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Aircraft Air Quality Incidents, Symptoms, Exposures and Possible Solutions

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Abstract Although air quality incidents in aircraft occur at low frequencies, ranging from 1 per 10 000 flights to 3.8 per 1000 flights depending on aircraft type, these are not rare events considering there are close to 30 000 flights per day in the USA alone. An analysis of the reports by pilots and flight attendants indicates that the majority of reported symptoms fall into the category of central nervous system impairment, followed by problems with the respiratory system. In addition, the majority of mechanical problems that were identified as the cause of these incidents were associated with oil contamination of the air compressor stages of the engine and the auxiliary power unit (APU). In addition, in some aircraft types, hydraulic fluid contamination of the APU air intake was also frequently reported. Analysis of jet engine lubrication oils and hydraulic fluids indicates these agents can be a source of carbon monoxide and tricresyl phosphates. Exposure to either of these agents has been linked to central nervous system impairment. Identification of contaminants released into the air during such incidents is virtually non- existent as it would require a large number of air quality monitors to be placed on aircraft in order to capture these rare events. As a solution to this problem a small inexpensive air sampler has been developed that is self- contained and can be activated by anyone. This sampler also has a direct- reading CO monitor that can be used to provide an objective criterion for triggering the air sampler during an event. The exposed sampler can then be forwarded to the laboratory for analysis of oil contaminants using gas chromatography–mass spectrometry (GC-MS). In this fashion a data base can be accumulated that provides an objective measure of exposures during these incidents and whether these exposures can be linked to the symptoms that have been reported by flight crew personnel. A GC-MS analysis has the additional benefit of identifying potential synergistic agents, such as the pesticides used to disinsect aircraft.

Keywords Aircraft · Air quality · Tricresyl phosphates · Carbon monoxide · Air sampling · Hydraulic fluids · Jet engine oils · Neurological symptoms · Synergistic effects

Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
APU	Auxiliary Power Unit
ATC	Air traffic controller
CAS no.	Chemical Abstracts identification number
COHb	Carboxyhaemoglobin
NAS	National Academy of Sciences
ppm	Parts per million on a volume/volume basis
STEL	Short-term exposure level
TCP	Tricresyl phosphate
TWA	Time-weighted average

1 Introduction

In any mode of transportation, events occur that influence the air quality to which passengers and crew members are exposed. The aircraft industry is no exception to this [1]. In this industry these abnormal events can similarly be traced to external sources, such as the aircraft taking in exhaust air from another aircraft on the tarmac, or from internal sources such as the malfunction of components in the air supply and handling system. On occasion, exposures to air contaminants from different sources can combine, resulting in unexpected synergistic effects. When this occurs exposed individuals could experience severe symptoms at exposure levels considered quite acceptable for each of the individual agents alone. Exposure levels to individual agents are well established in the occupational setting: exposure levels for mixtures, however, are rarely addressed [2] or are non-existent.

This chapter will limit itself to air quality incidents that are a result of some malfunction within the aircraft air handling system. In addition, some reference will be made to potential synergists that one might also encounter in the aircraft environment.

Poisoned pilots almost crashed It started with an insidious feeling of discomfort. The cabin attendants felt strange, experiencing an incredible pressure in their heads and bodies. One person described the feeling as like doing a "moonwalk". Another person detected a barely perceptible odour.

On the next flight, the discomfort returned and was now also experienced by the two pilots. During the third flight, the crew realized that there was something unusual in the air inside the aeroplane. And when the cabin manager went into the cockpit prior to landing, she discovered that both the pilots were wearing their oxygen masks. The captain felt so bad that he had handed over the controls for his first officer to land the plane.

We broke out the oxygen masks From the onset of the feeling of sickness, I very rapidly became worse and worse, feeling dizzy and groggy despite the oxygen. After about two minutes I slowly began to recover. As the first officer was feeling much better, he took over the controls,

So writes Captain Niels Gomer in his report regarding these incidents [3].

