓ | ✓ | | 3 |
| Numbness (fingers, lips, limbs), loss of sensation | | ✓ | | | ✓ | ✓ | ✓ | 4 |
| Light-headed, dizziness, feeling of intoxication | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 7 |
| Severe headache, head pressure | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 7 |
| Memory loss, memory impairment, forgetfulness, confusion | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 7 |
| Coordination problems | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | 6 |
| Word blindness | | | ✓ | | | | | 1 |
| Sleep problems | | | ✓ | | ✓ | ✓ | | 3 |
| Irritability | | ✓ | ✓ | | | ✓ | ✓ | 4 |
| Depression | ✓ | ✓ | ✓ | | | | | 3 |
| Nystagmus | | | | | ✓ | | | 1 |
| Irritation of eyes, nose and throat | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 7 |
| Eye pain, problems | | | ✓ | ✓ | ✓ | ✓ | | 4 |
| Vision problems | | | | ✓ | ✓ | ✓ | ✓ | 4 |
| Sinus problems | | | ✓ | | | ✓ | | 2 |
| Respiratory distress, difficulty in breathing | ✓ | | | ✓ | | ✓ | ✓ | 4 |
| Chest tightness | ✓ | ✓ | | ✓ | | | | 3 |
| Chest pain | | ✓ | | ✓ | | | | 2 |
| Increased heart rate, palpitations | ✓ | ✓ | | ✓ | | | | 3 |
| Nausea, vomiting | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | 6 |
| Abdominal pain, cramps, diarrhoea | ✓ | | | ✓ | ✓ | | | 3 |
| Sweating | | | | ✓ | | | | 1 |
| Rashes, blisters (uncovered body parts) | | | ✓ | ✓ | | ✓ | ✓ | 4 |
| Hair loss | ✓ | | | ✓ | | ✓ | | 3 |
| Joint pain, muscle weakness | | | | | ✓ | | ✓ | 2 |
| Fatigue, exhaustion | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | 7 |
| Chronic fatigue | ✓ | | ✓ | ✓ | | ✓ | ✓ | 5 |
| Metabolic difficulties | | | ✓ | | | | | 1 |
| Weight loss | | | | | ✓ | | | 1 |
| Swollen glands, glandular problems | | | ✓ | | ✓ | ✓ | | 3 |

| Symptom/Symptom cluster | Case Study No | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| Dysmenorrhoea | | | | ✓ | | | | 1 |
| Thyroid problems | ✓ | | | | | | | 1 |
| Immunodepression | | | ✓ | | | | ✓ | 2 |
| Food/alcohol intolerances | | | ✓ | | ✓ | ✓ | ✓ | 4 |
| Multiple Chemical Sensitivity | | | ✓ | | ✓ | ✓ | ✓ | 4 |

The consistency between some of the symptoms between these individuals is, in many cases, quite remarkable. The term aerotoxic syndrome was proposed in 1999 to describe the association of symptoms observed amongst crew exposed to hydraulic or engine oil smoke/fumes.[1,2]

Further, it is possible to separate out short term and long term symptoms.

### 3.3.1 Symptoms from short term exposure

Symptoms from single or short-term exposures include:

- neurotoxic symptoms: blurred or tunnel vision, nystagmus, disorientation, shaking and tremors, loss of balance and vertigo, seizures, loss of consciousness, parathesias;
- neuropsychological 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.

Neurotoxicity is a major flight safety concern, especially where exposures are intense.

### 3.3.2 Symptoms from long term exposure

Symptoms from long term low-level exposure or residual symptoms from exposure events include:

- neurotoxic symptoms: numbness (fingers, lips, limbs), parathesias;
- neuropsychological symptoms: memory impairment, forgetfulness, lack of co-ordination, 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;
- skin symptoms: skin itching and rashes, skin blisters (on uncovered body parts), hair loss;
- irritation of eyes, nose and upper airways;
- sensitivity: signs of immunosupression, 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.

One last point should be noted. In a US National Transport Safety Board (NTSB) 1983 study of problems of turbine oil by-product contamination, a statement appears which says:[3]

"*there 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.*"

The number of cases following exposure to irritating and toxic exposures in airline personnel suggests that a hypersensitivity reaction of this type may be occurring in an estimated 2 to 3% of the exposed. However, the intensity of the hypersensitivity reaction occurring would suggest that it is not of a life threatening form.

### 3.3.3 Symptom duration

It is also apparent that some symptoms occur immediately or soon after exposure, for example, many of the irritant, gastric, nervous and respiratory effects. However, others, such as nervous system impairment, immunosupression and chemical sensitivity, develop later, perhaps months after exposures may have ceased. Further, while some of these symptoms are fully reversible, others appear to persist for longer (in some of the longer cases, for at least five years). Debate is also continuing about the links between exposure and some of longer-term symptoms (such as chemical sensitivity).

### 3.3.4 Symptom severity

Symptom severity depends on a number of factors, including the range of contaminants present, the intensity, duration and frequency of exposure, toxicity of compounds (expectedly influenced by cabin environment factors such as humidity, decreased oxygen concentration and contaminants such as carbon monoxide), and individual susceptibility.

While single/long term exposure to aircraft engine lubricants and hydraulics (basically due to their chemical content and possible thermal decomposition products) is diagnosed as responsible for the reported symptoms, air crew or passengers exposed to same events or similar doses do not necessarily develop same symptom severity. Variation in symptom severity is attributed to individual sensitivity, and may also depend on other susceptibility factors, including prior exposure events.

In terms of toxicity, a large number of crew developed symptoms[4,5] following both short-term and long term repeated exposures.

Attempts by airlines to address this problem through design, maintenance and operational improvements and through staff support and medical care have not been successful, and in the main, continue to be reactive. Obviously, improving options such as engine design, using less toxic fluids, improved reporting systems, and better maintenance procedures are not within the sole sphere of activity of the operators. However, the manner in which some airlines have pursued workers compensation cases brought by staff with some of the longer term symptoms indicates a confrontational approach which is unlikely to be beneficial to all parties in the long-term.

## 3.4 Discussion

Direct exposure to smoke/fumes from hydraulic fluids and lubricants are known to be toxic, causing effects such as blurred vision, disorientation, memory loss, lack of coordination, nausea, which, if they occurred in flight crew, are direct threats to flight safety. Further, through documentation such as reports of cabin air contamination by engine oil and hydraulic fluids in engine logs and pilot reports, factual evidence is available that flight deck, cabin crew and passengers can be directly exposed to airborne chemicals on aircraft in sufficient concentrations to cause acute, immediate to long-term symptoms.

These exposures can and do produce symptoms of toxicity. Symptoms associated with cabin contamination clearly include irritancy, neurotoxicity and neuropsychological effects, as well as other symptoms typically correlated to chemical intoxication. Links between neurotoxic effects and certain contaminants known to be neurotoxic (such as the phosphate esters) are suspected.

These exposures, and the symptomology they produce, present significant issues with regard to the health of pilots, cabin crew and passengers, but most notably could jeopardise air safety if pilots are incapacitated and cabin crew cannot supervise cabin evacuations during emergencies. Health effects include short-term irritant, skin, gastro-intestinal, respiratory and nervous system effects, and long-term central nervous and immunological effects. Some of these effects are transient, others appear more permanent. The exacerbation of pre-existing health problems by toxic exposures is also highly probable.

Aviation has been a pioneering industry for decades. However, the industry is coming under increasing pressure to improve its standards. Public confidence in a traditionally safe, high technology industry, is eroding of "fly at any cost". Minimalist approaches to regulatory compliance, an almost total focus on profit making at the expense of other commercial priorities (such as safety or staff health), and strident denials that problems exist do little to build confidence.[6,7]

Human factors need, also, to be considered. Airline staff of the airlines are worried about job security and what might happen to them if they complain about working conditions and make their symptoms public. With only a handful of cases proceeding in the courts, little compensation has been awarded to airline workers affected by toxic fumes and several have already lost their jobs (for example: the pilot fired two months after incident in case study no 2; pilot in early retirement within one year after incident, early retirement by five years, in-flight engineer fired a few months after incident for "insubordination" in case study no 3; flying licence lost in case studies nos 5 and 7). Therefore, staff are reluctant to come forward until their health is jeopardised sufficiently that they can no longer fly without compromising their health and safety.

In one workers' compensation court proceedings in Australia, one airline has admitted that exposure events are significant enough to produce symptoms of irritation.[8] Debate about other effects, and about the significance of long term sequelae continues. The case was concluded as the exposures exacerbating a pre-existing medical condition.

The issue has generated considerable interest in the international community and various international programs are being started in the USA and Europe. This international dimension is of major importance since exposed and symptomatic crews have been identified in at least three continents, and all aircraft types have had leak problems.

## 3.5 Conclusion

Materials used in the operation of aircraft may contain hazardous ingredients, some with significant toxicities, and need care in handling and use. Some maintenance or operational activities, such as leaks or poorly controlled maintenance procedures, can, through contamination of aircraft cabin air, produce unwanted exposures to crew and passengers. Occasionally, such exposures (either short term intense or long term low level) may be of a magnitude to induce symptoms of toxicity.

These symptoms are associated with air crew exposure at altitude to atmospheric contaminants from engine oil or other aircraft fluids, temporally juxtaposed by the development of a consistent symptomology of short-term skin, gastro-intestinal, respiratory and nervous system effects, and long-term central nervous and immunological effects. Symptoms from seven case studies, from flight crew and flight attendants in four airlines operating in four countries and in three airplane models are listed. These symptoms may be reversible following brief exposures, but features are emerging of longer term problems following significant exposures. This has significant implications for safety in the aviation industry and occupational health.

## 3.6 References


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Chapter 4

# Chemical Products Used in Aviation: Case Study - The Jet Oils

Aircraft materials such as jet-fuel, de-icing fluids, engine oil, hydraulic fluids, contain a range of ingredients, some of which are toxic. The engine oils that are used in jet engines are precision synthetic oils that need to operate in extreme conditions.

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- Winder, C., Balouet, J.-C. The toxicology of commercial jet oils. *Environmental Research* **89:** 146-164, 2002.
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# 4 Chemical Products used in Aviation

## 4.1 Introduction

Air quality is an important aviation problem. Problems arise from a number of factors, including:

- *The problem of hypoxia.* Commercial flight levels typically range from 31,000 to 42,000 ft, and the aircraft cabin is pressurised to an hypobaric environment equivalent to 8,000 ft (2,315 m).
- *The problem of ventilation.* Studies indicate[1] that it is common in all modes of transport have ventilation rates are less than current ASHRAE 62 guidelines for commercial buildings.[2] This finding, of itself, does not imply poor air quality. However, it suggests that initiatives to reduce air quality should be resisted and indicates that opportunities to improve air quality should be encouraged. For example, a Canadian study of one aircraft type and airline found that 24 of 33 commercial flights did not satisfy the ASHRAE air ventilation criteria of fifteen cubic feet/occupant, and that 18 of 33 flights had less than ten cubic feet/occupant.[3]
- *The problem of contamination of air.* Chemical exposures in aircraft have been reported. In 1953, The US Aeromedical Association first expressed their concerns about the toxicity risks of cabin air contamination by hydraulics and lubricants.[4] The oils and hydraulics used in aircraft engines can be toxic, and specific ingredients of oils can be irritating, sensitising (such as phenyl-alpha-naphthylamine) or neurotoxic (for example, ortho-containing triaryl phosphates such as tri-ortho-cresyl phosphate). If oil or hydraulic fluid leaks occur, this contamination may be in the form of unchanged material, degraded material from long use, combusted or pyrolised materials. These materials can contaminate aircraft cabin air in the form of gases, vapours, mists and aerosols. Other risks have been identified more recently, either as part of the chemicals routinely used in maintaining airplanes,[5] or as products of the passengers or cargo.[1]
- Problems of combustion and emergency situations.[6] Passenger protective breathing equipment tests conducted by the UK Air Accidents Investigation Branch (AAIB) identify contaminants in combustion situations such as carbon monoxide, hydrogen cyanide, hydrogen

fluoride, hydrogen chloride, nitrogen oxides, sulphur dioxide, ammonia, acrolein, and other hydrocarbon compounds.[7]

Notwithstanding normal operational activities or emergency situations, a range of other situations can arise whereby aircraft cabin air can be contaminated.[8] These include:

- uptake of exhaust from other aircraft or on ground contamination sources,
- application of de-icing fluids,
- hydraulic fluid leaks from landing gear and other hydraulic systems,
- excessive use of lubricants and preservative compounds in the cargo hold,
- preservatives on the inside of aircraft skin;
- large accumulations of dirt and brake dust may build up on inlet ducts where auxillary power units extract air from near the aircraft belly;
- ingestion of oil and hydraulic fluid at sealing interfaces, around oil cooling fan gaskets and in worn transitions;
- oil contamination from synthetic turbine oil;
- engine combustion products (for example, defective fuel manifolds, seal failures, engine leaks).

Other air quality problems include ethanol and acetone, indicators of bioeffluents and chemicals from consumer products.[9] One additional problem is the lower partial pressure of oxygen that is present in the cabins of planes flying at altitude.[10]

International aviation legislation such as the US Federal Aviation Regulations (FAR) and airworthiness standards for aircraft air quality state "*crew and passenger compartment air must be free from harmful and hazardous concentrations of gases or vapors.*"[11] Where contamination of air in the flight deck and passenger cabin occurs that is sufficient to cause symptoms of discomfort, fatigue, irritation or toxicity, this contravenes such standards and legislation.

## 4.2 The Chemical Products Used in Aviation

The aviation industry has used fuels, lubricants, hydraulic fluids and other materials that can contain a range of toxic ingredients. Aircraft materials such as jet-fuel, de-icing fluids, engine oil, hydraulic fluids, and so on, contain a range of ingredients, some of which are toxic.[12,13,14,15] Significant contaminants include: aldehydes; aromatic hydrocarbons; aliphatic hydrocarbons; chlorinated, fluorinated, methylated, phosphate or nitrogen compounds; esters; and oxides.[16]

At the end of the 1950s, technological advances with turbojet modifications and increasing with flight speed, meant that jet oils needed to be modified to meet the newer, harsher requirements, particularly with high temperature and high pressure properties. The older diester based stocks were replaced by neopentyl esters, such as esters of pentaerythritol, dipentaerythritol and trimethyl propane with $C_5$-$C_{12}$ carboxylic acids. These newer oils had good thermal properties, and oxidative, hygroscopic and hydrolytic stability, and became a second generation of jet oils.[17] These requirements were standardised in the specification of (military) MIL-L-9236 (cancelled in 1972) and MIL-L-23699C (approved in 1978).

With the addition of antioxidants, lubricity agents, and other functional additives to the base stock, oils were obtained with a high level of thermal and thermal-oxidative stability, good lubricating properties, low volatility, high foam forming resistance and so on. Today, virtually all (and probably all) jet oil manufacturers supply oils conforming to MIL-L-23699.

A complex approval process exists for ensuring that materials used in aviation are manufactured to relevant standards. For example, jet fuels are specified by the American Society for Testing and Materials (ASTM D 1655 *Standard Specification for Aviation Turbine Fuels*)[18] and the United Kingdom Ministry of Defence (MOD Standard 91-91),[19] and the jet engine oil specification of the US Navy MIL-PRF-23699 is used for jet oils. This process of approval and re-approval for new product formulations has meant that there is some resistance to modifying formulations (for example, for health and safety reasons).

Consequently, changing approved formulations is not conducted without significant justification. In the case of the jet oil additive tricresyl phosphate (TCP, discussed below), manufacturers have been reluctant to modify product formulations by substituting toxic TCP additives that perform well in critical applications. This has meant that potentially toxic products have continued to be available and used long after their toxicity has been recognised.[20] It is not known if an approved formulation containing, for example 3% tricresyl phosphate, is considered a change in formulation if the proportion of individual isomers in the TCP mixture is altered, but the 3% remains unchanged. However, as Mobil indicate, only the base stock esters have been modified over the past thirty or so years, suggesting that the mixture of isomers in TCP stock has not been changed.

**Fuels** are based on the type on engine type (piston, turbo or jet) and operating conditions. They are similar to other petroleum products that have a boiling range of approximately 150°C to 300°C. The freezing point and flash point are the principal differences between the finished fuels. The main fuels used are the kerosene based Jet A (used in the USA or Jet A-1 (used around the world). Jet B is a modified fuel for use in cold climates. Chemical additives allowed for use in jet fuel are also defined in product specifications.[21]

Over two million workers are occupationally exposed each year to jet propulsion fuels. Approximately 220 billion litres of these kerosene-based jet fuels are annually consumed.[22]

Kerosene-based hydrocarbon fuels are complex mixtures of over 200 aliphatic and aromatic hydrocarbon compounds ($C_6$ to $C_{17}$), including varying concentrations of potential toxicants such as benzene, n-hexane, toluene, xylenes, trimethylpentane, methoxyethanol, naphthalenes (including polycyclic aromatic hydrocarbons [PAHs], and certain other $C_9$-$C_{12}$ fractions such as n-propylbenzene, trimethylbenzene isomers). Table 4-1 lists some of the components of an early sample of Jet Fuel A.[23]

***Table 4-1: Jet A Fuel Constitution***

| Constituent Composition | % Volume | |
|---|---|---|
| Simple Alkanes | | 53.7 |
| Includes: | | |
| Decane | 16.5 | |
| Undecane | 36 | |
| Methyl Alkanes | | 3.77 |
| Cycloalkanes | | 0.79 |
| Monocyclic Aromatic Hydrocarbons | | 31.8 |
| Includes: | | |
| Benzene | 0.02 | |
| Butylbenzene | 2 | |
| 1,2-Diethylbenzene | 0.24 | |
| 1,2-Diethyl-3-propylbenzene | 5.4 | |
| 1,4-Diethyl-2-ethylbenzene | 0.2 | |
| Ethylbenzene | 0.02 | |
| 1-Methyl-4-propylbenzene | 3.3 | |
| Propylbenzene | 3-5 | |
| 1,2,4,5-Tetramethylbenzene | 9 | |
| Toluene | trace | |
| 1,2,3-Trimethylbenzene | 6.6 | |
| Xylenes | 0.07 | |
| Polycyclic Aromatic Hydrocarbons | | 0.63 |
| Includes: | | |

| Constituent Composition | % Volume |
|---|---|
| Naphthalene | 0.14 |
| 2-Methylnaphthalene | 0.34 |
| 1,3-Dimethylnaphthalene | 0.15 |

This is consistent with proprietary commercial information, as available on product MSDS (although the aromatic fraction may have been reduced over the years (see Table 4-2).

***Table 4-2: Jet A Fuel Constitution (from Product MSDS)***

| Component | % present |
|---|---|
| Saturated Hydrocarbons (Paraffins and Cycloparaffins) | 70-80% |
| Aromatic Hydrocarbons | 17-20% |
| Unsaturated Hydrocarbons (Olefins) | 3-6% |

**Lubricants** are classified into either:

- mineral petroleum oils either straight mineral of the appropriate viscosity or blended with additives or part synthetic multigrade oils for piston engines; or
- mineral based (mainly for earlier models of jet engines) or synthetic or turbojet, turboprop or turbofan engines.

Oil types include: mineral oils; semi-synthetic oil; synthetic oils; jet oils; turbine oils; piston engine oils, gear oils.

**Hydraulic Fluids** are usually of the mineral or synthetic, normal or superclean type.

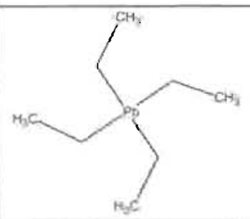
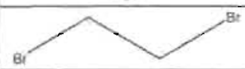
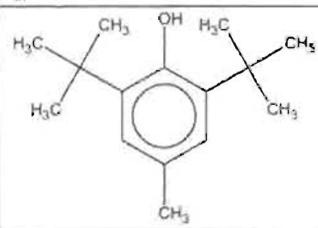
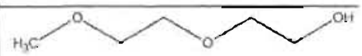
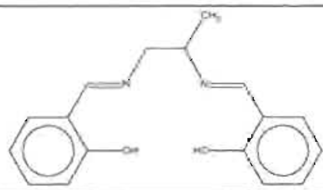
**Greases** usually containing mineral or synthetic base oils with metal soaps or organic thickeners or inorganic fillers.

**Speciality chemicals** include anti-seize compounds; bonded parts; coolants; corrosion preventatives; damping fluids; de-icing fluids; dry lubricants; instrument oils; lubricity agents; protectives; sealants, adhesives, epoxy resins; shock strut fluids.

A range of aviation chemicals is shown in Table 4-3.

***Table 4-3: Aviation Chemicals***

| Product Type | Ingredients | Formula |
|---|---|---|
| **Jet Fuels** | | |
| Jet A and Jet A-1 | A kerosene based fuel, based on ASTM Specification D1655) | Varies, depending on manufacturer |
| Jet B | A wide cut blend of gasoline and kerosene, rarely used except in very cold conditions | Varies, depending on manufacturer |
| Aviation gasoline | | Varies, depending on |

| Product Type | Ingredients | Formula |
|---|---|---|
| | | manufacturer |
| **Aviation fuel additives** | | |
| Anti-knock additives | Tetra-ethyl lead (TEL) |  |
| | Ethylene dibromide |  |
| Anti-oxidants | 2,6-ditertiary butyl-4-methyl phenol |  |
| Electrical conductivity/ static dissipater additives | Stadis®450 | Proprietary mixture |
| Corrosion inhibitor/ lubricity improver | "DCI-4a" | Proprietary mixture |
| Anti-icing additives | Di-ethylene glycol monomethylether |  |
| Metal deactivators | N,N'-disalicylidene-1,2-propane diamine |  |
| Biocides | Various | |
| Thermal Stability Improver additives | (mainly military applications) – "+100" | Proprietary mixture |
| Leak detection | Tracer A® | Proprietary mixture |
| Lubricants, based on | | |
| Mineral oils | Various | Proprietary mixtures |
| Synthetic oils | Various | Proprietary mixtures |
| Hydraulic fluids | | |
| Mineral types | Various | Proprietary mixtures |
| Synthetic types | Various | Proprietary mixtures |
| Greases | | |
| Speciality Chemicals | | |
| Anti-seize compounds | | Proprietary mixtures |
| Coolants | Various | Proprietary mixtures |
| Corrosion preventatives | | Proprietary mixtures |
| Damping fluids | | Proprietary mixtures |
| De-icing fluids | | Proprietary mixtures |
| Dry lubricants | | Proprietary mixtures |
| Instrument oils | | Proprietary mixtures |

| Product Type | Ingredients | Formula |
|---|---|---|
| Lubricity agents | | Proprietary mixtures |
| Protectives | | Proprietary mixtures |
| Sealants, adhesives, epoxy resins | | Proprietary mixtures |
| Shock strut fluids | | Proprietary mixtures |
| Bonded parts | | Proprietary mixtures |

The large number of "proprietary mixtures" makes this analysis somewhat problematic.

Inhalation is an important route of exposure, with exposure to uncovered skin being a second, less significant route (for example, following exposure to oil mists or vapours). Ingestion is unlikely.

A number of recently published studies reported acute or persisting biological or health effects such as human liver dysfunction, emotional dysfunction, abnormal electroencephalograms, shortened attention spans, decreased sensorimotor speed and immune system dysfunction from single, short term repeated exposure, or long term repeated exposure of humans or animals to kerosene-based hydrocarbon fuels, to constituent chemicals of these fuels, or to fuel combustion products.[24,25,26,27,28,29,30,31] Other reports suggest that other aviation chemicals may be toxic.[32,33]

Occasionally, such exposures may be of a magnitude to induce symptoms of toxicity. In terms of toxicity a growing number of aircrew are developing symptoms following both short term and long term repeated exposures, including dizziness, fatigue, nausea, disorientation, confusion, blurred vision, lethargy and tremors.[34,35,36] Neurotoxicity is a major flight safety concern especially where exposures are intense.[37]

Taken together, these indicate that air quality on aircraft is a significant aviation safety issue.[38]

## 4.3 Case Study: Jet Oils

The engine oils that are used in jet engines are precision oils that need to operate in extreme conditions. There are a range of products in the market, supplied by the main petrochemical producers (see Figure 4-1).

*Figure 4-1: Jet Oils in the Aviation Industry*


The main jet engine oils in use are manufactured by Shell, BP, Castrol and Mobil (ExxonMobil after the Exxon and Mobil companies combined in 1999).

Some of these commercial jet oils have been in use as engine oils in aviation for decades. For example, Mobil USA note that "Mobil Jet Oil II has been essentially unchanged since its development in the early 1960s" and "most changes have involved slight revisions of the ester base stock due to changes in raw material availability".[39]

Chemical exposures in aircraft are not unheard of. In 1954, Treon et al identified that products formed from thermal combustion of a synthetic jet lubricant were more toxic than mists of the original oil.[40] In 1953, the US Aeromedical Association first expressed their concerns about the toxicity risks of cabin air contamination by hydraulics and lubricants.[41] This was highlighted in 1956, by a paper in the Journal of Aviation Medicine, which indicated that air pollution problems, arising from the "production of smoke and chemical irritants was variable and umpredictable" in newly developed high speed aircraft.[42] Other risks have been identified more recently, either as part of the chemicals routinely used in maintaining airplanes,[43] or as toxicological factors in aviation accidents.[44,45]

## 4.4 Mobil Jet Oil II

Mobil USA notes that one of their jet oil products (Mobil Jet Oil II) has a market share of 49%. With such a large market share, and the potential for significant exposure, it would be appropriate to investigate this material in some detail.

Mobil Jet Oil II is a synthetic oil product imported into Australia. All product worldwide is manufactured by one manufacturing facility in the USA. The product is not labelled in accordance with Australian requirements under the Hazardous Substances Regulation, but is assumed to comply by default.[46]

This product is normally marketed in 0.946 L (1 US Quart) cans.

### 4.4.1 The Ingredients of the Oil

Various sources, such as the supplier's label on the cardboard box the cans are shipped in, the product Material Safety Data Bulletin (MSDB), and information from Mobil USA, lists the following ingredients:[47]

- synthetic esters based in a mixture of 95% $C_5$-$C_{10}$ fatty acid esters of pentaerythritol and dipentaerythritol;
- 1% of a substituted diphenylamine, variously reported as Benzamine, 4-Octyl-*N*-(4-Octylphenyl), (CAS No 101-67-7) or 0.1-1% N-Phenyl-benzeneamine, reaction product with 2,4,4-Trimethylpentene (CAS No 68411-46-1);
- 3% tricresyl phosphate (Phoshoric acid, tris(methylphenyl) ester, CAS No 1330-78-5);
- 1% phenyl-alpha-naphthylamine (PAN) (1-Naphthalenamine, N-phenyl, CAS No 90-30-2);
- a last entry "ingredients partially unknown" is also noted on some documentation.

In Australia, classification of materials as being hazardous substances under the Hazardous Substances Regulation use a list of hazardous substances[48] and approved criteria,[49] with reference to the list being the primary step.

Of the ingredients in Mobil Jet Oil II, the most toxicologically significant ingredients are:

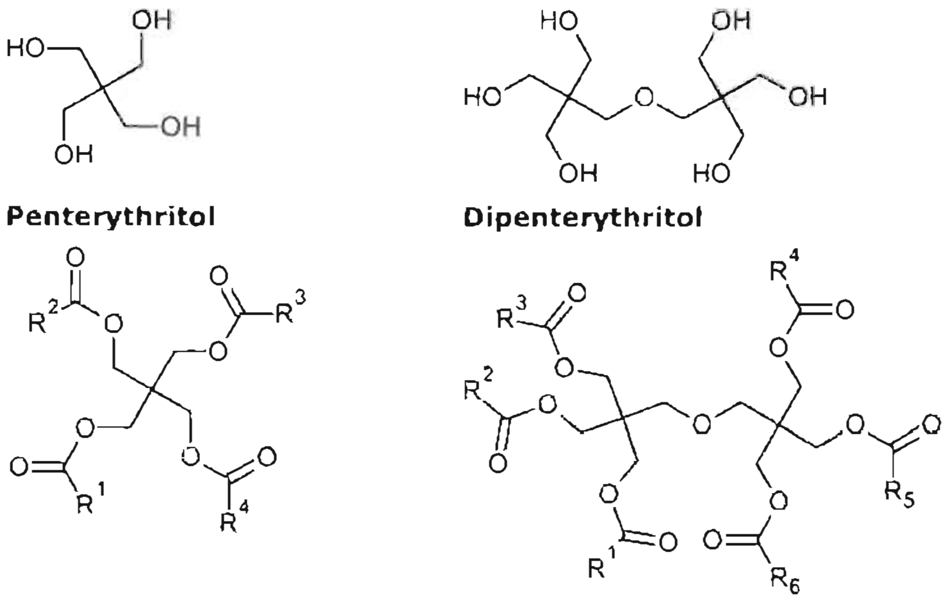
- the substituted diphenylamine, which may have ecotoxicological potential (not part of hazard classification processes in Australia);
- Phenyl-alpha-naphthylamine, which can contains a number of contaminants in trace amounts, including Phenyl-beta–naphthylamine (135-88-6), 1-Naphthylamine (CAS No 134-32-7) and 2-Naphthylamine (CAS No 91-59-8); and
- Tricresyl phosphate, a blend of ten tricresyl phosphate isomer molecules, plus other structurally similar compounds, including phenolic and xylenolic compounds.

There are a number of issues relevant to these ingredients, outlined below.

### 4.4.2 Pentaerythritol and Dipenterythritol and their Esters

The main constituent of most jet oils are esters of pentaerythritol (CAS no 115-77-5) and dipentaerythritol (CAS No: 126-58-9). The chemical structires of these molecules are shown in Figure 4-2.

***Figure 4-2: Pentaerythritol and Dipenterythritol and their Esters***



**Penterythritol** **Dipenterythritol**

**Penterythritol ester** **Dipenterythritol ester**

**The R groups ($R_1$-$R_6$) are $C_4$ to $C_9$ hydrocarbon chains**

There is little toxicity data on this group of chemicals, but generally these molecules are considered to have little toxicity.[50]

For Pentaerythritol, a UNEP SIDS document notes that toxicologically, the chemical caused only soft feces and diarrhoea in a repeated dose study, and the chemical is not considered as an irritant to skin and eyes; environmentally, the chemical is not readily biodegradable and toxicity to aquatic organisms is very low.[51]

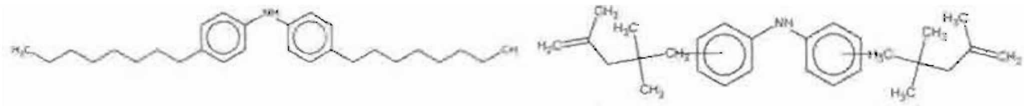
A similar document lists even less information for Dipentaerythritol, but conludes low toxicity and low environmental health problems.[52]

As the hydrocarbon chanisn in the esters can vary substantially, there is no specific information available for these chemicals.

### 4.4.3 Substituted Diphenylamine

The substituted diphenylamine is used as an antioxidant in lubricants, in concentrations not greater than 1% (see Figure 4-3).

***Figure 4-3: Substituted Diphenylamines***



| **Benzamine, 4-Octyl-*N*-(4-Octylphenyl)** | **N-Phenyl-benzeneamine, reaction product with 2,4,4-Trimethylpentene** |
|---|---|

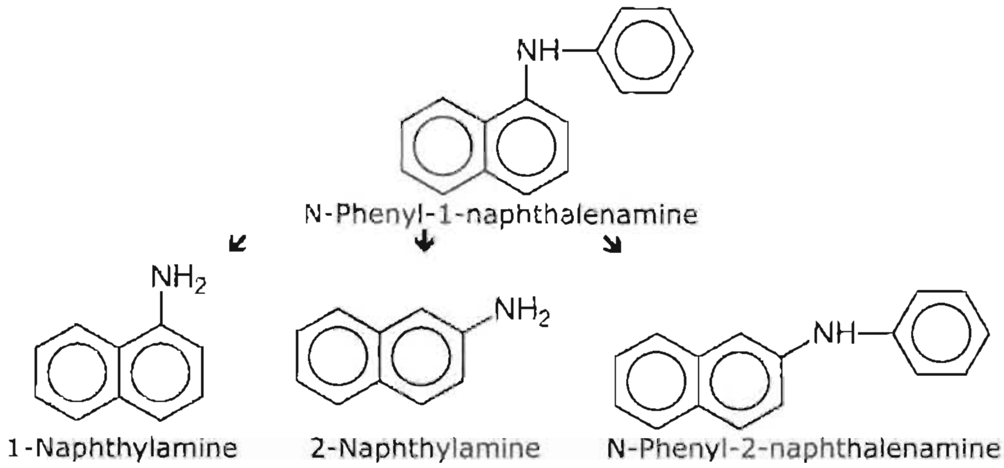
There is little toxicity data available, although it is not believed to be toxic by single exposure (no data on long term exposure). The disclosure of this ingredient in hazard communication by identity probably relates to its environmental effects, being poorly biodegradable, and toxicity to aquatic invertebrates.[53]

### 4.4.4 N-Phenyl-1-naphthalenamine

N-Phenyl-1-naphthylamine, (CAS No 90-30-2), also known as Phenyl-alpha-naphthylamine (PAN), is a lipophilic solid used as an antioxidant used 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% (its concentration in jet oils).

The commercial product has a typical purity of about 99%.[54] Named impurities are: N-Phenyl-2-naphthylamine (CAS No 135-88-6, 500 to below 5000 ppm), 1-Naphthylamine (below 100-500 ppm) and 2-Naphthylamine (below 3 to 50 ppm), aniline (below 100 to 2500 ppm), 1-naphthol (below 5000 ppm), 1,1-dinaphthylamine (below 1000 ppm) (see 2-Naphthylamine (CAS No 91-59-8) is also known as the established human carcinogen β-Naphthylamine;[55] similarly, 1-Naphthylamine is know as α-Naphthylamine (see Figure 4-4).

***Figure 4-4: N-Phenyl-1-naphthalenamine and possible contaminants***




PAN is readily absorbed by mammalian systems and rapidly converted to metabolites.[56] Both urine and faeces appear to be the main routes of excretion.[57]

By single dosing, PAN does not seem particularly toxic, with $LD_{50}$s above 1 g/kg. The chemical has a similar mechanism of toxicity of many aromatic amines, of methaemoglobin production. PAN is not irritating in primary skin and eye irritation studies. However, in a guinea pig maximisation test, PAN was shown to be a strong skin sensitiser.[58] This result is supported by case studies in exposed workers.[59,60] At the concentration used (1%), Mobil Jet Oil II meets cut off criteria (1%) for classification as a hazardous substance in Australia for sensitisation properties.

Most genotoxicity studies report negative results, suggested little genotoxicity potential.[57]

Most repeated dose toxicological studies focus on its potential carcinogenicity. An experimental study, using both PAN and the related compound N-phenyl-2-naphthalenamine administered subcutaneously to mice found a heightened incidence of lung and kidney cancers.[61] While the methodology used in this study makes evaluation of the results problematic (use of one gender, small sample sizes, limited number of dose groups, subcutaneous administration as an inappropriate route of exposure, and so on). A high incidence of various forms of cancer was also found among workers exposed to antirust oil containing 0.5% PAN.[62] While these animal and human results offer only limited information, they are at least supportive of a mild carcinogenic effect.

This must be contrasted with the results of long term carcinogenicity bioassays in rats and mice conducted by the US National Toxicology Program with the structurally related N-phenyl-2-naphthylamine (studies were not carried out on PAN), which have not reported any carcinogenic potential for this chemical.[63]

The formulation concentration of N-Phenyl-1-naphthalenamine in Mobil Jet Oil II is about 1%. As ingredients such as the naphthylamines have been deleted from product documentation such as the MSDB, the level of contamination of naphthylamines is presumed to be below the concentration cut off values for disclosure of Category 1 carcinogens specified in the 1999 Approved Criteria for Classifying a Hazardous Substance[49] of 0.01% (100 ppm). Indeed, information from Mobil Australia notes that the level of contamination of some of the contaminants in this material is partially known (50 ppm for N-Phenyl-2-naphthalenamine; 0.5 ppm for 2-Naphthylamine).[64]

2-Naphthlyamine is not listed on the 1999 Australian inventory of Chemical Substances (AICS),[48] and dependent on the amount present in the formulated product (0.2%), could technically breach the requirements of the Commonwealth Industrial Chemicals (Notification and Assessment) Act 1989. However, the probable concentration of this contaminant in Mobil Jet Oil II is too low to exceed requirements of this legislation. Further, this chemical is listed as a prohibited substance under the Australian Hazardous Substances Regulation.

#### 4.4.4.1 Regulatory Classification

PAN is not listed on the NOHSC Designated List of Hazardous Substances.

However, the NOHSC Approved Criteria for Classifying Hazardous Substances[49] note that mixtures containing sensitisers should be classified as an "Irritant" hazardous substance if included in the product at a concentration at or greater than 1%. Further, a product containing a skin sensitiser at or above this value should carry risk statement R43 – *May cause skin sensitisation by skin contact.*

The data on carcinogenicity of PAN is too limited to make a determination sufficient to allow classification for regulatory purposes.

Nevertheless, based on established sensitisation properties and possible carcinogenic properties, exposure to materials containing N-phenyl-1-naphthylamine should be avoided.

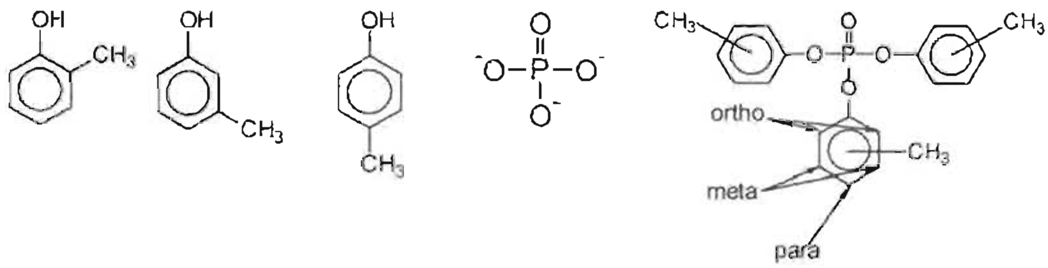
### 4.4.5 Tricresyl phosphate

Phosphoric acid, tris(methylphenyl) ester (CAS No 1330-78-5) is better known as Tricresyl phosphate (TCP) or Tritolyl phosphate.

