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Case Study: Analysis of Reported Contaminated Air Events at One Major US Airline in 2009-10

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Pyrolyzed engine oil sometimes contaminates aircraft environmental control systems, exposing aircraft occupants to oil fumes containing toxic chemical constituents. Exposure to oil fumes has been reported to cause both acute and chronic neurological and respiratory symptoms, and has been documented to compromise flight safety. Neither the frequency nor the causes and characteristics of fume events have been well-described, either at individual airlines or industry-wide. As a case study, the author identified reported air contamination events on one side of the operations of one major US airline over a two-year period. A total of 87 fume events were identified on 47 aircraft fleet-wide, but A319, B767, and E190 aircraft appear to be overrepresented. Crew reported unusual odors on 83 of 87 flights, most commonly described as "dirty socks." Although the odor was reported prior to take off on 44 flights, only 20 of those flights were either cancelled or delayed, while the rest flew to their planned destinations, many with crew health and potential flight safety consequences. Out of all 87 fume events, one or more crewmembers had symptoms serious enough to require emergency medical care after 27 flights (31%), follow-up medical care after 43 flights (49%), and lost work time after 37 flights (43%). Mechanical records confirmed that oil contaminated the air supply on 41 of the 87 flights. After 30 of the flights, no mechanical cause was identified but oil was suspected based on the event characteristics, highlighting the need for maintenance workers to be trained to perform more targeted troubleshooting with less time pressure to enable them to identify and remedy the primary sources of contamination. The significant crew health, flight safety, and operational impact of these events, all support recommendations for crew training to recognize and respond to events, maintenance worker training to more effectively troubleshoot systems, and design/maintenance measures to prevent events, including bleed air filters/monitors on commercial aircraft that supply engine bleed air to occupants.

I. Introduction

Pyrolyzed engine oil sometimes contaminates aircraft environmental control systems by virtue of the air supply system design that "bleeds" unfiltered air off engines, combined with either inadequate or improper maintenance protocols. The oil is heated to high temperatures (250-900ºF) in an engine, and when it contaminates the air supply system, aircraft occupants downstream can be exposed to fumes containing a complex mixture of toxic chemical constituents, including tricresylphosphates and, in some cases, carbon monoxide, and N-phenyl-1-naphthylamine.[1-5]

Exposure to oil fumes has been reported to cause both acute and chronic neurological and respiratory symptoms,[6-8] and has been documented to compromise flight safety.[9-16] Thus, it is important for airlines, manufacturers, and regulators to characterize the frequency, causes, and characteristics of fume events in order to define and implement effective preventive control measures. For almost 60 years, the exposure hazard[17] and the need for engineering solutions[18] have been recognized, but neither the frequency nor the causes or characteristics of oil fume events has been well-described. Reasons for this include weak regulatory oversight, a dearth of objective exposure data, the inaccessibility of aircraft mechanical records to outside parties, and a general unwillingness on the part of many airlines to recognize that fume events can compromise health and safety. As a case study, the author identified reported air contamination events at one major US airline over a two year period, and explored the causes of contamination, the impact of these exposures, and preventive control measures.

II. Methods

An industrial hygienist employed by the union that represents the flight attendants built a dataset of air supply contamination reports covering a two-year period from Jan. 1, 2009 through Dec. 31, 2010 on one side of the operations of a major US airline. Sources of data were: (1) reports from flight attendants to the airline/union; (2)

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reports from pilots to the airline/union; and (3) Service Difficulty Reports (SDR) submitted to the Federal Aviation Administration (FAA) by that airline.

At least one of the following two conditions had to met for an event to be included in the dataset: (1) one or more crewmembers on a given flight during the stated time period had to have documented either an unusual odor, a visible smoke/haze, symptoms consistent with exposure to oil or hydraulic fumes, or some combination thereof (hereafter referred to as "fume events") with the airline, and either the crewmember or their union representative had to have reported it to the author; or (2) the airline had to have reported the event to the Federal Aviation Administration (FAA) under 14 CFR 12.1.703(a)(5) or 14 CFR 121.703(c) Service Difficulty Reporting regulations for smoke/fume events. As well, it had to be more likely than not that the source of contamination was either engine oil or hydraulic fluid, based on documentation, professional judgment from mechanics or pilots, or circumstantial evidence strongly suggestive of oil fumes. The focus of this study was oil fume events, but a minority of events involving hydraulic fluid fume events was included. Incidents that clearly involved exposure to airborne contaminants other than either engine oil fumes or hydraulic fluid fumes (e.g., deicing fluid, exhaust fumes, malfunctioning galley equipment) were excluded. When incident reports had characteristics of engine oil fumes (e.g., dirty sock smell, crewmembers reported ongoing neurological symptoms, etc.), but the airline officially attributed them to mechanical failures inconsistent with the event (e.g., failed cosmetic seal on aft galley door), they were still included in the dataset.