These incidents took place on one BAe146-200 aircraft operated by Braathens Malmö Aviation on November 12, 1999, on three flights between Bromma and Sturup. They were designated by the Swedish Board of Accident Investigation, the airline company, and the aeroplane manufacturer as "extremely unusual and serious".

On November 7, 2000, the flight crew of a B757 flying from London Heathrow to Copenhagen noticed an oily metallic smell in the cabin. On the approach back to Heathrow, the air traffic controller (ATC) became concerned that the pilots were not responding to his communication as the aircraft had not reduced its speed in order to prepare for landing. Finally at 3.5 nautical miles from the airfield the pilots responded to the question from the ATC if everything was all right. The aircraft landed safely. It was discovered later that there was an oil leak in the auxiliary power unit (APU), allowing engine oil to be heated and released into the ventilation system of the aircraft [4]. The conclusion was that this was a serious incident, and the flight crew were partially incapacitated.

Santa Barbara News-Press, Saturday, March 13, 2004. A Bombardier CRJ 200 had to make an emergency landing at the Santa Barbara Airport on a flight to Las Vegas after the cabin filled with smoke after take off. Thirty-eight passengers had to be evacuated. No serious health problems with passengers and crew. Cause of the problem, a malfunctioning APU [5].

2 Frequency of Air Quality Incidents in the Airline Industry

The previously described air quality incidents are not isolated cases but occur at a regular frequency in the aircraft industry. A recent study of three aircraft companies, based on air quality incident reports submitted by crew members to the airline company, identified the frequency of these air quality incidents (C. van Netten, R.H.S Brands, S. Hoption-Cann, V. Lentino, 2001, unpublished report to the US National Academy of Sciences, NAS).

3 Problems Associated with Obtaining Objective and Comparable Data

The frequency of incidents can vary considerably between aircraft operators as this is highly dependent on the type of the aircraft and its maintenance. As an example, the aircraft company operating the BAe-146 aircraft, referred to in Table 1, has since made great improvements in maintenance procedures preventing many of these incidents from occurring.

There also appears to be a degree of reluctance of the flight crew members to fill out and submit an air quality incident report. This reluctance can be traced to a number of factors. The most important one is a lack of objective environmental input. Since most aircraft obtain their cabin air from the main engines as well as their APU, there is a temporary bad smell when the engines are started. This smell disappears within about 1 min and is related to the pooling of small quantities of oil in the engine when it is not operating. The flight crew members are somewhat "used" to this smell and do not report it, as it is a common occurrence. Sometimes this smell persists and, at the extreme, a blue haze or smoke appears in the cabin. Since there is a wide spectrum of severity of the exposure, one may well ask at what point does one decide that this is not a normal event but an incident. There is no problem deciding whether to submit a complaint on either side of this exposure spectrum. The large number of events that fall in between these exposures are a problem since the flight crew has no guidance or objective measurement to

Table 1 Air quality incident frequencies, based on flight incident reports submitted to three North American air carriers by flight crew members (C. van Netten, R.H.S Brands, S. Hoption-Cann, V. Lentino, 2001,unpublished report to the US National Academy of Sciences) [7]

Aircraft type	Average number of incidents per aircraft Per year	Per 1000 cycles*
BAe-146	6.4	3.88**
MD-80	1.01**	1.02**
A-320	1.67	1.29
B-747	0.34	1.25
DC-10	0.38	1.04
B-767	0.21	0.63
B-737	0.07	0.09

*A cycle is defined as a take-off, flight, and landing sequence.
**Based on incomplete data and estimates

assess the severity of the event. Often the triggering event in these instances is directly related to a health issue. These can range from an ill feeling to nausea, dizziness, to incapacitation.