#### 4.4.5.1 Chemistry of the Cresols and Tricresyl phosphate

Cresol is an aryl structure comprising a hydroxyl (-OH) and methyl ($CH_3$) group attached to a benzene molecule. Industrial cresol is a mixture of three isomers, ortho- para- and meta-cresol molecules in varying concentrations. The ortho-, meta- or para- prefixes denote how far apart the hydroxyl and methyl groups are apart on the cresol molecule (see Figure 4-5).

***Figure 4-5: Structure of Cresols and Tricresyl Phosphate***




**o-Cresol** **m-Cresol** **p-Cresol** **Phosphate** **TCP molecule (showing designation of o-, m- and p-cresyl groups)**

TCP is a blend of three cresyl (methylphenyl) groups linked to a phosphate group.

Industrially, the chemical is made by reaction of phosphorus oxychloride ($POCl_3$) with industrial cresol.

There are 27 ($3^3$) different combinations of meta, ortho and para cresyl groups in TCP. These are shown in Table 4-4:

***Table 4-4: Combinations of meta, ortho and para groups in Tricresyl phosphate***

| Group 1 | Group 2 | Group 3 | TCP Structure |
|---|---|---|---|
| meta- | meta- | meta- | tri-meta-cresylphosphate |
| meta- | meta- | ortho- | di-meta, mono-ortho-cresylphosphate |
| meta- | meta- | para- | di-meta, mono-para-cresylphosphate |
| meta- | ortho- | meta- | di-meta, mono-ortho-cresylphosphate |
| meta- | ortho- | ortho- | di-ortho, mono-meta-cresylphosphate |
| meta- | ortho- | para- | mono-meta, mono-ortho, mono-para-cresylphosphate |
| meta- | para- | meta- | di-meta, mono-para-cresylphosphate |

| Group 1 | Group 2 | Group 3 | TCP Structure |
|---|---|---|---|
| meta- | para- | ortho- | mono-meta, mono-ortho, mono-para-cresylphosphate |
| meta- | para- | para- | di-para, mono-meta-cresylphosphate |
| ortho- | meta- | meta- | di-meta, mono-ortho-cresylphosphate |
| ortho- | meta- | ortho- | di-ortho, mono-meta-cresylphosphate |
| ortho- | meta- | para- | mono-meta, mono-ortho, mono-para-cresylphosphate |
| ortho- | ortho- | meta- | di-ortho, mono-meta- cresylphosphate |
| ortho- | ortho- | ortho- | tri-ortho-cresylphosphate |
| ortho- | ortho- | para- | di-ortho, mono-para-cresylphosphate |
| ortho- | para- | meta- | mono-meta, mono-ortho, mono-para-cresylphosphate |
| ortho- | para- | ortho- | di-ortho, mono-para-cresylphosphate |
| ortho- | para- | para- | di-para, mono-ortho-cresylphosphate |
| para- | meta- | meta- | di-meta, mono-para-cresylphosphate |
| para- | meta- | ortho- | tri-meta-cresylphosphate |
| para- | meta- | para- | di-para, mono-meta-cresylphosphate |
| para- | ortho- | meta- | mono-meta, mono-ortho, mono-para-cresylphosphate |
| para- | ortho- | ortho- | di-ortho, mono-para-cresylphosphate |
| para- | ortho- | para- | di-para, mono-ortho-cresylphosphate |
| para- | para- | meta- | di-para, mono-meta-cresylphosphate |
| para- | para- | ortho- | di-para, mono-ortho-cresylphosphate |
| para- | para- | para- | tri-para-cresylphosphate |

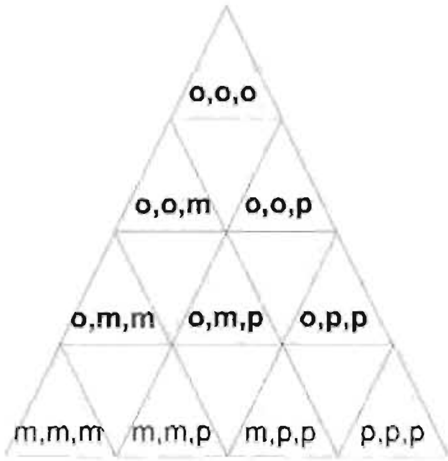
Chemically, because the molecule has a three dimensional structure, structures with similar numbers of cresyl groups (such as ppm, pmp and mpp) are considered the same structure, being optical isomers of each other. This gets the 27 down to the ten isomers conventionally used.

#### 4.4.5.2 Isomers of TCP

Generally, the chemical known as TCP comprises a mixture of unspecified ortho- para- and meta-cresol molecules (as cresyl groups, see above), which can be formed into a number of separate structures with similar chemical formulas (isomers).

Technically, there are ten possible tri-cresyl phosphate structures. These are shown below (see Figure 4-6 and Figure 4-7).

*Figure 4-6: Possible Isomers of Tricresyl phosphate*




o ortho-cresyl group

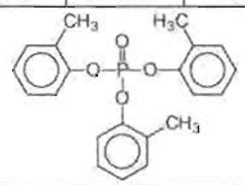
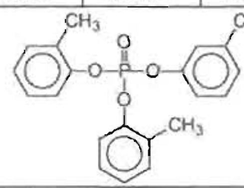
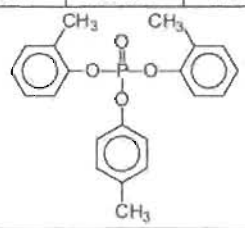
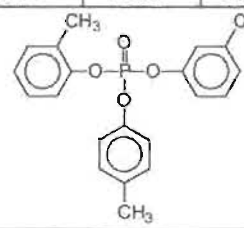
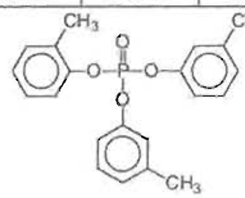
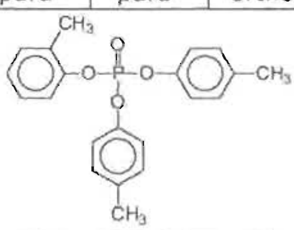
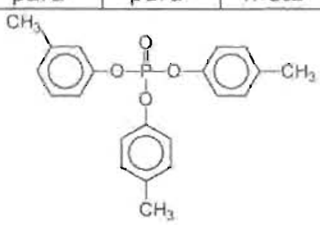
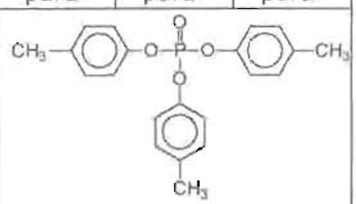
m meta-cresyl group

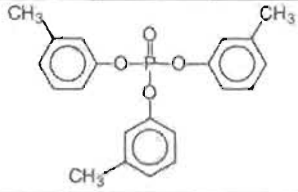
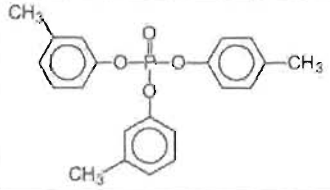
p para-cresyl group

ortho-cresyl group containing molecules are highlighted in **bold**

The structures of the ten different isomers are shown in Figure 4-7.

*Figure 4-7: Possible Tricresyl phosphate Structures*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ortho- | ortho- | ortho- | ortho- | ortho- | meta- | | | |
|  | | |  | | | | | |
| tri-ortho-cresyl phosphate | | | di-ortho-meta-cresyl phosphate | | | | | |
| para- | ortho- | ortho- | para- | meta- | ortho- | meta- | meta- | ortho- |
|  | | |  | | |  | | |
| di-ortho-para-cresyl phosphate | | | ortho-para-meta-cresyl phosphate | | | ortho-di-meta-cresyl phosphate | | |
| para- | para- | ortho- | para- | para- | meta- | para- | para- | para- |
|  | | |  | | |  | | |
| ortho-di-para-cresyl phosphate | | | meta-di-para-cresyl phosphate | | | tri-para-cresyl phosphate | | |

| meta- | meta- | meta- | meta- | meta- | para- |
|---|---|---|---|---|---|
|  | | |  | | |
| tri-meta-cresyl phosphate | | | para-di-meta-cresyl phosphate | | |

The different isomers of TCP have different properties, and indeed, different toxicities. Most notably, tri-orthocresyl phosphate (TOCP) is a well established neurotoxicant (see below).

#### 4.4.5.3 TCP Nomenclature

Describing Tricresyl phosphate isomers chemically can be a complicated task. However, the Chemical Abstracts Service (CAS) has simplified this process by allocating four unique identifying CAS registry numbers to Tricresyl phosphate mixtures. These are listed on the Australian Inventory of Chemical substances:[65]

- CAS No 1330-78-5 Phosphoric acid, tris(methylphenyl) ester ($C_{21}H_{21}O_4P$), which denotes Tricresyl phosphate (unspecified cresyl groups);
- CAS No 78-30-8 Phosphoric acid, tris(2-methylphenyl) ester ($C_{21}H_{21}O_4P$), which denotes Tricresyl phosphate (containing ortho-cresyl groups);
- CAS No 563-04-2 Phosphoric acid, tris(3-methylphenyl) ester ($C_{21}H_{21}O_4P$), which denotes Tricresyl phosphate (containing para-cresyl groups);
- CAS No 78-32-0 Phosphoric acid, tris(4-methylphenyl) ester ($C_{21}H_{21}O_4P$), which denotes Tricresyl phosphate (containing meta-cresyl groups).

In the past, disclosure of tricresyl phosphate ingredients in products containing this chemical invariably used the nonspecific 1330-78-5 CAS number (still a common practice by jet oil suppliers). Unfortunately, this provides no information about the various isomers in the mixture.

In its classification systems for hazardous substances, the European Union (EU) has introduced modifications of two of the CAS descriptions for tricresyl phosphate chemicals, being:

- CAS No 78-30-8 Tricresyl phosphate (containing o-o-o, o-o-m, o-o-p, o-m-m, o-m-p, o-p-p isomers);
- CAS No 78-32-0 Tricresyl phosphate (containing m-m-m, m-m-p, m-p-p, p-p-p isomers). It is assumed that the

maximum concentration of ortho-containing isomers in this mixture is below 0.2% (a concentration cut off for classification of systemic toxicity).[49]

The reason for this change was to discourage use of the general TCP mixture CAS Number 1330-78-5 (which was proposed to be deleted but remains in use), and encourage better disclosure of ortho-cresyl containing mixtures. Newer documentation by jet oil manufacturers suggests this has not yet happened, with the older 1330-78-5 CAS Number still in use on product information. It can be argued that the continued use of the older 1330-78-5 number by industry indicates that they are ignorant of the changes at the EU level and the implications of these changes for disclosure on labels and material safety data sheets.

The new CAS numbers will assist in identifying those products that contain the toxic ortho-cresyl ingredients. At the moment, it may be presumed that from a marketing perspective, disclosure of the new CAS number that indicates the presence of ortho-cresyl containing TCP in commercial products is undesirable, and therefore companies are persisting with the older generic CAS number. From this, it may be assumed that the absence of the non-ortho-cresyl containing TCP CAS number indicates that ortho-cresyl groups are present in the mixture. This is further supported by the absence of positive statements about the absence of ortho-cresyl containing isomers in TCP products.

The EU chemical names and numbers are listed in the Australian List of Designated Hazardous Substances which forms a major part of the classification of hazardous substances under the hazardous substances regulations.[48,49] Suppliers of tricresyl containing materials should be referring to the new CAS numbers and chemical descriptions as soon as practicable. Further, a requirement to "state on the label whether the substance is a specific isomer or a mixture of isomers" is included in the List.

#### 4.4.5.4 Commercially Available TCP

Commercial grade TCP is a complex mixture of structurally related compounds, some of which are known to have neurotoxic properties. These are produced from the ortho-alkyl substituted phenols or xylenol present in the manufacturing process. ortho-Methyl phenols (cresol) or ortho-ethyl phenols lead to toxic components, whereas ortho-substituted xylenols do not.[66]

Initially, TCP contained high levels of all isomers. The neurotoxic potential of orthocresyl isomers, most notably triortho-cresyl phosphate (TOCP), was recognised quite early.[67] Indeed much research has been carried out on the toxicity of TOCP, presumably on the basis that as it had three cresyl groups, it must be more toxic than molecules with less.

There have been substantial modifications of TCP containing materials. Earlier TCP products, such as "torpedo oil" used in World War II, were highly toxic, containing perhaps 25-40% ortho-cresol. Notably, this product was more toxic than TOCP itself.[68] This is a critical finding, because it meant that the conventional view that the toxicity of TCPs was correlated to their triortho-cresol content was incorrect. The presence of other ortho-cresyl containing molecules (not just TOCP) needs consideration in evaluating the overall toxicity of TCP.

Manufacturers reduced the levels of ortho-cresyl and ortho-ethylphenyl isomers to reduce the potential for neurotoxicity. Changes to the phenolic mixture used to manufacture TCP, introduction of processing alternatives and improved purification methods all assisted in reducing ortho-cresol content. By the 1950s, commercially available TCP contained about 3% ortho-cresol isomers. Further refinements in the 1980s to 1990s have decreased the ortho-cresol content further. How much these refinements had removed the toxic impurities outlined above is not known. Indeed, toxicity was still being detected in commercially available products in 1988.

It is difficult to obtain data on the amount of TOCP contamination in commercially available materials now being marketed world-wide containing TCP. Data from a 2005 paper indicate that the main components of tri-cresyl phosphate (TCP) are approximately 15-25% tri-*meta*-cresyl phosphate, 5-10% tri-*para*-cresyl, 60-75% mixed *meta*- and *para*-cresyl phosphates, and small amounts of *ortho*-cresyl isomers (mainly in the mono-*ortho*-cresyl form with low amounts of di-*ortho*-cresyl isomers and minute amounts of the tri-*ortho*-cresyl isomer, resulting in more than ten cresyl isomers.[69] Conservative estimates of about 0.1-1% (100-1000 ppm) seem realistic. This suggests that a product containing 3% TCP would contain about 0.003-0.03% TOCP (3-30 ppm). The "new generation" materials are claimed to have an even lower TOCP content, although data on content is sparse. Importantly however, is that the focus of attention on the toxicity of TOCP has masked the study of the toxic potential of other orthocresyl Isomers. Further, work by Henschler and colleagues in the 1950s (published, but published in German) was not reconsidered until the 1990s.

Typically, jet turbine engine oils are formulated with about 3% TCP. This includes Mobil Jet Oil - 3% TCP is stated on MSDB, and is supported by data published in elemental analyses,[70] where a Mobil Jet Oil was shown to contain 0.29% Phosphorus, which extrapolates to about 3.5% organophosphate.

#### 4.4.5.5 Uses of TCP

TCP has been a commercially useful material, and has been used as a plasticiser, lubricant, hydraulic fluid, paint additive, oil additive, dust suppressant and do on.[71,72] Most commercial uses have now ceased.

In jet oil, TCP is used in the formulation of lubricants as an antiwear additive to enhance load bearing properties and improve tolerance to increasing speed of rotating or sliding motion. It also has flame retardant properties. While some other triaryl phosphates have similar properties and may also be used as oil additives, the antiwear properties of TCP are considered unique. For example, pure tri-para-cresyl phosphate is considered to have poorer lubricating properties than commercial TCP.[73]

#### 4.4.5.6 Toxicity of Tricresyl phosphates

**Toxicology of the Organophosphates**

Human toxicity to organophosphorus compounds has been known at least since 1899, when neurotoxicity to phosphocreosole (then used in the treatment of tuberculosis) was reported.[74]

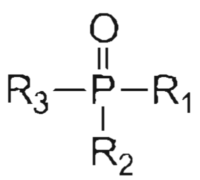
The study of the toxicity is extensive, with two very well established mechanisms on esterases and on neurotoxic esterases (NTE).

**Poisoning with Organophosphates**

The organophosphorus compounds are generally characterised by a toxicity of inhibition of the esterase enzymes, most particularly cholinesterases[75] and neurotoxic esterases.[76] The mechanism of effect is phosphorylation.[77] The effect is a specific mechanism of organophosphate toxicity

An organophosphorus molecule can be represented by the general structure shown in Figure 4-8.

***Figure 4-8: General Structure of an Organophosphorus Molecule***



Where P is the Phosphorus atom, O is an oxygen atom and $R_1$-$R_3$ represent organic structures which can give the molecule a wide range of properties.

Because cholinesterases break down endogenous choline esters, inhibition of these enzymes produces an accumulation of levels of choline esters. The most critical of these esters is acetylcholine, a neurotransmitter molecule released throughout the cholinergic nervous system. Any organ or tissue that receives a cholinergic input will become more active or excited if cholinesterases are not available to catalyse the breakdown of acetylcholine. Indeed, cholinergic overstimulation produces most, if not all, of the symptoms of poisoning from single and short term exposure to organophosphates.

Signs of low level intoxication include headache, vertigo, general weakness, drowsiness, lethargy, difficulty in concentration, slurred speech, confusion, emotional lability and hypothermia.[78] The reversibility of such effects has been questioned.[79]

Signs of poisoning are usually foreshadowed by the development of early symptoms related to acetylcholine overflow and include salivation, lacrimation, conjunctivitis, visual impairment, nausea and vomiting, abdominal pains and cramps, diarrhoea, parasympathomimetic effects on heart and circulation, fasciculations and muscle twitches.[80]

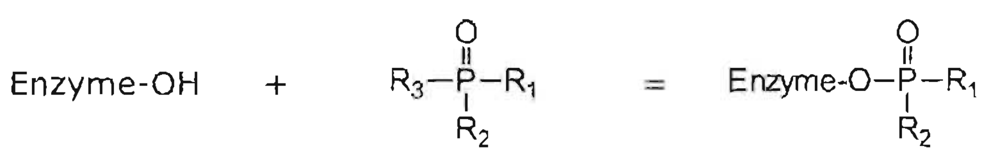
This is the basic site of inhibition for all OP molecules.[81,82]

**Organophosphate Induced Delayed Neuropathy (OPDIN)**

There is a second reaction that leads to further neurotoxic and neuropathological changes.

Inhibition of neurotoxic esterases (NTE) can lead to a neuropathological condition of progressive neuronal damage, called organophosphorus induced delayed neurotoxicity (OPIDN).[83,84] The mechanism of toxicity is now fairly well understood, as indeed are the organophosphorus structures which are predicted to cause OPIDN.[85] Basically, all OP molecules react with any -OH groups on the active site of the enzyme, as shown in *Figure* 4-9:

***Figure 4-9: Mechanism of Toxicity, OP molecules***

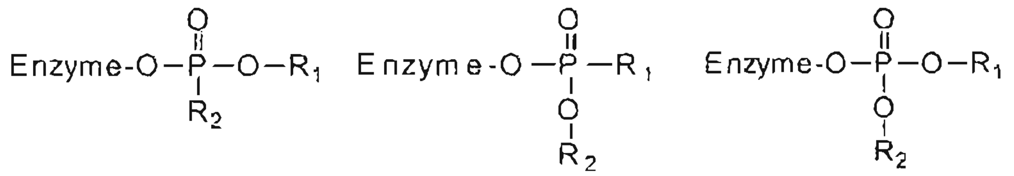



The basic process is the initial phosphorylation of a group of esterases called the neurotoxic esterases (NTE). This is followed by a second reaction of enzyme "aging", where the enzyme structure (or its microenvironment) was modified so that it can no longer function properly. The basic mechanism is a break in the P-O-R bond, resulting in a negatively charged P-O⁻ group, and a free -R group. A determinant of toxicity is the extent of inhibition of these enzymes, in that marked toxicity occurs after inhibition of over 50%.[86]

Several theories about the significance of these events in the development of OPIDN,[87] and a pathway of events have been proposed.[88]

The likelihood of this reaction occurring is dependent on the molecular structure of the OP molecule. Where either or both of the $R_1$ or $R_2$ groups are linked to the phosphorus with a P-O-R bond (instead of a P-R bond), OPIDN can develop. These OP structures are shown in Figure 4-10.

***Figure 4-10: The Neurotoxic Organophosphorus Molecules***



The main classes of organophosphorus molecules that have the potential to cause OPIDN are phosphates (two P-O-R bonds) and phosphonates (one P-O-R bond). A further group known to cause OPIDN are the phosphoroamidates, where the oxygen in the P-O-R bond is replaced by nitrogen (R-N-R).

Where the OP molecule only contains P-R bonds, aging (and therefore delayed neuropathy) will not occur. The main classes of organophosphorus molecules that have these structures are the phosphinates.[89]

Not all animal species are susceptible to developing OPIDN: for example, rodents are not particularly sensitive[90] (although neurological damage can be produced in the rat[91]). However, along with the cat[92] and chicken,[93,94] humans are considered to be among the most sensitive species.[95]

OPIDN is caused when the organophosphate molecule binds with NTE in the long processes of the nerves (the axons). The enzymes have functions related to transport of nutrients and energy molecules from the cell body to the end of the nerves. Phosphorylation of such proteins results in localised disruption of axoplasmic transport. If prolonged, these effects are followed by swelling of the axon, followed by degeneration from the site of the damage to the end of the axon. If exposure continues, this process can continue up the axon by the phosphorylation of more proteins. Lesions are characterised by degeneration of axons followed by degeneration of the cells that surround (and contribute to the insulation of the fibres) the myelin containing support cells.[95] This effect can occur in sensory or motor nerves in either the central or peripheral nervous systems.[96] Initially, the condition arises as a distal symmetrical sensori-motor mixed peripheral neuropathy mainly affecting the lower limbs with tingling sensations, burning sensations, numbness and weakness. In severe cases paralysis may develop.[97] Longer nerves are affected more, probably because or their requirements for active nutrient supply (shorter nerves may continue to get supplied through passive mechanisms, such as diffusion). Regeneration is possible if exposure ceases and damage is not too extensive.[98,99]

**The Intermediate Syndrome**

OPIDN has a severe pathology. It is quite likely that such a severe condition would be presaged with a range of clinical and pre-clinical signs and symptoms. These have been reported extensively, and an "intermediate syndrome" was defined in 1987.[100] Symptoms of the intermediate syndrome include: proximal limb paralysis, weakness of neck muscles, inhibition of respiratory muscles and cranial nerve involvement. The mechanism of effect is different from poisoning or OPIDN effects, and is considered to be due to the effect of the organophosphate at the level of the neuromuscular synapses.[101]

**Chronic Organophosphate Neuropsychological Disorder (COPIND)**

More recently, chronic exposure to organophosphates has been associated with a range of neurological and neuropsychological effects.[102,103,104,105,106] Such symptoms (mainly neurological and neurobehavioural symptoms) may also be seen in exposed individuals who have been sufficiently fortunate in not having exposures that were excessive enough in intensity or duration to lead to clinical disease.

A distinct condition - chronic organophosphate neuropsychological disorder (COPIND) has been described, of neurological and neuropsychological symptoms.[107] These include:

- diffuse neuropsychological symptoms (headaches, mental fatigue, depression, anxiety, irritability);
- reduced concentration and impaired vigilance;
- reduced information processing and psychomotor speed;
- memory deficit and linguistic disturbances;

COPIND may be seen in exposed individuals either following single or short term exposures leading to signs of toxicity,[108] or long term low level repeated exposure with (often) no apparent signs of exposure.[109] The basic mechanism of effect is not known, although it is not believed to be related to the esterase inhibition properties of organophosphorus compounds. It is also not known if these symptoms are permanent.

In addition, since the introduction and extensive use of synthetic organophosphorus compounds in agriculture and industry half a century ago, many studies have reported long-term, persistent, chronic neurotoxicity symptoms in individuals as a result of acute exposure to high doses that cause acute cholinergic toxicity, or from long-term, low-level, subclinical doses of these chemicals.[110,111,112] The neuronal disorder that results from organophosphorus ester-induced chronic neurotoxicity (OPICN), which leads to long-term neurological and neurobehavioral deficits.[113]

**Toxicology of TCP and TOCP**

Much of the early study of OPIDN was investigated not just with organophosphorus compounds, but with the tricresyl phosphates [114, 115] following outbreaks of poisoning after accidental or criminal adulteration of food or beverages with TCP containing products. A large literature is now available on the toxicity of the tricresyl phosphates (most particularly, TOCP) and the basic mechanisms are well established.[116] TCP produces acute poisoning based on cholinesterase inhibition, and a well defined syndrome of neurological degeneration (either from short term or long term repeated dose exposure). As well as affecting the nervous system, TCP also has toxic effects in the adrenal glands, ovaries and testes.[117]

Neurotoxicity has been reported in TCP manufacture.[118] The toxic effects of oils containing TCP have also been long recognised.[119]

The toxic properties of tri-ortho-cresyl phosphate have been recognised for decades, and the presence of this isomer in products containing TCP presents a significant occupational health problem. Further, as noted above, there are five other orthocresyl phosphate isomers:

- two di-ortho-cresyl phosphates (di-ortho-mono-meta-cresyl phosphate or o-o-m and di-ortho-mono-para-cresyl phosphate or o-o-m); and
- three mono-ortho-cresyl phosphates that contain only one ortho-cresyl group but various combinations of meta-cresyl and para-cresyl groups (o-p-p, o-p-m, o-m-m).

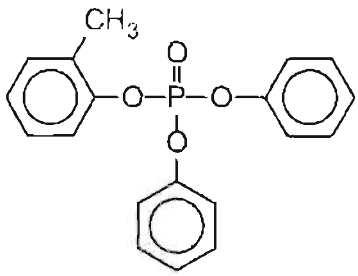
These mono- and di- ortho-tricresyl phosphates are reported to have measurable toxicities similar to the neurotoxicity produced by TOCP.

**Other ingredients**

Tricresyl phosphate will also contain mixed esters of orthophosphoric acid with different cresyl radicals, of the mono- and di-cresyl types.

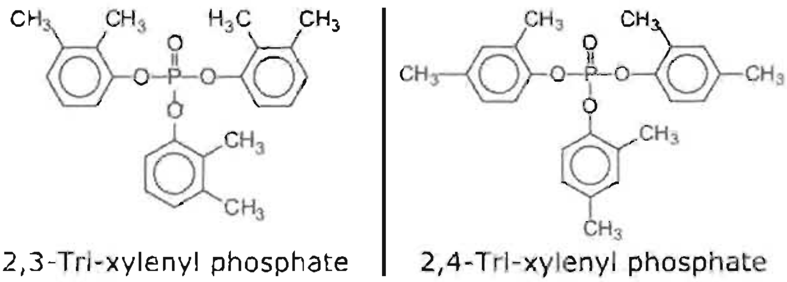
Other contaminants, such as ortho containing dicresyl phosphates may also be toxic. Further, mono-ortho-cresyl-diphenyl phosphate (that is, an organophosphate molecule with one cresyl group (see Figure 4-11) appears to be the most toxic molecule of all.[120]

***Figure 4-11: Structure of Mono-ortho-di-phenyl phosphate***




Further, other ortho-containing molecules, such as 2,3-Tri-xylenyl phosphate and 2,4-Tri-xylenyl phosphate, are weakly neurotoxic (this is a cresyl molecule with an extra methyl group, the 2- indicates the ortho- position, see Figure 4-12).[121]

***Figure 4-12: Possible Tri-xylenyl phosphate Structures***




Other trixenyl phosphates, such as 2,5, 2,6, 3,4 and 3,5 were not neurotoxic.

Still other impurities, such as triphenyl phosphate, diphenylmonocresyl- phosphate, diphenylmono-xylenyl phosphate and trixylenyl phosphate may also be neurotoxic. The presence of structures with methyl groups adjacent to the ester –O-P bond, needs consideration in evaluating the overall toxicity of TCP.

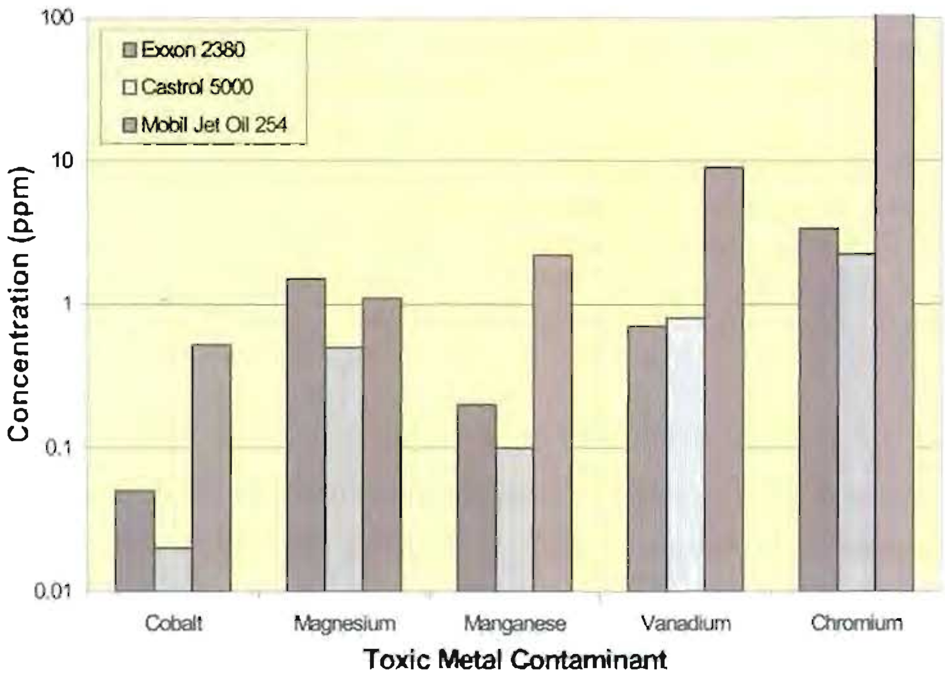
Recent research has focused on identifying a dose response relationship for TOCP. Results of a short term repeated dose study in hens of aviation engine oil containing various amounts of commercial TCP suggest that oil containing 1% TCP (a TCP equivalent of 20 mg/kg/day) was considered a no observable effect level. [122] Similar findings were reported in a later study.[123]

Finally, it is generally assumed that most exposure to TOCP is by the inhalational route. However, absorption through skin exposure should not be discarded, as significant exposure (maximally estimated at a transdermal flux rate of 0.01 $mg/cm^2/hr$) at through this route is possible.[124]

***Non-Organic Contaminants***

One additional point that should be made is that these materials do not just contain organic molecules. They also contain low levels of other contaminants. The elemental analysis conducted by van Netten referred above [125] investigated elemental concentrations of a range of elements in three commercially available jet oils (see Figure 4-13).

***Figure 4-13: Toxic Metal Contaminants in Commercial Jet Oils***




While concentrations of some metals are in ppm and even ppb concentrations, it is misleading to ignore the possible effects of these and other exposures either singly, or in combination.

### *Relative Toxicity of the ortho-Cresyl Containing Tricresyl phosphate Isomers*

The ten isomers that make up TCP are toxicologically different, and it is well established that the ortho containing isomers are the most toxic. Much research in the past has concentrated on the tri-orthocresyl phosphate isomer (TOCP), which has shown to be associated with organophosphate induced delayed neuropathy (OPIDN). TCP manufacturers have expended considerable energy in reducing levels of TOCP in commercial grades of TCP.

However, what is less well known is that there are other ortho containing isomers in TCP, three mono-ortho (MOCP) isomers and two di-ortho (DOCP) isomers. All these compounds are neurotoxic in the same manner as TOCP - however they are known to be more neurotoxic. For instance the DOCPs are five times more toxic, and the MOCPs ten time more toxic, than TOCP.[120,121] The total toxicity of a particular mixture is therefore dependent on consideration of the proportion of each ingredient, their relative toxicities, and the effect of any interaction between mixtures of chemicals.

In evidence to the Australian Senate Aviation Inquiry by Mobil USA notes that Mobil Jet Oil II contains less than 5 ppb (0.005 ppm) TOCP.[126] This is an impressively low amount, and suggests that the neurotoxic potential from a chemical containing such a low level would be vanishingly small. However, concentrations from other neurotoxic ingredients are not so readily available. In evidence to the Australian Senate Aviation Inquiry, it became apparent that DOCPs were present in TCP at a concentration of 6 ppm, and MOCPs were present at a concentration of 3070 ppm. As these ingredients are present in higher concentrations than TOCP, and have a significantly higher toxicity than TOCP, it is suggested that a statement of low TOCP content is misleading as it underestimates the toxicity of the –OCP ingredients by a factor of 30,000 (see Table 4-5).

***Table 4-5: Tricresyl Phosphate: Toxicity of Isomers***

| Isomer | Concentration (ppm) | Relative Toxicity | Equivalent Toxicity |
|---|---|---|---|
| **TOCP** | 0.005 | 1 | 1× |
| **DOCP** | 6 | 5 | 30× |
| **MOCP** | 3,070 | 10 | 30,700× |
| | | **Total** | **30,731×** |

Further, the chemically similar organophosphates such as xylenols and phenolics are also present in as contaminants in tricresyl phosphate. These also have a similar neurotoxicity to the cresyl isomers, which would add to the relative toxicity listed above.

Tricresyl phosphate will also contain mixed esters of orthophosphoric acid with different cresyl radicals, of the mono- and di-cresyl types. The important issue with these data is that the level of all ortho-cresyl phosphates should impact on the regulatory classification of materials containing TCP.

New products are being introduced into the market. Claims that they are organophosphate clear are untrue. Mobil 291, one such replacement oil contains less than 1 ppb TOCP, 1.1 ppm DOCP and 1760 ppm MOCP.[143] This gives an equivalent toxicity of 17,606, which is about half that of the previously used product, Mobil Jet Oil II. While this is a significant decrease in -OCP containing monomers, it is not phosphate free.

**Regulatory Classification**

Tricresyl phosphate is listed on the NOHSC Designated List of Hazardous Substances.

The first edition of the Designated List was current from 1994 to 1999.[48] This edition contains three entries for Tricresyl phosphate.

The first entry for Tricresyl phosphate (as Tri-tolyl phosphate) uses the CAS No 1330-78-5. This entry notes that mixtures this ingredient should be classified as "Harmful" hazardous substances if included in the product at a concentration at or greater than 0.2% and "Toxic" hazardous substances if included in the product at a concentration at or greater than 1%. Further, a product containing this ingredient at or above 0.2% should carry risk statement R23/24/25 – *Toxic by inhalation, in contact with skin and if swallowed* and R39 – *Danger of very serious irreversible effects.*

There are two other entries in the 1994 edition of the Designated List, based on two other chemical descriptions - Tricresyl phosphates (below 1% ortho-cresol) and Tricresyl phosphates (above 1% ortho-cresol). Regulatory requirements for the former are classified as Harmful if present in a mixture above 5% with risk phrases R21/22 - *Harmful in contact with skin and if swallowed.* Regulatory requirements for the latter are the same for Tri-tolyl phosphate (CAS No 1330-78-5).

A final entry also is listed for Triortho-cresyl phosphate under the CAS No 78-30-8, but no classification cut-off values are listed or risk phrases suggested. This chemical placed on the list as it had an Australian exposure standard. Such listings were anomalous, and were removed in 1999.

Entries on product documentation have invariably used the 1330-78-5 description, perhaps because of the problem of obtaining a true estimate of all the various structures containing the "o-cresol" groups.

The second edition of the designated list has been current since 1999.[127] All entries for TCP have been deleted, with two new entries:

- CAS No 78-30-8 Tricresyl phosphate (o-o-o, o-o-m, o-o-p, o-m-m, o-m-p, o-p-p);[†]
  - Classified as "Harmful" at concentrations above 0.2%, with the risk phrases R21/22 – *Harmful in contact with skin and if swallowed.*
  - Classified as "Toxic" at concentrations above 1%, with the risk statements R23/24/25 – *Toxic by inhalation, in contact with skin and if swallowed* and R39 – *Danger of very serious irreversible effects.*
- CAS No 78-32-0 Tricresyl phosphate (m-m-m, m-m-p, m-p-p, p-p-p)
  - Classified as "Harmful" at concentrations above 5% with the risk phrases R21/22 – *Harmful in contact with skin and if swallowed.*

While these two new entries have attempted to clear up the confusion apparent in the earlier entries, it is not known at which point that contamination of a non-ortho-cresyl-TCP with ortho-cresyl containing monomers converts a low hazard "non-o-TCP" to an o-TCP.

Use of these two new entries is not widespread, with the 1330-78-5 CAS number remaining in common use. Unless an accurate measure of the ortho-cresyl (and probably the "ortho"-xenyl isomers) can be made, it is prudent to continue to assume that the TCP mixture contains significant levels of ortho-containing isomers.

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[†] This CAS No is also used to describe the entry for Tri-ortho-cresyl phosphate (TOCP), suggesting that any Tricresyl phosphate containing ortho-cresyl containing isomers, can now be loosely called TOCP.