The author searched the FAA's online SDR database (http://av-info.faa.gov/sdrx/Query.aspx) for additional documentation for the fume events that crewmembers had reported to the airline/unions. The author submitted queries to the database by aircraft number for three month search intervals during the two year study period. Limiting each query to three month intervals avoided having the system generate more than 1500 reports which is the maximum number that the system will list on the query results screen. The author conducted each SDR database searches at least two months after the reported event to ensure adequate time for the FAA to enter airline reports in its online system. This process generated some additional fume event reports because, sometimes, the airline did not file a report for the incident of interest, but had filed one or more fume event reports for the same aircraft number on different dates within the same three month period.

To supplement the information in the crew reports and SDR, airline mechanics reviewed relevant aircraft mechanical records and pilot logbook entries, when available, and described any relevant mechanical failures to the author. The aircraft records were filed under ATA maintenance manual chapters 21 (air conditioning), 29 (hydraulic power), 49 (auxiliary power unit; APU), and 79 (oil). If any data source had alluded to a possible electrical cause, then mechanics also reviewed records filed under ATA maintenance manual chapter 24 (electrical).

The goal of these data collection efforts was to answer the questions listed in Table 1 for the fume events reported over a two-year period in order to generate hypotheses about cause, impact, and preventive measures. When one or more of the items listed in Table 1 was not addressed in either the flight attendant reports, pilot reports, SDR, or aircraft mechanical records/pilot logbook entries (per mechanics' reviews), then the author telephoned the flight attendants (and the pilots, when possible, by coordinating with the pilots' union) to obtain the information. The flight attendants' telephone numbers were provided by the union's membership department staff at the international office in Washington, DC.

Table 1. Items of interest during review of reported contaminated air events

Date (for tracking purposes), departure city, arrival city
Aircraft number, aircraft type
Odor? If so, what did it smell like?
Visible smoke/haze? If so, what did it look like?
Odor/smoke/haze during what phase of flight?
Change in flight plan?
Flight attendants/pilots reported symptoms inflight/post-flight?
Airline file SDR?
≥1 crewmember seek emergency medical care (within 48 hours of arrival)?
≥1 crewmember seek follow-up medical care (post-arrival > 48 hours)?
Lost work time?
Mechanical cause(s) of air supply contamination identified?

III. Results

During this 24-month period, 87 events on 47 aircraft met the inclusion criteria. The sources of contaminated air reports are listed in Table 2. All but one of the events reported to a crew union were also reported to the airline. The exception was an event that a pilot reported to his union only. Although the author only found a SDR for 33 of the 87 events, 66 appear to meet the SDR reporting requirements. In 64 of the 87 events, mechanics reviewed relevant aircraft mechanical records and pilot logbook entries.

Table 2. Sources of contaminated air reports

Source	Number of events
Crew report(s) to the airline, union(s), or both	48
Crew report(s) + Service Difficulty Report (SDR)	18
SDR only	15
Cross-referenced in aircraft mechanical records and pilot logbook entries that mechanics reviewed for another event, but not reported to either the union or the FAA	6
Total	**87**

Crewmembers reported contaminated air events on all eight aircraft types operated by the airline during the study period. The author attempted to assess whether an aircraft type was over- or under-represented in the fumes dataset by comparing the percentage of each aircraft type in the dataset to the percentage of that aircraft type in the airline fleet (fifth column in Table 3), so a value of "one" would be expected. The A319, B767, and E190 aircraft appear to be over-represented, while B737 aircraft appear to be under-represented. These findings may not be statistically significant, however, and normalizing parameter data (e.g., miles flown, total number of take offs and landings, etc.) were not available.