Another reason why the reporting system is inconsistent between aircraft companies and between crew members is an intimidation factor. Compared with flight attendants, pilots are generally less likely to report an incident when it produces mild symptoms. As in any population of individuals, one can observe differences in susceptibility to a particular exposure and pilots are no exception. Unlike flight attendants, however, pilots are totally dependent on their medical certificate to allow them to follow their chosen career. Since, during an exposure event, no objective feedback is provided to the pilots, they are totally dependent on making a subjective assessment. Under these circumstances a pilot does not want to complain about a health issue based on an exposure when his colleague sitting next to him does not experience it because it would target his health status and his medical certificate. Consequently the companies receive more air quality incident reports from the flight attendants, who are usually well protected from intimidation by means of their union affiliation.

In order to obtain reliable information one has to remove the burden of this subjective assessment of the air quality within the aircraft from the pilots. This should be replaced with sensitive environmental monitoring that provides an objective evaluation of the air quality. In addition, strict guidelines should be provided by an external agency as to when to report these incidents. Only with these criteria in place would pilots feel free to provide the feedback that is required to create an objective data base.

Another important link in obtaining an objective assessment of these air quality incidents is to be able to correlate them to the mechanical records of the aircraft in question. This would provide information, for instance, of whether a reported exposure event coincides with leaking oil seals in the engine. Mechanical records are most difficult to obtain and are generally not voluntarily parted with by the aircraft company [8].

4 Symptoms Associated with Air Quality Incidents

Within the aircraft not all areas are exposed to the same quality of air. The cockpit, for instance, gets 100% fresh air compared with the 60/40% recirculated air that is present in the cabin (US NAS). Since the source of this fresh air is the engines, any contamination event would be first felt by the pilots in the cockpit. This has serious consequences, i.e. they are exposed sooner and to a higher degree, hence the observed problems in the Malmö and Birmingham incidents when the flight attendants discovered that the pilots were on oxygen in the cockpit.

Although pilots are highly vulnerable to air quality incidents, they have reported few symptoms, likely owing to the problems identified earlier. Most of the symptoms that are experienced by flight crew members have been reported by the flight attendants. These results are summarized in Table 2.

In addition to the acute effects described previously, there are also long-term chronic effects. These health problems are even more difficult to trace to an exposure event, or events, as these chronic effects are often the combined result of a number of exposures that have been present at low concentrations over many years. By the time a pilot experiences these often poorly reversible symptoms, it is too late, he/she fails the medical and a career as a pilot is gone. In addition, since no data were collected during these air quality incidents, it is very difficult for that pilot to substantiate any claim that his/her poor health was related to occupational exposures. As indicated in Table 2 there seems to be a high incidence of neurological problems, some of which have been classified as Parkinson's disease like.

5 Source of Air in Aircraft

In order to obtain an understanding of the nature and extent of these possible exposures, and their associated symptoms, it is important to investigate the source of the air that ventilates the cabin in aircraft.

Table 2 Frequency and type of symptoms reported by flight crew members. Of company X, (MD-80 aircraft) and company Y (mixed fleet of aircraft) (C. van Netten, R.H.S Brands, S. Hoption-Cann, V. Lentino, 2001,unpublished report to the US National Academy of Sciences)

	Number of incidents		Percentage of incidents with symptoms		Percentage of all incidents	
Company	X	Y	X	Y	X	Y
Any symptom	467	244	78.1	81.6		
Eyes, ears, nose, throat	93	76	19.9	31.1	15.6	25.4
Eye	62	26	13.3	10.7	10.4	8.7
Nose	19	31	4.1	12.7	3.2	10.4
Throat	45	22	9.6	9.0	7.5	7.4
Ear	6	19	1.3	7.8	1	6.4
Central nervous system	428	192	91.6	78.7	71.6	64.2
Intoxication	419	188	89.7	77.0	70.1	62.9
Neuropsychiatric	19	6	4.1	2.5	3.2	2.0
Other	113	23	24.2	9.4	18.9	7.7
Respiratory system	94	83	20.1	34.0	15.7	27.8
Cardiovascular system	19	7	4.1	2.9	3.2	2.3
Gastrointestinal system	117	62	37.9	25.4	29.6	20.7
Skin	47	10	10.1	4.1	7.9	3.3
Other	43	22	9.2	9.0	7.2	7.4

* Not all air quality incidents that have been reported were associated with symptoms and one individual could have multiple symptoms.