# 4.5 Issues that can Impact on Exposure to Jet Oils

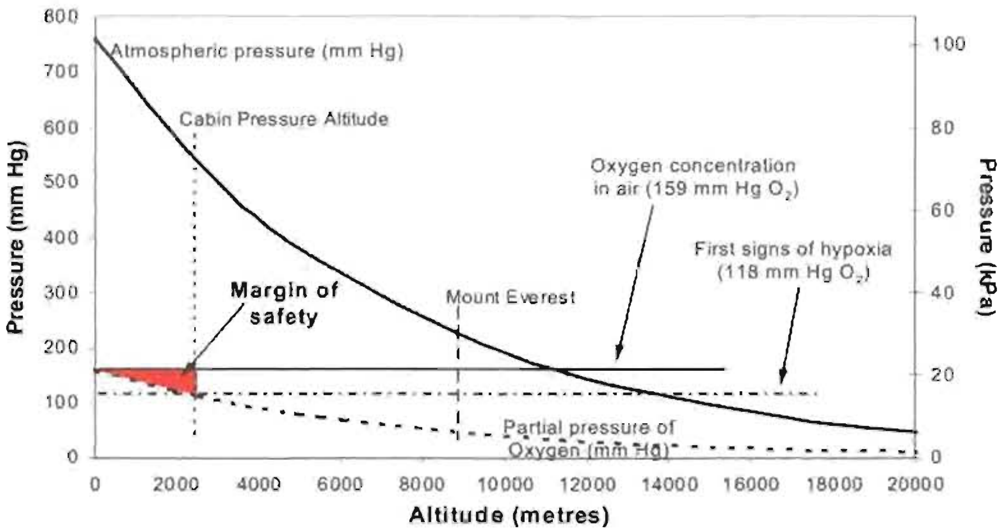
## 4.5.1 The Impact of Altitude

The concentration of oxygen at increasing altitude remains constant, at 20.9%. This suggests that oxygen levels are unchanged. This is not true. Basically, as altitude increases, the atmospheric pressure declines. While the proportion of oxygen in air remains unchanged, the actual amount of oxygen in air decreases.

Atmospheric pressure at sea level is 760 mm Hg, with the corresponding partial pressure of oxygen in air is 159 mm Hg (20.9% of 760 mm Hg). The minimum $O_2$ concentration for work is considered to be about 136 mm Hg (18 kPa or 18%) $O_2$ in air at sea level.[128] A minimum oxygen partial pressure of 118 mm Hg (equivalent to an altitude of 2438 m/8000 ft) is required to prevent hypoxic cabin air in commercial aircraft during normal operations. This partial pressure is maintained by the cabin pressure system (a second requirement for release of oxygen dispensing units at 4572 m/15,000 ft is recommended).[129]

The altitude at which the partial pressure of 136 mm Hg is reached is also quite close to the pressure at which aeroplane cabins are pressurised (118 mm Hg). There is little margin of safety in people working at altitude, and in many cases, such workers may start to become hypoxic.[130] This is shown in Figure 4-14, where the area bounded by the dashed partial pressure of Oxygen in Air curve, and the dotted line representing the minimum physiological demand line represents the margin of safety at which workers can be considered to have sufficient oxygen to work safely). Further, the position of the cabin pressurisation line shows that in some cases, workers at altitude may not be obtaining enough oxygen for their physiological requirements.

*Figure 4-14: Pressures and Oxygen Concentrations at Altitude*




**Assumptions:**

Atmospheric pressure: 101 kPa (760 mm Hg) at sea level

Proportional concentration of $O_2$ in air: 20.9% (21 kpa or 159 mm Hg) at sea level)

Aircraft Pressurisation Pressure: Equivalent to an altitude of 2500 m (about 8000 ft).

This is further complicated by the effect of continued exposure to the hypoxia of flying. A Boeing presentation to a 1997 meeting of the ASHRAE Aviation Subcommittee indicated that for an eight hour flight, a flight attendant with a blood oxygen saturation level of 98% at the start of a shift would find this level reduced to the high 80s to low 90s by the end of the workday. Adequate rest would be needed to raise the blood oxygen saturation back to a normal level.

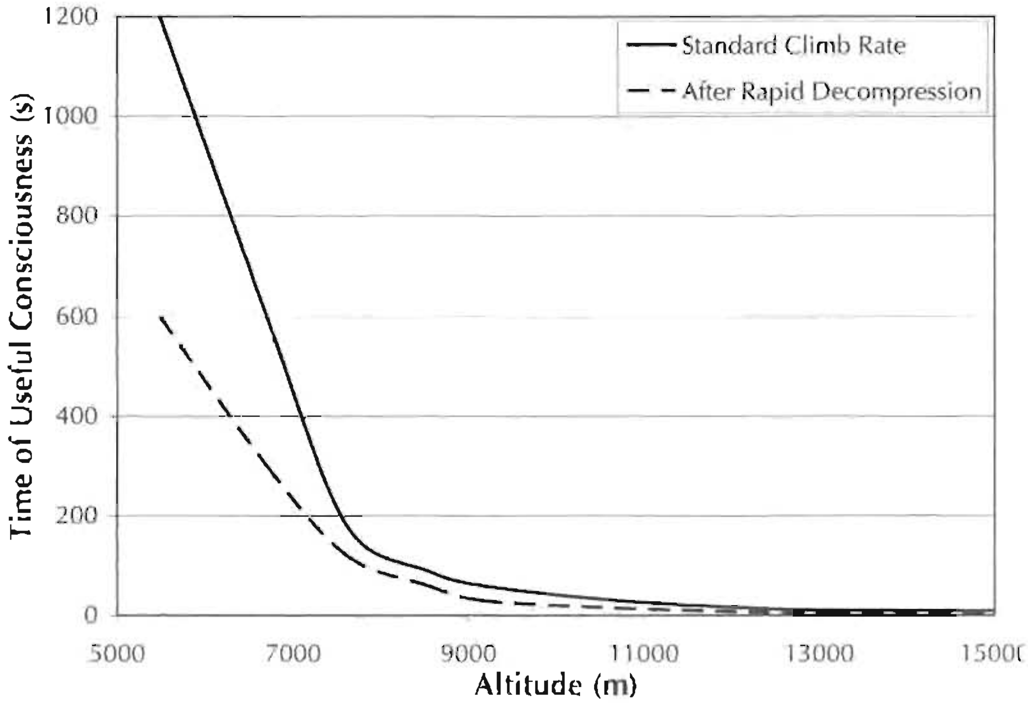
Other problems with lowered oxygen concentrations include changes in sensitivity to toxic exposures (for example, the toxicity of carbon monoxide is 50% higher at 8,000 ft than at sea level), and the possibility that incipient hypoxia may lead to higher respiratory rates and therefore increased exposure.[131,132]

Other factors due to the manner in which air is circulated in planes, may also have an effect, such as humidity, temperature, or contaminants such as carbon dioxide, carbon monoxide, ozone and particulates.[133]

The International Civil Aviation Organisation (ICAO) has established a standard temperature and pressure model of 15°C and 1013.25 mb. While conditions can vary across the planet's surface, the model is a useful approximation. The model also predicts that for altitudes where aviation occurs, the temperature drops by 2°C for every 1000 feet of altitude and 1 mb every 30 feet of altitude.

Hypoxia can occur in unpressurised airplanes as they climb or in pressurised airplanes undergoing sudden or rapid decompression. The time of effective performance of aircrew at altitude without supplementary oxygen is known as the "Effective Performance Time." [134] A similar, perhaps less euphemistic term, is the US FAA's "Time of Useful Consciousness" (TUC).[135] This is defined as the amount of time in which a person is able to effectively or adequately perform flight duties with an insufficient supply of oxygen. The TUC for standard airplane climbing rates or after rapid decompression is shown in Figure 4□15.

***Figure 4-15: Time of Useful Consciousness***
(adapted from [135])




As with all these values, the TUC is an estimated average and is based on normal, healthy individuals (usually young, fit male volunteers).[135]

### 4.5.2 Issues Related to Minimal Oxygen Content

Outside of the aviation industry, other industries may also have problems of oxygen content in places where workers are working. The authorative American Conference of Government Industrial Hygieneists (ACGIH) establishes exposure standards for many workplace contaminants and has examined the issue of minimal oxygen content in workplaces. The ACGIH

Document for the 2008 TLVs® and BEIs® recommends a minimal ambient oxygen pressure of 132 mm Hg, which is equivalent to an altitude of 5,000 feet or ~1,500 m.[136]

This recommendation suggests that an airplane pressured to an altitude of 8000 m (or 118 mm Hg) falls outside of what the ACGIH consider a minimal oxygen concentration for workers. As such, workers in such an environment are working in a specialised environment.

### 4.5.3 Issues Related to Vapours and Particulates

Airborne contaminants are generally divided into two types: gas/vapour and particulates.[137]

**Gases/Vapours:** A gas is those molecules of a chemical that exist in a gaseous phase. Where all the molecules of a chemical are in the gaseous phase, the chemical is considered a gas. A vapour is the gas phase of a liquid at room temperature. Therefore, a vapour is that amount of liquid that evaporates into air (or dissolves into air). Gases and vapours form true solutions in air. The amount of evaporation is dependent on the individual vapour pressure of the contaminant. Where vapour pressure is low, only a small amount of the contaminant will evaporate. Generally, vapour pressure increases with temperature.

Where volatile organic chemicals (VOCs) have high vapour pressures, they will be present in air in high concentrations, are more likely to reach toxic concentrations and are amenable to sample collection and analysis using sorbent or gas collection methods. Where semi-volatile or poorly volatile chemicals have low vapour pressures, they are less likely to reach toxic concentrations unless they are highly toxic, and sorbent or gas collection methods are less useful for sample collection.

**Particulates:** These are materials that are suspended, not dissolved, in air, and include fumes, smoke, mists, aerosols, dusts, fibres and so on. Particulates may be in liquid phase (such as mists), solid phase (smokes, fumes and dusts) or mixed phases (aerosols). Precise criteria for these terms exist based on particle size and phase, but are unnecessary for the present discussion.[138]

Where a particulate is present in air and contains a volatile component, the volatile components will evaporate at a rate dependent on individual vapour pressures. However, depending on the amount of particulate present in air, it is possible to exceed the vapour pressure of an individual contaminant. Where a contaminant has a low vapour pressure, particulate exposure is more important than exposure to vapour.

Therefore, particulates containing a large proportion of volatile components will evaporate quickly (sometimes even before settling), indicating that the vapour phase of the contaminant is more important. Particulates containing poorly volatile components will stay in particulate form for a long time, until gravity or turbulence causes them to settle. Once settled, particles coalesce onto or adhere to surfaces, and any remaining volatile components become subject to evaporation through their vapour pressures. Where evaporative pressures are low, long term, low-level contamination leading to residual exposures will occur.

Further, because particulates can settle on exposed skin and be subject to absorption through skin, sometimes after airborne exposure has ceased, it is important to consider both the inhalational and skin routes when estimating exposure.

Particulates are not amenable to the same sampling and collection methods that are required for gases and vapours. They require specialised sampling, usually by filtration or gravimetric methods. Further, because particulates can exist in different sizes and diameters, an estimate of that fraction of the particulate that is taken into the respiratory system may be more critical than an estimation of the total concentration of particulate. Consideration of the type of airborne contaminants, whether in vapour, a particulate or mixed phase is quite critical for the success and relevance of a monitoring program.

### 4.5.4 Issues Related to Combustion and Pyrolysis

Any chemical or chemical mixture is subject to degradation processes, such as oxidation or reduction. Over time, these can cause substantial loss of original chemical structures and properties. This process occurs more rapidly at higher temperatures and pressures, in accordance with the laws of thermodynamics. However, for most commercial purposes (except perhaps in the production of food), the processes of breakdown in chemical materials are slow, and can be disregarded.

However other breakdown processes are also possible. For example, a material subject to a source of heat energy can burn. This is called thermal degradation. The process of thermal degradation is a chemical process in which oxygen and energy are used to transform the original chemical into its oxidised form. For example, carbon containing materials will, in the presence of energy and oxygen, produce the two oxides of carbon: Carbon dioxide ($CO_2$) and Carbon monoxide (CO). The first of these ($CO_2$) is produced in the presence of an abundance of oxygen, the second (CO), where stoichiometric concentrations of oxygen are lacking (usually in conditions of incomplete combustion). Both of these oxides are gases, one (Carbon monoxide) is quite toxic at low concentrations, causing toxic asphyxiation. Single or short term exposure to CO insufficient to cause asphyxiation produces headache, dizziness, and nausea; long term exposure can cause memory defects and central nervous system damage, among other effects.[139]

Where oxygen is completely lacking, the process of thermal degradation can still proceed, but this time, any carbon in a material, will be reduced from the chemical form it is located, to molecules containing proportionally more carbon (and proportionally less volatile components) and ultimately, carbon atoms. This process is called pyrolysis. Both oxides of carbon are gases, but elemental carbon is a solid (usually seen as smoke or soot). Further, the process of reducing carbon containing materials to carbon depends on the chemical nature of the source material, and will produce different pyrolysis products as the reaction process proceeds. Pyrolysis products may be fairly pure in carbon content, but are more usually found with other organic or inorganic breakdown products. The processes inherent in pyrolytic degradation are very complex, and vary depending on the source materials, the temperature and duration of combustion, and the progressive combustion of pyrolysis products that occur in the thermal degradation process.

Many combustion and pyrolysis products are toxic. The toxic asphyxiants, such as carbon monoxide or hydrogen cyanide were discussed above. Some thermal degradation products, such as acreolin and formaldehyde are highly irritating. Others, such as oxides of nitrogen and phosgene, can produce delayed effects. Still others, such as particulate matter (for example, soot) can carry adsorbed gases deep into the respiratory tract where they may provoke a local reaction or be absorbed to produce systemic effects.[140]

Of course, in a situation where a fire occurs, all three processes can occur. Where there is no oxygen, pyrolysis products (such as smoke) will be formed, where there is incomplete combustion carbon monoxide will form, and where there is complete combustion, carbon dioxide is formed. Further, this process may proceed sequentially, as oxygen becomes available to the burning material.

Therefore, as well as particulate and gas/vapour phases, consideration of the type of airborne contaminants, whether in unchanged, degraded, combusted or pyrolised forms is also critical for the success and relevance of a monitoring program.

## 4.6 Exposure to Jet Oils in the Occupational Environment

### 4.6.1 Exposure standard

The only ingredient in Mobil Jet Oil II with an exposure standard is TOCP, with a 40 hr/week time weighted average concentration of 0.1 $mg/m^3$.[128] There is no exposure standard for other isomers, although at least some are known to be more toxic. Therefore estimating "acceptable" exposures based on monitoring for TOCP alone will severely underestimate exposure.

This is critical in the interpretation of the results of experimental and exposure studies. For example, chickens exposed to TCP mixtures containing about 1.5% TOCP (then the US Navy specification) developed OPIDN within five days of oral dosage, and sixty days of inhalational exposure at 23 $mg/m^3$ or more.[141] While this provides a measure of comparison of oral to inhalational exposure, it can not provide a true picture of the toxicity of TCP, as the concentrations of other orthocresyl containing TCP isomers in the mixture used were not known. If, as shown above, the proportion of such isomers is 30,000 times the concentration of TOCP, then using an exposure standard for one contaminant as an estimate of exposure is virtually meaningless.

### 4.6.2 Exposure situations

***On ground Engineering operations***

Exposure to jet oil is possible during maintenance operations on airplane engines where the engine contains the oil. Personnel at risk in such operations are ground crew involved in engineering and maintenance. These operatives get relevant information (for example through engineering handbooks and maintenance), training, and are warned about the toxicity of Mobil Jet Oil II by warnings on the label. For example:

- Engine maintenance manuals note: Do not keep the oil on the skin for a long time. If you do not clean the oil off, the oil can cause injury and Do not let the oil stay on your skin. You can absorb poisonous materials from the oil through your skin. This suggests that oil is not harmless. This information is obviously aimed at maintenance personnel, and presumably envisages that no one else will come into contact with the oil. Further, new notices warning against the inhalation of mists were added in 1997-8. Further, the exposure in maintenance operations is probably mainly by skin contact, as the oil does not have an appreciable vapour pressure in ambient conditions. Such operational conditions can be seen to keep the risk of exposure to the oil under control.
- The label for the pre-1998 container stated the following risk and safety phrases:

**Caution: Avoid spilling on insulation, plastic, rubber or paint**

**Warning! Contains Tricresyl Phosphate.**
**Produces paralysis if taken internally.**
**Do not use as medicine or food product.**
**Wash thoroughly after handling.**

- The label for the post-1998 container stated the following warnings, risks and safety phrases:

**Avoid spilling on insulation, plastic, rubber or paint**

**WARNING!**
**Contains Tricresyl Phosphate.**
**Swallowing this product can cause nervous system disorders, including paralysis.**
**Prolonged or repeated breathing of oil mist, or prolonged or repeated skin contact can cause nervous system defects.**

**PRECAUTIONS:**
**Never swallow. Wash hands after handling and before eating. Never use in or around food. Avoid prolonged or repeated overexposure to skin or lungs.**

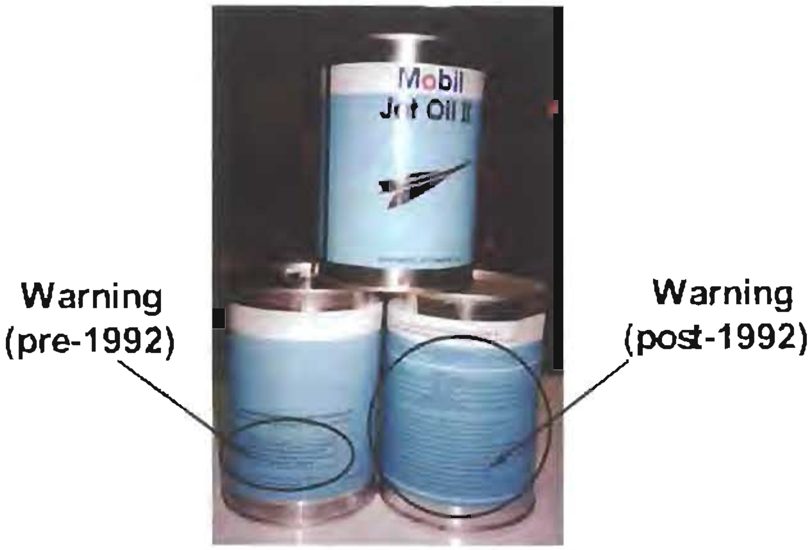
**FIRST AID:**
**If swallowed, seek immediate medical attention. If medical attention is delayed, induce vomiting. In case of contact, wash skin with soap and water. Remove contaminated clothing.**

**FOR INDUSTRIAL USE ONLY**
**Not intended or suitable for use in or around a household or dwelling. Never use empty container to carry water or food. Do not cut or weld on empty container.**

(In thirteen languages) **When using do not eat, drink or smoke. After contact with skin, was immediately with plenty of soap and water.**

The change in warning information in the two labels is quite significant (see Figure 4-16).

*Figure 4-16: Warnings: Mobil Jet Oil II*




Ansett provided a draft notice to maintenance workers handling Mobil Jet II for the new label when it was introduced in 1998, which noted:

> Communications with Mobil's Research and Development in the United States indicate that the new container meets with the most stringent rules for their global market.[142]

In evidence to the Senate Aviation Inquiry, Mobil note:

> Additional joint toxicology studies by Mobil and a major manufacturer of TCP confirmed that an oil with 3% TCP could produce toxic effects in animals administered very high doses. This led Mobil to adopt a very conservative labeling approach for its jet oils by including language recommending minimizing exposure by all routes and by emphasising the importance of good personal hygiene practices. The decision was made in 1997 and labeling was phased in during the year.[143]

Further, the exposure in maintenance operations is probably mainly by skin contact, as the oil does not have an appreciable vapour in ambient conditions. Such operational conditions can be seen to keep the risk of exposure to the oil under control.

### *In flight exposure*

There is one other potential exposure to engine oils. This is when the engine leaks in flight, and leaking engine oils contaminate air flowing to the flight deck or passenger cabin. There are two possible exposure scenarios:

- o exposure to the oil;
- o exposure to a thermally degraded oil.

In such circumstances, exposed crew and passengers are exposed to airborne contaminants that are leaking directly into air, and they are unaware of the toxicity of the contaminants they are inhaling.[144] There is little control of exposure.

If exposure is to oil, it will be at least partially in a particulate (mist) form, where it can attain higher airborne concentrations than might be predicted from vapour pressures (even at elevated, but rapidly cooling, temperatures). Further, the potential for skin exposure is greatly increased, as the mist can settle onto exposed skin, where it will then be available for dermal absorption. Further, the emission of oil vapours/smoke/mists into the passenger cabin would produce contamination of the cabin. Particulates would settle out onto surfaces (such as ducting, cabin walls, furniture and equipment), which would thereafter slowly vapourise, the rate of evaporation being dependent on individual contaminant vapour pressures. This residual contamination would continue until cleaned off or until it had evaporated.

While the toxicity of the oil has been established, little is known about the possible transformations that may have occurred in the oil while in operation. A leak of such an oil from an engine operating at altitude would see most of the oil pyrolise once it leaves the confined conditions of temperature and pressure operating in the engine. While it seems reasonable that any ingredients with suitable autoignition or degradation properties that allow such a transformation after release from the engine could be radically transformed, it is possible to speculate in only general terms about the cocktail of chemicals that could form.

Presumably this would include:

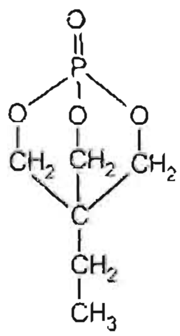
- combustion gases such as carbon dioxide and carbon monoxide;
- other irritating gases, such as oxides of nitrogen;
- partially burnt hydrocarbons (including irritating and toxic by-products, such as acreolin and other aldehydes); and
- TCP (which is fairly stable at high temperatures) or TCP thermal degradation products, such as highly toxic phosphorus oxides (TCP boils at 420°C; TOCP boils at 410°C).

These contaminants will be in gas, vapour, mist and particulate forms.

If the exposure is to thermally degraded oil then as well any exposure to the oil mist (as outlined above), exposure can also include particulates such as soots; thermally degraded chemicals such as acreolin, and combustion gases such as carbon monoxide.

There is one final issue that should be given consideration on potential contaminants within thermally decomposed jet oil. A number of papers discuss the possibility of formation of the strong neurotoxicant Trimethylolpropane phosphate (TMPP) in tricresyl phosphate containing aircraft lubricating oils.[145,146,147,148] The precursor base oil constituent Trimethyl propane (TMP) may react with TCP. TMP is used in at least one commercially available Jet Oil product (BP Turbo Oil 2380) in a 60%:35% (approximate) mixture with Dipentaerythritol ester. TMP may combine with TCP to produce TMPP, which will therefore have an organophosphate structure (see Figure 4-17) and is known to be very neurotoxic.

***Figure 4-17: Structure of Trimethylolpropane phosphate***




Operational temperature conditions for the maximal formation of TMPP (15%) is 550°C.[149] Aircraft engines operate at such temperatures, although other conditions (presence of suitable reaction intermediates) may not be present. Indeed, laboratory investigation into the release of contaminants at 525°C from two jet oils found no TMPP.[150] However, the toxic potency of TMPP is such that only a small amount formed in thermal degradation could provoke signs of toxicity.

## 4.7 Discussion

The jet oils are a commercially useful product. They are known to contain toxic ingredients. While the continued use of toxic materials is always a matter requiring caution and forethought, a full deliberation of risks and benefits may overcome such considerations.

This has occurred with the jet oils. Known to contain toxic ingredients, they have been used relatively unchanged for decades. The conservatism inherent in a complicated approval process, the reluctance to change toxic ingredients known to perform well in circumscribed situations, and the apparent lack of exposure scenarios where the toxicity could become apparent all produced a conclusion that everything was within acceptable limits. Even the apparent toxicity of jet oil reported from animal experiments in 1988 was not viewed as a significant problem.

However, an increasing number of oil leaks in the 1990's around the world and the increase in a number of flight attendants and flight crew reporting signs of toxicity after such events suggests the toxicity of the jet oils should be reconsidered:

- Firstly, the exposure scenario at altitude is utterly different from conventional exposures to the oils while using them in maintenance situations. Exposed individuals do not know to what they are being exposed, exposure by inhalational and dermal exposures can occur, the possibility of escape is absent, the possibility of cleaning or decontamination is absent).
- Secondly, options for the control of exposure are all but absent. Switching off an engine or bleed air system may offer some assistance, but is less useful if an entire ventilation system is contaminated.
- Thirdly, the exposure may be not only to gases and vapours, but also to particulates (such as oil mists or soots) that can be in proportionally greater concentrations than they would be for vapours.
- Fourthly, the exposure may to unchanged oil mists, or combusted or pyrolised contaminants. The chemical make up of such a mixture would be difficult to deduce; the toxicity of exposure to such a mixture would be difficult to predict.

However, these contaminants could not be classified as being of low toxicity. The interactions of such effects with a specific toxic exposure is not known, but not presumed to be benign. The possible problems that might arise from exposure to such a cocktail cannot be dismissed without proper consideration.

Many of the signs and symptoms of exposure being reported by exposed flight crew [151] (and to a lesser extent, passengers) appear consistent with the toxicity of some of the ingredients of the oils. These include hydrocarbon neurotoxicity from exposure to organic chemicals, COPIND from organophosphate exposure, or long term low level toxicity from exposure to carbon monoxide. These health problems need to be evaluated with more care than is apparent in the aviation industry at present.

### 4.7.1 The Classification of Jet Oil II as a Hazardous Substance

Using the NOHSC classification processes:[†]

- these processes classify as hazardous substances –
  - 2-Naphthylamine (a NOHSC Category 1 carcinogen),
  - Tricresyl phosphates, and
  - Triortho-cresyl phosphate (as Tritolyl phosphate, for its neurotoxic effects),
- it should be noted that classification for hazardous substances for the Tricresyl phosphates also have entries for "Tricresyl phosphates containing less than 1% o-cresol" and "Tricresyl phosphates containing more than 1% o-cresol". o-Cresol is a separate compound from tri-orthocresyl phosphate. An incorrect assumption is made in applying these two entries in the classification of Tricresyl phosphates because it is assumed that the term "containing less (or more) than o-cresol" means "containing less (or more) than tri-orthocresyl phosphate". As the amount of o-Cresol in Mobil Jet II is not known, these two entries cannot be used in the hazard classification process, and must not be used in classifying on the basis of tri-orthocresyl phosphate.
- the Hazardous Substances Regulation also classifies formulated products as hazardous substances if they contain hazardous ingredients above cut off values recommended by Worksafe Australia. For 2-Naphthylamine, the value is 0.01%; for Triorthocresyl phosphate the value is between 0.2% and 1%, for classification as "Harmful" and above 1% for classification as "Toxic". Formulated products containing at least these amounts are classified as hazardous substances that then fall into the requirements of the regulation.
- the proportion of ingredients listed as "ingredients partially unknown" is not known.

It is critical to note that the issue of the classification of Jet Oil II as a hazardous substance in Australia requires specific and

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[†] NOHSC (the National Occupational Health and Safety Coimmission), became the Australian Safety and Compensation Commission in 2005 and SafeWork Australia in 2007.

nonequivocal information about identity of ingredients and amounts present in the formulated product. Neither of these is readily available.

### 4.7.2 The Material Safety Data Bulletin (MSDB)

The material safety data bulletin (MSDB) for Mobil Jet Oil II is issued by Mobil Australia, but is based on that issued by the US parent company, in Princeton, New Jersey, with some minor amendments added locally for Australian requirements. As such, it is written to the US MSDS requirements and not those required in Australia under the hazardous substances regulation. However, it is possible that the information in this document satisfies Australian requirements, again by default.

A range of MSDB have been released over the past decade, with various versions being issued either in the USA or Australia in 1988, 1992, 1994, 1997 and 1998. The information is these versions have varied substantially, and in some cases, has been inconsistent from version to version.

In each version, the MSDB has made the point that the chemical is "safe under normal conditions of use" but does not provides an opinion of safety under conditions that are not normal. The MSDB further recommends the use of respiratory protection in exposures and cholinesterase monitoring for cases of overexposure.

The 1998 MSDB classifies Jet Oil II as being non-hazardous in Australia. This entry is incorrect. This MSDB contains an entry which identifies a specific ingredient by name and CAS Number, and by amount present, as:

CAS No 1330-78-5 Tritolyl phosphate 1-5%

This exceeds the cut-off concentration for this ingredient (of 1%) stipulated in the Designated List of Hazardous Substances for classification as "Toxic" (and hazardous).

### 4.7.3 The Label

As a result of this incorrect hazard classification, the MSDB also includes incorrect risk and safety phrases:

R40 Possible risk of irreversible effects.

R20/R21/R22 Harmful by inhalation, in contact with skin and if swallowed.

A product containing more than 1% Tritolyl phosphate should contain the risk phrases:

R39 Danger of very serious irreversible effects.

R23/R24/R25 Toxic by inhalation, in contact with skin and if swallowed.

These are significant differences, and serve to show that users of Mobil Jet II may be unaware of the significance of the material they are using, and serve to illustrate why airline staff continue to be misinformed about the hazard of this material. Other parts of the MSDS, such as "This product is not expected to produce ... effects under normal conditions of use and appropriate personal hygiene practices" perpetuate the notion that Mobil Jet Oil II is not a harmful material.

Further, these risk phrases are not specific inclusions on the label, as required by the hazardous substances legislation in Australia.

The label for the pre-1998 container was shown in Figure 4-16.

Therefore, jet oils are specialised synthetic oils used in high performance jet engines. The have an appreciable hazard based on toxic ingredients, but are safe in use by engineering personnel who handle the product routinely provided that:

- health and safety iinformation such as labels, material safety data sheets, manufacuturers manuals and the like are obtained and consulted;
- a suitable risk assessment is carried out that identifies hazards and assesses risks, and recommends suitable controls and precautions;
- maintenance personnel follow the appropriate controls and safety precautions as recommeded in health and safety information and risk assessments; and
- the oil stays in the engine.

Aircraft engines that leak oil may expose others to the oils through uncontrolled exposure. Airplanes that use engines as a source of bleed air for cabin pressurisation may have this source contaminated by the oil engine leaks. If such leaks occur, exposed crew and passengers do not have access to the health and safety information, risk assessments or advice on controls that engineering staff have; where such information or advice is lacking, they may be at additional risk.

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Chapter **5**

# Air Monitoring Studies

A range of air monitoring studies has been carried out in an attempt to assess the problems of contaminants at altitude. Much of this literature cannot be used to evaluate problems of contaminated bleed air.

Most of the material in this chapter was published in:

- Winder, C. Air monitoring studies for aircraft cabin contamination. *Current Topics in Toxicology* **3:** 33-48, 2006.

A case study that analyses the volatile organic compound levels reported in one study is also included. This has not been published.

# 5 Air Monitoring Studies

## 5.1 Introduction

Chemical exposures in aircraft in flight have been reported. In 1953, The US Aeromedical Association first expressed their concerns about the toxicity risks of cabin air contamination by hydraulics and lubricants.[1] Other risks have been identified more recently, either as part of the chemicals routinely used in maintaining airplanes,[2] or as toxicological factors in aviation accidents.[3] Passenger protective breathing equipment tests conducted by the UK Air Accidents Investigation Branch identify contaminants such as carbon monoxide, hydrogen cyanide, hydrogen fluoride, hydrogen chloride, nitrogen oxides, sulphur dioxide, ammonia, formaldehyde, acrolein, and other hydrocarbon compounds in combustion situations.[4]

Notwithstanding emergency situations, there are a range of other situations that can arise whereby airplane cabin air can be contaminated.[5] These include:

- ingestion of exhaust from other aircraft or on ground contamination sources,
- application of de-icing fluids,
- hydraulic fluid leaks from landing gear and other hydraulic systems,
- excessive use of lubricants and preservative compounds in the cargo hold,
- preservatives on the inside of aircraft skin;
- large accumulations of dirt and brake dust may build up on inlet ducts where auxiliary power units extract air from near the aircraft belly;
- ingestion of oil and hydraulic fluid at sealing interfaces, around oil cooling fan gaskets and in worn transitions;
- oil contamination from synthetic turbine oil;
- engine combustion products (for example, defective fuel manifolds, seal failures, engine leaks).

Although these chemicals are usually retained in the engines and equipment into which they have been added (such as auxiliary pack units or APUs), they can sometimes find their way into cabin air where crew and passengers are located, through incidents such as engine oil leaks, seal failures and fluid ingestion by APU/engines.

## 5.2 Aviation Oil Leaks

The oils and hydraulics used in aircraft engines can be toxic, and specific ingredients of oils can be irritating, sensitising (such as phenyl-alpha-naphthylamine) or neurotoxic (for example, ortho-containing triaryl phosphates such as tri-orthocresyl phosphate).[6,7] If oil or hydraulic fluid leaks occur, this contamination may be in the form of unchanged material, degraded material from long use, combusted or pyrolised materials. These materials can contaminate aircraft cabin air in the form of gases, vapours, mists and aerosols.[8]

Some of these contamination problems can persist for decades. For example, a problem of oil contamination of the air conditioning system of the BAe 146 was first noted by the aircraft manufacturer in 1984,[9] and was the subject of a specific term of reference to an Australian Senate Aviation Inquiry held 1999-2000, over fifteen years later.[10]

While changes in product formulations have attempted to make less toxic products,[6] concern still exists as to the potential toxicity that exposure to these materials may cause.[11]

Hundreds of in-cabin leak/smoke events are documented annually, often correlated to aircraft fluid leak events. There is a spectrum of defects and malfunctions in an airplane engine ranging from the trivial, to the serious, to the catastrophic. Fume events are much more frequent, correlated to less important aircraft fluid leaks, sometimes in the order of hundreds a year (see Section 1.5). However, as trivial malfunctions can escalate into serious events, it is necessary to ensure that all types of malfunctions are identified, investigated and rectified.

For the purposes of discussion below, events leading to leak, smoke or fume incidents will be combined as "leak/smoke/fume events" or "exposure events". Because of the ways in which the conclusions of individual reports are interpreted and used by various sectors of this industry, it is necessary in this paper to provide quotes from the individual reports so that a better understanding of statement and conclusions can actually illustrate the points being made.

The aviation industry itself acknowledges that air quality exposure events are primarily due to oil leaking into the air supply. The issue of poor design of exhaust systems on aircraft have been known for over thirty years. In a 1974 Handbook published by the Garrett Corporation (a manufacturer of aircraft engines and auxiliary power units) it is noted that the least favourable location of an exhaust inlet "is an inlet located well aft at the bottom surface of the fuselage. Fluids likely to be ingested with this type of inlet include those that may be spilled within the aircraft fuselage, fuel-tank-leakage and vent-system discharge, leakage from the hydraulic system etc".[12] Yet this is precisely where the exhaust inlet is located on many models of aircraft, including those equipped with Garrett engines.

In 1981, the Society of Automotive Engineers (SAE) noted in an Aerospace Information Report: *Engine compressor bearings upstream of the bleed ports are the most likely sources of lube oil entry in the engine air system and thence into the bleed system contaminating the cabin/cockpit air conditioning system.*[13]

In 1983, Mobil Oil (manufacturer of a number of aviation jet oils) noted in correspondence to a customer that *If cabin air becomes contaminated with any lubricant and/or its decomposition products, in sufficient quantities, some degree of discomfort due to eye, nose and throat irritation could be experienced. Problems like these can be generally traced to improper design, improper maintenance or malfunctioning of the aircraft.*[14]

In December 1984, British Aerospace (an aircraft manufacturer) issued the BAe 146 Service Information Leaflet "Oil Contamination of Air Conditioning System" acknowledging that oil contamination of ducting was a problem, and suggesting ways in which such problems might be resolved.[9] Among other things, this leaflet recommended the development of an operational procedure called an Air Conditioning Pack Burnout Procedure, *Operating the system, before the first revenue flight of the day, in hot mode for five minutes (manually controlling the duct temperature at 70°C). This will help purge residual oil from the packs and ducting.* This leaflet was replaced by another outlining a totally different engineering based process in 1995.[15]

In 1989, the Garrett APU Division of Allied Signal issued a Service Bulletin regarding the compressor seal assembly, noting that *the current compressor seal has shown an unacceptable rate of failure which can result in smoke in the cabin* and *The failure of the compressor seal assembly allows gearbox oil to leak into the compressor inlet resulting in smoke in the cabin. The new seal has been redesigned to improve sealing characteristics and reliability.*[16] However Service Bulletins are not mandatory. All Garrett/Allied Signal could recommend was that aircraft operators should make replacements at their convenience. In fact, for one aircraft type alone, the BAe 146, there are over 200 sources of data relating to contaminated air including service bulletins, service information leaflets, all operator messages, engineering data and airworthiness directives.[17]

While all parties acknowledge that a problem exists, and has existed for a long time,[18] most sectors of the aviation industry then paradoxically deny that leaks are a serious matter, suggesting that it is not an air safety issue, rather an OHS, general health or comfort issue.[19] This was further confirmed in a December 2004 internal CASA letter, which notes: *CASA does not have any regulatory responsibility in relation to occupational health and safety of aircrew* and *To the extent that the Commonwealth civil aviation law regulates such matters as certification of aircraft (including oxygen systems), medical standards for flight crew, and flight and duty times, that law is directed to the safety of air navigation, not to the personal health and welfare of aircraft crew.*[20]

This view was also prevalent within the airlines. For example, in 1998, an expert panel convened by Ansett Australia to investigate engine oils leaks on the BAe 146 concluded: *The panel accepts that short term symptoms associated with odours that have been reported on the BAe 146 and other types are substantiated. These have been generally linked with inadequate ventilation together with aircraft system defects.*[21]

In evidence to the Australian Senate Inquiry in 1999, British Aerospace stated that *Reports of cabin air odours have been received from time to time and have predominantly been determined to be due to minor systems failures such as leaks from oil seals on the aircraft engines or APU.*[22]

Regulatory agencies indicate that "serious impairment" includes the loss of crew's ability to see flight deck instrumentation or perform expected flight duties. However, they also suggest this excludes purely psychological aspects of the concern of odours, and concerns about long-term exposure.[23] In evidence to the Australian Senate Inquiry in 1999, the Civil Aviation Safety Authority (CASA) of Australia suggested that: *all aircraft suffer fumes as a feature of the design of air conditioning systems in aircraft.*[24] In correspondence to an inquiry from a pilot union, the UK Civil Aviation Authority advised that crew discomfort such as headaches, nausea and irritation due to contamination is not their responsibility unless the safety of flight and landing are affected.[25]

When a leak occurs, it may be dismissed by the pilot as being a nuisance, in that it appears to have no apparent effect or is considered a normal part of flying. Or it may be considered minor and reported within the company and fixed without record (anecdotally, some pilots report leak events to ground crew verbally or unofficially, for example, on scrap paper or even cocktail napkins). In this, there is inappropriate subjective interpretation of the terms "undue discomfort" and "harmful or hazardous levels of gases or vapours" specified in aviation regulations, and interpretation of this often errs on the side of convenience. Or a record may be made, but with the defect regarded as "not safety of flight or not major defect" and not considered sufficiently serious to report to aviation regulators, either voluntarily or as part of mandatory requirements. Lastly, as aviation regulations impose strict guidelines on how aircraft defects are defined, must be reported, investigated and dealt with, some leaks may actually be reported to aviation regulators. These reports tend to cover the serious problems, but not always so. However, with substantial under-reporting and a culture of complacency between operators and regulators, no aviation regulatory authority can honestly consider that the reports they receive from the industry represent anything other than a very small tip of a very large iceberg of leak or exposure events.