Table 3. Number and proportions of incident aircraft, contaminated air events, and aircraft in fleet, all by aircraft (AC) type

AC type	N (%[a]) incident AC	N (%[a]) events	N (%[a]) AC in fleet	% incident AC/ % AC in fleet	Over- or under-represented?[b]
A319	16 (34)	30 (34)	54 (25)	1.4	over
A320	4 (8.5)	6 (6.9)	23 (11)	0.77	-
A321	9 (19)	11 (13)	38 (17)	1.1	-
A330	3 (6.4)	6 (6.9)	16 (7.3)	0.88	-
B737	3 (6.4)	10 (11)	47 (22)	0.29	under
B757	3 (6.4)	3 (3.4)	15 (6.9)	0.93	-
B767	4 (8.5)	15 (17)	10 (4.6)	1.8	over
E190	5 (11)	6 (6.9)	15 (6.9)	1.6	over
TOTAL	47	87	218		

a. Totals may not add to 100% exactly because of rounding.
b. Qualitative analysis only; may not achieve statistical significance.

One contaminated air event was reported on 29 of the 47 aircraft in this dataset, and multiple events were reported for the remaining 18 aircraft (Table 4). The majority of the repeat events were on A319 aircraft, with the exception of one B767 aircraft with 12 reported events during the study period.

Table 4. Frequency of events by aircraft type for total of 87 events on 47 aircraft

Aircraft type	1 event	2 events	3 events	>3 events
A319	7	5	3	1 (4 events)
A320	3	0	1	0
A321	8	0	1	0
A330	1	1	1	0
B737	0	1	1	1 (5 events)
B757	3	0	0	0
B767	3	0	0	1 (12 events)
E190	4	1	0	0
TOTAL aircraft	**29**	**8**	**7**	**3**
TOTAL events	**29**	**16**	**21**	**21**

In all but four reported events, there was a noticeable odor, whether noted in crew reports to the airline, airline SDR to the FAA, aircraft mechanical records, pilot logbook entries, or follow-up telephone interviews with one or more crewmembers. Of these odor descriptors, dirty socks/smelly feet is the most common (Table 5). In 50 of the 83 events with an odor, more than one odor descriptor was used. Descriptors reported in five or fewer events during the study period were: acrid/sour, bad cheese, band aids, barnyard, burning/burnt, burnt cloth, burning dust, burning leaves, burning plastic, exhaust, garbage, gasoline, kerosene-like, metallic, paint-like, scorched, skunk, smoky, stale, sulfur, sweet, and urine. Only three of the 87 reported events involved a haze (2) or smoke (1) and in all three cases, the smoke/haze was reported during ground operations and the flights were cancelled/delayed.

Table 5. Nature and frequency of odors associated with contaminated bleed air events during two year period

Description of odor	Frequency
Dirty socks/smelly feet	35
Musty/moldy/mildew	17
Foul/funky/horrible/noxious	13
Strong/intense/pungent/overwhelming	11
Oil/oily/burning oil	11
Vomit	9
Chemical	7
Burning wire/electrical	6

In 44 of the 87 documented events, an unusual odor was reported prior to take off, and in 34 of the events, an odor was reported when the aircraft was airborne (Table 6). In five events, it was not clear if the odor was reported prior to take off. Four events had no reported odor, but were included in the dataset based on crew symptoms inflight and recent/subsequent documentation of oil in an engine/APU.

Table 6. Description of when odor was reported; whether or not prior to takeoff and phase of flight

Odor reported prior to take off?	Phase of flight during which odor first reported	
Yes	Boarding/at gate	26[a]
	Taxi out	18[b]
	Total	**44**
No	Take off/climb	15
	Descent	11
	Cruise	6
	No odor	4
	En route but phase not specified	2
	Total	**38**
Don't know		**5**
TOTAL		**87**

a. Of these, 14 were cancelled/delayed at the gate.
b. Of these, 6 returned to the gate.

Reported information on the crew health, flight safety, and operational impact, as well as relevant mechanical failures, for the 44 flights during which one or more crewmembers reported an unusual odor *prior to take off* is described in Table 7.