5.1 Ram Air

The earlier Douglas and Boeing aircraft used outside air that was introduced into the cabin by means of an air-scoop which was located on the outside of the fuselage allowing air to force itself into the aircraft during flight, hence the name "ram air" [9]. Although the source of this air is clean and generally only vulnerable to contamination from external sources, it was discontinued on later models in favour of a bleed air source for economic reasons.

5.2 Bleed Air

Bleed air comes from the jet engine. Since the jet engine operates on the basis of compressing outside air to a high degree prior to entering the combustion chambers it was decided that some of this highly compressed air could be extracted, i.e. "bled off" and used to ventilate the cabin. This bleed air is not only vulnerable to potential contaminants present in the outside air, but is also vulnerable to potential contaminating events in the compressor stages of the engine. The temporary smell of oil when the engines are started, as described earlier, is a direct consequence of this.

6 Oil and Hydraulic Fluid Contaminants

6.1 Jet Engine Lubricating Oils

When an oil seal in the compressor stage of a jet engine is not sealing properly, jet engine lubricating oil enters the airstream, is aerosolized, compressed, and heated to a high degree before it enters airpack units (environmental control systems) and enters the cabin. Temperatures in excess of 450 °C have been reported [10–12] at pressures as high as 175 psi [7].

6.2 Hydraulic Fluids

MD-80 aircraft often experience one additional source of exposure owing to the location of the air intake of the APU. This air intake is located immediately behind a small hole in the aircraft fuselage that allows any hydraulic fluid and/or oil that has accumulated in the bilge of the aircraft to be dumped overboard. In the MD-80 these agents are sucked into the air intake of the APU when it is operating and supplies air to the cabin during certain phases of the flight where maximum engine power is required, such as during take-off.

In order to find a connection between air quality incidents and symptoms experienced by passengers and crew, one needs to know the individual constituents of these oils and hydraulic fluids.

Table 3 summarizes the constituents in a number of oils and fluids that are reported in the material safety data sheets supplied by the manufacturer.

Table 3 Composition of some jet engine lubricating oils and hydraulic fluids as reported in their material safety data sheets

Type of oil/fluid	Reported composition	CAS no.
Engine oils.		
Mobil jet oil 254	Tricresyl phosphate (1–5%)	1330-78-5
Mobil jet oil II	Tricresyl phosphate (1–5%)	1330-78-5
	1-Naphthalamine, *N*-phenyl (1%) (Mobil)	90-30-2
Mobil jet oil 291	No reportable ingredients (Mobil Australia Ltd.)	
Hydraulic fluids.		
Skydrol 500B-4	Tributyl phosphate	126-73-8
	Dibutyl Phenyl phosphate	2528-36-1
	Butyl diphenyl phosphate	2752-95-6
	(Monsanto Company St Louis)	
Skydrol LD-4	Tributyl phosphate	126-73-8
	Dibutyl Phenyl phosphate	2528-36-1
	Butyl diphenyl phosphate	2752-95-6
	2,6-ditert-butyl-*p*-cresol	128-37-0
	(Monsanto Company St. Louis)	
	Epoxy modified alkyl esters	Not provided
HyJet IV	Tributyl phosphate (70–80%)	126-73-8
HyJet IV-A^{+}	Tributyl phosphate (79%) (Chevron)	126-73-8
HyJet XL	Tributyl phosphate (79%)	126-73-8
	Trialkylphenyl phosphate (12%)	68937-41-7
	Cyclic aliphatic epoxide (2%)	3388-03-2
	Additives (7%)	
	(Chevron)	

CAS no. Chemical Abstracts unique identification number for the actual compound

6.3
Pyrolysis Products

When these oils and fluids were exposed to simulated temperature conditions present in the aircraft it was reported that, among other compounds, carbon monoxide (CO) was released into the atmosphere, indicating that pyrolysis of some of the constituents had taken place. Engine lubricating oils generated more CO than hydraulic fluids under the same temperature conditions [10–12].