From review of available sources and reported and accessible information, it is apparent that only a small fraction of the known incidents are reported. Evidence is available that suggests that there are a substantial number of leak incidents on airplanes, especially on certain models of aircraft.[8] Many of these leaks go unreported to aircraft operators. Of those leak incidents that are reported to aircraft operators, many are not reported to regulatory authorities. Of those leak incidents that are reported to regulatory authorities, not all are added to relevant databases. Ultimately, only a very small number of leak incidents are investigated fully.

## 5.3 Aviation Air Quality Monitoring Studies

During the last twenty years there have been a number of studies carried out in relation to aircraft air quality and chemical contaminants entering the cabins of aircraft. Some of this research is not available in the public domain, and in some cases, it may be difficult to critically examine its findings.

Studies on contamination of the aircraft cabins began in the late 1970s. Such studies tend to be of two types:

- Studies looking at the possible contents of aviation engine oils and other products.
- Studies looking at the chemical content of air in aircraft during flight.

### 5.3.1 Studies on Aviation Oils

A summary of studies on the jet oil are shown in Table 5-1. These findings are discussed further below.

***Table 5-1: Studies on the Jet Oil***

| Reference (first author, year[ref]) | Comment | Monitoring | |
|---|---|---|---|
| | | **For?** | **Present?** |
| Paciorek, 1979[26] | Laboratory simulation of thermal degradation of oils and fluids | Organic contaminants | Formaldehyde, acreolin, formates |
| Wizniak, 1983[27] | Ground level based analysis of turbine oil contamination | Turbine oil by product contamination | No |
| Crane, 1983[28] | Toxicity study in rats and chickens to six commercially available jet oils | Toxic effects | Incapacitation considered to be due to carbon monoxide |
| Dickey, 1989[29] | Laboratory analysis of synthetic oil on hot surfaces up to 370°C | Fluids not thermally degraded up to 370°C | |
| van Netten, 2000-01[31,32] | Laboratory analysis of two jet oils on hot surfaces to 525°C | CO, $CO_2$, $NO_2$, HCN, OPs and volatiles | $CO_2$, CO (above 100 ppm). TCP in bulk oil |
| CAA, 2004[33] | Laboratory analysis of unused and contaminated BAe 146 cabin air supply ducts | Contaminated ducts contained carbonaceous material (including TCP/TOCP) consistent with the pyrolysis products of aircraft engine oil | |
| Solbu, 2007[34] | Development of a GC/MS method for analysing trialkyl and triaryl organo-phosphates | Organo-phosphates | trialkyl phosphate, triphenyl phosphate (including o-, m- and p- isomers of TCP |

In 1979, a series of lubricating oils and hydraulic fluids were examined for their potential to contaminate cabin air.[26] This test confirmed that tests simulating line rupture with fluid spilling onto a hot 450°C metal surface in the presence of air resulted in excessive fluid degradation, with significant concentrations of hydrocarbons, carbonyls and alcohols produced, including formaldehyde, acrolein, formic acid and formates.

Studies by the US Transportation Board in April 1983 investigated the potential problem of turbine oil by-product contamination of an aircraft's cabin from a cracked front main shaft compressor carbon seal element in a Garrett TPE-331 turboprop engine might allow engine oil to leak into the cabin.[27] This issue had arisen from several accident investigations. Test procedures were simulated on the ground using Exxon Turbo 2380 lubricating oil in a Garrett TPE 331 Turboprop engine on a test stand at the Garrett plant in Arizona in 1981. The study concluded that pilot incapacitation from engine oil contamination was without validity, although the extrapolation of ground based studies to flying conditions is highly dubious. To cover the possibility of sensitisation, the report noted: *the results of the test program are applicable only to aircraft using Garrett TPE 331 engine compressor bleed air for cabin environment system.* It noted that: *There are instances in which chronic or repeated exposure may sensitize a person to certain chemicals so that concentrations in the ppb range may elicit an acute hypersensitivity type reaction.*

A study of the inhalation toxicity of six commercially available products was conducted by the US Federal Aviation Administration (FAA) in 1983.[28] This report was linked to the Wizniak 1983 study (see above) and investigated exposure of rats and chickens to decomposition products. The toxicity endpoints measured were time to incapacitation or time to death. These are crude measures of toxicity which do not measure effects such as irritancy or sensitisation. Results suggest that the toxicity of decomposition products were related to production of carbon monoxide. The results of this study, again carried out at ground level, provide little about exposures at altitude. It was additionally noted that the NTSB Wizniak investigations *did not eliminate the possible presence of an additional component with significant animal toxicity.*

A 1989 study by Dickey and Wilson investigated contaminants arising from air flowing over a vessel of heated synthetic oil.[29] The oil was of a Mil L 23699 specification, heated at 250°, 450° and 700°F (120°, 230° and 370°C), and from a cabin air sample taken from an un-named aircraft over the UK with a "slight odour of oil". Results indicate that the oil found in the cabin was not chemically altered from the oil in the engine.

In 1990, a Discussion Paper on developing a limit for total organic material in cabin bleed air was prepared for the SAE

E31 Cabin Air Sub Committee.[30] This paper noted that it had long been recognised that *contamination of the cabin bleed air by engine generated organic material may occur as a result of fuel or oil leaks or thermal degradation of these contaminants and or elastomer seals*. Further, it noted various ways of expressing such contamination, eventually recommending that the maximum allowable concentration of total organic material should be in the order of 0.1 parts per million by weight, or 0.2 parts per million by volume (0.2 $ml/m^3$). This is an exceptionally low level, compared with the conventional exposure standard for low toxicity oil mists (at 5 $mg/m^3$).

A 30 May 1991 Datachem report for Richard Fox of Allied Signal Aerospace suggested breakdown of engine lubricant by excessive heat probably did not occur.[ref lost]

A 2000 report by van Netten and Leung in investigated the release of CO, $CO_2$, $NO_2$, HCN, and volatiles under laboratory conditions at 525°C from two jet oils, measured using gas chromatography (GC). Volatiles included tricresyl phosphates (TCPs) and trimethyl propane phosphate (TMPP).[31] TMPP was not found in these experiments. Some $CO_2$ was generated along with CO, which reached levels in excess of 100 ppm. HCN and $NO_2$ were not detected. The presence of TCPs was confirmed in the bulk oils and in the volatiles. GC compositions of the two bulk oils and their breakdown products were almost identical.

A 2001 report by van Netten and Leung investigated pyrolysis products from an engine oil noted that the oil was an important source of carbon monoxide, volatiles, and organophosphate constituents, including phenyl and tricresyl phosphates.[32] The authors suggested that during oil leaks, localised condensation products in ventilation ducts became re-mobilised when cabin heat demand increased, and could account for mid-flight incidents.

A UK CAA 2004 report conducted by the Defence Science and Technology Laboratory at Porton Down evaluated unused and contaminated cabin air supply ducts removed from two different BAe 146 aircraft after flying for long periods.[33] The conclusions drawn were that: (i) The unused ducting contained no detectable toxic compounds; (ii) Ducts extracted from airplanes in operation "*were contaminated with a carbonaceous material containing chemicals entirely consistent with the pyrolysis products of aircraft engine oil*": (iii) a variety of compounds were identified, as well as TCP isomers including TOCP, which was found in the used ducts in concentrations higher than in the parent oil (however, analysis for the more toxic orthocresyl isomers was not carried out). The ducting was removed some weeks before the analysis was carried out and it highly probable that volatile materials would have evaporated in the intervening period (see Figure 5-1).

***Figure 5-1: Uncontaminated and Contaminated Ducting***
From UK CAA[33]

**An unused duct supplied brand new from BAE Systems**

**A used duct removed from a BAe 146 airplane with a history of cabin odours but no reported crew symptoms (the duct had accumulated 26,061 flight hours)**

The report also stated that:

*fumes from engine oil leaking into the bleed air system and hence into the cabin air supply, is the most likely cause of the incidents.*

Also:

*There are over 40 different chemicals contained in oil breakdown products and many have no published toxicity data so it is not possible to be certain whether any of these products contribute to, or are the sole cause of the recorded incidents.*

A 2007 report by Solbu et al developed a methodology for personal occupational exposure assessment by active combined aerosol and vapour sampling of airborne trialkyl and triaryl organophosphates using a combined fibre glass (for aerosol capture) and sorbent (for vapour capture) and gas chromatography/mass spectrometry (GC-MS) techniques.[34]

Importantly, the GC-MS methods used in this study show a clear separation of ToCP, TmCP and TpCP isomers (see *Figure 5-2*; from Solbu et al[34]).

***Figure 5-2: CG-MS Chromatogram***

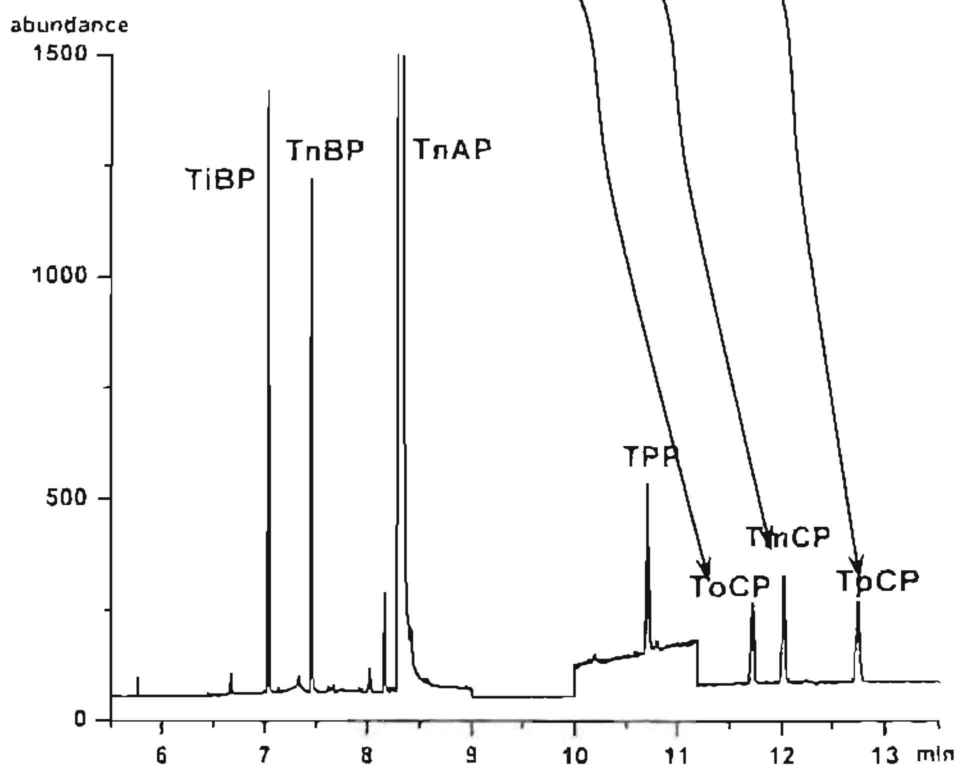



Fig. 2. GC–MS (SIM) chromatogram from splitless injection of 30 pg TiBP, TnBP, TPP ToCP, TmCP and TpCP and 3 ng volumetric internal standard (TnAP). The organophosphates were separated on a VF-5ms CP8957 capillary column (30 m × 0.32 mm, $d_f$ = 1.00 μm) with a carrier gas flow rate at 1.5 mL/min. The GC-oven temperature was 40–320 °C during a total time of 14 min. Injector temperature was set to 280 °C.

Further, in operational studies in a mechanical workshop where the jet oil was being used, tricresyl concentrations of 0.24 and 0.28 mg/m$^3$ were obtained.[34]

### 5.3.2 Air Quality Studies

A summary of Air quality studies is shown in Table 5-2. These findings are discussed further below.

***Table 5-2: Air Quality Studies***

| Reference (first author, year[ref]) | Comment | Monitoring For? | Monitoring Oil leak? |
|---|---|---|---|
| Wilkins, 1992[35] | Attempt to identify source of odour | Not reported | ✗ |
| Fox, 1991[36] | Air quality testing on BAe 146 | Oil identified as source of odours | ✗ |
| Vasak, 1992[37] | Oil mist levels | Oil 1.5 mg/m$^3$ | ✓ |
| Rhyder, 1992[38] | Feasibility study for analytical method | | ✗ |
| Nagda, 1992[39] | Air quality study of routine flights on airplanes | $CO_2$ 1756 ppm | ✗ |
| NIOSH, 1993[40] | Air quality study of 40 routine flights | Oil identified as source of odours | ✗ |
| CSS, 1994[42] | Air quality study of routine 35 flights, 8 models | $CO_2$ 5000 ppm<br>CO 0.7 ppm<br>VOCs | ✗ |
| Currie, 1995[43] | Short term (15 min) oil mist sample collection on two BAe 146 flights after landing where leaks had occurred | Oil mist Nil | ✓ |
| Dechow, 1996-97[44,45] | Routine Airbus flights | VOCs 2.2 ppm | ✗ |
| Lee, 1997[46] | Air quality study on routine non-revenue BAe 146 flights | "nothing untoward" | ✗ |
| Lee, 1997[47] | Bulk air sampling during pack burn | "TCP found at low ppm" | ✗ |
| Fox, 1997-98, 2000[48,51,52] | Air quality studies on routine revenue and non-revenue BAe 146 flights | "Measurable levels of contaminants" | ✗ |
| Spengler, 1997[53] | Air quality survey for Boeing during routine flights | $CO_2$ 1400 ppm<br>CO 1.3 ppb<br>$O_3$ 10 ppb<br>Partic 10 μg/m$^3$<br>VOCs 3.2 ppb | ✗ |
| van Netten, 1998[54] | Air quality on a BAe 146 airplane the day after a oil leak | No contamination identified | ✗ |
| AHRAE/CSS, 1999[55] Pierce, 1999[56] | Air quality study on routine flights | $CO_2$ 1469 ppm<br>CO 7 ppm<br>$O_3$ 122 ppb<br>Partic 10 μg/m$^3$<br>VOCs 0.9 ppm | ✗ |
| Haghihat, 1999[57] | Air quality study of 43 routine flights | $CO_2$ 2013 ppm | ✗ |

| Reference (first author, year[ref]) | Comment | Monitoring For? | Monitoring Oil leak? |
|---|---|---|---|
| Lee, 1999[58] | Air quality study of 16 routine flights | $CO_2$ 2900 ppm<br>CO 4 ppm<br>$O_3$ 90 ppb<br>Partic 2 $\mu g/m^3$ | ✘ |
| Ross, 2000[59] | Air quality study including VOCs on routine B777 flights | VOCs | ✘ |
| Dumyahn, 2000[60] | Air quality survey of 28 routine flights on 9 airplane types | $CO_2$ 5000 ppm<br>CO 0.7 ppm<br>VOCs "similar to buildings" | ✘ |
| Nagda, 2001[61] | Air quality of 10 routine flights on the B737, B747 and B767, including bleed air | $CO_2$ 4238 ppm<br>CO 9 ppm<br>$O_3$ 1 ppm<br>Part 380 $mg/m^3$ | ✘ |
| Lindgren, 2000-03[65,66,67] | Air quality study of 26 routine B767 flights | $CO_2$ 1000 ppm<br>CO 0.7 ppm<br>$O_3$ 37 $mg/m^3$<br>$CH_20$ 15 $mg/m^3$<br>$NO_2$ 66 $mg/m^3$<br>RspP 49 $mg/m^3$ | ✘ |
| Waters, 2002[73] | Air quality study of 6 routine flights | $CO_2$ 1000 ppm<br>CO 0.7 ppm<br>$O_3$ 37 $mg/m^3$<br>$CH_20$ 15 $mg/m^3$<br>$NO_2$ 66 $mg/m^3$<br>RspP 49 $mg/m^3$ | ✘ |
| BRE, 2002[84] | Air quality study of 13 routine flights on BAe 146 and B737 flights | $CO_2$ 3500 ppm<br>CO 7 ppm<br>VOCs "many" | ✘ |
| Spicer, 2004[74] | Air quality study of 4 routine flights on the MD80, B737 and B757 | $CO_2$ 2800 ppm<br>CO 3.5 ppm<br>Total VOCs 11-1140 $\mu g/m^3$ | ✘ |
| Kibby, 2005[76] | Study of bleed air contamination of military airplanes | TCP Isomers 4 $\mu g/m^3$<br>Aryl amines < 1 $\mu g/m^3$ | ✓ |
| van Netten, 2005[77] | GC-MS analysis of B757 filters and swab samples of B757 surfaces | TCP present in all samples | ✘ |
| Muir, 2008[78] | Method feasibility study of BAe 146 on the ground and B757 in flight. Results indicate: Tributyl-phosphate always present. Organic compounds present when APU switched on. TCP detected when APU and ECS running | | ✘ |
| | A "fume event" (an oily smell) occurred during a B757 flight | "sharp rise in ultrafines" and "higher levels of TCP" | ✓ |

A 1991 microbiological study by Wilkins and Kendal of Pall Europe of an objectionable odour described as "old socks or cheese" arising in the APU of a Dan-Air BAe 146 failed to find anything unusual under various conditions of cabin air recirculation.[35] The authors concluded that the APU related odour was not caused by microbial contamination.

A 22 July 1991 memorandum prepared by Richard Fox of Allied Signal Aerospace reports the results of air quality testing for Dan-Air London.[36] This report notes that "*several BAe 146 aircraft are having reports of objectionable odours described as 'dirty socks' or 'musty'.*" The report also notes that "*the odour appears to be coming from breakdown products of the oil*" and that "*no contaminant appeared to be that great, but they do act in synergism and their combined effect could be enough to trigger the odour complaints.*"

In 1992, Vladimir Vasak, consultant occupational hygienist working with Ansett Australia in Sydney, investigated APU filter samples and air quality samples from revenue flights.[37] There are a number of procedural and methodological problems with these studies, and in some cases, suitable conclusions could not be made. However, these studies report oil mist levels in the cockpit of 1.5 $mg/m^3$, and in the cabin of 1.3 $mg/m^3$, with a similarity noted between the oil in the cabin and Mobil Jet II. The exposure standard for conventional hydrocarbon oil mist is 5 $mg/m^3$, although the applicability of the standard for synthetic oils containing phosphate esters and other toxic ingredients used in aircraft is questionable. This study is the first to report oil contamination of the cabin, although no tricresyl phosphate was detected.

As a follow up to Vasak's work, the NSW WorkCover Authority conducted an occupational hygiene feasibility study in August 1992. Monitoring consisted of testing whether a gravimetric method (one for dust monitoring) would be suitable: not surprisingly, it wasn't.[38]

In 1992, British Aerospace contracted Domnick Hunter to work with BAe to analyse air samples which led to the introduction of the BAe cabin air filtration system.[22] No toxicity issues were identified, however this work is unavailable for review.

In 1992, a study by Nagda et al investigated air quality on aircraft.[39] Air quality measurements were only made during routine flights (that is, there were no unusual air quality incidents during the study). However, carbon dioxide levels (reported at 1756 ppm) were sufficiently high to cause potential comfort problems for passengers.

A 1993 study of cabin air undertaken by the US National Institute of Occupational Safety and health on behalf of Alaskan Airlines involved approximately 40 flights.[40] It was noted that the acute crew symptoms reported were: *more like those reported among US Air Force flight crew members involved in cockpit exposure incidents* where oil was most frequently identified as the source of the smoke fume or odour.[40, 41] However, it was noted that due to the unpredictable occurrence of air quality incidents: *it was not possible to arrange for satisfactory monitoring of air quality during an incident.*

In 1994, a study by Consolidated Safety Services monitored volatiles and particulates during 35 flights on eight models of aircraft.[42] Air quality measurements were only made during routine flights (that is, there were no unusual air quality incidents during the study). However, measurements were made of carbon dioxide (a mean of 1162 ppm), particulates (as $PM_{10}$) a mean of 176 $\mu g/m^3$, and volatile organic compounds, a maximum of 2.2 ppm.

Two 1995 studies conducted by Ansett Australia[43] collected air for oil mist assessment for fifteen minutes in a plane on the ground following a report of passenger and crew vomiting, and for 360 and 497 minutes on later days in other planes on scheduled services, when no oil leak was reported. Oil mist concentration was reported to be below the level of detectability (below 0.02 $mg/m^3$) in all samples. However, oil mists collected in Tedlar sampling bags are likely to coalesce against the side of their container, and when extracted for analysis would only be available in gas or vapour form. As oils tend to have low vapour pressures, the validity of this technique, and the conclusions that can be drawn from them, are highly dubious. Again, with the exception of a 15 minute sample after a plane had landed after some passenger and crew symptoms (insufficient for detecting anything other than massive levels of oil) no monitoring was carried out during an exposure event. Further monitoring studies using Tedlar bags continued throughout 1997 and 1998 with similar findings.

A 1996 study by Dechow for Airbus[44] reports concentrations of volatile organic compounds at 2.2 ppm, and levels of the irritant formaldehyde at 0.026 ppm. Again, air quality measurements were only made during routine flights (that is, with no unusual air quality incidents reported). The report stated that all detected VOCs were found to be in concentrations similar or lower than other indoor spaces and did not influence health and comfort. A 1997 follow up report was made by Dechow et al, also for Airbus.[45] Monitoring was carried out on Airbus aircraft A310 and A340, again during normal flights with no unusual air quality incidents reported. No unusual contaminants were identified, and most volatiles and particulates were concluded to have been emitted by passengers (mainly ethanol and tobacco smoke).

A 1997 report carried out by Lee actually installed a gas chromatograph on a BAe 146 (all other studies collect samples for later laboratory analysis). [46] Basically, these analyses report: *nothing untoward was detected by the gas chromatograph, and none of the crew complained of any unusual smell*. Again, this indicates monitoring was conducted in the absence of an exposure event. Using a somewhat novel technique, air sampling was also conducted during a pack burn out, by pumping cabin air through a vessel cooled with liquid nitrogen, in an attempt to capture everything in the air sample. Subsequent analysis identified tricresyl phosphate in the sample. The possibility that all other monitoring studies were unable to detect tricresyl phosphate as the chemical is poorly volatile, or eludes sorption onto sampler, or for some other reason makes virtually all monitoring carried out to date highly questionable. A later report of this study indicates: *on one occasion, tricresyl phosphate was detected at low ppm level in an aircraft cabin during a pack burn*.[47] This again suggests that even in the absence of exposure events, low levels of tricresyl phosphates are possible.

A 25 November 1997 report on air quality measurements on BAe 146 aircraft in service at Ansett Airlines was prepared by Fox of Allied Signal.[48] The investigations took place on non-revenue and revenue flights on airplanes with and without new filters. Airplanes had measurable levels of contaminants, which were within an order of magnitude (30-40%) of recommended exposure standards, and above such values (100-130%) in the aft galley. This finding applied to contaminants with exposure standards and not to those contaminants that do not have exposure standards – the majority of detected compounds did not have such values, suggesting that the unacceptability of exposure would have been increased even further if all contaminants were considered. Irritating and toxic chemicals included formaldehyde, tetrahydrofuran and cumene. While no tri-orthocresyl phosphate was found, another phosphate ester Tributyl phosphate was detected (in minutes from an October 1997 Ansett Australia BAe 146 Odour Committee it was noted that: *a full report from Richard Fox would be due in two weeks and that trace quantities of TCP were found in the filters but none in the cabin air. Tar looking substances were also found).*[49] These findings were absent from final reports from

Allied Signal). This report strongly criticised the practice of pack burnouts, suggesting damage to filters and increased off gassing of contaminants (formaldehyde was noted to be at a level 30% of its exposure standard). Recommendations for suspension of pack burn outs as an acceptable operational procedure date from this report. A method of assessing filter life was also recommended. There is some doubt that the monitoring techniques used in this investigation (collection of contaminated air into summa canisters, see Figure 5-3 below) could capture poorly volatile contaminants such as the tricresyl phosphates, and overall, the monitoring in this study was not associated with a definable exposure event. Analysis of air conditioning system filters (the amount of air flow through them was not identified, but likely to be very large) found: *a significant amount of higher molecular weight residues that could not be identified* as well as: *a number of odour producing compounds not previously identified.* It was noted that these higher weight hydrocarbons can generate *foul odours* or *could be the cause of the dirty sock odours.* Despite reporting that the quality of the supply to the aircraft was within safety limits, it was also reported that: *bleed air contamination-monitor results indicate other areas of the system are contaminated.* Further, in air monitoring for volatile organic vapours, this study notes concentrations were at, or below 3,000 $\mu g/m^3$ (3 $mg/m^3$). This is not a concentration "orders of magnitude" below anything that could be considered a problem, but is at the lower level of a "discomfort range."[50] While the report noted that the aircraft selected had previously reported odours, again the tests were undertaken during normal conditions and not during any flights where exposure events had occurred. A follow up report by the same author in 1998 listed many VOCs found in cabin air and noted the major sources of aircraft internal contamination were oil seal leakage from oil seal failure and engine exhaust from combustor component failure.[51] A further follow up report by Fox in 2000 reviewed this earlier work.[52] Measurements were made of carbon dioxide (4700 ppm in a galley when no dry ice was present), and volatile organic solvents (0.11 to 4.43 $mg/m^3$). In all three reports the validity of using traditional exposure standards was clearly questioned and advised as inappropriate for an aviation setting. This was not considered in later studies.

A 1997 air quality survey was conducted by Spengler et al for Boeing.[53] Air quality measurements were only made during routine flights (that is, with no unusual air quality incidents), and subsequently, the predictable conclusion drawn: *aircraft environments compare favourably to other forms of public transport.* However, levels of combustion products and solvents were often detected, and measurements were made of carbon dioxide (a mean of 1400 ppm), carbon monoxide (a mean of 0.0013 ppm), Ozone (0.01 ppm), particulates (a maximum of 10 $\mu g/m^3$) and volatile organic compounds, a mean of 3.2 ppm.

A 1998 report by van Netten on air quality on the BAe-146 carried out air monitoring on the BAe 146 during non-revenue flights on a plane the day after an exposure event.[54] The author notes that the problem in this plane relates to leaks of seals in engine bearings one and nine. The plane used Castrol 5000, which was replaced with Exxon 2380 after the incident (and possibly Mobil Jet Oil 254). Air monitoring used techniques for volatile organic chemicals and "*potential aerosolised oils*". It is likely that the day after an oil fume event that volatile components or aerosol mists will have dispersed. This proved to be the case.

A 1999 report by ASHRAE/CSS investigated air quality measurements during routine flights (that is, with no unusual air quality incidents).[55] Measurements were made of carbon dioxide (a mean of 1469 ppm), carbon monoxide (a mean of 7 ppm), Ozone (0.122 ppm), particulates (a maximum of 10 $\mu g/m^3$) and volatile organic compounds, a mean of 0.9 ppm. Detection levels used for some analytical procedures were too high to allow exposure levels to be interpreted consistent with concerns for the general public. It was concluded that: *there were not significant air quality related health hazards present for either passengers or crew*. A consolidation of this project was published in the ASHRAE Journal in 1999.[56]

A 1999 report by Haghighat et al investigated air quality and thermal comfort on 43 commercial flights.[57] Limited measurements were taken only including temperature, relative humidity and carbon dioxide, with a maximum value of 2013 ppm. Again, no measurements were undertaken during non routine or incident events.

A 1999 report by Lee et al investigated air quality on 16 commercial flights over 14 months.[58] Measurements were made of carbon dioxide (a maximum of 2900 ppm), carbon monoxide (a maximum of 4 ppm), Ozone (a maximum of 0.09 ppm), and particulates (a maximum of 2.0 $\mu g/m^3$), however VOCs were not measured. No measurements were taken during abnormal incident events yet the report concludes that the overall air quality was deemed satisfactory.

A 2000 report by the Building and Research Establishment for BAe by Ross et al conducted cabin air quality in Boeing 777s.[59] Quantitative results for three volatile organic compounds, including aldehydes and ketones were reported. Again, none of the measurements were taken during incident events.

A 2000 comparison of the environments of transportation vehicles was reported by Dumyahn et al including 28 flights on nine aircraft types.[60] Aircraft averages for measured contaminants were: carbon dioxide 1000 ppm; carbon monoxide 0.7 ppm; and VOC concentrations listed as being similar to those found in office buildings and homes. In general, the air quality was reported to pose no health risks although, as usual, none of the measurements were taken during incident events.

A 2001 consultants report for ASHRAE by Nagda et al,[61] also looked at air quality on routine flights on ten sectors on the B737, B767, B747. This is the only study apart from Fox's 1997[52] study to examine air quality in bleed air. Measurements were made of carbon dioxide (a maximum of 4238 ppm), carbon monoxide (a maximum of 9 ppm), Ozone (a maximum of 1 ppm), and particulates (a maximum of 380 $\mu g/m^3$), with SVOCs noted as low under normal operating conditions. The conclusions drawn were that: *overall bleed air quality was excellent, generally exceeding desired levels of air quality for supply air in other environments*. However the report clearly stated that focus of the research was to measure possible contaminants under normal operating conditions and *not intended to detect or measure contaminants that might occur under failure or episodic conditions*.

A 2001 commercially confidential report by Marshman[62] of the UK Defence Evaluation and Research Agency determined aircraft supply air contaminants in the engine bleed air supply system on commercial aircraft. This report remains unavailable for peer review being listed as 'Restricted Commercial with data remaining the property of BAe Systems'; only references from other reports to this study are available (for example, the 2004 UK CAA *Cabin Air Quality Report*[33]). These indicate that Tricresyl phosphate (TCP) esters (but not necessarily triortho-cresyl phosphate) and other contaminants were identified by GC-MS in pyrolysis products of new and used oils, although which oil(s) were tested remains unknown.

A second 2001 commercially confidential report by Jenner et al,[63] of the UK Defence Science and Technology Laboratory provided an assessment of the toxicity of the contaminants identified by Marshman.[62] As with the Marshman report, this report remains unavailable for peer review. Other reports note that this study concludes: *no single component or set of components would definitely cause the symptoms reported in cabin air quality incidents* and that *the oil lubricants pose no health risk, ... although symptoms of irritation could be induced during pyrolysis of aircraft lubricants.* However, it is probable that the study never actually investigated the effect of reduced cabin pressure, the report appears to be mistaken about the toxicity of the different orthocresyl isomers of TCP, and took a fairly dismissive view as to the spectrum of short term and long term health problems from TCP or its orthocresyl isomers. The CAA Cabin Air Quality report of 2004 uses this report as the basis of its conclusions (see above). It is difficult to assess the adequacy of such conclusions without access to reports on which they are based, and the continuing unavailability of such reports appears to be unnecessarily precautionary.

A 2001 monitoring study undertaken by BRE (formerly the Building Research Establishment, Watford, UK) on behalf of British Airways was undertaken on the B757, this report remains unavailable for review. All that is known is a summary note in an industry magazine that: *the concentrations of all oil compounds detected in cabin air on the B757 were each less than 100 ppb.*[64] It is not known how many aircraft were monitored or what contaminants were measured, or whether monitoring was conducted during an exposure event.

Work by Lindgren and others has measured air quality and studied air crew perceptions of air quality on aircraft.[65] A survey of 26 Boeing 767 flights measured $CO_2$ (4% above 1000 ppm), $O_3$ (maximum 37 $\mu g/m^3$), $NO_2$ (maximum 66 $\mu g/m^3$) formaldehyde (maximum 15 $\mu g/m^3$) and respirable particles (a maximum 49 of $\mu g/m^3$ during smoking conditions and a maximum 3 $\mu g/m^3$ during no smoking conditions), and concluded that overall, levels were low.[66,67] However, as usual, this was background monitoring of a few contaminants and no monitoring took place during an exposure event. This research also provided evidence on the contribution that smoking made to cabin air quality and was part of the research that lead to smoking bans on flights during the 1990s.[68,69]

These authors have also investigated the role of humidity, and notes that air humidification could increase the sensation of better air quality,[70] and reduce ocular, nasal and dermal symptoms and headaches.[71] Similar findings were reported in an analysis of responses from pilots.[72]

A 2002 review by Water et al undertook monitoring on six commercial aircraft.[73] The maximum carbon dioxide was recorded at 4902 ppm, carbon monoxide at 2.9 ppm, total particulates at 0.197 mg/m$^3$. The conclusion was that: *in general contaminant levels were low compared to standards*. However, again no sampling took place during abnormal exposure events.

A 2003 study of VOCs in different passenger aircraft by the BRE is the most complete passenger aircraft VOC investigation currently available (see further analysis of this data in Section 5.4 below). The report includes VOC data from seven flights on BAe 146 aircraft and six flights on Boeing 737-300 aircraft under normal flying conditions.[74] Over fifty different VOCs were identified, although some were at low concentrations. VOC concentrations were normally lowest during the cruise stage of the flight cycle, with the ground, descent and, for a few VOCs, the ascent stages alternating between the highest and second highest concentrations. Total VOC concentrations ranged from 11-1140 µg/m$^3$. The total amount of TVOCs appears to be inaccurate and the maximum carbon dioxide level was 3500 ppm and the maximum carbon monoxide level was 7 ppm. This study notes that one source of VOCs is from passengers, but that another source of a number of specific VOCs was the bleed air system. The research did not seek to identify the sources of the VOCs found.

A 2004 report undertaken by Spicer et al for Battelle on behalf of ASHRAE sought to relate a potential link between perceived health symptoms and discomfort and aircraft cabin environmental conditions and human factors.[75] Monitoring was undertaken on four flights on two MD-80 aircraft, one B757-200 and one B737-800 with bleed air samples taken for a few minutes during the four flights. Carbon monoxide levels were reported at a maximum of 3.5 ppm, Carbon dioxide at a maximum of 2800 ppm with a long list of VOCs and SVOCs recorded with no significant conclusions drawn. No reference was made to any particular air quality incidents during monitoring.

A 2005 report by Kibby et al[76] investigation engine bleed air contamination in Australian Defence Force military aircraft, noted the presence of tricresyl phosphates, phenyl-alpha-naphthylamine and dioctylphenylamine. The maximum concentration of TCP isomers reported was 4 µg/m$^3$, and the oxidants phenyl-alpha-naphthylamine and dioctylphenylamine below 1 µg/m$^3$.

A 2005 report by van Netten[77] undertook GC-MS analysis of swab samples taken from B757 flight deck filters, B757 precirculation filters, B757 HEPA filters, B757 forward lavatory ceiling filters and found TCP in all samples analysed. Swab samples taken from BAe 146 flight deck walls near the side vent and on a BAe 146 pilot's trousers also identified TCP (0.17 µg/pair of trousers).

A Cabin Air Sampling Functionality Test was carried out as contracted research for the UK Department for Transport by Muir et al in 2008.[78] This study tested monitoring technologies in a BAe 146 on the ground in a hangar and a B757 in flight. The methodologies used suffer from many of the criticisms outlined in this chapter, and include monitoring on the ground, sampling for volatiles/semi-volatiles and not mists or particulates, and assuming that workplace exposure standards apply at altitude, something that is untrue (see Discussion section below), and in a technical report that might be used by Government agencies to set policy or make recommendations, is unusually misinformed.

The results, such as they were, collected the usual range of volatile organics, indicated that during the BAe 146 tests (held on the ground):

- Tributylphosphate was present at all times within the cabin, even before switching on the APU. This is a major component of hydraulic fluids and indicates residual contamination;
- Kerosene range ($C_9$-$C_{15}$) compounds and Lubrication oil range ($C_9$-$C_{15}$) compounds were detected when the APU was switched on (indicating unburned fuel and oil were being taken into the air conditioning system);
- 2,5-Diphenylbenzoquinone was detected when the APU was switched on;
- Tricresyl phosphate was detected when the APU and ECS systems were running.

During the B757 tests (held in flight):

- A qualitatively similar variety of volatile/semi-volatile organic compounds were found as on the BAe 146;
- Similar levels of Tributylphosphate were found as on the BAe 146;

- Higher levels of Tricresyl phosphate were found than on the BAe 146.

This study identified that two techniques; (i) the pumped thermal desorption technology and (ii) the photoionisation detection (PID) technique were the most appropriate techniques for determining the compounds likely to be present on aircraft. However, with regard to sample collection and desorption techniques collection of non-volatiles in mists would probably be poorly extracted during desorption for analysis. Further, the use of PID technology in this study failed for technical reasons, and there is no evidence in the report to support the authors' suggestion that PID may be better using other equipment.

Most importantly, during the flight of the B757, a "fume event" occurred, noticeable by "a distinct oily type odour which persisted for less than a minute before dissipating," and which formed part of a pumped sample collected over an eighteen minute period. Monitoring indicated that there was a sharp rise in "ultrafine particles", higher concentration of Jet Oil II, and higher levels of tricresyl phosphate.

Limited though these results may be, this study did identify the presence of tricresyl phosphate on an airplane associated with a fume event. Further, it indicated that APU operation released a range of compounds into the airplane environment, something that can no longer be denied. And, for the first time, albeit incomplete and non-quantitative, evidence is available that particles (designated as ultrafines), volatiles, and tricresyl phosphate are released during an (in this case, minor) "fume event."