Table 7. Reported information on crew health, flight safety, operational impact and mechanical failures for 44 flights with unusual odors reported prior to takeoff

(a) 20 flights cancelled/delayed due to unusual odors reported prior to takeoff			(b) 24 flights that flew to destination despite unusual odors reported prior to takeoff		
N (%) flights			N (%) flights		
≥1 FA reported symptoms	17 (85)	(2 DK[a])	≥1 FA reported symptoms	21 (88)	
≥1 pilots reported symptoms	4 (20)	(7 DK)	≥1 pilots reported symptoms	9 (38)	(4 DK)
≥1 crew sought emerg. med. care	6 (30)	(1 DK)	≥1 crew sought emerg. med. care	12 (50)	(1 DK)
≥1 crew sought follow-up med care	12 (60)	(1 DK)	≥1 crew sought follow-up med care	13 (54)	(1 DK)
Cancelled/delayed prior to departure	14 (70)		Next flight conf. cancelled/delayed	6 (25)	
Returned to the gate during taxi out	6 (30)				
≥1 crew lost work time	10 (50)	(1 DK)	≥1 crew lost work time	13 (54)	(1 DK)
Confirmed oil leak in APU	10		Confirmed oil leak in APU	8	
Undefined APU contamination	2		Confirmed/susp. oil leak in engine	4	
Undefined pack contamination	2		Confirmed/susp. oil leak in ACM/pack	3	
Hydraulic fluid in APU	1		Undefined APU contamination	4	
Unknown	5		Unknown	5	

a. DK = don't know

Reported information on the crew health, flight safety, and operational impact, as well as relevant mechanical failures, for all 87 contaminated air events is described in Table 8.

Table 8. Reported information on crew health, flight safety, operational impact and mechanical failures for 87 contaminated air events

Crew health, flight safety, and operational impact	Number (%) of flights		
Crew health/flight safety	≥1 FA reported symptoms	68 (78)	8 DK
	≥1 pilots reported symptoms	27 (31)	27 DK
Medical attention	≥1 crew sought emerg. med. care	27 (31)	14 DK
	≥1 crew sought follow-up med care	43 (49)	15 DK
Impact on operations	Flight cancelled/delayed at gate	14 (16)	
	Flight returned to gate/diverted	7 (8.0)	
	Next flight confirmed cancelled/delayed	14 (16)	
	≥1 crew lost work time	37 (43)	15 DK
Mechanical failures	Confirmed/susp. oil in the APU	23 (26)	
	Confirmed/susp. oil in an engine	12 (14)	
	Confirmed/susp. oil in ACM/pack	6 (6.9)	
	Undefined APU contamination	7 (8.0)	
	Undefined ACM/pack contamination	6 (6.9)	
	Hydr. fluid contamination in air supply	3 (3.4)	
	Unknown	30 (34)	

a. DK = don't know

The author did collect information on types of symptoms from all data sources, where available. The most commonly reported inflight symptoms were headache, nausea, coughing, and disorientation. Other reported symptoms included bloodshot eyes, blurred vision, burning eyes, chest tightness, difficulty with balance, disorientation, flu-like symptoms, inability to take a full breath, metallic taste, lightheadedness, nosebleed, red skin (looked like sunburn), sore throat, tingling in mouth, vomiting, and watery eyes.

The most commonly reported post-flight symptoms were difficulty concentrating, difficulty with word recall, fatigue, headache, and memory deficits. Other reported symptoms included abnormal gait and balance, blurred vision, breathing difficulties, coughing, diarrhea, dry eyes, high blood pressure, hoarse voice, impaired motor skills, insomnia, irritated eyes, irritated throat, joint pain, muscle twitching, myalgias, nausea, neuropathy, sensitivity to unrelated chemicals (e.g., cleaning products, car exhaust, gasoline fumes, and makeup), and tremors.

IV. Discussion

Flight attendants have limited protection from exposure to bleed air contaminants in the cabin. They do not have the authority to refuse an aircraft that they think may be operating with pyrolyzed oil in the air supply system, nor can they make the decision to divert once a flight is in progress. Also, they are not trained to use the portable oxygen bottles stored in the cabin in response to an unusual odor. In two of the 87 events in this dataset, flight attendants were told to ferry the aircraft with a contaminated air supply system back to a maintenance base without protection, while the pilots breathed oxygen in the flight deck for at least part of the flight. In 68 of the 87 events, flight attendants reported symptoms, and in almost half of those events, the symptoms were serious enough to necessitate emergency medical care for at least one of the flight attendant, and sometimes the pilots as well.