In addition, it was observed that the tricresyl phosphates (TCPs) and other oil constituents could be captured from the air at 25 °C. It appears that these low volatility compounds condense out of the air but remain airborne as an aerosol or are associated with particulate matter, making these compounds accessible to the respiratory route of exposure.

These findings have identified potential exposures to agents which represent two main categories, i.e. those resulting in acute effects such as incapacitation from exposure to CO, and those resulting in long-term chronic effects, such as delayed neurological problems from exposure to TCP and its isomers as well as CO.

7 Available Data and Required Data

At this point in time one has a data base of symptoms that are experienced by passengers and crew members. There also is an extensive data base in the scientific literature on the effects associated with exposures to CO and TCP. The symptoms reported by aircraft crew members appear very consistent with the known symptoms of CO and TCP. At this time the missing link is a data base of exposure measurements in aircraft during these air quality incidents. Such information is crucial in connecting the observed symptoms experienced by flight crew members to those that have been reported for these agents in the scientific literature.

7.1 Problems in Capturing Rare Air Quality Events in Aircraft

One of the main reasons why these exposure measurements are not available at present is due to the sporadic nature of these incidents and a lack of appreciation as to what to measure. Although CO was identified as an agent of interest to be monitored and recommended by the US NAS committee on Airline Cabin Environment and Health of Passengers and Crew (C. van Netten, R.H.S Brands, S. Hoption-Cann, V. Lentino, 2001, unpublished report to the US NAS), little has been done to date and CO monitoring in aircraft is virtually absent.

Another reason why exposure data are not available is the reluctance of the industry to do the monitoring in their aircraft. The data that are provided by the industry generally relate to non-incident flights on aircraft that are well-serviced and maintained.

The argument is that, given the sporadic nature of these incidents, it would be too cumbersome and expensive to place a set of instruments on each aircraft and wait for an incident to occur. Although this is a legitimate argument based on the very elaborate instrumentation that was used to monitor air quality in non-incident flights, which usually tries to measure very low concentrations, this should not be used as an excuse for not trying to capture these incidents.

This argument is therefore not acceptable when efforts are made to capture incidents which are associated with exposures well above normal making them much easier to capture with relatively inexpensive instrumentation. The only additional problem is to ensure that such instrumentation is available at the time when an incident is taking place.

At present data-logging CO monitors are available which could be provided by the airline company to a designated crew member to be turned on during an event. Although this was one of the NAS recommendations, at this point in time the industry has been rather reluctant to provide aircraft or a crew member with such an instrument. As a consequence crew members have resorted to carrying their own instruments to be able to obtain objective data during an incident.

The data obtained from one pilot using such a data-logging CO monitor (Dräger) over a 2-month period when a crew member smelt fumes and/or felt unwell in BAe 146 aircraft that he was flying, identified consistent peak levels of CO ranging from 15 to 21 ppm. These values compare poorly with the CO levels that were monitored on similar non-incident flights which consistently read 0 ppm. These findings also clearly indicate that air virtually devoid of CO is possible with proper maintenance. The fact that this pilot was not willing to be identified is a sad reflection of the intimidation factor that prevents pilots from coming forward and providing the industry with an early-warning system before an incident becomes an accident.

Although CO monitoring appears to be a good indicator of the aircraft air handling system based on the performance of the APU and engine, it does not address the long-term chronic symptoms associated with possible organophosphate exposure such as TCP from engine oils and hydraulic fluids.