### 5.3.3 Air Quality Reviews

A summary of Air quality reviews is shown in Table 5-3. These findings are discussed further below.

***Table 5-3: Air Quality Reviews***

| **Reference** (first author, year[ref]) | **Comment** | **Conclusion** |
|---|---|---|
| NRC, 1986[79] | General review of aviation air quality | Unable to separate health and safety |
| NRC, 2002[80] | Air quality survey | Oils contain toxic ingredients that may affect air quality during abnormal flying conditions |
| Australian Senate, 2001[10] | Inquiry into air quality on the BAe 146 | Aviation safety regulator not enforcing its own legislation Cabin contamination occurred. Under reporting of leaks was a problem |
| House of Lords, 2000[81] | General review of air travel and health | Air quality did not present any significant risk to passengers |
| Nagda, 2000[82] | Review of air quality studies where monitoring was conducted | Only studies reporting monitoring from routine flights were reviewed |
| European Parliament, 2001[83] | General review of environmental and health impacts of aviation | Some concern that air to the carbon sometimes contained VOCs |
| Hocking, 2002[84] | Overview of air quality problems during routine flights | |
| House of Lords, 2007[85] | General review of air travel and health | Link between fume events and health effects is still unproven |

The first general review on aviation air quality was the 1986 report of a committee of the National Research Council (NRC), the principle operating arm of the US National Academy of Sciences and the National Academy of Engineering produced the report: "*The Airliner Cabin Environment: Air Quality and Safety*". This report noted, among other things, that the NRC "*attempted, but abandoned, the separation of issues of health from those of safety*". [79] The report also recommended minimum standards for a range of air quality issues, including ventilation rates, carbon dioxide, ozone, tobacco smoke (it suggested prohibition of smoking on flights) and aerosols. However, the report was unable to assess the potential health hazards to passengers or crew from other contaminants, such as volatile organic compounds.

In 2002, the NRC was again requested to conduct another study to assess airborne contaminants in commercial aircraft, to evaluate their toxicity and associated effects, and to recommend approaches to improve cabin air quality. The report mainly concentrated on contaminants in cabin air during normal flying conditions, but did acknowledge that during abnormal flying conditions, that: "*The engine lubricating oils and hydraulic fluids used in commercial aircraft are composed of a variety of organic constituents, including tricresyl phosphate, a known neurotoxicant. If the oils and fluids and their potential degradation products (e.g., CO and formaldehyde) enter the aircraft cabin, they will adversely affect cabin air quality.*"[80] The committee recommended that wipe samples of aircraft cabin, cockpit and ventilation ducts as well as filters should be taken and analysed after air quality incidents.

A committee of the Australian Senate undertook an inquiry into air safety with particular reference to the BAe 146 aircraft.[10] Part of their remit was to look at abnormal conditions where engine oil leaks had caused cabin air contamination. As such this was a first report to go beyond considerations of flying under normal conditions. The report of the Committee criticised the overly narrow definition of air safety cherished by the regulators and the airlines, and indicated that their responsibility was worker health as well as aviation safety. They noted that under-reporting of leaks was a major problem; that regulators poorly enforced the air quality provisions of civil aviation legislation; that cabin contamination continued to occur; and that even with the inability of medical science in Australia to objectively appraise the evidence of the health problems, this had led to short-term and medium-term health problems for a number of BAe 146 flight crew.

The 2000 UK House of Lords Inquiry concluded differently, noting that "*under normal operating conditions, volatile organic compounds in cabin air were found to be either undetectable or at very low levels of up to 3 parts per million (ppm)*" and concluded "*that cabin atmosphere levels of volatile organic compounds present no risk to cabin occupants under normal operating conditions*".[81] This was a report that considered only flying conditions in the absence of abnormal conditions, and is of little assistance should such circumstances arise. The report's view that there were no significant risks to passengers as there were no cases of clinical triortho-cresyl phosphate poisoning (largely based upon evidence stating that there were no formal records being kept at the London National Poisons information Centre of aircrew TOCP poisoning cases) is particularly obtuse.

A number of the studies listed above in Table 5-2 were reviewed in Nagda et al, 2000.[82] This review notes "*None of the monitored flights included any unusual or episodic events that could effect cabin air quality.*" Making use of monitoring data from such flights is of little use in consideration of chemical contamination during oil leaks, except perhaps to provide baseline data.

In a 2001 report on the environmental and health impact of aviation, the European Parliament noted "*there is some concern that the air fed to the aircraft cabin during flight, which is usually drawn from the engine's air intake, sometimes contains high levels of volatile organic substances (VOCs)*".[83]

A 2002 review of air quality problems on aircraft by Hocking[84] provided an overview of the problems of air quality, but again focuses on normal flying conditions.

An update of the 2000 House of Lords Inquiry on Air Travel and Health was published in 2007.[85] With regard to air quality, the Inquiry panels considered that "*although much anecdotal evidence has been submitted ... to this inquiry regarding fume events, this evidence still falls short of conclusive proof*" but that "*we recommend that research to settle this issue one way or another be taken forward as a high priority*".

## 5.4 Case Study: The Role of VOCs and Ventilation in Passenger Cabin Air Quality

The term "aerotoxic syndrome" has been coined to describe adverse health consequences of indoor air quality problems in aircraft.[86,87] The causes of aerotoxic syndrome are currently not well understood. Until recently, detailed data on aircraft contaminants and other data of the type used to solve building air quality problems have not been readily available. Data are beginning to become available (see for example, Table 5-2).

### 5.4.1 Sources and Analysis of Data

The main source of data on VOCs in different passenger aircraft in this case study is the BRE (formerly Building Research Establishment, Watford, UK) 2002 report.[74] This is the most complete passenger aircraft VOC investigation currently available. The report includes VOC data from seven flights on BAe 146 aircraft and six flights on Boeing 737-300 aircraft. The report does say that the results for these two older aircraft were broadly in line with results for a newer aircraft IAQ study that is not publicly available.

The VOC data this study has been analysed into the following tables:

- Table 5-4 lists individual VOCs (µg/m$^3$) in the passenger cabin during cruising flight;
- Table 5-5 lists TVOC data;
- Table 5-6 lists VOC Concentrations through the Flight Cycle;
- Table 5-7 Lists VOC Concentrations during the Flight Cycle in the BAe 146 and the B737-300.

### 5.4.2 Results

The tables below provide a comparison of various aspects of air quality factors between office and aircraft environments.

#### 5.4.2.1 Volatile Organic Compounds in Passenger Cabins of Aircraft in Flight

Table 5-4 shows the concentrations of individual volatile organic compounds (VOCs) identified in the cabins of passenger aircraft during flight (from[74]), as determined from collection of workplace atmospheres and analysis using gas chromatology using the standard NIOSH Method. Individual VOCs were identified from peaks in the chromatogram by reference to standard curve and library data on known standards.

***Table 5-4: Individual VOCs (µg/m$^3$) in the Passenger Cabin During Cruising Flight***

| Rank | Individual VOC | Some VOC characteristics/possible sources | µg/m$^3$ |
|---|---|---|---|
| 1 | Propan-2-ol (Isopropanol, 2-Propanol) | VP: 59 hPa at 25°C. Irritant. Rubbing alcohol. Solvent for resins, aerosols, antifreeze, carpet tile adhesive, caulking, latex paint, photocopier exhaust. Carrier solvent for flavouring preparations in soft drinks. Minor human metabolite. | 338.8 |
| 2 | Ethanol | VP: 58 hPa at 20°C. Pleasant odour. Produced by human metabolism, fungi, fermentation, photocopier fuser, photocopier exhaust, unleaded gasoline, personal care products, air freshener, solvents, disinfectant, caulking, latex paints, cleaning products. | 173.6 |
| 3 | Propylene glycol (1,2-Propanediol, Methyl glycol) | VP: 2.7 hPa at 20°C. Odourless and tasteless. Polyester and alkyd resins, paints and coatings, antifreeze, coolants, heat transfer fluids, plasticizers, household detergents, industrial solvents, aircraft deicers, artificial smoke, foods (to maintain moisture), pharmaceutical (medicines) and personal care products (cosmetics). | 59.5 |

| Rank | Individual VOC | Some VOC characteristics/possible sources | µg/m³ |
|---|---|---|---|
| 4 | Acetone (2-Propanone) | VP: 245 hPa at 20°C. Dipolar aprotic solvent (C=H double bond). Pleasant, ethereal odour. Bioeffluent. Engine exhaust. Air freshener, photocopier fuser, photocopier exhaust, jet fuel, gasoline, cleaning solvent, lubricating oil, ETS, glued wood products, plastic laminates, linoleum, carpet, decomposition/mould product (e.g. destructive distillation of wood). | 44.5 |
| 5 | Acetonitrile Methyl cyanide | VP: 93 hPa at 20°C. Clear, colourless liquid at room temperatures (BP: 81.6°C). Suspected mutagen. Breaks down into cyanide if swallowed, can become a fatal internal asphyxiant. Exposure at ppm levels can cause face flushing, itching, headache, nausea, and chest tightness. Found in vehicular exhaust, tobacco smoke, and combustion of organics. Solvent, used in pesticides, solvents, nail glue remover, perfume, floor polish, water proofing, antistatic, detergent, water softeners, brighteners for metals, manufacture of photographic films. Laboratory reagent. | 35.7 |
| 6 | 2-Butoxy-ethanol (Ethylene Glycol Monobutyl Ether) | VP: 1 hPa at 20°C. Glycol ethers. Unpleasant odour. Used in cleaning products, linoleum, rubber based flooring. | 14.5 |
| 7 | Chloroform (Trichloromethane ) | VP: 300 hPa at 20°C. Chlorinated solvent. Toxic to liver and kidney. Formed by the chlorination of organic materials in water- drinking water, gray water, swimming pools. Minor human metabolite. | 13.2 |
| 8 | Bromodichloromet hane | High concentrations in animal studies can damage liver, kidney and brain. Small amounts formed naturally by algae in oceans. Formed as a by-product when chlorine is added to water supply systems. Used in past as solvent and flame retardant. | 11.5 |
| 9 | Dibromochloromet hane | Formed as a by-product when chlorine is added to water supply systems. Used in past as solvent and flame retardant. | 11.2 |
| 10 | Carbon tetrachloride (Tetrachlorometha ne) | VP: 122 hPa at 20ºC. Non-polar solvent. Carcinogen, mutagen. Mainly phased out. Formerly propellant in aerosol cans, spot remover, metal degreaser, refrigerant, solvent for oils, fats, lacquers, varnishes, rubber waxes, resins; chemical intermediate; grain fumigant; dry cleaning agent; fire extinguisher. | 9.4 |
| 11 | Limonene | VP: 87 hPa at 20ºC. Characteristic lemon odour. Widely used as a masking odour, in cleaners, air fresheners, lubricating oil, ETS, deodorants, photocopier exhaust, adhesives/sealants, rubber rejuvenator, under-carpet and mould | 9.4 |
| 12 | Toluene | VP: 22 hPa at 20ºC. Aromatic solvent. Photocopier fuser, photocopier exhaust, heating oil, diesel oil, lubricating oil, ETS, high-octane gasoline, jet fuel, solvent, cleaning products, combustion product; solvent-based paints, lacquers, carpet, under carpet, linoleum, vinyl flooring, silicone concrete sealer. | 8.9 |
| 13 | Nonanal | In paints, fragrances and detergents. | 8.5 |
| 14 | 1,2-dichloroethene | Pleasant smell. Carcinogen. Used in the production of the PVC monomer vinyl chloride. Formerly used as a solvent. Lead scavenger in leaded petrol. | 7.5 |
| 15 | Tetrachloroethylen e | Degreasing solvent | 7.3 |
| 16 | Acetaldehyde (Butyraldehyde) | VP: 122 hPa at 20ºC. Very unpleasant odour. Used in synthetic resins, plasticisers. | 5.4 |
| 17 | Decamethylcyclo-pentasiloxane | VP: 0.3 hPa at 20ºC. BP above 200ºC. Solvent, lubricant and penetrating oils. High affinity for particulate matter. Photocopier fuser/exhaust, cleaning products, personal care products, surface treatment. | 5.0 |

| Rank | Individual VOC | Some VOC characteristics/possible sources | µg/m³ |
|---|---|---|---|
| 18 | 2-Hexanone (Methyl n-butyl ketone, Propyl acetone) | Toxic solvent now no longer in use. It is formed as a waste product resulting from industrial activities such as making wood pulp and producing gas from coal, and in oil shale operations. | 4.9 |
| 19 | Formaldehyde | Pungent suffocating odour. Carcinogen. Very reactive, combines readily with many substances. Engine exhaust. Formed by incomplete combustion of many organic substances including natural gas. Present in coal and wood smoke, wood finishes, adhesives, UFFI, ETS, mould. Indoor air contaminant from particleboard. Highest in new homes, especially kitchens. | 3.9 |
| 20 | 1,2-dibromoethane (Ethylene dibromide) | Uses today include treatment of logs for termites and beetles, control of moths in beehives, and as a preparation for dyes and waxes. No longer used as a pesticide in soil, and on citrus, vegetable, and grain crops. Formerly use as an additive in leaded gasoline. Not found in the building studies. | 3.3 |
| 21 | Butanal | VP: 1050 hPa at 20ºC. Fruity pungent odour. Incomplete combustion product (engine exhaust, wood combustion, ETS). Fibreboard, particleboard, resilient flooring, photocopier exhaust, cleaning products. Photochemical oxidation in ambient air. Solvent in paper industry. Used in manufacture of perfumes. Minor human metabolite. | 2.9 |
| 22 | 1,1,2,2-Tetrachloroethane | It is volatile and has a sweet odor. Toxic solvent now no longer in use. Formerly was used as a chemical intermediate, solvent, and in paints and pesticides. | 2.8 |
| 23 | Trichloroethene | Degreasing solvent, chemical intermediate, cleaning solvent, correction fluid, paint removers, adhesives, and spot removers. | 2.6 |
| 24 | 1,1,1-Trichloroethane (Methyl chloroform) | Used for metal degreasing, lubricating oil. Cleaning plastic moulds, solvent for waxes and natural resins. ETS, minor human metabolite. | 2.4 |
| 25 | 1,2-Dichloroethane | Solvent | 2.3 |
| 26 | *cis*-1,2-Dichloroethene | | 2.3 |
| 27 | 2-Butanone (Methyl ethyl ketone) | VP: 94 hPa at 20ºC. Acetone-like odour. In engine exhaust, fuels. Used in solvents (cleaners, solvent based paints, spray paints, caulking, vinyl and acrylic resins, de-waxing of lubricating oils, silicone acrylic concrete sealer). Produced during mould growth, ETS. Minor human metabolite. | 2.2 |
| 28 | 1,1,2-Tricholorethane | Solvent | 2.1 |
| 29 | *trans*-1,3-Dichloropropene | Minor solvent | 1.9 |
| 30 | *cis*-1,3-Dichloropropene (Perchloethylene) | VP 13 hPa at 20ºC. Carcinogen. Dry cleaning solvent; textile processing; degreasing metals; solvent; cleaning products, production of fluorocarbons, insulating fluid and cooling gas in electrical transformers. Grain fumigant. Minor human metabolite. | 1.8 |
| 31 | p-Tolualdehyde | | 1.7 |
| 32 | Bromoform (Tribromo-methane) | | 1.7 |
| 33 | Vinyl acetate | VP: 133 hPa at 22ºC. Solvent, plastics monomer. | 1.7 |

| Rank | Individual VOC | Some VOC characteristics/possible sources | µg/m³ |
|---|---|---|---|
| 34 | Propanal (2-Methylacrolein, Isobutenal, Methacrylaldehyde, Methacrylic aldehyde, 2-Methyl-2-propenal) | VP: 5.35 PSI at 20ºC. In engine exhaust. | 1.6 |
| 35 | Crotonaldehyde | Irritating, pungent, and suffocating odour. Engine exhaust. Used as an odorant and warning agent in fuel gases. | 1.5 |
| 36 | Methacrolein (Propionaldehyde, 1-Propanone) | VP: 361 hPa at 20ºC. Aldehyde. Unpleasant suffocating fruity odour. In engine exhaust, photocopier exhaust, waste incineration, wood combustion, gasoline, diesel, disinfectants, preservatives, rubber, plastics. | 1.5 |
| 37 | Hexane | VP: 162 hPa at 20ºC. Constituent of petroleum (fuel oil, diesel oil, jet fuel, gasoline, natural gas). Adhesives, solvents, paint, cleaning products, ETS. Lubricating oils and greases. Mould. Found in outdoor air. Minor human metabolite | 1.3 |
| 38 | Undecane | Constituent of petroleum, diesel oil, jet fuel, gasoline. Carpet, under-carpet (glue), paints and coatings, LPG, building materials, cleaners, adhesives, silicone acrylic concrete sealer. Minor human metabolite. | 1.3 |
| 39 | Methyl butyl ketone (4-Methylpentan-2-one) | Solvent | 1.3 |
| 40 | Pentanal (n-pentanal, n-valeraldehyde) | Used to produce dithiodipentyl phosphate (a raw material for lube oil additives dipentyl thiophosphates) In engine exhaust. | 1.1 |
| 41 | Chlorobenzene | Formerly used in manufacture of chlorinated pesticides, such as DDT. Solvent. | 1.1 |
| 42 | 1,4-Dichlorobenzene | VP: 13 hPa at 55ºC. BP: 174ºC at 1 A. Carcinogen. Formerly used as a space deodorant (washroom deodorant, air freshener), and insecticidal fumigant/moth repellent. | 1.1 |
| 43 | Hexanal (Carproaldehyde) | VP: 13.3 hPa at 25ºC. Glued wood (particle board), linoleum, mould, and human metabolite. Photocopier exhaust, cleaning products, ETS, combustion product. | 1.1 |
| 44 | 1,2-Dichloropropane | | 0.7 |
| 45 | 2-Ethylhexan-1-ol | | 0.7 |
| 46 | Acrolein (2-Propenal) | One of the most irritating of aldehydes found in indoor air. In engine exhaust. Used as an aquatic herbicide and algaecide in irrigation canals, as microbiocide in oil wells, liquid fuels, cooling water towers, water treatment ponds, combustion product. | 0.6 |
| 47 | 1,2-Dichlorobenzene | | 0.6 |
| 48 | 1,3-Dichlorobenzene | | 0.6 |
| 49 | Benzene | VP: 140 hPa at 20ºC. Carcinogen. Aromatic solvent. Found in petroleum. Photocopier fuser, oil, natural gas, broadloom carpet, adhesives, cleaning products, solvents, paints, vinyl rubber flooring, ETS. | 0.6 |
| 50 | Benzaldehyde | Irritating aldehydes. In engine exhaust, foods, photocopier exhaust, vinyl rubber flooring. | 0.6 |

| Rank | Individual VOC | Some VOC characteristics/possible sources | µg/m³ |
|---|---|---|---|
| 51 | Xylenes | *meta*-Xylene VP: 8.2 hPa at 20°C. *para*-Xylene VP: 8.7 hPa at 20°C. Aromatic solvent. Photocopier fuser, photocopier exhaust, heating oil, diesel oil, gasoline, jet fuel, ETS, lubricating oil, solvents (solvent-based paints), cleaning products, lacquers, adhesives/sealants, rubber rejuvenator, silicone concrete sealer, vinyl rubber flooring. Mould product. | 0.4 |
| 52 | Styrene (Vinyl benzene, Ethenyl benzene). | VP: 6 hPa at 20°C. Strong irritant. Sources include rubber, plastics, insulation (e.g. polystyrene insulation), carpets, under carpets, office machines, combustion product, ETS. | 0.2 |
| 53 | Ethylbenzene | VP: 9.3 hPa at 20°C. Cleaning products, carpet, under-carpet, ceiling tiles, ETS, office machines, diesel oil, jet fuel, gasoline, lubricating oil, paints, lacquered furniture finish, silicone concrete sealer. Combustion product. Mould. | 0.2 |
| | | Total quantified VOC µg/m³ | 783.4 |

The highest cruise concentration aircraft VOC measured was Propen-2-ol or iso-Propanol. The BRE report indicated that some or all of this VOC might have been introduced by their particle sampling equipment, however they conducted no investigation to determine if this compound was primarily an artefact and what compounds it might be masking other than Acetonitrile at the concentrations measured. Source of this VOC include antifreeze and rubbing alcohol.

The second, third and fourth highest average cruise concentration aircraft VOCs were Ethanol, Propylene glycol and Acetone. Sources of Ethanol and Acetone include occupant bioeffluent and fuels. Sources of Propylene glycol include antifreeze and refrigerants.

The fifth highest cruise concentration aircraft VOC, Acetonitrile may have been an artefact introduced by the aldehyde samplers. This was not noted as such in the BRE report.

The sixth highest cruise concentration aircraft VOC, 2-Butoxyethanol, has a very unpleasant strong odour. It is normally associated with cleaning compounds, for example, as a HVAC system cleaner.

The seventh, eighth and ninth highest cruise concentration aircraft VOC, are halogens whose sources include water supply and grey (recycled) water.

There were a number of lower concentration halogenated hydrocarbons in the aircraft cabin air.

#### 5.4.2.2 Total Volatile Organic Compounds/Totalled Individual Volatile Organic Compounds

Table 5-4 shows concentrations of individual volatile organic compounds in aircraft in flight. It is also possible to obtain data on total VOCs (TVOC). This can be calculated by summing concentration data on individual compounds, which was reported in the BRE report. However, summing the identified components on a sample chromatogram can be misleading as it excludes those peaks that were not identified. A more accurate measurement of the total VOC concentration would be to quantify the area under the curve of the chromatogram – this would provide a measure of identified and unidentified contaminants collected for analysis. TVOC data are shown in Table 5-5.

***Table 5-5: TVOC Concentrations (Sample Chromatograms/Total of Quantified VOCs)***

| | Aircraft Investigation (Average) | | | | |
|---|---|---|---|---|---|
| | Ground oper-ations | Ascent | Cruise | Descent | Whole Flight |
| **TVOC (Summed individual), µg/m³** | 419.1 | 178.0 | 126.0 | 98.8 | |
| **TVOCs, (Quantified) µg/m³** | 1,218.8 | 1,009.4 | 783.4 | 896.7 | 1,022.8 |
| **Rate** | 12% | 18% | 16% | 11% | |

A cross check found that the BRE TVOC (summed) concentrations underreported TVOC (quantified) exposures by 11-18%.

TVOC (summed) concentration alone is not an indicator of the degree to which VOC exposures will contribute to the occurrence of SBS/SAS symptoms as compounds vary in their irritation and toxicity.

#### 5.4.2.3 VOCs Levels through the Flight Cycle

The data in Table 5-4 shows airborne contaminant concentrations through the flight cycle of ground operations, take off/ascent, cruise, and descent. Two of these contaminants may have been artefacts of the sampling and analysis process. These are Propan-2-ol, which may have originated in part with the ultra fine particle counter used by BRE in the aircraft measurements and Acrylonitrile, introduced by the aldehyde sorbent cartridge and sampling pumps used to collect air samples. These are excluded from further consideration below, but leaves 51 separate compounds (see Table 5-6).

***Table 5-6: VOC Concentrations through the Flight Cycle***

| Rank Cruise | Individual VOC | Aircraft Averages (TVOC Quantified, (µg/m³) | | | | |
|---|---|---|---|---|---|---|
| | | Ground | Ascent | Cruise | Descent | Whole flight |
| 1 | Ethanol | 249.0 | 207.8 | 173.6 | 469.7 | 186.8 |
| 2 | Acetone | 58.4 | 37.3 | 44.5 | 55.0 | 27.7 |
| 3 | Propylene glycol | 493.1 | 134.4 | 59.5 | 50.1 | 195.0 |
| 4 | Chloroform | 18.1 | 27.0 | 11.5 | 20.4 | 18.1 |
| 5 | 2-Butoxyethanol | 28.2 | 24.6 | 14.5 | 11.8 | 17.5 |
| 6 | Bromodichloromethane | 18.1 | 27.0 | 11.5 | 20.4 | 18.1 |

| Rank Cruise | Individual VOC | Aircraft Averages (TVOC Quantified, (µg/m³) | | | | |
|---|---|---|---|---|---|---|
| | | Ground | Ascent | Cruise | Descent | Whole flight |
| 7 | Dibromochloromethane | 18.5 | 26.3 | 11.2 | 19.7 | 17.4 |
| 8 | Carbon tetrachloride | 15.8 | 22.3 | 9.4 | 16.7 | 14.7 |
| 9 | Limonene | 10.0 | 16.2 | 9.4 | 4.0 | 9.7 |
| 10 | 2-Hexanone | 8.1 | 11.6 | 4.9 | 8.1 | 7.4 |
| 11 | 1,2-Dibromoethane | 5.5 | 7.9 | 3.3 | 6.0 | 5.2 |
| 12 | Decamethylcyclo-pentasiloxane | 7.4 | 5.1 | 5.0 | 4.5 | 4.9 |
| 13 | Acetaldehyde | 10.1 | 4.8 | 5.4 | 4.9 | 6.8 |
| 14 | Butanal | 4.1 | 5.3 | 2.0 | 4.4 | 0.8 |
| 15 | 1,1,2,2-Tetrachloroethane | 4.6 | 6.6 | 2.8 | 5.1 | 4.4 |
| 16 | Trichloroethene | 4.5 | 6.3 | 2.6 | 5.0 | 4.1 |
| 17 | 1,1,1-Trichloroethane | 4.0 | 5.8 | 2.4 | 4.5 | 3.8 |
| 18 | *trans*-1,2-Dichloroethene | 12.2 | 34.0 | 7.5 | 10.7 | 16.0 |
| 19 | 1,2-Dichloroethane | 3.9 | 5.5 | 2.3 | 4.4 | 3.7 |
| 20 | *cis*-1,2-Dichloroethene | 3.9 | 5.5 | 2.3 | 4.4 | 3.7 |
| 21 | Toluene | 13.8 | 9.1 | 8.9 | 1.4 | 12.2 |
| 22 | 1,1,2-Tricholorethane | 3.5 | 5.0 | 2.1 | 3.7 | 3.3 |
| 23 | Formaldehyde | 9.2 | 4.2 | 3.9 | 2.7 | 4.9 |
| 24 | p-Tolualdehyde | 2.5 | 3.5 | 1.7 | 2.5 | 2.6 |
| 25 | *trans*-1,3-Dichloro-propene | 3.0 | 4.2 | 1.9 | 3.1 | 2.7 |
| 26 | Tetrachloroethylene | 8.6 | 13.8 | 7.3 | 5.5 | 3.7 |
| 27 | *cis*-1,3-Dichloropropene | 3.1 | 4.0 | 1.8 | 2.9 | 2.8 |
| 28 | 2-Butanone | 5.9 | 3.8 | 2.2 | 3.1 | 3.4 |
| 29 | Bromoform | 2.8 | 3.9 | 1.7 | 3.0 | 2.6 |
| 30 | Vinyl acetate | 2.8 | 3.9 | 1.7 | 3.1 | 2.6 |
| 31 | Hexane | 2.4 | 2.9 | 1.5 | 2.3 | 1.9 |
| 32 | Propanal | 4.3 | 3.2 | 1.6 | 2.5 | 1.9 |
| 33 | Crotonaldehyde | 2.2 | 2.7 | 1.5 | 3.4 | 0.4 |
| 34 | Methacrolein | 2.2 | 2.7 | 1.5 | 2.2 | 0.4 |
| 35 | Methyl butyl ketone | 1.9 | 2.6 | 1.3 | 2.0 | 3.1 |
| 36 | 1,4-Dichlorobenzene | 1.2 | 1.7 | 1.1 | 1.3 | 1.5 |
| 37 | Pentanal | 1.9 | 2.8 | 1.1 | 2.0 | 1.7 |
| 38 | Chlorobenzene | 1.9 | 2.6 | 1.1 | 2.0 | 1.8 |
| 39 | Undecane | 3.2 | 3.8 | 1.3 | 1.1 | 2.1 |
| 40 | Benzaldehyde | 0.7 | 1.0 | 0.6 | 0.9 | 0.8 |
| 41 | 1,2-Dichloropropane | 1.1 | 1.7 | 0.7 | 1.2 | 1.1 |
| 42 | 1,2-Dichlorobenzene | 0.9 | 1.3 | 0.6 | 0.9 | 0.9 |
| 43 | 1,3-Dichlorobenzene | 0.9 | 1.3 | 0.6 | 0.9 | 0.9 |
| 44 | Acrolein | 1.4 | 1.0 | 0.6 | 0.9 | 0.2 |
| 45 | Hexanal | 2.1 | 1.4 | 1.1 | 0.7 | 1.5 |
| 46 | 2-Ethylhexan-1-ol | 1.3 | 1.0 | 0.7 | 0.6 | 1.1 |
| 47 | Xylenes | 2.5 | 0.7 | 0.4 | 0.3 | 0.9 |
| 48 | Benzene | 1.6 | 0.7 | 0.6 | 0.3 | 1.6 |
| 49 | Styrene | 0.8 | 0.3 | 0.2 | 0.2 | 0.3 |
| 50 | Ethylbenzene | 1.0 | 0.4 | 0.2 | 0.2 | 0.3 |
| 51 | Nonanol | 12.9 | 8.5 | 8.5 | 5.1 | 8.7 |
| | **Total Summed VOC µg/m³** | **1085.5** | **726.9** | **448.1** | **796.7** | **640.0** |

VOC concentrations were normally lowest during the cruise stage of the flight cycle, with the ground, descent and, for a few VOCs, the ascent stages alternating between the highest and second highest concentrations. For the human bioeffluent VOCs, it can be expected that concentrations of these would increase with the higher metabolic rates associated with boarding and deplaning, for the same cabin ventilation rate.

However, the fairly consistent higher concentrations of the non-bioeffluent VOCs during ascent and descent suggest either carry-over from ground contamination in the case of the ascent stage, lower ventilation rates for both these stages, or bleed air contamination during these stages at these times, or some combination of these possibilities. Ventilation rates are not provided in the BRE report. These rates can be estimated from $CO_2$ concentrations and assumptions of occupant metabolic rate during each stage. However, this estimation is not possible for the ascent and descent stages as $CO_2$ data are not provided for them, $CO_2$ concentrations are provided only during cruise and on the ground.

Ethanol and propylene glycol are significant contributors (above 10% to the total) to airborne contaminants, with other contaminants in the 1-10% range, including Acetone, Acetaldehyde, 2-Butoxyethanol, Bromodichloromethane, Carbon tetrachloride, Chloroform, Dibromochloromethane, 1,2-Dichloroethene, 2-Hexanone, Limonene, Nonanol and Toluene. However most illuminating, as shown in Table 5-4 and Table 5-6 is the large range of other contaminants present, albeit some at quite low levels.

While many of these contaminants are present at low levels, some are known toxicants. Some, such as the aldehydes, are irritating. Others, as they are volatile organic compounds, are known to have effects on the central nervous system. Others have specific toxic effects such as neuropathy (n-Hexane), leukaemia (Benzene), liver damage (carbon tetrachloride or chloroform). It is not possible to speculate except in general terms about the toxicity of exposure to such a cocktail of chemicals. However, the possible effects should not be dismissed without proper consideration. This is especially significant when the additional factor of the hypoxia of flying is considered.

#### 5.4.2.4 VOC Concentrations during the Flight Cycle in the BAe 146 and the B737-300

Table 5-7 provides calculations of aircraft cabin ventilation rates (these were not were not calculated in the BRE report) and VOC levels for two models of airplanes (the BAe 146 and the B737-300) during different phases of the flight cycle.

***Table 5-7: Ventilation Rate Dataand VOC Concentrations throughout the Flight Cycle for the BAe 146 and the B737-300***

| Rank | Air quality parameter/ VOC level | BAe 146 Averages | | | | | B737-300 Averages | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ground | Ascent | Cruise | Descent | Total | Ground | Ascent | Cruise | Descent | Total |
| | Carbon dioxide (ppm) | 1217 | | 1026 | | 1084 | 1941 | | 1637 | | 1639 |
| | Assumed passenger met level | 1.2 | | 0.9 | | 1 | 1.2 | | 0.9 | | 1 |
| | Assumed ambient $CO_2$ (ppm) | 450 | | 380 | | 380 | 450 | | 380 | | 380 |
| | Calculated ventilation rate (cfm) | 14 | | 12 | | 13 | 7 | | 6 | | 6 |
| | **Total VOCs (µg/m³)** | **1363** | **1026** | **1090** | **1289** | **1346** | **1075** | **993** | **477** | **507** | **699** |
| 1 | Ethanol | 221.5 | 148.4 | 222.8 | 839.8 | 128.1 | 276.6 | 267.1 | 124.4 | 99.6 | 245.5 |
| 2 | Acetone | 54.7 | 43.6 | 49.9 | 72.2 | 17.6 | 62.0 | 31.0 | 39.2 | 37.8 | 37.8 |
| 3 | Propylene glycol | 737.0 | 118.4 | 45.1 | 44.0 | 235.3 | 249.3 | 150.3 | 73.9 | 56.1 | 154.8 |
| 4 | Chloroform | 16.0 | 30.2 | 17.1 | 26.7 | 19.0 | 29.4 | 35.2 | 9.3 | 24.8 | 22.3 |
| 5 | 2-Butoxyethanol | 28.2 | 24.6 | 14.5 | 11.8 | 17.5 | | | | | |
| 6 | Bromodichloromethane | 11.7 | 24.8 | 14.4 | 21.8 | 15.6 | 24.6 | 29.2 | 8.5 | 19.1 | 20.6 |
| 7 | Dibromochloromethane | 3.0 | 24.2 | 14.0 | 21.3 | 15.2 | 24.0 | 28.4 | 8.5 | 18.2 | 19.5 |
| 8 | Carbon tetrachloride | 11.2 | 20.4 | 11.8 | 17.9 | 12.6 | 20.4 | 24.2 | 7.0 | 15.5 | 16.9 |
| 9 | Limonene | 5.2 | 24.2 | 9.0 | 1.6 | 8.0 | 14.8 | 8.1 | 9.7 | 6.5 | 11.4 |
| 10 | 2-Hexanone | 5.7 | 10.7 | 6.1 | 9,6 | 6.7 | 10.5 | 12.5 | 3.6 | 6.5 | 8.1 |
| 11 | 1,2-Dibromoethane | 3.8 | 7.3 | 4.2 | 6.5 | 4.5 | 7.2 | 8.6 | 2.5 | 5.5 | 5.8 |
| 12 | Decamethylcyclopentasiloxane | 3.4 | 3.5 | 3.9 | 3.9 | 2.9 | 11.4 | 6.8 | 6.1 | 5.2 | 7.0 |
| 13 | Acetaldehyde | 9.7 | 3.2 | 3.5 | 4.9 | 6.0 | 10.5 | 6.4 | 7.3 | 4.8 | 7.5 |
| 14 | Butanal | 2.6 | 4.4 | 3.5 | 3.8 | 0.9 | 5.7 | 6.2 | 2.3 | 5.0 | 0.8 |
| 15 | 1,1,2,2-Tetrachloroethane | 3.2 | 6.1 | 3.5 | 5.4 | 3.8 | 5.9 | 7.1 | 2.1 | 4.8 | 4.6 |
| 16 | Trichloroethene | 3.3 | 5.8 | 3.3 | 5.2 | 3.6 | 5.7 | 6.8 | 2.0 | 4.8 | 4.6 |
| 17 | 1,1,1-Trichloroethane | 2.8 | 5.3 | 3.0 | 4.7 | 3.3 | 5.2 | 6.2 | 1.8 | 4.4 | 4.3 |
| 18 | *trans*-1,2-Dichloroethene | 2.7 | 5.1 | 2.9 | 4.5 | 3.2 | 21.7 | 63.0 | 12.1 | 16.8 | 28.8 |
| 19 | 1,2-Dichloroethane | 2.7 | 5.1 | 2.9 | 4.5 | 3.2 | 5.0 | 6.0 | 1.7 | 4.2 | 4.2 |
| 20 | *cis*-1,2-Dichloroethene | 2.7 | 5.1 | 2.9 | 4.5 | 3.1 | 5.0 | 6.0 | 1.7 | 4. | 4.2 |
| 21 | Toluene | 6.4 | 5.1 | 2.8 | 0.9 | 4.2 | 21.1 | 13.1 | 14.9 | 1.9 | 20.2 |
| 22 | 1,1,2-Tricholorethane | 2.4 | 4.6 | 2.7 | 4.0 | 2.9 | 4.5 | 5.4 | 1.6 | 3.5 | 3.7 |
| 23 | Formaldehyde | 9.4 | 2.9 | 2.3 | 2.3 | 4.6 | 9.0 | 5.6 | 5.6 | 3.2 | 5.6 |
| 24 | p-Tolualdehyde | 1.7 | 3.0 | 2.3 | 2.7 | 2.3 | 3.3 | 4.0 | 1.2 | 2.4 | 2.8 |
| 25 | *trans*-1,3-Dichloropropene | 2.1 | 3.9 | 2.3 | 3.5 | 2.4 | 3.8 | 4.5 | 1.4 | 2.7 | 3.0 |
| 26 | Tetrachloroethylene | 3.5 | 2.4 | 2.2 | 2.0 | 1.8 | 13.7 | 25.3 | 12.3 | 9.1 | 5.5 |
| 27 | *cis*-1,3-Dichloropropene | 2.1 | 3.9 | 2.2 | 3.4 | 2.4 | 4.1 | 4.1 | 1.3 | 2.3 | 3.1 |
| 28 | 2-Butanone | 3.6 | 3.1 | 2.1 | 2.8 | 2.6 | 8.2 | 4.4 | 2.3 | 3.4 | 4.2 |
| 29 | Bromoform | 1.9 | 3.6 | 2.1 | 3.2 | 2.3 | 3.6 | 4.3 | 1.2 | 1.2 | 2.9 |
| 30 | Vinyl acetate | 2.0 | 3.6 | 2.1 | 3.2 | 2.3 | 3.6 | 4.3 | 1.2 | 1.2 | 2.9 |

The BAe 146 had approximately twice the ventilation rate of the B737-300 at the three stages measured, but on average, approximately double the VOC concentrations of the B737-300. This indicates that BAe 146 non-bioeffluent VOC source strengths were some four times those of the B737-300, and that bleed air contained high quantities of bioeffluent VOCs such as ethanol and acetone. Both of these VOCs have other sources, including fuel and aviation fluids. Turbine bearing lubricating oil seal leaks into the bleed system is a well established systemic problem in the aviation industry. Such leaks are most likely to occur during flight path changes from ascent to cruise, or from cruise to descent. If the engine is heavily contaminating the bleed air, then higher ventilation rates will increase the cabin VOC concentrations, not decrease them.