Commercial pilots are instructed to follow a "smoke/fumes checklist" if they are exposed to airborne contaminants inflight. They are instructed to don their oxygen masks, and if the contaminants are in the supply air, to systematically troubleshoot the system to identify the location and nature of the contaminants, and decide if a diversion is necessary. Anecdotally, pilots will reliably don their masks if they see a smoke or haze, but no training is provided to ensure that they don their masks if they notice an unusual odor without any visible signs of contamination. Of the 87 contaminated air events in this dataset, crew reported a visible smoke/haze on only three flights, but one or more crewmembers (usually a flight attendant) reported an unusual odor on 83 flights. Pilots reported symptoms during 31% of these flights, which is likely an underestimate because pilot health data were not provided for 31% of the events.

Some of the pilots in this dataset developed chronic neurological symptoms post-flight, including two who lost their FAA medical license to fly because of ongoing neurological symptoms after confirmed inflight exposure to oil fumes that they did not smell and had not been trained to associate with their acute symptoms. The flight attendants on that aircraft had reported a dirty sock odor while the aircraft was still at the gate, but neither the flight attendants nor the pilots had been trained to recognize the odor as possible oil fumes, and the pilots did not refuse the aircraft. Four of the five flight attendants on that crew have not returned to work as of this writing (16 months later) due to ongoing neurological and respiratory symptoms. In addition to the crewmembers on that flight, seven passengers were taken to the emergency room upon arrival, but their health status is unknown.

Neither pilots nor flight attendants are trained to recognize the odors and symptoms associated with exposure to oil fumes. They are not trained to consider air supply contamination as a potential threat to crew health and flight safety, although these data clearly demonstrate that bleed air contamination can disrupt operations and compromise health, both inflight and post-flight.

Interestingly, even within a crew on the same aircraft, the perception of odor associated with contaminated bleed air can vary. For example, in reference to an event on an A320 at this airline in 2010, the SDR describes a flight turn back due to a "strong, vile odor in the cabin [with] fumes of unknown origin [that] caused one passenger to become ill." Afterwards, the captain described the odor as "parmesan cheese gone bad," while two of the flight attendants described it as "heated garbage" and "dirty socks," respectively. In 2003, a major aircraft manufacturer reported that "[a]t least two operators have reported that partial combustion of BPTO 2197 [engine oil] can manifest itself as an electrical smell, similar to the smell produced by a defective light ballast."[19] At airlines that service aircraft with BPTO 2197 aviation engine oil, at least (including the airline in this study), crews need to be trained to recognize that electrical smells may be pyrolyzed oil in the bleed air.

Both the aggregate data and the referenced examples highlight the need for pilots and flight attendants to be trained to recognize unusual odors as a potential threat to flight safety/health/operations, to communicate these potential hazards to each other, to refuse aircraft that may have oil in the air supply, and to act quickly to limit exposure to contaminated bleed air.

In addition to the findings described above, this fume event dataset is rich in examples of the challenges that maintenance workers face in troubleshooting systems, and the problems that can arise when an aircraft is (either knowingly or unknowingly) dispatched with a contaminated aircraft air supply system.

In some cases, maintenance cleaned or replaced an oil-contaminated air supply system component but did not address the primary source of the contamination (i.e., either an engine, APU, or air cycle machine, ACM). For example, when maintenance investigated the cause of a crew report of a stale, dirty socks smell that started during takeoff, they found contamination in the left-side water separator bag (WSB), but did not identify the primary source of contamination. Five days later, a new crew on the same aircraft documented a dirty sock odor that started during takeoff, and maintenance found oil in the left-side ACM that had also contaminated the left-side WSB downstream. Maintenance again replaced both components but did not appear to investigate whether an upstream engine or APU was the primary source. After another five days, another crew on the same aircraft documented a dirty sock odor throughout the flight, but maintenance did not identify the source of the contamination, and instead replaced the recirculated air filters. Finally, three days later, another crew on the same aircraft documented a foul odor that started during takeoff and maintenance identified oil contamination in the engine that supplies bleed air to the left-side ACM and WSB. The leaking engine was likely the source of all four contaminated air events, but it was not identified for 13 days. Once the engine was replaced, there were no further reports of contaminated air on this aircraft. Excerpts from the SDR for this aircraft are listed in Table 8.