7.2 Benefits to the Industry of Monitoring Changes in Air Quality

Routine monitoring for CO on aircraft, besides identifying a health hazard, has an additional benefit. A change in CO levels within the aircraft, although in the "acceptable range" that is consistent with, for instance, the activation of the APU or the engines, provides an early-warning system of a possible seal failure. This was observed in a BAe-146 which showed elevated levels of CO in the 9 ppm range 1 week before a seal failure in the APU resulted in an air quality incident [13].

8 Available Avenues of Obtaining Air Quality Measurements in Aircraft

8.1 Aircraft Filter Analysis

Currently, one way of obtaining a rough qualitative measure of the constituents that might be present in the cabin air is to obtain air filters that have been used within the aircraft. A small number of these have been analysed (personal observation). A set of filters from a Boeing 737 galley and lavatory, for instance, did not show any evidence of TCP and its isomers by the analytical procedure used, but did show the presence of many other constituents, such as caffeine, in both locations. In addition, the lavatory filter also showed the presence of cocaine and amphetamines. A modification of the analysis applied to another, similar filter from a lavatory did clearly indicate the presence of TCP isomers, indicating respiratory exposure. The data provided by these analyses indicate integrated exposure to these agents since the filters were installed, but does not provide the data that are needed to describe the acute events that result in symptoms.

8.2 Coalescer Bag Analysis

Another source of information regarding the quality of the air entering the cabin is to analyse the coalescer bags. These bags are woven cloth socks located in the air supply system prior to the air entering the cabin. Their function is to extract excess water from the bleed air supply. Analysis of extracts from an MD-80 coalescer bag showed the presence of TCP and its isomers. This indicates the release of these oil constituents into the ventilation air but does not necessarily show exposure, as the argument could be made that the coalescer bag actually filters out these contaminants before the air enters the cabin.

Although these analyses indicate an interesting capability of these filters and coalascer bags to reflect the past history of the aircraft and potential exposure, they do not tell when these events occurred and for how long.

8.3 Monitoring Aircraft Air Quality During Flight

During aircraft air quality incidents that are related to APU and engine problems, many gases and agents appear to be present in the smoke and/or fumes that have been observed by flight crew members [14]. Existing protocols for monitoring gases released during these events require the use of electronic sensors specific to each gas of interest. These direct-reading, data-logging, instruments provide a clear description of what is present in the air, at what concentration, and for how long. Existing protocols for monitoring constituents in aerosols and/or particulate matter involve an air filtering arrangement using filter cassettes and an appropriate pumping device to provide an airflow in the range 1–2 l/min through the filter [15]. This filter can then be sent to an appropriate analytical laboratory for analysis.

Data-logging gas-sensing instruments can be quite costly and in general are currently too expensive to be deployed on a large scale as is required to capture sporadic events. Similarly, currently available cassette filter systems are also prohibitively expensive and, in addition, usually require the presence of an industrial hygienist.

8.4 Indicators of Air Quality During Incidents

If one could reduce the number of agents monitored for to only a few that are representative of the incident, then costs could be reduced, allowing larger numbers to be available.

It appears from the information available to date that the most likely candidates that could serve as reliable indicators of air quality during these sporadic events are CO and oil components, such as TCPs. Exposure to CO represents acute toxic effects, whereas exposure to TCPs appears to be an indicator for chronic effects. Nevertheless, monitoring for these two agents still needs elaborate and expensive equipment, making it too unrealistic for the large-scale use that is required to capture these sporadic events.

9 Development of a New Air Monitor

In order to address this issue, a new type of filter-based air sampler has been developed that is small, i.e. a plastic cylinder 7-cm tall and 5 cm in diameter, is self-contained, self-sealing and, above all, inexpensive, allowing many to be placed in the occupational setting [16]. In order to activate this sampler all one has to do is twist the cap 45°, which activates the centrifugal pump allowing air to flow through the filter at a rate of 2 l/min for a 20-min period of time. After exposure the cap is rotated in the opposite direction, which turns off the pump and seals the filter from further exposure. The whole unit is forwarded to the laboratory for analysis.