Either the ventilation rates decreased on both aircraft types during ascent and descent or bleed air contamination increased during those periods, or both.

### 5.4.3 Case Study: Discussion

Recommendations for ventilation rates in aircraft have evolved over the past fifty years. The cabin of an airplane is a specialised environment with a limited air supply and an absence of access and egress. A range of other situations can arise whereby aircraft cabin air can be contaminated. These were described in Section 5.1.[10]

Other air quality problems include ethanol and acetone, indicators of bioeffluents and chemicals from consumer products.[88] One additional problem is the lower partial pressure of oxygen that is present in the cabins of planes flying at altitude.[89]

The analysis in this case study has shown:

1. The standard analytic method used for determining building TVOC concentrations of using the detector response to toluene only, underestimated VOC exposures in two models of passenger aircraft (BAe 146 and B737-300) by one order of magnitude. The main reason for this anomaly is that the standard method underestimates the contribution of some types of VOCs, such as halogenated hydrocarbons for example, which were at higher concentration in these aircraft than is typical of buildings.
2. The BAe 146 passenger cabins had stronger non-bioeffluent VOC source strengths than the cabins in the B737-300. One such source appeared to be the bleed air ventilation system. Bleed air ingestion of VOCs likely is coincident with ingestion of VOCs, exposure to which poses both SAS and more serious health risks. Such ingestion in fact has attracted international concern for flight crew health and safety, and is the current subject of a multi-million dollar FAA research project to develop a monitoring system.[90] This possibility was not identified in the BRE report on their data, probably because they did not look at air conditioning ventilation rate.
3. Either the air conditioning ventilation rates decreased on both aircraft types during ascent and descent, or bleed air contamination increased during those periods, or both. In

any event, airborne contaminant concentrations surged during both activities.

4. Operating with one pack instead of two approximately doubles VOC exposures during cruise with contaminant free bleed air such as appeared to be the case with the B7373-300 during cruise.

5. Operating with one pack instead of two will more than double VOC exposures during ascent when engine demand for maximum thrust reduces its ability to provide ventilation air.

6. Increased air conditioning ventilation in aircraft can both resolve and cause SAS problems, depending upon whether the bleed air is, for example, contaminant free or heavily contaminated with bearing lubricating oil seal leaks.

7. In the case of the BAe 146, bleed air incidents are more commonplace, as this thesis would suggest, than in the case of most other aircraft. In the case of aircraft such as the older B737-300, bleed air contamination may be mostly at "background" levels with heavily oil-coated ventilation ducts sorbing combustion pollutants while on the runway and desorbing them later in flight. In either case, low or high-level bleed air contamination adds to VOC contaminant exposure dose (particularly for flight crew).

8. The inclusion by BRE of acetonitrile as one of the principal VOCs present in both aircraft during all flight cycle stages could be a measurement artefact. If not an artefact, the source might be combustion fumes, which if present, would certainly be of concern.

9. The inclusion by BRE of isopropanol as the highest concentration VOC present in both aircraft during all flight cycle stages could also be primarily a measurement artefact. The fact that BRE did not clear up whether the primary source of the isopropanol was a measurement artefact introduced by the ultra fine particle sensor or not seems incongruous. Its presence could not only have masked acetonitrile, another potential artefact but also other VOCs with similar retention times.

10. The inaccuracy of the TVOC data and the possible introduction of two artefacts as apparent principal VOCs present in the aircraft air are not the only items of concern. Normally, in any serious investigation, the origins of all major compounds would be investigated and resolved. Only in this way can one determine the VOCs

and SVOCs and other gases and particles of lower VP that might have been present in the aircraft and not measured. To assess sources and other potential air contaminants present, one needs to measure nearer or at the main potential sources. Possible VOC/SVOC sources that seem obvious and were not reported on in this investigation include the contaminants in engine bleed air and envelope air at the time. The bleed air VOCs appeared to be heavily contaminated with combustion hydrocarbons while the envelope was even more heavily contaminated with hydrocarbon VOCs from the light oil used to coat the fuselage against corrosion, and with microbial VOCs.

## 5.5 Discussion

The cockpit or cabin of an aircraft is a unique environment. It is a specialised working environment for air crew that cannot (indeed, must not) be equated with workplaces at sea level, or workplaces where specialised ventilation and escape are possible.

The process of aircraft pressurisation means that the working environment is hypoxic. Flying crew are required to conduct complex operations requiring high order cognitive skills and coordination expertise. Flight attendants may be required to direct emergency procedures requiring composure and confidence. Anything that may have an impact on the provision of these tasks can have serious consequences. A lowered level of oxygen may in turn have an impact on the emergence of adverse health problems to toxic exposures. A leak of such an oil from an engine operating at altitude would see most of the oil pyrolise once it leaves the confined conditions of temperature and pressure operating in the engine. While it seems reasonable that any ingredients with suitable autoignition or degradation properties that allow such a transformation after release from the engine could be radically transformed, it is possible to speculate in only general terms about the cocktail of chemicals that could form. Presumably it would include carbon dioxide, carbon monoxide, partially burnt hydrocarbons (including irritating and toxic by-products, such as acreolin and other aldehydes), and TCP (which is stable at high temperatures). These contaminants will be in gas, vapour, mist and particulate (smoke) forms. These contaminants could not be classified as being of low toxicity, and indeed, product information such as labels or MSDS for commercially available jet oils note:

- Prolonged or repeated breathing of oil mist, or prolonged or repeated skin contact may produce nervous system effects.
- Toxic fumes may be evolved on burning or exposure to heat.
- Product may decompose at elevated temperatures or under fire conditions and give off irritating and/or harmful (carbon monoxide) gases/vapours/fumes. Symptoms from acute exposure to these decomposition products in confined spaces may include headache, nausea, eye, nose, and throat irritation.

Where exposure may be to high levels of airborne contaminants, it is not unreasonable for signs of irritancy and discomfort to be observed. A substantial number of studies have been carried out investigating chemical contamination of aircraft air. However, in considering the situation where an engine oil leak occurs, it is difficult to extract useful information from these studies.

The cabin of an airplane is a specialised working environment and should be considered as such. Standard occupational health and safety practices are constrained in such conditions where the possibility of escape to fresh air (in flight) is lacking.

Most studies of air quality on aircraft indicate that cabin air quality is satisfactory. However, few have investigated air quality after engine oil or hydraulic fluids leaks and are therefore unsuitable for comparison purposes. There are a number of problems with interpreting this data:

- Investigations that do not mimic the conditions of flying will not be representative of conditions during flight. Studies conducted on the ground, with aircraft doors open and with engines not on full load will not allow suitably representative data to be collected.
- Investigations that report contaminants during normal flight are basically worthless in considering the types of contaminants and their concentrations that may occur during oil leaks. A number of studies, including authorative reviews such as those of the US National Research Council,[79,91] ASHRAE,[92] or the UK Civil Aviation Authority[33] miss this significant point and continue to persist with the argument that as levels during normal flights are within acceptable levels, there is no problem. Most studies fail to appreciate this key point. The argument is especially fallacious when any air quality

study did not attempt to measure the range of contaminants that may possibly be found. Only analysis during an oil leak can measure contaminants arising from an oil leak.

- Investigations have not attempted to capture the possible range of contaminants that may be found on aircraft. Many studies have captured conventional contaminants with mandated standards, such as carbon dioxide, carbon monoxide and ozone. Some others have attempted to capture volatile organic compounds or particulates. Few have specifically looked for contaminants of interest, such as phenyl-alpha-naphthylamine or ortho-isomers of tricresyl phosphate. Yet all too often, all such studies are cited uncritically by industry spokespersons that there is no contamination problem.

- Investigations have been conducted using inappropriate sampling techniques. One of the most serious problems is sample collection for later analysis. The volume of Tedlar bags and Summa canisters may not allow collection of sufficient amounts of airborne contaminants for analysis (see Figure 5-3).

***Figure 5-3: Occupational Hygiene Airborne Contaminant Capture Equipment***

**Tedlar Bag**

**Summa Canister**

Further, while gases and vapours form true solutions in air, suspended materials do not. Mists and aerosol particulates will settle under the force of gravity, and where they coalesce or adhere to the walls of their container, the concentration of the mist in air would drop dramatically, leaving only a very low vapour residual. Subsequent extraction of this sample for analysis would be as the residual vapour, and only very low levels would be measured. This will lead to a false negative analysis when collection of a mist of a low volatile material at relatively high levels is then extracted in low concentrations as a low vapour pressure vapour. Any sampling method that relies on sample collection of an air sample containing a mist, and analysis of a residual vapour (when all the mist has settled) could underestimate exposure by orders of magnitude. Virtually all monitoring outlined above which relies on sample collection for later analysis is severely flawed.

- Investigations have been conducted using inappropriate or poorly selected analytical methods. Methods for the analysis of volatile organic contaminants, will provide inaccurate measurements of semi-volatile chemicals and will not provide measures non-volatile chemicals, such as tricresyl phosphate. Such chemicals are detected only in a method where the entire sample is captured and not allowed to disperse (such as the cryogenic sampling outlined in the Lee studies[46,47]). This again allows the possibility of false negative results to occur.

- Investigations have been conducted with inadequate chain of custody arrangements for collected samples. While the earlier investigations were not conducted to the modern requirements of laboratory practice, later studies should be compliant with the necessary administrative processes.

- Many studies report that measured air concentrations commonly conclude that their observed results are within "acceptable levels" as specified by occupational threshold limit values or similar. There are a number of criticisms of this approach –

  - Organisations who recommend values for exposure standards have never maintained that their recommended values protect all workers. Most exposure standard setting bodies are careful to point out that at best, their recommendations only protect "nearly all workers"; that is, they do not protect all workers. The uncritical acceptance of these values by workers in the aviation industry as a suitable reason to accept the findings of some reports hinders appropriate debate.

  - Exposure standards are established to assist in the protection of workers. They do not apply to people who are not working on the aircraft (for example, passengers). They do not apply to the young, or the elderly, or the sick, or the chemically sensitive. All may be found as passengers on aircraft.

    - Exposure standards are not available for all chemicals, including many chemicals reported in some studies investigating contaminated cabin air.
    - Exposure standards apply to individual chemicals and the synergistic effects of chemicals in the aircraft cabin air or bleed air supply have never been properly considered.
- Exposure standards do not apply at altitude.
    - Atmospheric pressure at sea level is 101.33 kPa (or 760 mm Hg, 1 atmosphere, or 29.92 inches of mercury, or 14.7 psi). As altitude increases, the atmospheric pressure declines. Most standards setting bodies recommend that occupational exposure standards should not be used below 90 kPa (675 mm Hg; equivalent to a height of about 1000 m). Cabin air in commercial aircraft during normal operations is required to be maintained to an altitude equivalent to 2438 m/8000 ft. The atmospheric pressure at this equivalent height is 69.6 kPa (or 520 mm Hg). This pressure is maintained by the cabin pressure system. A second requirement for release of oxygen dispensing units at 4572 m/15,000 ft is also recommended (at 50.7 kPa or 380 mm Hg).
    - The concentration of oxygen at sea level is 20.9%. While the proportion of oxygen in air remains unchanged (20.9%) as altitude increases, the actual amount of oxygen in air decreases. The partial pressure of oxygen in air at sea level is 20.27 kPa (or 159 mm Hg). Recommended exposure standards for oxygen in working environments have been established at 19.5%. This is a level which may be hazardous to workers, and is routinely used for such tasks as confined space entry. This concentration is equivalent to about 150 mm Hg of oxygen. So while the partial pressure of oxygen at sea level is 159 mm Hg, and the recommended exposure standard for oxygen is (19.5% (150 mm Hg), the corresponding partial pressure of oxygen at the cabin pressurisation pressure is 108 mm Hg. This difference again supports the inapplicability of exposure standards at altitude.
    - Other problems with atmospheric pressure and lowered oxygen concentrations include changes in sensitivity to toxic exposures (for example, the toxicity of carbon monoxide is 50% higher at 8000

ft than at sea level), and the possibility that incipient hypoxia may lead to higher respiratory rates and therefore increased exposure.

- The interaction effects of hypoxia/low humidity have not been studied adequately, but are unlikely to be insignificant.

- Airborne monitoring ignores exposure from skin absorption, known to be a significant route of exposure for at least some organic phosphates, including triorthocresyl phosphate.[93]
- Where exposure may be to two or more contaminants, the individual exposure standards for each individual contaminant should be reduced proportional to its concentration. Statements that all chemicals were within their representative exposure standards are not appropriate in exposures to mixtures of chemicals, especially at altitude.
- In interpreting the results of monitoring studies, most reports exclude the impact of the hypoxia of flying in a pressurised cabin. Flying crew must conduct complex operations requiring high order cognitive skills and coordination expertise. Flight attendants may be required to direct emergency procedures requiring composure and confidence. Anything that may have an impact on the provision of these tasks (for example, chemical contamination) can have serious consequences. A lowered level of oxygen may in turn, have an impact on the emergence of adverse health problems to toxic exposures.
- Other factors due to the manner in which air is circulated in planes, may also have an effect, such as humidity, temperature, or contaminants such as carbon dioxide, carbon monoxide, ozone and particulates.
- There is a difference between the requirements of exposure standards and the air quality levels that will provide an acceptable level for customer satisfaction. Contaminant levels may be below recommended levels in currently recognised exposure standards, but still may not meet customer expectations with respect to odours or discomfort.
- Exposure standards do not consider synergistic effects between contaminants and may be outdated, may not have incorporated more recent scientific and medical evidence. Additionally extenuating circumstances on

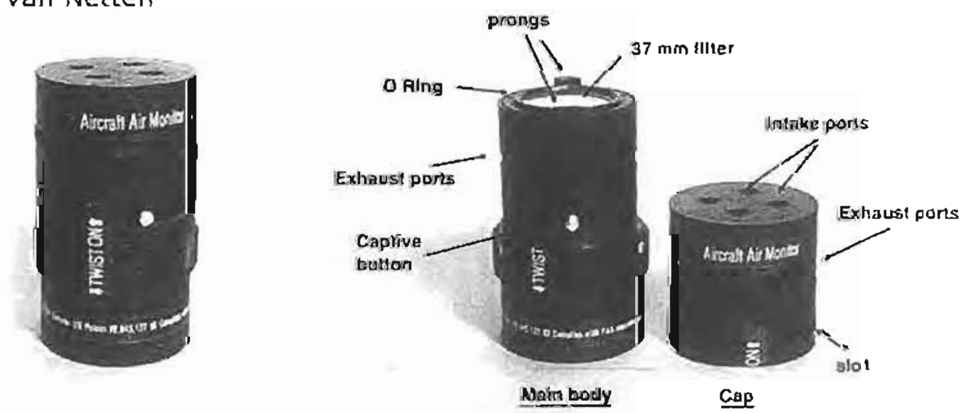
board aircraft such as humidity and cabin pressure have not been considered.[48]

Therefore, there are methodological problems with these studies:

- o the monitoring was carried out using inappropriate conditions, such as testing at ground level;
- o the monitoring was carried out using inappropriate methods, such as analyses of samples collected in summa canisters or Tedlar bags, when mists could coalesce onto the surface of the sample container;
- o storage of sample containers was too long (for example, over 72 hours after sample collection when some compounds could be lost, or non-volatile or semi-volatile compounds would adhere to the inside of the container);
- o little evidence is presented to indicate if monitoring was carried out after scheduled maintenance, or seal, oil or filter changes, so it is difficult to assess whether the monitoring was representative of typical exposures;
- o most importantly, no monitoring was conducted out at a time when an odour incident had occurred.

More recently, technology has become available that allows better collection of contaminants (for example, the VN-sampler [94] ) or real time monitoring including combined vapour/particulate monitoring techniques.[95]

***Figure 5-4: The VN Sampler***
From van Netten[94]




**The assembled sampler** **Details of unassembled sampler**

The aviation industry continues to suggest that such complaints are really due to poor cabin air quality or to other factors inherent in-flight such as lowered barometric pressure, hypoxia, low humidity, circadian dysynchrony, work-rest cycles, vibration, as well as aspects relevant to cabin air quality such as volatile organic compounds (VOCs), carbon dioxide ($CO_2$), carbon monoxide (CO), ozone ($O_3$), particulates, and microorganisms (including the cabin ventilation system), to discern possible causes and effects of illness contracted in-flight.[96]

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# Chapter 6

## The Health Survey

The issue of aircraft air contamination due to oils and hydraulic fluids leaking into the aircraft air supply is a known problem in the aviation industry. There are a range of regulations that are in place to ensure all cases of fume contamination are reported and therefore investigated. However, there is strong evidence that the reporting system to regulatory agencies is not working, and consequently, under-reporting is occurring. There are a variety of reasons for this occurring including commercial pressures, fatalism about long standing and apparently insurmountable engineering problems, operational procedures that focus keeping aircraft flying and a culture to minimise health and safety risks. These have significant health and safety implications for crew and passengers. The term aerotoxic syndrome was proposed in 1999 to describe the association of symptoms observed amongst flight crew such as pilots and flying officers or cabin crew such as flight attendants, cabin managers (both groups henceforth called aircrew) exposed to hydraulic or engine oil vapours or mists. A health survey was conducted of exposed air crew.

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- Winder, C., Fonteyn, P., Balouet, J.-C. Aerotoxic syndrome: A descriptive epidemiological survey of aircrew exposed to in-cabin airborne contaminants *Journal of Occupational Health and Safety - Australia and New Zealand* **18:** 321-338, 2002.

# 6 The Health Survey

## 6.1 Introduction

The oils and hydraulics used in airplane engines can be toxic, and specific ingredients of oils can be irritating, sensitising and neurotoxic, (such as phenyl-alpha-naphthylamine and triaryl phosphates such as tri-orthocresyl phosphate).[1,2] If oil or hydraulic fluid leaks occur, this contamination may be in the form of unchanged material, degraded material from long use, combusted or pyrolised materials. These materials can contaminate airplane cabin air in the form of gases, vapours, mists and aerosols. There are a number of possible situations that can arise whereby airplane cabin air can become contaminated.[3] Significant contaminants include: aldehydes; aromatic hydrocarbons; aliphatic hydrocarbons; chlorinated, fluorinated, methylated, phosphate, nitrogen compounds; esters; and oxides.[4,5,6] One additional problem is the lower oxygen concentration operating in the cabins of planes flying at altitude.[7]

To date, most studies that have been carried out to measure atmospheric contamination in airplanes by engine oil leaks or hydraulic fluids are sufficiently flawed on procedural and methodological grounds as to render their conclusions invalid. Further, no monitoring has occurred during a leak.

International aviation legislation such as the US Federal Aviation Regulations (FAR) and airworthiness standards for aircraft air quality state "*crew and passenger compartment air must be free from harmful and hazardous concentrations of gases or vapors.*"[8] Where contamination of air in flight deck and passenger cabin occurs that is sufficient to cause symptoms of discomfort, fatigue, irritation or toxicity, this contravenes such standards and legislation.

A 2005 health perception survey by Lindgren and Norback provides a background to health problems in air crew. Common symptoms reported by aircrew were: fatigue (21%), nasal symptoms (15%), eye irritation (11%), dry or flushed facial skin (12%) and dry/itchy hands; this paper notes these occurred at higher rates than in a control groups of office workers. The most common complaint in 53% of respondents was dry air.[9]

Inhalation is an important route of exposure, with exposure to uncovered skin being a second, less significant route (for example, following exposure to oil mists or vapours). Ingestion is unlikely.

Occasionally, such exposures may be of a magnitude to induce symptoms of toxicity. In terms of toxicity a growing number of aircrew are developing symptoms following both short term and long term repeated exposures, including dizziness, fatigue, nausea, disorientation, confusion, blurred vision, lethargy and tremors.[10,11,12] Neurotoxicity is a major flight safety concern especially where exposures are intense.[13]

The earliest case found in the literature was reported in 1977.[14] A previously healthy member of an aircraft flight crew was acutely incapacitated during flight with neurological impairment and gastrointestinal distress. His clinical status returned to normal within a day. The aetiology of his symptoms was related to an inhalation exposure to aerosolised or vapourised synthetic lubricating oil arising from a jet engine of his aircraft.

Other studies of exposures in airplanes exist in the literature, including a 1983 study of eighty nine cases of smoke/fumes in the cockpit in the US Air Force,[15] a 1983 study of Boeing 747 flight attendants in the USA (this paper linked symptoms to ozone),[16] a 1990 study of aerospace workers,[17] and a 1998 study of BAe 146 flight crews in Canada over a four-month period.[10] A report of seven case studies considered representative of the common symptoms of irritancy and toxicity described similar symptoms was reported in Chapter 3.[12] These studies investigated different exposures and situations, and the range of symptoms in these studies was quite broad, affecting many body systems. However, there are common themes in symptom clusters in these studies, as shown in Table 6-1 below.

***Table 6-1: Studies reporting Signs and Symptoms in Aircrew (Prior to 2001)***

| **Reference** | **15** | **16** | **17** | **10** | **12** |
|---:|---|---|---|---|---|
| **Number of cases/reports** | **89** | **248** | **53** | **112** | **7** |
| Irritation of eyes, nose and throat | | | | | 7/7 |
| Eye irritation, eye pain | 35% | 74% | 57% | 24% | 4/7 |
| Blurred vision, loss of visual acuity | 11% | 13% | | 1% | 4/7 |
| Skin irritation, rashes, blisters (uncovered body parts) | | | 36% | | 4/7 |
| Sinus congestion | 35% | 54% | | 5% | 2/7 |
| Nose bleed | | 17% | | | 1/7 |
| Throat irritation, burning throat, gagging and coughing | 2% | 64% | 57% | 43% | 2/7 |
| Cough | | 69% | | | 2/7 |
| Difficulty in breathing, chest tightness | | 68% | | | 3/7 |
| Loss of voice | | 35% | | | 1/7 |
| Chest pains | 7% | 81% | | 6% | 2/7 |
| Respiratory distress, shortness of breath, | | 73% | | 2% | 4/7 |

| Reference<br>Number of cases/reports | 15<br>89 | 16<br>248 | 17<br>53 | 10<br>112 | 12<br>7 |
|---|---|---|---|---|---|
| breathing problems requiring oxygen | | | | | |
| Fainting/loss of consciousness/grey out | 4% | 4% | | | 3/7 |
| Shaking/tremors/tingling | 9% | | | 3% | 3/7 |
| Numbness (fingers, lips, limbs), loss of sensation | | | 8% | 2% | 4/7 |
| Dizziness/loss of balance | 47% | | | 6% | 4/7 |
| Light-headed, feeling faint or intoxicated | 35% | 54% | | 32% | 7/7 |
| Disorientation | 26% | | | 15% | 4/7 |
| Severe headache, head pressure | 25% | 52% | | 26% | 7/7 |
| Trouble thinking or counting, word blindness, confusion, coordination problems | 26% | 39% | 42% | | 6/7 |
| Memory loss, memory impairment, forgetfulness | | | 42% | | 7/7 |
| Behaviour modified, depression, irritability | 26% | 20% | 60% | | 4/7 |
| Nausea, vomiting, gastrointestinal symptoms | 26% | 23% | 15% | 8% | 6/7 |
| Abdominal spasms/cramps/diarrhoea | 26% | | | | 3/7 |
| Change in urine | | 3% | 6% | | |
| Joint pain, muscle weakness, muscle cramps | | 29% | | | 2/7 |
| Fatigue, exhaustion | | | | | 7/7 |
| Chemical sensitivity | | | 32% | | 4/7 |

While this Table shows a long list of symptoms, it is possible to characterise many symptoms more consistently. For example, different papers report dizziness or loss of balance or light-headed or feeling faint or feeling intoxicated or disorientation. It would be incorrect to regard such symptoms as being entirely different from each other – they point to a basic neuropsychological dysfunction affecting balance. But rather than dismissing such symptoms as being multitudinous and variable, [18] it may be more appropriate to re-categorise symptoms with clearer definitions, so that the artificial distinctions between symptom reporting can be clarified, and a shorter list developed.

Against this background, a descriptive epidemiological study was conducted of flight crew and flight attendants, investigating the development of symptoms during flight through mail out of a self-administered questionnaire. Because of industry sensitivities with regard to such a survey, it was designed to be independent from the aviation industry (for example, airplane manufacturers, airline operators or unions were not involved in design or conduct). Therefore, there was no formal process of requesting nominations, nor was there a description of survey objectives provided prior to nomination.

One aim of the present study to identify whether aerotoxic syndrome was definable, and if so, identify the symptoms that might be considered indicative of such a condition.

## 6.2 Methodology

### 6.2.1 Ethics Approval

As part of the UNSW processes for the conduct of research involving human beings, this project was subject to an ethics application in 1999. Ethics advice on questionnaire was received as part of the approvals process (see below), discussion was held with the Chair of the Ethics Committee in November 1999 as part of the application process, and approval for the project was provided in late 1999/early 2000 (HREC Project 99247: *Aerotoxic syndrome in airplane personnel*).

The project was finalised in July 2002, and a paper published.[19]

### 6.2.2 The Survey

**Selection process:** This was a volunteer survey. Survey participants were those aircrew who took the effort to identify themselves to the research project team as being interested in the survey, and then to agree to complete and return the survey.

As noted above, there was no information or publicity prepared or circulated by the research team about the proposed survey. Officers in both flight attendant and pilots unions were aware of the study, and a statement was issued by the Australian Flight Attendants Association that they were not involved with the survey. Further, information flows rapidly within the Australian aviation industry and the principal investigator received many telephone and email inquiries. Some inquirers were suspicious about the independence of the survey, about the source of research funding and about the possibility that the survey had any undue influence from companies or unions. Many nominations were made only when guarantees of funding independence and assurances of nominator anonymity were provided by the research project team.

The aircrew volunteer database was compiled over a four month period in late 2000. It was originally proposed to survey between 30 and 50 nominations, but it became apparent that this was an underestimate of the number interested in participating. Eventually there were 117 aircrew nominations who volunteered to be part of the survey. Of these, one hundred were nominations from aircrew within Australia.

**Survey mail out:** Survey questionnaires were sent out in January 2001. A response period of four months was specified. After this time, no further responses were included. Other responses have been received since the cut off date, including 18 from two US airlines. Because the highest response rate was made from aircrew within Australia, data from Australian respondents are presented in this chapter, with a comparison between Australian and US findings later.

**Response rate:** Ultimately, 100 survey forms were sent out to Australian nominations and fifty replies were received, a response rate of 50%. As distinct from many other surveys, the research team did not send follow up reminders to non-respondents. It is not known why fifty volunteers initially planned to be involved in the survey but then later declined. A response rate of 50% to a single mail out is considered excellent, and could have been higher if there had been a follow up to non-respondents.

## 6.3 Development of Survey Questionnaire

A three page structured questionnaire was developed to survey aircrew volunteers. The questionnaire consisted of open and closed ended questions with white space for opportunities for comment.

The questionnaire was derived from pre-existing questionnaires developed for collecting information at interviews that assessed the experience of aircrew following adverse health outcomes from exposure to contaminants while flying.[35] Additions and modifications were made to the questionnaire to suit the present study. The questionnaire was reviewed by the University of New South Wales Ethics Committee. It was considered that the questionnaire should not "lead" or prejudice the respondent, and extensive modification was made of early drafts to ensure neutral language. The final questionnaire did not contain concepts such as air leaks, contamination or aerotoxic syndrome. The questionnaire was then trialled with ten aircrew. Further modifications were made as a result of the trial.

Aircrew were initially asked to identify what if any health symptoms they had experienced whilst flying and the duration of these symptoms. These questions were open ended and invited opportunities for in depth, qualitative responses. Respondents were asked to describe factors that may have contributed to any adverse health symptoms and outcomes.

The second part of the questionnaire consisted of a relatively long list of signs and symptoms within the following symptom categories: Neuropsychological, Neurological, Senses, Eye and Skin, Respiratory, Cardiovascular, Gastrointestinal, Renal, Endocrine, Immunological and Reproductive. Respondents were asked to report whether they had experienced any of the listed symptoms.

### 6.3.1 Data Analysis

Descriptive data was analysed by using SPSS for Windows, version 9.05. Given the possibility of selection and reporting bias, statistical hypotheses were not tested on these data.

Data was downloaded into Microsoft Excel (version) for graphical purposes.

Qualitative open ended responses were documented and descriptive quotations are included below.

## 6.4 Results

### 6.4.1 Demographic Characteristics

Table 6-2 contains a demographic overview of respondents.

***Table 6-2: Overview of the Aviation Employees Surveyed***

| Aviation Employee Characteristics | Categories | Number of Responses | |
|---|---|---|---|
| | | N | % |
| **Gender** | Male | 14 | 28 |
| | Female | 36 | 72 |
| **Age** | 20-29 | 4 | 8 |
| | 30-39 | 25 | 50 |
| | 40-49 | 13 | 26 |
| | 50-59 | 8 | 16 |
| **Years experience in aviation industry** | 1-9 | 13 | 26 |
| | 10-19 | 19 | 38 |
| | 20-29 | 11 | 22 |
| | 30-39 | 5 | 10 |
| | 40+ | 2 | 4 |
| **Occupation** | Flight crew | 16 | 32 |
| | Cabin crew | 34 | 68 |
| **Airline** | Ansett | 36 | 72 |
| | National Jet Systems/Airlink | 12 | 24 |
| | Northwest Airlines | 2 | 4 |
| **Type of Airplane'** | BAe 146 | 46 | 92 |
| | A320 | 28 | 56 |
| **Alcohol** | None | 8 | 16 |
| | Mild | 36 | 72 |
| | Moderate | 5 | 10 |
| | Heavy | 1 | 2 |
| **Smoking** | Current Smoker | 4 | 8 |

| Aviation Employee Characteristics | Categories | Number of Responses | |
|---|---|---|---|
| | | N | % |
| | Non Smoker | 46 | 92 |

* This was a multiple response question, so the per cent was calculated by each item as a total of fifty responses

Of the 50 crew surveyed, 28% were male and 72% were female.

A majority of respondents were cabin crew (70%), with flight crew comprising the remaining 30%.

The age of respondents ranged from 26 years to 59 years with a mean age of 40 ± 8 years (the median was 38 years).

Years of experience in the industry ranged between 2 and 40 years. The mean number of years experience in the aviation industry was 16 ± 10 years.

Ansett employed 72% and National Jet Systems 22% of respondents. Most flew on BAe 146 aircraft (92%), with 56% flying the A320 aircraft. Several cabin-crew flew both aircraft types).

The vast majority of respondents (92%) reported they were non-smokers and tended to either abstain from alcohol (16%) or consume small quantities of alcohol occasionally (72%).

### 6.4.2 Contributing Factors

Aviation aircrew were asked to describe any factors that may have contributed to their symptoms. These questions were unprompted and individual open-ended comments were requested. Most of the respondents (88%) reported that their symptoms occurred after assumed exposure to oil gases and fumes in the cabin. The common use of the word "fume" was often incorrect on technical grounds. Technically, a fume is an aerosol of solid particles generated by condensation from the gaseous, volatile or oxidised atomic state, not as what were almost certainly vapours (the gaseous phase of a liquid at room temperature) or mists.

Invariably, respondents attributed these gases and "fumes" (vapours and mists) to possible oil leaks. As the nature of these exposure events cannot be adequately described in statistics and graphs, a few extracts from some of the respondents are reproduced below. These sometimes better describe the more alarming aspects of such exposures.

- **Pilot; age 59:** "I consider the symptoms suffered are a direct result of cockpit fumes on the BAe146 aircraft. The greater the incidence of detectable fumes the more apparent the symptoms ...also related to rate of flying. On leave the symptoms reduced."

- **Flight attendant; age 48:** "I had an increased exposure of fumes on BAe 146 when the cabin filled up with smoke, I could not see past row two on the aircraft. Since that incident both the Captain and First Officer have developed lung disease, I had breast cancer and another Flight Attendant has sued the airline because of health problems"
- **Flight attendant; age 37:** "Following the fume occurrence on BAe 146 I had a metallic taste in my mouth, headache over the right eye, sore throat. Short term symptoms included nausea, dizziness, lack of concentration, memory loss, stiff neck, stinging/itchy, weepy eyes, difficulty in concentrating whilst driving, 'heavy' head, unable to stand in shower without falling over"

Over half of the respondents (54%) cited air-conditioning problems as a reason for adverse health symptoms. Other factors included hypoxia (18%) and pressurisation problems (16%).

### 6.4.3 Onset of Symptoms

Adverse health symptoms as a result of exposure to oil fumes were reported by 47 (94%) of the respondents.

Almost all (96%) respondents reported adverse symptoms immediately whilst flying or on the same day as flying. Respondents also experienced adverse symptoms continuing for at least one month from the time of exposure (82%). Many respondents reported having symptoms occur for at least six months after exposure (74%). The term "long term effects" indicates an effect(s) persisting over a long period of time; however, the duration of what might be considered "a long period of time" has generated debate in this industry. Some view this as being at least over six months, others over decades. For the purposes of this paper, an effect is considered long term if it has been present for over a year. Long term symptoms that remained or developed after at least one year of exposure were reported by 76% of respondents.

### 6.4.4 Amelioration of Effects of Exposure

Data on the manner in which effects of exposure were ameliorated is shown in Table 6-3.

***Table 6-3: Amelioration of Effects of Exposure***

| Gender | What Happened | | | | | Total % |
|---|---|---|---|---|---|---|
| | **Fresh air/rest/ sleep on landing** | **Oxygen Used** | **Hospital-ised** | **Doctor visited** | **N/A or no Symp-toms** | |
| Male[*] | 10 (20%) | 2 (4%) | 0 | 0 | 2 (4%) | 14 (28%) |
| Female[*] | 11 (22%) | 14 (28%) | 8 (16%) | 3 (6%) | 0 | 36 (72%) |
| **Total[*]** | **21 (42%)** | **16 (32%)** | **8 (16%)** | **3 (6%)** | **2 (4%)** | **50 (100%)** |

[*] data expressed as number of respondents (%), Total n = 50

Under half of the respondents (42%) had mild symptoms that reduced on vacating the plane and subsided further after extended rest.

Those with more moderate symptoms (32%) used the oxygen on board the aircraft.

- **Flight Attendant; age 37:** "At times due to maintenance problems aircraft are flown with one air conditioning pack in service. I usually feel hypoxic on these flights and use oxygen. On other occasions the problem is with oil leaks and then my symptoms re-occur. As I have removed myself from flying on the BAe 146 my symptoms have subsided."
- **Flight Attendant; age 40:** "After the mechanical failure, hydraulic fuel leaked into the cabin. All the cabin crew and four passengers became ill. Flight deck was on oxygen when crew reported dizziness, nausea and confusion and extreme head pain"

One pilot was so affected by exposure that the plane was grounded until the symptoms subsided. Almost one quarter of respondents (22%) experienced severe symptoms and collapsed after exposure. Hospitalisation was necessary for 16% who were taken off the airplane on a stretcher or wheelchair suffering from exposure to toxic fumes.

- **Flight Attendant; age 40:** "All the cabin crew and some passengers were exposed to the fumes. My legs gave way ... I had to harness myself into my jump-seat. After landing the crew was taken by company van to an emergency room. Hospitalised, the physician's diagnosis five hours after landing was probable inhalation injury - cognitive problems, speech slurred, headache, nausea. Twenty-four hours after exposure Internist Doctor noted ataxia, coordination problems - diagnosis Toxic Encephalopathy. Day 3 Neurologist documents Toxic Encephalopathy with significant cognitive dysfunction, memory loss, speech disorder – I cannot set a clock and cannot draw a cube. MRI was given two days after incident, tissue damage found in white matter, high signal intensity spots on the frontal lobe of the brain. Still experience long term effects".

- **Flight Attendant; Age 24:** "On the day of the incident, within the first hour of smelling the fumes I had difficulty breathing and talking. I had spasms in my legs, was faint and felt very hot. On disembarking I fell to the floor, they put me on oxygen and wheeled me off in a wheel chair. I was on oxygen for the first hour in the first aid room and was unable to talk for the first hour. I was taken to the medical centre during which time I was in and out of consciousness".

On a gender basis, the proportion of fresh air and sleep reduced symptoms for almost equal numbers of males (71%) and females (31%), however females generally experienced more severe symptoms that required greater medical intervention. Females (38%) were over five times more likely to use oxygen than males (14%). Hospitalisation was required for (22%) females in comparison with no males requiring hospitalisation. Three women (8%) required attendance by a doctor, as opposed to no reported requirements for males seeking medical assistance (see Table 6-3).

### 6.4.5 Data on Signs and Symptoms

Data on symptoms is presented below on the basis of grouped symptoms or organ systems. Data will be presented in graphical form, with the same axis dimension for respondents showing symptoms, to allow ease of comparison. Where possible, data on background incidence of such symptoms in the Australian population is provided to allow a comparison with background incidence, although comparison of the data below with the other forms of data may be problematic (for example, self reported as opposed to physician collected data). There are also problems with comparing total populations with workers in that the "healthy worker effect"[20] may bias results, as would comparing males with females.[21]

### 6.4.6 Irritancy symptoms in eyes, skin and respiratory system

Data on eye and skin symptoms are shown in Figure 6-1, and respiratory symptoms and cardiovascular effects in Figure 6-2.

There are high levels of irritancy symptoms in this data, including eye irritation (76%) and skin problems (58%). These are consistent with exposure to an irritant, but this may not be the only cause – they could also be caused by for example, the low humidity of flight. There are some gender differences, although these could be related to gender samples sizes.

Similarly, a number of the symptoms in Figure 6-2 show respiratory irritation, with 64% of respondents reporting breathing problems (75% in females) and 48% showing chest tightness/wheezing.

***Figure 6-1: Data on Signs and Symptoms on Irritation of Eye and Skin***

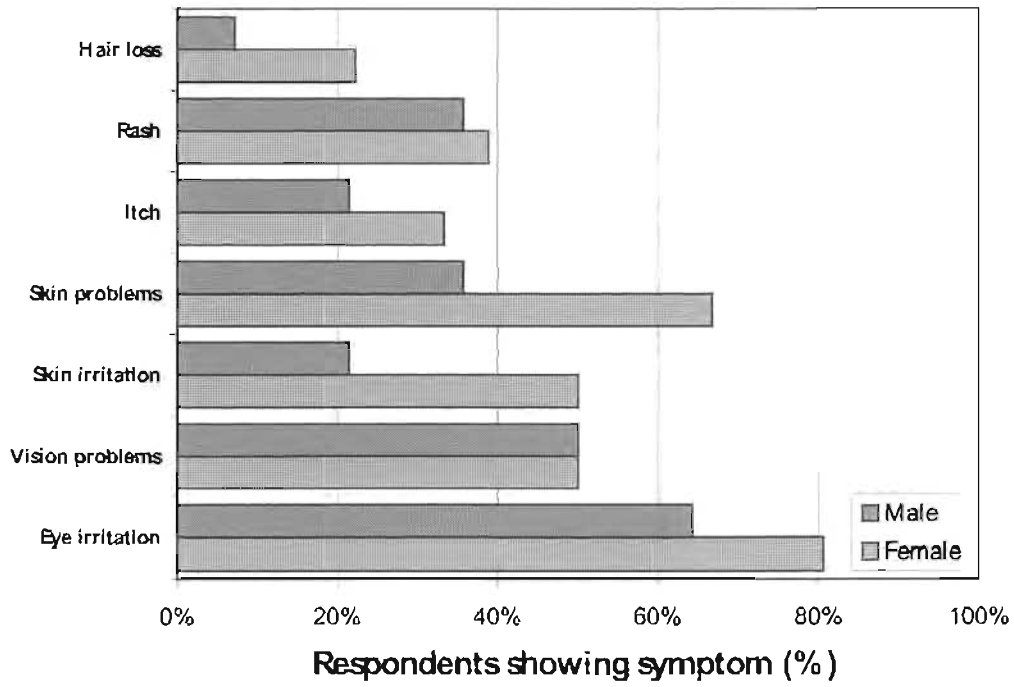
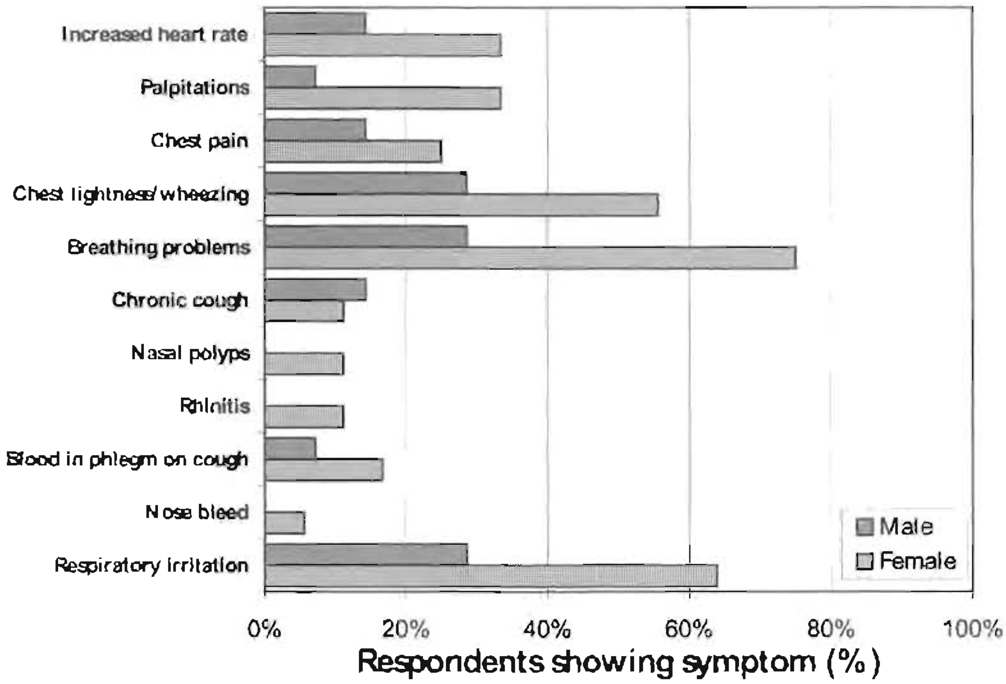


*Figure 6-2: Data on Respiratory and Cardiovascular Signs and Symptoms*



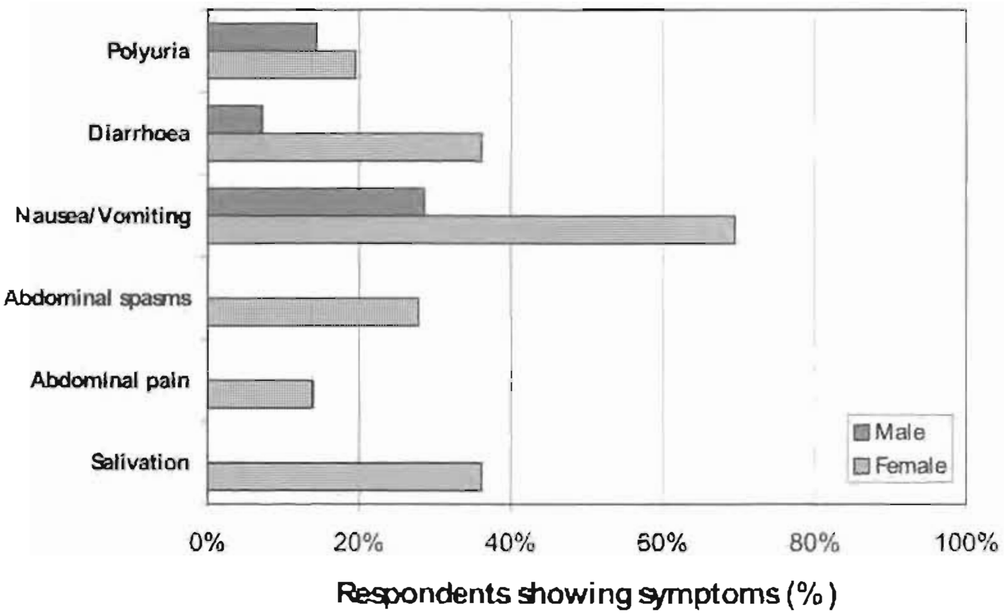

There are problems in categorising self reported symptoms such as breathing problems or respiratory irritation. There are some gender differences here, with apparently high rates of respiratory irritation in females.

Adverse respiratory health effects from exposures to among others, oxides of nitrogen, ozone, sulphur dioxide and particulates either singularly or in combination such as in exposure to aviation fuel or jet stream exhaust has been known for some time (see for example,[34,36,45]). Tunnicliffe et al found an association between high occupational exposures to aviation fuel or jet stream exhaust and excess upper and lower respiratory tract symptoms, in keeping with exposure to a respiratory irritant.[22] In their study 51% of aviation workers had upper and lower respiratory symptoms including cough with phlegm and runny nose.

### 6.4.7 Gastrointestinal/Renal Signs and Symptoms

Nausea and vomiting is a relatively common symptom,[23] and was reported by 58% respondents. In most cases these symptoms were associated with intensifying gastrointestinal symptoms (mainly in females) of abdominal spasms (20%), abdominal pain (10%) and diarrhoea (28%). These results are shown in Figure 6-3.

*Figure 6-3: Data on Gastrointestinal/Renal Signs and Symptoms*

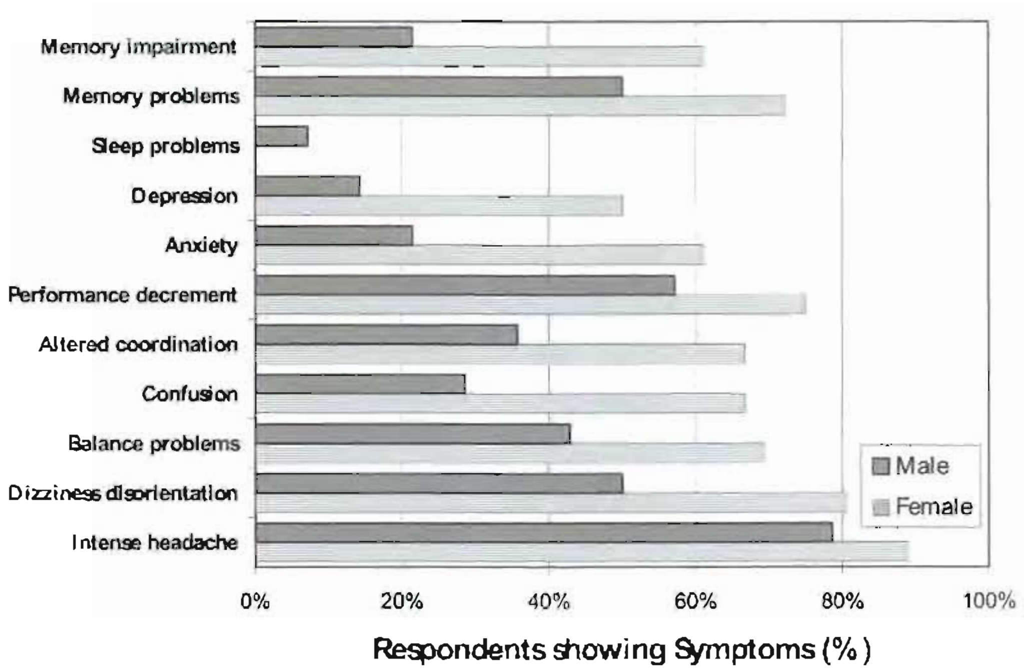



### 6.4.8 Neuropsychological Signs and Symptoms

Data on neuropsychological symptoms are shown in Figure 6-4 and neurological symptoms in Figure 6-5.

Symptom reporting rates were very high for many neuropsychological symptoms, including intense headache (86%), dizziness and disorientation (72%), performance decrement, including changes in cognitive function (70%), memory and recall problems (66%), balance problems (62%), and so on. Other symptoms, such as anxiety (50%) and depression (40%) are more global and harder to interpret. The consistency of neurological symptoms is quite striking, suggesting neuropsychological impairment of a general nature, as seen for example, in exposure to volatile organic compounds, [24] organophosphate compounds, [25] or carbon monoxide. [26] The significance of such phenomena remains problematic. [27]

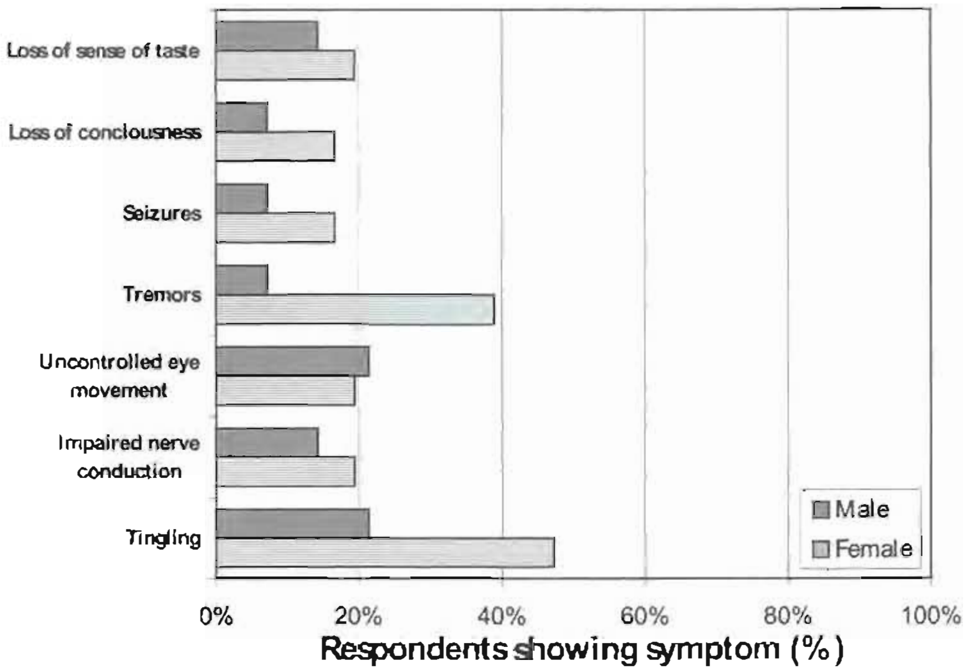
***Figure 6-4: Data on Neuropsychological Signs and Symptoms***




While neuropsychological effects are often dismissed as being subjective or unquantifiable, intense headache at 86%, dizziness/disorientation at 72%, performance decrement at 70% or memory problems at 66% are not symptoms that should be dismissed in aircrews in the performance of their duties. The high rate of respondents reporting such effects is difficult to interpret, owing to the self selection of respondents to, and reporting bias in, this survey.

The incidence of neuropsychological symptoms in aircrew, especially in females, appears excessive.

*Figure 6-5: Data on Neurological Signs and Symptoms*

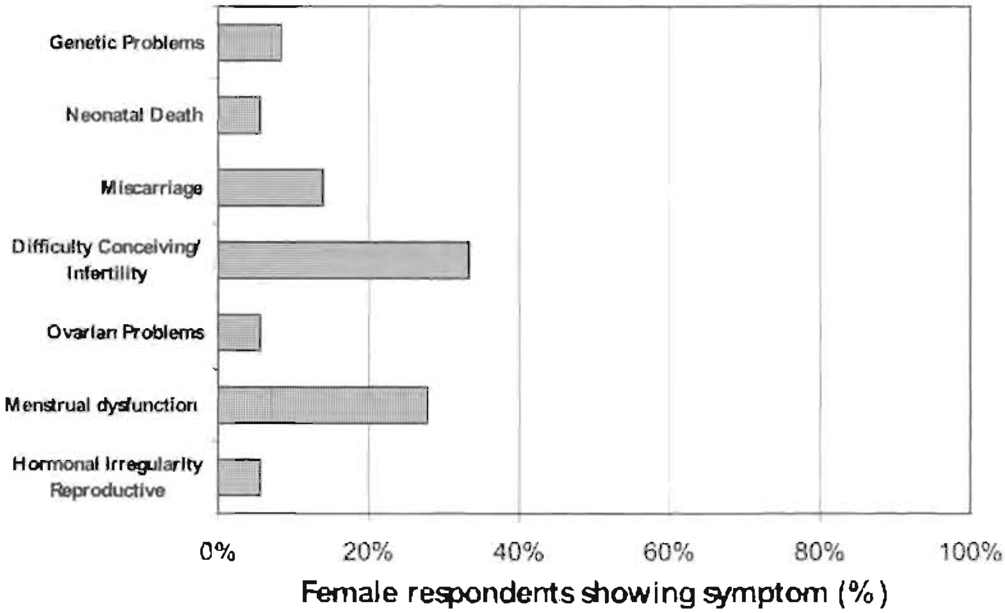



While self reporting of neuropsychological or neurological symptoms may contain elements of subjectivity, the incidence in both genders of neuropsychological or neurological symptoms such as tingling (40%), tremors (30%) or seizures or loss of consciousness (14%) was based on reporting of symptoms after a respondent had been examined by a medical practitioner. These are significant symptoms that point to a toxic aspect of the exposures reported by respondents. Further, there may be a neurotoxic component to other symptoms, such as vision problems or disorientation or balance problems.

### 6.4.9 Reproductive Signs and Symptoms

There were 36 female respondents. All were of reproductive age, many of whom were planning or having families during the time of their employment. Working women tend to have a lower fertility rate than non-working women, although this is for employment, rather than biological reasons.[28] Fertility rates are falling in the developed nations for a range of reasons, and are estimated at 7-10%.[29] The data from respondents for reproductive symptoms is shown in Figure 6-6. Infertility was reported by 33% of respondents. This appears to be above population norms.

*Figure 6-6: Data on Reproductive Signs and Symptoms*




Menstrual dysfunction (variously reported as heavy periods, irregular periods or dysmennorrhoea) were reported by 28% of female respondents, miscarriage in 14% and multiple miscarriage in two respondents. Of particular significance is the problem of neonatal death in two respondents and genetic problems in the offspring of three respondents. While the sample size is small, these are noteworthy findings.

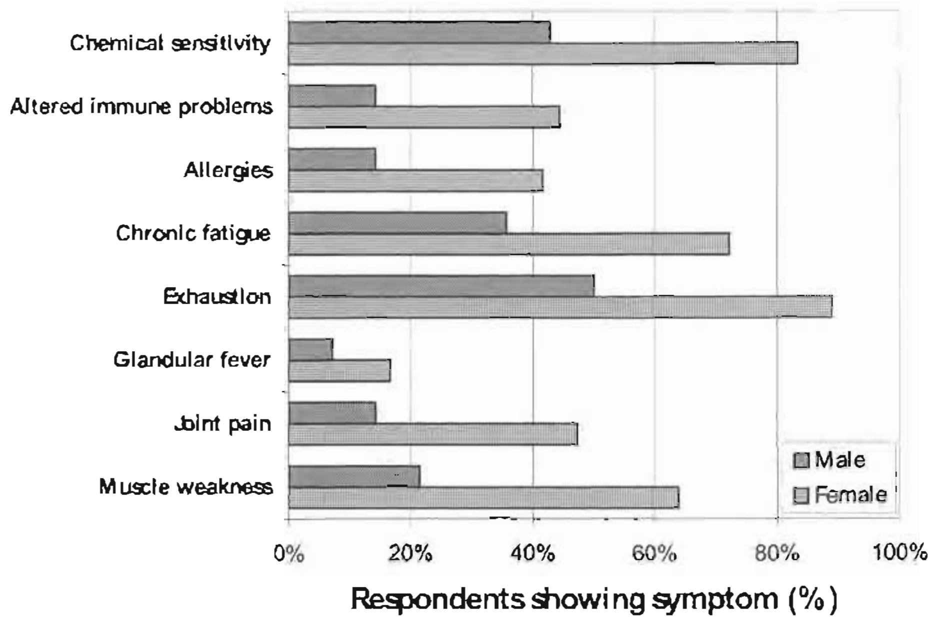
### 6.4.10 General Signs and Symptoms

As well as signs and symptoms in specific organ systems, a range of multi-organ or general symptoms were reported. These are shown in Figure 6-7.

Joint pain (arthralgias) and muscle pain (myalgias) .are common symptoms resulting from a variety of disease processes.[30,31] Despite the poorly understood pathogenetic mechanisms underlying myalgia and arthralgia, they are common in chronic fatigue and chemical sensitivity syndromes.

Out of all the symptoms reported in this survey, exhaustion was the second most common, being reported by 78% of all respondents (and 89% of female respondents). Fatigue is an established hazard in aviation, from the perspective of the impairments in alertness and performance it creates in pilots.[32] The exhaustion reported by respondents escalated into 72% of respondents reporting chronic fatigue. Prolonged or chronic fatigue is reported by about 25% of all patients presenting to Australian general practice.[33] Such fatigue states represent a continuum of severity ranging from the mild and transient symptoms through to the rarer, severe and prolonged fatigue disorders. In about 1% of patients attending general practice in Australia, the fatigue state will meet diagnostic criteria for Chronic Fatigue Syndrome.[33] Figure 7 shows chronic fatigue at 36% for males and 72% for females. While there may be differences between diagnostic criteria for, and self reporting of, chronic fatigue, these rates (particularly in females) are still very high.

***Figure 6-7: Data on General Signs and Symptoms***




A second cluster of symptoms was observed with chemical sensitivity. Allergies were reported by 34% of respondents, altered immune problems in 36% of respondents, and chemical sensitivity in 72% of respondents (83% in female respondents). Again, these are high rates that would almost certainly be well above any population background rate.

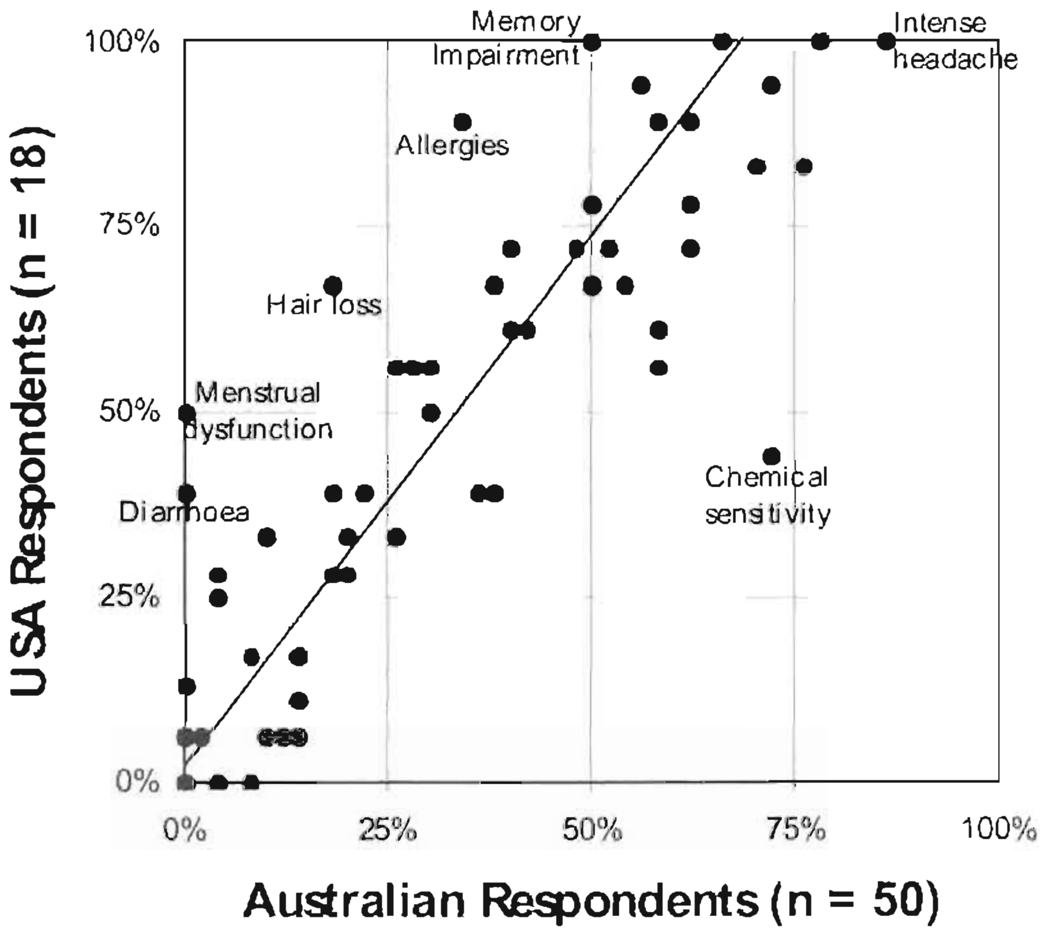
The co-occurrence and overlapping of many of the symptoms reported by the respondents is in keeping with comparable investigations. Co-morbidity of chronic fatigue, irritable bowel syndrome, chemical sensitivity, chronic headache and other unexplained conditions has only recently been systematically studied. [34] Comparative investigations in referral clinic populations have reported that in 53% to 67% of persons with the chronic fatigue syndrome, illness worsens with exposure to various chemicals. Many patients with the chronic fatigue syndrome also have irritable bowel syndrome (63%), multiple chemical sensitivity (41%) and other unexplained illness.[34]

## 6.5 The American Questionnaires

Eighteen questionnaires were submitted from respondents with addresses in North America (sixteen female; two male). Again, these were analysed descriptively. Rather than present the same data again as shown in Figure 6-1 to Figure 6-7, the symptom incidence for each symptom was plotted using a X-Y scatter plot, with the horizontal axis (X-axis) being the Australian percentages and the vertical axis (Y-axis) being the US percentages. This is shown in Figure 6-8.

These data show some symptoms where there is some difference between Australian and US symptom incidences, although in a few cases these outliers suggest diagnostic differences between the two countries (for example chemical sensitivity/allergy). Nevertheless, there is a remarkable correlation between these data (correlation coefficient, r = 0.859, and an $r^2$ = 74%).

***Figure 6-8: A Comparison of Australian and US Symptom Incidences***




## 6.6 Discussion

The term aerotoxic syndrome was proposed in 1999 to describe the association of symptoms observed among aircrew exposed to hydraulic or engine oil smoke/fumes.[35]

With regard to the use of the term "syndrome", this is used to describe a set of symptoms that occur together, although generally there is no specification for the type and number of symptoms. Further, practice would suggest that the range and types of symptoms in such a symptom cluster would not be large.[18]

With regard to exposure to contaminants, while such exposures were not common, they were relatively frequent in certain models of airplanes. This study found two main types of exposure:

1) An "exposure event", where there was at least one self reported intense exposure to contaminated air from an engine oil or hydraulic fluid leak.

2) Self reported residual exposure to odours and non-visible contamination.

While the majority of exposure events occurred during flight it should be stressed that a number of leaks and exposures occurred on the ground. Engine seals are less efficient during engine warm up, during ground manoeuvring, and at transient operations (acceleration/deceleration). Further, prior to 1998, an operational procedure on some models of airplanes called an APU pack burn out was carried out every day, whereby heated engine air was pumped through the passenger cabin to decontaminate heat exchangers, air ducts and filters. While operational procedures expressly excluded any person on the plane during pack burns, in 1992-1997, it was common for flight attendants to be present on planes carrying out early morning pre-flight checks during pack burns. Therefore, this process also exposed aircrew to contaminants. So while major exposure events occurred during flight, ground operations should not be excluded as a source of exposure.

Although it was not possible to quantitatively assess exposure during exposure events, descriptions from visible haze to dense smoke suggest significant exposure.

Immediately after exposure, the symptoms are essentially those that can be observed in individuals exposed to toxic irritants, such as eye irritation, respiratory irritation, headache and other short term neuropsychological effects, skin problems and nausea. These usually recede after cessation of exposure. At least two Australian airlines have admitted that exposure events are significant enough to produce symptoms of irritation.[36,37]

What became apparent was that not all symptoms were acute around the time of exposure. Some chronic symptoms became more debilitating. The headache became so intense that it lasted for weeks and would not respond even to the most powerful over-the-counter analgesics. Neuropsychological symptoms became more generalised and affected more functions - cognitive symptoms and recall problems became more significant. Skin itch became skin rash. Respiratory irritation became chest pain and/or difficulty in breathing. The intensification process was more likely to occur if exposure continued, but occasionally, would intensify even if exposure had ceased.

Further, new symptoms began emerging, including chronic fatigue, parathesias and numbness, myalgias, arthralgias, alcohol and food intolerances, and chemical sensitivity. Most of these symptoms continued even after exposure had ceased. Further, these and many of the neurological and neuropsychological symptoms worsened.[34,36]

The number of cases that emerged over the 1996-1999 period in Australia, North America and Europe became significant, to the extent an appropriately designed epidemiological survey of aircrew was needed. The possibility of an industry sponsored study seemed unlikely. Therefore, the present independent survey was conducted.

This survey was a questionnaire survey of 117 individuals who nominated themselves to a database to receive a copy of the survey questionnaire. There were no criteria used to select study participants. The survey was carried out after a well publicised Australian Senate inquiry into air quality in the aviation industry,[38] and this may have increased interest in some individuals to self-nominate. The fact that so many respondents returned questionnaires who had flown on those airplanes where engine leaks had occurred was not intrinsically part of the survey. It is almost certain that self-nominations occurred through word of mouth through contacts in the Australian aviation industry and that for this reason, there is a selection bias in the study respondents. No claim is made to suggest that the respondents in this survey are representative of any group in the aviation industry. The respondents represent themselves.

The survey questionnaire was designed to contain no leading or biased questions. It was finalised after a trial with aircrew. Eventually, fifty individuals returned completed surveys from Australia. Analysis of their surveys established similar findings as earlier studies (for example, see Table 1), with a moderate sized group of respondents. Sixteen respondents returned questionnaires from North America - these were analysed separately.

In most cases it is not known whether the respondents' self-reporting was subjective or based on objective clinical or laboratory findings. This is a shortcoming in this survey. For example, the number of synonyms that exist for fatigue – lack of energy, weakness, effort sleepiness, tiredness, lassitude, exhaustion and so on indicate the problems of assessing just one symptom.[39] In many cases, objective criteria exist for physicians to use in the diagnosis of such conditions. In some cases, respondents knew this and reported accordingly.

Patient diagnosis may also be influenced by practice patterns in which their physicians specialise. In other cases, agreement on case definitions of certain symptoms is not universal.[39] This overlap of symptoms and syndromes makes diagnosis complex.[34]

The range of possible epidemiology studies varies, and the predictive power of each type of study varies depending on design, methodological, analytical and interpretational factors. This survey is a descriptive survey of a group of nonrepresentational individuals who qualitatively describe workplace exposure scenarios and self-report symptoms from such exposures. For this reason, no attempt is made to ascribe causality or make inferences of a general nature. However, even with such procedural limitations, it is possible to draw a number of conclusions from this survey.

Firstly, the hydraulics and lubricants used in the aviation industry containing a number of irritating and toxic ingredients and can be toxic.[16]

Secondly, this study has shown exposure to such contaminants, if they get into airplane cabin air, can produce symptoms of toxicity.

Thirdly, the symptom clusters in aerotoxic syndrome can be described. These are:

- Symptoms of dysfunction in neurological function immediately after intense exposures, including loss of positional awareness, vertigo and loss of consciousness. These are a significant aviation safety problem if they occur in a pilot.
- Symptoms of skin, eyes, nose and respiratory irritation immediately after exposure. Further exposures exacerbate the symptoms, often spreading them to other respiratory and cardiovascular effects.
- Symptoms of gastrointestinal discomfort immediately after exposure. While these recede with cessation of

exposure, there is a suggestion that nausea and diarrhoea can persist.

- o Some symptoms of impairment of neuropsychological function such as headache, dizziness, disorientation and intoxication immediately after exposure. These symptoms become more debilitating after time, with problems of loss of cognitive function and memory problems emerging.
- o General symptoms of exhaustion progress to chronic fatigue. It was common in respondents that they spent layovers, weekends and holidays sleeping for days to overcome the symptoms of exhaustion.
- o General symptoms of immune suppression developing some time after exposure, including food and alcohol intolerances, allergies and chemical sensitivity. These worsen with continuing exposure and may worsen after exposure ceases.

Fourthly, many surveys of workers report that working populations generally enjoy a higher level of health that the populations from which they arise. This is the healthy worker effect, a commonly observed phenomenon by which lower death rates (or injury or disease rates) are observed in workers relative to the general population.[20,40] While this may be due to selection bias problem, aircrew had incidences of symptoms at much higher rates than population backgrounds, suggesting (in many cases) that they were unhealthier than the general population. However, aircrew undergo regular health checks, (pilots regularly, flight attendants less so) suggesting that levels of fitness and health in such individuals should be better than population norms.

Lastly, there are also indications in the data in this study that need further study. Particularly, the findings of neurological impairment, respiratory system effects, reproductive dysfunction and other long term effects cannot be dismissed without a fuller consideration.

Aerotoxic syndrome presents significant issues with regard to the health of pilots, cabin crew and passengers, but most notably with regard to air safety if pilots are incapacitated and cabin crew cannot supervise cabin evacuations during emergencies. Health effects include short term irritant, skin, gastrointestinal, respiratory and nervous system effects, and long term central nervous and immunological effects. Some of these effects are transient, others appear more permanent. The exacerbation of pre-existing health problems by toxic exposures is also highly probable.

This is a hidden issue. Staff of the airlines in Australia are worried about job security and what might happen to them if they complain about working conditions and make their symptoms public. This is especially apparent following the demise of a major Australian airline. At present, with only a few cases proceeding in the courts, little compensation has been awarded to airline workers affected by toxic gases, vapours and fumes. Therefore, many crew are flying while further compromising their health and safety, and will only come forward when they become concerned that they may not be able to continue flying, or worse, when they are no longer able to fly.

## 6.7 Acknowledgements

The author would like to thank all participants who volunteered to participate in this survey. The author would like to thank the University of New South Wales Ethics Committee for the review of the survey questionnaire, and the University of New South Wales Faculty of Science and Technology for providing funds for this survey.

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# Chapter 7

## Aerotoxic Syndrome

The symptoms reported by exposed air crew were sufficient enough to warrant study. The term "Aerotoxic syndrome" was introduced when some commonality of adverse health problems was surmised. This chapter investigates the available evidence, and compares these findings with the Bradford Hill criteria for epidemiological causality. Some of of the material in this chapter was extracted from:

- Winder, C., Fonteyn, P., Balouet, J.-C. Aerotoxic syndrome: A descriptive epidemiological survey of aircrew exposed to in-cabin airborne contaminants *Journal of Occupational Health and Safety - Australia and New Zealand* **18:** 321-338, 2002.
- Winder, C. Hazardous chemicals in jet aircraft: Case study – jet engine oils. In: *Contaminated Air Protection Conference: Proceedings of a Conference held at Imperial College, London, 20-21 April 2005*, Winder, C., editor. BALPA/UNSW, Sydney, pp 8-36, 2005.

# 7 Aerotoxic Syndrome

## 7.1 Introduction

As already noted, the association of health symptoms reported by flight crew with fume events was given the name Aerotoxic syndrome in 1999 (Etymology: aero refers to aviation, toxic to toxicity of exposure and associated symptoms). The term is not officially recognised in lists of diseases reportable in workers compensation systems, and as such, is controversial.

## 7.2 The Published Evidence

In Chapter 6, Table 6-1 shows the number of studies of symptoms in aircrew prior to 2001.[1,2,3,4,] Since publication of the findings in Chapter 2,[5] and Chapter 6,[6] other studies have been published, including surveys of aircrew in the BAe 146 and the Boeing 757,[7,8] and two medical surveys of pilots and flight attendants in Western Australia.[9,10] Therefore, this Table has been revised (see Table 7-1). Further, other health studies have also been published, looking at:

- Neuropsychological assessment of eight BAe 146 aircrew, that noted significant impairments of reaction time, information processing speed and fine motor skills;[11]
- Respiratory disease in fourteen BAe 146 aircrew, including breathlessness, cough and heightened sensitivity;[12]
- Toxic encephalopathy in twenty six MD 80 flight attendants diagnosed from neuropsychological examination and position emission tomography (PET) functional brain scan;[13]
- Ill health in flight crew associated with exposure to contaminated air;[14]
- Cognitive function in eighteen pilots at work was significantly impaired including being unable to retain or confusing numerical information from Air Traffic Control;[15]

As with the studies in Chapters 3 and 6, these studies indicate a consistent picture of symptoms and effects.

## *Table 7-1: Studies Reporting Signs and Symptoms in Aircrew*

| Reference | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Number of cases/reports | 89 | 248 | 53 | 112 | 7 | 50 | 21 | 106 | 60 | 40 |
| Irritation of eyes, nose and throat | | | | | 100% | 76% | 16% | 37% | 48% | 13% |
| Eye irritation, eye pain | 35% | 74% | 57% | 24% | 57% | 68% | | | | 70% |
| Blurred vision, loss of visual acuity | 11% | 13% | | 1% | 57% | 49% | 5% | 4% | 8% | 8% |
| Skin irritation, rashes, blisters (uncovered body parts) | | | 36% | | 57% | 58% | 5% | 8% | 17% | 5% |
| Sinus congestion | 35% | 54% | | 5% | 28% | | | | | |
| Nose bleed | | 17% | | | 14% | 6% | | | | |
| Throat irritation, burning throat, gagging and coughing | 2% | 64% | 57% | 43% | 28% | 64% | | | 28% | 75% |
| Cough | | 69% | | | 28% | 12% | | | | |
| Difficulty in breathing, chest tightness | | 68% | | | 42% | 48% | | 4% | | 55% |
| Loss of voice | | 35% | | | 14% | | | | | |
| Chest pains | 7% | 81% | | 6% | 28% | 20% | | | | |
| Respiratory distress, shortness of breath, breathing problems requiring oxygen | | 73% | | 2% | 57% | 47% | | | | |
| Fainting/loss of consciousness/grey out | 4% | 4% | | | 42% | 14% | | | | |
| Shaking/tremors/tingling | 9% | | | 3% | 42% | 40% | | | | |
| Numbness (fingers, lips, limbs), loss of sensation | | | 8% | 2% | 57% | | 5% | 12% | | 33% |
| Dizziness/loss of balance | 47% | | | 6% | 57% | 72% | | 3% | | 43% |
| Light-headed, feeling faint or intoxicated | 35% | 54% | | 32% | 100% | | | | | |
| Disorientation | 26% | | | 15% | 57% | 62% | 5% | 8% | | 30% |
| Severe headache, head pressure | 25% | 52% | | 26% | 100% | 86% | 21% | 33% | 58% | 68% |
| Trouble thinking or counting, word blindness, confusion, coordination problems | 26% | 39% | 42% | | 6% | 70% | 16% | 21% | 50% | 73% |
| Memory loss, memory impairment, forgetfulness | | | 42% | | 100% | 66% | 10% | 11% | | |
| Behaviour modified, depression, irritability | 26% | 20% | 60% | | 57% | 50% | | | 37% | 28% |
| Nausea, vomiting, gastrointestinal symptoms | 26% | 23% | 15% | 8% | 86% | 58% | | 15% | 35% | 60% |
| Abdominal spasms/cramps/diarrhoea | 26% | | | | 42% | 28% | | | | 20% |
| Change in urine | | 3% | 6% | | | 17% | | | | |
| Joint pain, muscle weakness, muscle cramps | | 29% | | | 28% | 25% | 5% | 9% | 10% | |
| Fatigue, exhaustion | | | | | 100% | 54% | 21% | 30% | 48% | 80% |
| Chemical sensitivity | | | 32% | | 57% | 72% | 5% | 4% | | 43% |

## 7.3 The Bradford Hill Criteria for Causation from Epidemiological Research

Despite descriptive studies being the least useful form of epidemiological study, the results of the case series study in Chapter 3 (published in 2001) and the questionnaire survey in Chapter 6 (published in 2002) were, for their time, the only independently published evidence describing the health problems in aircrew when exposed to leak events, and therefore, the best available evidence. Since then, other studies have been published, indicating general, respiratory, neuropsychological and other effects. Health effects are not limited to aircrew but may also affect passengers.