This sampler has been used on several flights between Canada and Australia in order to capture the nature and the extent of pesticides used for disinsection purposes.

9.1 Benefits to the Industry from Monitoring for CO

There are two reasons why we need CO monitoring. First and foremost are safety reasons, especially when the aircraft has been outfitted with an activated carbon filter, as any tell-tale odour, visible smoke, or aerosol would initially likely be adsorbed, preventing early detection. The second reason is to monitor any deterioration in bleed air quality, specifically how it is dependent on the efficiency of the oil seals to prevent engine oil from entering the ventilation system. CO spikes when the APU is turned on during flight, only to disappear when this equipment is turned off, indicating possible oil seal deterioration.

Although both reasons are somewhat different they can be addressed effectively with a common approach.

Since in many aircraft the pilots get more outside air, their location in the aircraft makes them more vulnerable to any malfunction in the air supply system. For this reason alone the pilots should have access to an ambient CO level at all times. In addition, the pilots know when certain types of equipment are turned on or off, such as an APU, and consequently can make the correlation with changing CO levels. Pilots also have access to information that allows them to discriminate between a possible internal source and an external source of CO, i.e. they would know whether they are in the exhaust stream of another aircraft.

Most aircraft have at least two air supply systems and different sections of the aircraft receive air from different engines. The cockpit in the BAe 146, for instance, is provided with air from jet engines 1 and 2, whereas the cabin gets air from engines 3 and 4. In this instance a CO monitor in the cockpit would not be representative of the cabin air quality. It would therefore be prudent to monitor for CO in each section of the aircraft that is serviced by different engines. The readout of these monitors should be in the cockpit in order to provide feedback to the pilots and other flight crew members regarding the status of these vulnerable components of the aircraft.

10 Standards of Exposure

Alarm levels could be set at the current airworthiness standard set by the US Federal Aviation Administration of 50 ppm. The problem is that the period of time is not specified, making this difficult to interpret when spikes of varying duration occur, i.e. does one become concerned when 50 ppm of CO is measured for 1 s or when this level is present for 15 min? In other words this standard is neither enforceable nor practical.

The American Conference of Governmental Industrial Hygienists (ACGIH) has a time-weighted average (TWA) (8 h) of 25 ppm [2]. A short-term exposure level (STEL) would be useful in order to suggest a spike duration; however, a STEL is not available from this or other regulatory agencies.

Another approach in identifying what an appropriate sampling time should be, in order to set a time limit for "spikes", has been put forward by Roach and others [17, 18]. This approach is realistic and defendable based on the biological half-life of the agent of interest, which is a measurable entity. With respect to CO, the half-life of carboxyhaemoglobin (COHb) is not clearly defined as it depends on conditions such as altitude (i.e. partial pressure of oxygen) and the concentration of CO_2. The former agent will decrease the half-life to 80 min, whereas the latter will compound the problem by increasing acidosis [19]. The half-life for COHb has been estimated to be around 2 h [17] to 4 h [19]. The suggested sampling duration is one tenth of this period, which amounts to 12–24 min. Roach [17] suggests 10 min. If a "spike" lasts for this period of time and exceeds an acceptable standard, an alarm signal could be communicated to the flight crew.

The ACGIH TWA (8 h) of 25 ppm [2] standard could be argued with, as it relates to the occupational setting and to healthy workers (5–95th percentile) and not to the general public. Several groups in the population have been identified as being at risk from exposures to low levels of CO (i.e. even at outdoor levels as low as 3 ppm) and include those individuals with heart disease, chronic respiratory disease or that are pregnant [20]. The US Environmental Protection Agency has an 8-h limit of 9 ppm [7], which would be more appropriate to protect the general public. A 10-min spike at this concentration could be used as a triggering event and indicates some inherent problem after outside sources have been eliminated. This level is also quite reasonable, since properly maintained aircraft are capable of having CO levels close to 0.0 ppm.