The response of the medical profession to this problem has been variable. The terms "Aerotoxic Syndrome" and "Multiple Chemical Sensitivity" polarise health professionals with a wide spectrum of responses. At one end of the spectrum there is rejection of the existence of an effect from a chemical (toxic) exposure (often including the view that there has been no chemical exposure). Moving away from this end of the spectrum includes the viewpoints to minimise the severity of symptoms, to assert that any symptoms that may have arisen are due to some other cause, a tendency towards inaction on the grounds of insufficient evidence and a reluctance to intervene on the basis of self interest (especially by aviation or insurance industry professionals). Further, towards the other end of the spectrum there is an admission of ignorance. Health effects appear to be related temporally with exposure events, but mainstream clinical tests, mechanisms of illness and injury and diagnosis are difficult to clarify. Towards the other end of the spectrum there is acknowledgement of the presence of disabling illness following toxic exposures, but includes a realisation that further enquiry and research is needed.

### 7.3.1 The Bradford Hill Criteria

The question of whether these signs and symptoms have an occupational dimension is of central concern. For this to be examined, there is a need to look at causality, as the ability of epidemiological studies to show an association between cause and effect can be problematic.[16]

Epidemiology is the study of health related phenomena in groups of people. It attempts to identify the distribution and determinants of health related phenomena.[16]

Sir Austin Bradford Hill made a significant contribution to the application of epidemiological data to causation with his groundbreaking 1965 paper.[17] In this paper, Hill's paper outlined nine causation criteria that should be taken into consideration when establishing any relationship between environmental (including occupational) exposure and effect. For this purpose Bradford Hill's Criteria of Causation provide a framework which Bradford Hill himself described as "the application of common sense".[18] His criteria help answer the question: "Is this condition or illness environmental?"[†]

Bradford Hill's criteria are:

| | | |
|---|---|---|
| 1. | **Strength** | There are degrees of differences that exist among individuals in their sensitivity to environmental agents |
| 2. | **Consistency** | Have the effects been repeatedly observed by different persons, in different places, circumstances and times? |
| 3. | **Specificity** | Is the association is limited to specific workers and to particular sites and types of disease and there is no association between the work and other types of effects |
| 4. | **Temporality** | Are the effects associated with specific causal factors |
| 5. | **Dose Response/ Biological Gradient** | Is any association revealed by a dose response relationship or other form of biological gradient |
| 6. | **Plausibility** | Are the effects plausible with regard to causes and effects. This will depend upon the plausibility of knowledge of the day |
| 7. | **Coherence** | Is any association coherent with other knowledge |
| 8. | **Experiment** | Can other evidence be obtained from experimental or semi experimental evidence |
| 9. | **Analogy** | Does other different but similar evidence apply |

Hill's nine criteria are not stringent and advocate that analytical assessments should be taken only when circumstances are warranted. He also advocated flexibility in interpretation and application of these criteria, rather than an "all or nothing" concept to causation.

*"... before deducing "causation" and taking action we shall not invariably have to sit around awaiting the results of the research. The whole chain may have to be unravelled or a few links may suffice. It will depend on circumstances."*[17]

† In the 1960s, the term "environmental" included what is now described as "occupational".

### 7.3.2 Application of the Bradford Hill Criteria to the Evidence for Aerotoxic Syndrome

Taking the nine criteria that Hill has set out to distinguish association with causation and applying them to the results of outlined in this thesis, the following synthesis is obtained.[†]

#### 1. *Strength*

In the case of exposure of aircrew to chemicals during fume events, there have been many occasions whereby chemical exposures while working on airplanes in flight have been reported to produce adverse effects. Further, there has been partial admission by at least one airline operator in the aviation industry that some of these effects are substantiated from chemical exposures in fume events.[19]

#### 2. *Consistency*

The stronger the relationship between the independent variable and the dependent variable, the less likely it is that the relationship is due to an extraneous variable. In this case, there is considerable repetition of circumstances, observations and experiences among crew in different aircraft in different places and at different times. For example, Chapter 3 showed symptoms in seven case studies, from flight crew and flight attendants in three airplane models in four airlines operating in four countries. Further, these effects are repeatedly observed by different people in different places. Lastly, this work has been published in the peer reviewed literature (see Chapters 3 and 6).

#### 3. *Specificity*

Hill's indication to specificity has strong arguments for causation that may be produced by false negatives (such as not being able to diagnose) or false positives (such as misdiagnosis).

However, if specificity exists, causation can be drawn as it has only one causal inference. On the other hand, if it is not, then health related phenomena can produce varying causes making specificity is more difficult to prove.

From a scientific analysis perspective of the data set forth in this thesis, the possibility of the existence of Aerotoxic syndrome indicates a varying range of causalities, such as it is a psychological disorder, an infection, malingering, due to an artefact in the observations, due to a different chemical

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† I am extremely grateful to Dr Andrew Harper for assistance with this analysis.

exposure (whether within or outside of the occupational environment) or toxicants or some alterative medical diagnosis, and so forth, which makes it much more difficult to ascertain a true causal inference.

However, there is *specificity* in the observations of adverse health problems in exposed aircrew, in that: (i) the onset of symptoms among pilots and flight attendants is specific to those who are flying and is not reported among (for example) ground staff; and (ii) symptoms have been reported at low incidence in passengers.

### 4. *Temporality*

Invariably, there is a close time relationship between exposure to chemicals and the onset of signs and symptoms. In most cases signs/symptoms arise after an inciting exposure is identified. While mostly symptoms arise after detection of exposure has occurred (for example, detecting a smell) there have been cases where symptoms arise and are only latterly found to be associated with an unknown exposure (for example, after a leak had been reported). Further, there is minimal lag time and the initial onset of symptoms is not being reported at other times.

### 5. *Dose Response Relationship or Biological Gradient*

Hill's fifth criteria, application of dose response relationship principles, does not apply well, in that while some exposures are intense and associated with adverse health problems, many other reports of signs and symptoms occur at lower exposures: there is an apparent wide variation in response to exposure events, presumably due to variation in individual susceptibility.

The exact or likely mechanisms of action of many environmental toxicants and toxins are not well known, particularly at low exposures, especially at or below the "threshold" of conventional toxic effects below which no effects are likely to occur (for example, not mediated through immune system processes). There is a need to conduct further research in chemically exposed humans to seek and attempt to understand the mechanisms of toxicity apply to the dose response relationship as it applies at lower exposures.[20]

### 6. *Plausibility*

It is easier to accept an association as causal when there is a rational and theoretical basis for such a conclusion. The occurrence of signs and symptoms of chemical (toxic) exposure in aircrew is plausible in terms of:

- exposure (that exposure to a toxicant containing sensitising and neurotoxic ingredients has occurred);

- engineering (the engine and APUs supply bleed air to the airplane cabin and that engines and APUs leak oil, thereby contaminating the air supplied to the cabin);
- biology (that exposure to a toxicant that contains a sensitiser and neurotoxicants causes sensitisation, neurotoxicity and neuropsychological effects).

### 7. *Coherence*

Hill's coherence criteria can enhance the strength of the causality where evidence exists. It may also be used where evidence may be lacking, as evidence of lack is not lack of evidence. In this case, evidence exists. The causal interpretation of any data should not conflict with general known facts about the disease under scrutiny.

A cause and effect interpretation of the association between illness and flying has *coherence* with the biology of crew, the toxicology of exposure and the natural history of a neurotoxic disorder.

### 8. *Experiment*

Hill's criterion for experimental evidence is hard to apply in this case as appropriately designed experiments with suitable controls of extraneous factors are yet not possible. Furthermore, no animal model yet exists for the effects of low level chemical sensitivity other than those for allergenicity.

At best, when describing symptom onset following exposure with subsequent recovery and then recurrence, each crew member self reports their own experimental evidence.

In summary, perhaps, there need for further research in humans to seek and attempt to make some sense of the existing and unexplained data and to satisfy the relationship between the cause and effect hypothesis.

### 9. *Analogy*

This criterion draws a comparison between two concepts with similarities between one thing (that is, a causal inference) and with another. Simply speaking, a commonly accepted phenomenon in one area can be applied to another. With regard to development of non-specific illness following exposure at work to synthetic chemicals the cabin air experience is *analogous* to a number of other occupational groups, most notably the Australian F-111 maintenance workers, Vietnam and Gulf War veterans and agricultural workers exposed to organophosphate pesticides. This reasoning suggests a causative relationship.

In summary, the use of Bradford Hill's criteria allows additional information for recognising Aerotoxic syndrome. These additional add-ons are plausible in that they further identify Aerotoxic syndrome specifically rather than generalising on the whole (see Table 7-2).

***Table 7-2*: *Application of Bradford Hill Criteria for Causality to Aerotoxic Syndrome***

| Bradford Hill Criteria | | Causality |
|---|---|---|
| 1) | **Strength** | ✓ |
| 2) | **Consistency** | ✓ |
| 3) | **Specificity** | ✓ |
| 4) | **Temporality** | ✓ |
| 5) | **Dose Response/Biological Gradient** | × |
| 6) | **Plausibility** | ✓ |
| 7) | **Coherence** | ✓ |
| 8) | **Experiment** | × |
| 9) | **Analogy** | ✓ |

In applying Bradford Hill's criteria to the evidence, and arriving at a conclusion that the association between exposure and effect is much more likely than not, better incentives are provided for the assessment of risk; control of unacceptable risks, and more appropriate action for aircrew (and others) who have been exposed to contaminated air and report adverse signs and symptoms following those exposures.

Alternatively, is there any explanation for this problem which is not occupationally related and does not arise from a chemical toxin within the cabin air? Possible alternative explanations are the occurrence of a psychogenic disorder, an infection, malingering, an artefact in the observations, a non-work related chemical toxicant or some alterative medical diagnosis. Having considered all these alternatives, each one appears improbable.

Bradford Hill himself has sounded a warning regarding new health problems. He has said that any observed association "may be new to science or medicine and must not therefore be too readily dismissed as implausible or even impossible. When faced with a material difference between two groups but with limited evidence, Bradford Hill advised concluding "not proven" rather than "no problem".[18]

## 7.4 A Description of Aerotoxic Syndrome

There are differences between these studies, and while Table 7-1 shows a long list of symptoms, it is possible to characterise many symptoms more consistently.

For example, different papers report dizziness or loss of balance or light-headed or feeling faint or feeling intoxicated or disorientation. It would be incorrect to regard such symptoms as being entirely different from each other – they point to a basic neuropsychological dysfunction affecting balance. But rather than dismissing such symptoms as being multitudinous and variable,[21] it may be more appropriate to re-categorise symptoms with clearer definitions, so that the artificial distinctions between variable symptom reporting can be clarified, and a shorter list of "symptom clusters" be developed. For example:

- Loss of consciousness/Inability to function;
- Symptoms of direct irritation to eye, airways or skin;
- Respiratory symptoms secondary to irritation;
- Skin symptoms secondary to irritation;
- Gastrointestinal symptoms;
- Neurotoxic symptoms;
- Neurological symptoms related to basal nervous system function;
- Cognitive/neuropsychological symptoms related to higher nervous system function;
- Nonspecific general symptoms.

Such symptom descriptions could go some way in developing consistent reporting of signs and symptoms reported by affected individuals.

Ultimately, what emerges in the analysis of this data, is a pattern of symptoms related to local effects to exposure to an irritant, overlaid by development of systemic symptoms in a number of body systems, including nervous system, respiratory system, gastro-intestinal system, and possibly immune system and cardiovascular system. These symptoms may be expressed specifically to these symptoms, or may be seen more generally, such as headache, behavioural change or chronic fatigue.

The symptoms reported by exposed individuals as shown in Table 7-1 are sufficiently consistent to indicate the development of a discrete occupational health condition, and the term aerotoxic syndrome has been introduced to describe it. Features of this syndrome are that it is associated with air crew exposure at altitude to atmospheric contaminants from engine oil or other aircraft fluids, temporarily juxtaposed by the development of a consistent symptomology including short-term skin, gastro-intestinal, respiratory and nervous system effects, and long-term central nervous and immunological effects (see Table 7-3). This syndrome may be reversible following brief exposures, but features are emerging of a long term syndrome following significant exposures.

***Table 7-3: Aerotoxic Syndrome: Short and Long Term Symptoms***

| 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;<br>○ **Neuropsychological or Psychotoxic symptoms:** memory impairment, headache, light-headedness, dizziness, confusion and feeling intoxicated;<br>○ Gastro-intestinal symptoms: nausea, vomiting;<br>○ **Respiratory symptoms:** cough, breathing difficulties (shortness of breath), tightness in chest, respiratory failure requiring oxygen;<br>○ **Cardiovascular symptoms:** increased heart rate and palpitations;<br>○ **Irritation** of eyes, nose and upper airways. | ○ **Neurotoxic symptoms:** numbness (fingers, lips, limbs), parathesias;<br>○ **Neuropsychological or Psychotoxic symptoms:** memory impairment, forgetfulness, lack of co-ordination, severe headaches, dizziness, sleep disorders;<br>○ **Gastro-intestinal symptoms:** salivation, nausea, vomiting, diarrhoea;<br>○ **Respiratory symptoms:** breathing difficulties (shortness of breath), tightness in chest, respiratory failure, susceptibility to upper respiratory tract infections;<br>○ **Cardiovascular symptoms:** chest pain, increased heart rate and palpitations;<br>○ **Skin symptoms:** skin itching and rashes, skin blisters (on uncovered body parts), hair loss;<br>○ **Irritation** of eyes, nose and upper airways;<br>○ **Sensitivity:** signs of immunosupression, chemical sensitivity leading to acquired or multiple chemical sensitivity<br>○ **General:** weakness and fatigue (leading to chronic fatigue), exhaustion, hot flashes, joint pain, muscle weakness and pain. |

The presence of contaminants in flight decks and passenger cabins of commercial jet aircraft should be considered an air safety, occupational health and passenger health problem.

## 7.5 Conclusions

The implication of the results of the studies reporting health problems following fume events is that aircrew are experiencing a real problem, a dangerous problem and a disabling and chronic problem, which is continuing. Medically the condition is commonly misdiagnosed or undiagnosed. The problem is environmental and work-related and when it occurs it is nearly universally accompanied by cognitive and neurological symptoms.

- As shown in Section 1.5 (on leaks), incidents involving leaks or engine oil and other aircraft materials into the passenger cabin of aircraft occur frequently and are "unofficially" recognised through service bulletins, defect statistics reports and other sources. It is apparent that the rates of occurrence of incidents are higher than the aviation industry admits, and for some models of aircraft are significant. These need appropriate reporting, follow up investigations and health investigations for those exposed.
- As shown in Chapter 4, the oils used in aircraft engines contain toxic ingredients which can cause irritation, sensitisation and neurotoxicity. This does not present a risk to crew or passengers *as long as the oil stays in the engine.* However, if the oil leaks out of the engine, it may enter the air conditioning system and cabin air. Where these leaks cause crew or passenger discomort, irritation or toxicity, this is a direct contravention of the US Federal Aviation Authority's and the European Joint Aviation Authorities' airworthiness standards for aircraft ventilation (FAR/JAR 25.831).
- As indicated by manufacturer information and industry documentation (outlined in Chapter 4), aviation materials such as jet oils and hydraulic fluids are hazardous and contain toxic ingredients. If such fluids leak into the air supply, cabin and flight deck, toxic exposures are possible. Presently, the aircraft manufacturers, airline operators and the aviation regulators deny that this is a significant problem. Such leaks may be considered of a nuisance type, but where they affect the health and performance of crew, or the health of passengers, this is to be considered a flight safety and health issue and must be given appropriate priority.
- It is apparent that pilots continue to fly when experiencing discomfort or symptoms. There is a lack of understanding by pilots regarding the toxicity of the oil

leaks, occupational health and safety (OHS) implications and the necessity to use oxygen. This is further compounded by the airline health professionals who, when confronted with a pilot who has been exposed in a fume event and who is concerned about its consequences, have a poor understanding of the short and long-term medical issues that may arise and tend to be dismissive about their implications.

- Attempts by the industry to minimise this issue, such as acceptance of under-reporting of incidents, inadequate recognition of the extent of the problem, inadequate adherence/interpretation of the regulations, inadequate monitoring, inappropriate use of exposure standards and care provided to crew reporting problems, have perpetuated this problem.
- The health implications both short and long-term, following exposure to contaminants being reported by crew and passengers must be properly addressed. A syndrome of symptoms is emerging, suggesting these exposures are common and a sufficiently large enough group of affected individuals exists.
- Where contaminants impair the performance or affect the ability of pilots to fly planes, as has been reported for a number of incidents, this is a major safety problem. Where contaminants cause undue discomfort or even transient health effects in staff and passengers, this is a breach of FAR 25.831 and other regulations.

Contaminants in the air of an occupational environment should, under normal circumstances, alert management to a potential problem.[22] Proper medical and scientific research needs to be undertaken in order to help airline management and crew to better understand both the short-term and long-term medical effects of being subjected to air contamination.

Over the past fifty years, the concept of duty of care has emerged as one of the most important legal responsibilities for employers. In the workplace, the duty of care of an employer to its workers has been crystallised into OHS legislation. Aviation safety is something that a person outside of the industry would understand to cover all aspects of safety, including the health and safety of its workers. However, this does not seem to be how all industry insiders see it. Many in the industry see aviation safety as being about making sure the planes keep flying. Both the aviation regulators and the airlines themselves think that OHS is not their business — which is strange, because if *they* do not look after the health and safety of workers in the industry, then who will?

More scientific and medical research is needed on the short and long-term effects of exposure to contaminated air and, until this is completed, all areas of the aviation industry should take fume exposure events seriously. It is vital that the above recommendations are taken seriously; they should be seen as an important part of educating crew and the aviation industry, thereby addressing the problem.

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Chapter 8

# Discussion, Conclusions and Recommendations

# 8 Discussion, Conclusions and Recommendations

## 8.1 Introduction

This section of this thesis discusses its main findings (as individual findings were discussed within the relevant chapters), the conclusions that may be drawn from them, and suggestions for further work and research.

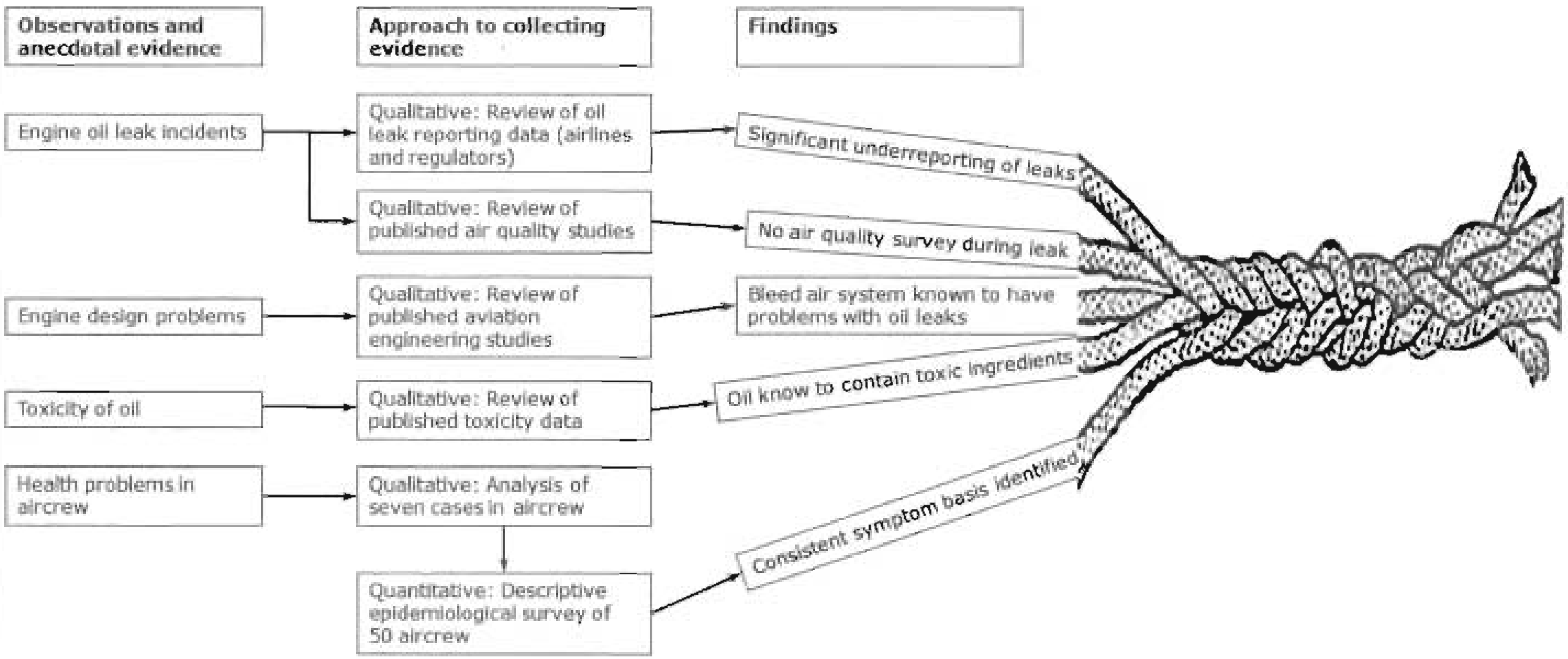
Chapter 2 outlined the mixed methods research approach taken in this thesis, and Figure 2-1 outlined the various qualitative and quantitative approaches taken.

The findings of each of the individual components of this thesis are shown in Figure 8-1, are discussed below and, like the strands that make up a cable, can, when all bound around each other together, considered a better, amalgamated whole.

## 8.2 Discussion

Oil leaks of jet engine oil into the flight deck of some models of commercial airplanes have been reported as a cause of health problems in aircrew (pilots and flight attendants) and passengers. In the early study of puzzling symptoms and signs in a small but ever increasing number of aviation industry workers that appear to have a consistent nature, there comes a point when an apparent trend needs exploring. Initially, study of symptoms from seven case studies, from flight crew and flight attendants in four airlines operating in four countries and in three airplane models suggested that signs and symptoms may be reversible following brief exposures, but features were emerging of longer term problems following significant exposures.

*Figure 8-1: Mixed Methods, as Used in this Thesis*



This project investigated the underlying issues, including toxicity of the jet oils, air monitoring studies that have been carried out, the numbers if incidents where oil leaks have been reported, signs and symptoms following exposure in air crew. Also considered was a range of official and informal documentation which suggested that the problem of jet oil leaks was well known, but officially considered by all sectors in the aviation industry as a "non-problem".

### 8.2.1 Toxicity of jet oils

The oils and hydraulics used in airplane engines are toxic, and specific ingredients of such materials are irritating, sensitising and neurotoxic. If oil or hydraulic fluids leaks out of engines, this contamination may be in the form of unchanged oil/fluid, degraded oil/fluid from long use in the engine, combusted oil/fluid or pyrolised oil/fluid, in the form of gases, vapours, mists and particulate matter. If leak incidents occur and the oil/fluid is ingested into bleed air and is passed to the flight deck and passenger cabins of airplanes in flight, aircrew and passengers may be exposed to contaminants that can affect their health and safety. This may contravent the employer duty of care provisions og OHS legialstion. Where contamination of air in flight deck and passenger cabin occurs that is sufficient to cause symptoms of discomfort, fatigue, irritation or toxicity, this contravenes the air quality provisions of Aviation Regulations, most notably FAR and JAR 25.831.

### 8.2.2 Air Monitoring Studies

Air quality on aircraft in flight has been studied extensively. Most studies indicate that the current recommendations for air quality on the flight deck and in passenger cabins of aircraft are of low risk providing that relevant legislation is complied with, relevant airworthiness standards are met, and relevant engineering and operational systems function properly. However, where problems arise, and aviation fluids such as hydraulic fluids or jet oils pass to the environment where air crew or passengers are found, the potential exists for adverse exposures to occur, and for adverse health problems to arise. Evidence is available to suggest that the number of exposure events is not small.

Most studies of air quality on aircraft indicate that cabin air quality is satisfactory. However, few have investigated air quality after engine oil or hydraulic fluids leaks and are therefore unsuitable for comparison purposes. Problems with such studies include: studies that were conducted on the ground, studies that were conducted in the absence of an exposure event such as an oil leak, studies that use the wrong sampling techniques, studies that measure the wrong contaminants, analytical techniques with poor limits of detection, poor chain of custody and the like. This has not stopped inappropriate use of such studies, or inappropriate conclusions being drawn from them. There is a real need for monitoring the cabin environment during exposure events, so that a suitable understanding of levels, toxicity and impact of chemical exposures can be established.

### 8.2.3 Numbers of Oil Leak Incidents

The issue of aircraft air contamination due to oils and hydraulic fluids leaking into the aircraft air supply is a known problem in the aviation industry. There are a range of regulations that are in place to ensure all cases of fume contamination are reported and therefore investigated. However, there is strong evidence that the reporting system to regulatory agencies is not working, and consequently, under-reporting is occurring and the numbers of oil leak events taking place are considerably higher than the aviation industry is willing to admit. There are a variety of reasons for this occurring, including commercial pressures, fatalism about long standing and apparently insurmountable engineering problems, operational procedures that focus keeping aircraft flying and a culture to minimise health and safety risks. These have significant health and safety implications for crew and passengers.

### 8.2.4 Health effects in air crew

Initial study of seven case studies from flight crew and flight attendants in four airlines operating in four countries and in three airplane models, it became apparent that the reported symptoms had a degree of consistency.

This lead to a second, descriptive epidemiological study, which was conducted to investigate health effects of aircrew through a questionnaire mail-out. One hundred and seventeen aircrew contacted me and one hundred nominated themselves to be entered into a database to take part in a survey of symptoms from flying. Because of the anonymity assured in the nomination process, this sample cannot be concluded to be representative of flight crew or flight attendants. All 100 nominated individuals were sent a questionnaire; fifty were returned – 36 female, 14 male; and 34 flight attendants, 16 flight crew. Most of the respondents (88%) reported that symptoms occurred after exposure to engine oil or hydraulic leaks causing odours and/or visible contamination in the cabin. A range of general, neurological, neuropsychological, respiratory, gastrointestinal, reproductive and irritancy symptoms were reported, some with significant gender differences. For example, intense headache was reported in 88% of respondents; exhaustion (80%); eye and upper airway irritation (76%); dizziness and disorientation (74%); chemical sensitivity (74%); performance decrement (72%); memory problems (68%); breathing problems (62%); nausea and vomiting (60%). Invariably, aircrew directly attributed their symptoms to exposure to in-cabin airborne contaminants.

### 8.2.5 Aerotoxic syndrome

There was sufficient commonality in reported symptoms in these two studies, and in other studies in the scientific literature, to conclude a symptom basis for aerotoxic syndrome. Features of this syndrome are that it is associated with aircrew exposure to in-cabin atmospheric contaminants from engine oil or hydraulic fluids, temporally juxtaposed by the development of a consistent symptomology of irritancy, neurotoxicity and chemical sensitivity. This syndrome may be reversible following brief exposures, but features such as memory impairment, chronic fatigue, altered immune function and allergies/chemical sensitivity are indicative of long term effects following further exposures.

### 8.2.6 How much did the industry know?

The main problem with the issue of engine oil leaks on the BAe 146 was the incorporation of cabin pressurisation from the bleed air system coming from the engines/APUs as a widespread industry practice in the 1970s. By adopting this process, the opportunity of leaks from the engine into the air system becomes possible. Implicit in this solution is that the oil stays in the engine. The engines used on the BAe 146 (and indeed, the BAe 146 itself) have been rated as airworthy by all regulatory agencies in those nations in which this aircraft is registered, including Australia.

However, statistically, the airplanes flown in Australia were more prone to engine oil leaks, and sometimes, when such leaks were substantial, health problems emerged in some exposed pilots and/or flight attendants. It is difficult to establish the precise cause of this problem. Certainly, engines and APUs were identified as the source of the leaks. Certainly, failed seals, poorly maintained filtration systems, and other airplane system defects were linked with short term symptoms.

At Ansett Australia, the airline operator with the largest fleet of BAe 146 airplanes in Australia, there was considerable effort from about 1991 to identify and fix this problem. New seals, filters, and revised maintenance procedures were all tried as engineering solutions. Some were successful in reducing the problem. However, a legacy emerged of employees and former employees who had been exposed and who continued to report health problems. After some workers compensation cases, the approach by Ansett and National Jet Systems in the latter part of the 1990s was focussed on denial and confrontation. Much of this became problematic after Ansett was placed in receivership in 2003 after the downturn in air travel following the 11 September 2001 terrorist attacks in the USA.

## 8.3 Conclusions

In 1962, John Tukey, writing about the future of data analysis, wrote: "Far better an approximate answer to the *right* question, which is often vague, than an *exact* answer to the wrong question, which can always be made precise."[1]

In this project research questions (and their answers) were:

- Are the chemical products used in aviation toxic?

  The answers to this question are:

  1. The oils and hydraulics used in airplane engines are toxic, and specific ingredients of oils are irritating, sensitising or neurotoxic.
  2. Information provided by oil manufacturers to airplane manufacturers and airline operators understates the toxicity of their oil products, and this has been accepted uncritically by airplane manufacturers and airline operators and is used by them in a manner that misleadingly understates risk.
  3. If oil leaks out of engines, this contamination may be in the form of unchanged oil, degraded oil from long use in the engine, combusted oil or pyrolised oil.
  4. If hydraulic fluids leak from where they are contained, this contamination may be in the form of unchanged fluid, degraded fluid from long use in the aircraft, combusted or pyrolised fluid.
  5. If oil or hydraulic fluids leak from where they are contained, this contamination may be in the form of gases, vapours, mists and particulate matter.
  6. Where exposures may to be mixed forms of contaminants, an additional component of toxicity exists whereby irritant or toxic vapours or gases

may be adsorbed onto the surface of mists or particulates. Under such circumstances, the dose response characteristics of the gas or vapour may be altered.

- Has any monitoring of the airplane cabin environment been conducted, and if so, what did such monitoring find?

  The answers to this question are:

  7. A substantial number of air quality studies have been undertaken.

  8. However, all studies that have been carried out to measure atmospheric contamination in airplanes by engine oil leaks or hydraulic fluids are sufficiently flawed on methodological inadequacies to render their conclusions invalid.

  9. No monitoring study has been conducted during a fume event.

- Are exposure events where the airplane cabin environment has become contaminated with chemical contaminants been reported to airline operators or aviation safety regulators?

  The answers to this question are:

  10. Where fume events occur, not all are reported. Where reports are made, some may be reported to the airline operator. Some of these reports may be reported to the national aviation regulator. The regulatory authorities may then investigate some of these reports, and publish their findings, although the number of such publications is small.

  11. The true extent of the problem remains largely unknown, as significant under-reporting occurs (this is acknowledged).

- What are the possible effects of exposure to chemical contaminants in exposure events to employees working in the airplane cabin?

  12. If oils leaks out of engines or hydraulic fluid is ingested into bleed air and is passed to the flight deck and passenger cabin, exposed staff and passengers do not have access to appropriate information that can advise them as to hazard, risk or control of exposure.

  13. If oil leaks out of engines or hydraulic fluid is ingested into bleed air and is passed to the flight deck and passenger cabins of airplanes in flight,

*Table 8-1: Senate Recommendations and CASA Recommended Actions*

| Senate Recommendation | | CASA Recommended action |
|---|---|---|
| 1a | Reassess an incident in July 1997 | Not considered necessary |
| 1b | Reassess air quality monitoring | Refer to CASA Reference Group |
| 1b | Reassess maintenance procedures | Not considered necessary |
| 2 | Adopt modifications recommended by aircraft manufacturer | Already completed |
| 2 | Review registration of BAe 146 | Not considered necessary |
| 3 | Develop test for fume events | Refer to CASA Reference Group |
| 4 | Refer cabin air quality to NOHSC | Not a matter for CASA - refer to NOHSC |
| 5 | Refer to NHMRC for a research program | Not a matter for CASA - refer to NHMRC, who declined to be involved |
| 6 | Appoint a judge to review outstanding compensation cases | Not considered necessary |
| 7 | Refer to NICNAS for a review toxicity of Mobil Jet Oil II | Not a matter for CASA - refer to NICNAS |
| 8 | Install high grade filters | Refer to CASA Reference Group |

Basically, each recommendation was dealt with in a manner such that no action was required, or that it be referred to a References Group. This References Group met twice in 2003-04, and never made any follow up. This proved sufficiently embarrassing for the incoming labour government in 2007, that an Expert Panel on Aviation Air Quality (CASA EPAAQ) was established in 2008 to again look at this issue. A report is due from the panel sometime on 2010.

However, the issues that were investigated in 1999-2000 remain the same, and the main recommendations of this thesis are:

- Jet oils used in jet engines should be appropriately evaluated for their toxicity to humans, especially to employees exposed to air contaminated with oil mists from fume events while flying.
- Information on jet oils should be revised so that it correctly informs users and others who may be exposed to jet oil mists as to its hazards, and how the risks from exposure to such hazards can be prevented or controlled.
- Tricresyl phosphate should be removed as an ingredient of jet oils.

airline staff and passengers may be exposed to contaminants that can affect their health and safety.

14. The use of exposure standards such as threshold limit values to conclude that exposures are acceptable is inapplicable in certain situations in the aviation industry. TLVs should not be applied at altitude, or in situations where the possibility of escape to fresh air is lacking.

15. Acceptability criteria for chemical exposures at altitude must consider the interaction of reduced oxygen, skin exposure to mists, and interactions with other contaminant exposures.

16. There is a significant aviation safety matter to flight crew where oil leaks affect the ability of pilots and flying officers to fly planes safely.

17. There is a significant health and safety matter to airline staff and passengers where oil leaks affect their health.

18. Where contamination of air in flight deck and passenger cabin occurs that is sufficient to cause symptoms of discomfort, fatigue, irritation or toxicity, this contravenes air quality provisions of aviation safety legislation.

19. Symptoms reported by exposed staff are consistent with the development of a discrete occupational health condition, termed aerotoxic syndrome.

One final point should be made. It is a fundamental principle of OHS legislation that the employer has an obligation to provide and maintain a workplace that is safe and free of reasonably foreseeable risks to health. Where foreseeable risks are identified, a risk assessment should be conducted to establish the acceptability (or otherwise) of the risk.

For the research conducted in this thesis, the answer to the question: "Are jet oil leaks foreseeable?" seems to be: Yes. The oil is toxic, oil leaks are being reported, and health effects in exposed crew are occurring. However, the aviation industry seem to be acting as if the answer to this question, is No.

## 8.4 Recommendations

In 2001, the Australian Senate published its report of its Inquiry into Air Quality on the BAe 146.[2] This report made eight recommendations. These, and the Civil Aviation Safety Authority (acting on behalf of the Australian Government) response to them,[3] are shown in Table 8-1.

## 8.5 References


1. Tukey, J.W. The future of data analysis. *Annals of Mathematical Statistics* 33: 1-67, 1962.
2. Australian Senate. *Air Safety and Cabin Air Quality in the BAe 146 Aircraft*. Parliament of Australia, Canberra, 2000.
3. CASA. *Air Safety and Cabin Air Quality in the BAe 146 Aircraft: Governmental Response to the Recommendations of the Senate Rural and Regional Affairs and Transport References Committee Report*. Civil Aviation Safety Authority, Canberra, June 2002.

- Research should be conducted into identifying and manufacturing a jet oil that can be used in jet engines that does not contain toxic ingredients.
- Research should be conducted into identifying a suitable real time analytical test that identifies the presence of toxicants in flight deck and cabin air.
- Fume events (of all types) should be properly reported to the airline operator, properly forwarded to the relevant aviation regulator, and recorded and made accessible to the public.
- Those aviation workers who report that their health has been affected by exposure to contaminated air while flying should be properly investigated.
- A proper database on the symptoms, diagnosis, efficacy of treatment and prognosis of individuals should be maintained so that any health basis (or not) of Aerotoxic syndrome can be established.
- Research should be conducted into finding other sources of cabin air other than bleed air. For example, it is noted that the new (but delayed) Boeing 787 Dreamliner does not use bleed air.

Whether or not Aerotoxic syndrome exists as a real condition remains debatable. The term certainly polarises opinion and this may not be helpful for those individuals seeking assistance.

At best, the condition can be considered a form of multiple chemical sensitivity associated with fume events while working in the aviation industry. Many medical practitioners remain unaware of the condition, and will therefore diagnose sufferers with illnesses such as psychological or psychosomatic disorders, chemical sensitivity, chronic fatigue, depression, anxiety, stress, sleep disorders, unknown viral infections, and the like. In fact, some of these diagnoses may actually be symptoms or features of Aerotoxic syndrome, and need to be better contextualised in the description of the condition.

Research to get to the root of the problem has been undertaken by various bodies, regulatory authorities and research groups, but so far no conclusive proof has been found to establish a definitively acceptable link between contaminated cabin air and long term health problems. Independent studies, however, have provided evidence of this link. Corporate profit, conflicts of interest and ineffective control by regulatory authorities means that even after over ten years of action, the aviation industry as a whole remains in denial about this problem.