Currently there are CO monitors available that are small, data-logging, cannot be switched off, and will last for 6 months. The continuous monitoring function of these CO detectors can be used to provide an objective measure of air quality at any time. When, for instance, a 10-min spike of 9 ppm is encountered, this can be an objective triggering event and can be used to activate the air sampler described before. Both devices, in fact, can be combined into one functional air monitoring unit with CO measuring acute events and effects and the filter providing exposure measurements that are likely associated with more chronic effects.

11
Identification of Potential Synergistic Agents

The use of indicators to monitor the extent and character of rare air quality incidents can be very useful as it reduces the complexity of tracking the event. At the same time there is always a tendency by those using these indicators to forget that they are only a surrogate measure of a complex event and that they provide an oversimplification of the event itself. The presence of other agents that are able to alter the toxicity of a particular exposure could be ignored. In this respect a comprehensive chemical analysis of the exposed filters from the monitors that were activated during an event will provide a data base of other agents that might be present in the cabin air. Some of these agents might have a synergistic toxic effect with other agents present. These bad combinations of exposures might explain why certain individuals show symptoms at reported levels of exposure well below the limits for each of the individual agents. The use of insecticides in aircraft is a typical example. Permethrins are required by certain countries for the disinsection of aircraft and can be found in most of the larger aircraft capable of international flight. On the basis of the scientific literature, such synergistic effects were postulated between organophosphates and permethrins [7, 21]. Experience of the "Gulf War syndrome" and experiments performed by Abou-Donia [22, 23] have confirmed this.

An additional synergistic effect between CO and permethrins has been postulated [21] and needs to be evaluated in the aircraft environment as there appears to be a potential for these agents to act synergistically, resulting in a loss of nighttime vision.

12
Exposure Data Acquisition

In order to obtain a data base that accurately reflects the nature and extent of air quality incidents, one needs to have many monitors out with flight crews in order to be able to capture an event when it occurs. As an example there were 27 501 domestic airline flights per day in October 2003, in the USA [24]. If one were to use a conservative frequency of one incident per 2000 flights, then there are approximately 13 incidents per day. If 2000 monitors were available to the industry one should be able to capture on average at least one event per day. At this rate, a reliable exposure data base would become available to the public, flight crews, and the industry within a very reasonable time span, allowing one to identify the extent of, and the connection between, the symptoms experienced by flight crews and the contaminants in the air supply of aircraft.

13
Alternate Solutions

It should be emphasized that most of the air quality incidents are directly linked to the poor quality of the bleed air that is supplied to the cabin either from the APU or the engines [7]. These problems could easily be eliminated if ram air is used along with compressors and a heat-exchange system. Although this approach was terminated, for economic reasons, in favour of bleed air, it is interesting to note that the new Boeing 7E7, also for economic reasons, has designed an air supply system that is not based on bleed air [25].

14
Conclusion

A majority of aircraft air quality incidents can be traced to contamination of the ventilation system from jet engine oils and/or hydraulic fluids. The symptoms reported by flight crew members often identify the central nervous system as being affected, followed by the respiratory system. Exposure to agents that could explain these symptoms and which are likely to be present during an incident have been identified as CO and TCPs. Exposure measurements of these agents during these incidents has not been done as it requires large numbers of expensive equipment to be present on aircraft in order to capture these sporadic events. A new air sampler has been developed that has the ability to address this issue and which could quantify exposures during these incidents and the role these oil and fluid components might play in explaining the symptoms experienced by flight crew members. An alternate solution to the health problems that have been associated with bleed air ventilation systems in aircraft is to use another source of air within the cabin.

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