Table 8. Excerpts from SDR and a description of maintenance actions in response to four cabin odor reports on one aircraft over 13 days

Month/year	Excerpts from Service Difficulty Reports	Notes
Oct. 2010	"Pilot reported strong mildew odor/stale air in cabin. Flight crew was able to isolate the odor to the left pack. Maintenance R&R dirty water separator bags..."	"Dirty" left pack WSB were replaced but source(s) of contamination were not identified or remedied.
Oct. 2010	"Pilot reported strong odor from air in cabin. Flight crew was able to isolate the odor to the left pack. Maintenance R&R dirty water separator bags..."	Oil in left pack ACM suspected as source of oil in downstream left pack WSB. Replaced both components.
Oct. 2010	"Pilot reported the cabin air…smells like dirty laundry. Maintenance replaced the cabin air recirc filers."	Cabin odor report but mechanical source(s) not identified or remedied.
Oct. 2010	"Pilot reported the cabin air…smells like dirty laundry. Maintenance replaced the cabin air recirc filers."	Cabin odor report but mechanical source(s) not identified or remedied.

The incidents listed in Table 8 also highlight the importance of service life. As a cost-savings measure to extend service life, some US airlines replace engines, APUs, and ACMs on an "on condition" basis (i.e., fix or replace it when part of it fails) instead of on a "hard time" replacement schedule based on an estimated reasonable service life. This airline does not track APU service life (hours) on most of its aircraft, which is likely standard practice at other US airlines. According to the SDR, the ACM and engine that failed in this example are well beyond expected service life. Replacing engines, APUs, and ACMs before they reach the end of their expected service life should reduce the frequency of oil fume events.

Although the FAA is responsible for crew health and flight safety, it does not require either manufacturers or airlines to protect either crew or passengers from exposure to oil-contaminated bleed air. In 2002, the agency noted that it "has not kept pace with public expectation and concern about air quality and does not afford explicit protection from particulate matter and other chemical and biological hazards...because no airplane design incorporates an air contaminant monitoring system to ensure that the air provided to the occupants is free of hazardous contaminants."[20] Despite this admission, agency officials have not promulgated any regulations for either crew training or bleed air monitoring/cleaning equipment since then.

The author was only able to locate 33 SDR in the FAA's online SDR database for fume events on the aircraft in this dataset during the two-year period of interest, although 66 of the 87 events appear to meet the SDR reporting criteria for smoke/fumes. In 2006, the FAA acknowledged poor airline compliance with SDR reporting rules for smoke/fume events.[21] If the data presented here are representative, they suggest that airline compliance has not improved.

Of these 87 contaminated air events on 47 aircraft, 29 were reported in 2009 and 58 were reported in 2010. For comparison, this airline operation reported a total of 107 smoke/fume reports (all types) to the FAA during the same time period, including 44 in 2009 and 63 in 2010.[22] It appears that there were more smoke/fume events in 2010 compared to 2009, but it is not clear if this difference is explained by an actual worsening in cabin air quality, improved airline reporting to the FAA, improved crewmember reporting to the airline, or some combination thereof.

As a post-script, at the end of April 2011, management representatives from this airline reported an average of 10 confirmed oil/hydraulic fluid smoke/fume events per month airline-wide from Jan. 2010 through April 2011 and an additional 10 smoke/fume events per month with no identified cause during the same period. A direct comparison of those data described in this paper and those collected by the airline is not possible. However, the discrepancy between the monthly average number of events in each dataset raises questions about the adequacy of smoke/fume event reporting protocols at this airline, which are probably typical within the US airline industry.

V. Limitations

A medical records review of crewmembers who reported illness after exposure to fumes was beyond the scope of this case study; instead, information on crewmembers' symptoms was largely self-reported. In some cases, media coverage and airline documents confirm that paramedics met an aircraft, for example. Also, sometimes, crew symptoms are documented in pilot logbook entries and SDR submissions.

The impact on pilot ill health, both acute and chronic, is likely underestimated, in part because pilots on 31% of the flights did not document whether or not they experienced either acute or chronic symptoms, and did not respond to phone messages in time for their experiences to be included in this review. Also, there is evidence that pilots may be motivated to downplay ill health out of fear of losing their license to fly.[23]

The crew union and airline reporting protocols for fume events are imperfect and crewmembers are not trained to recognize and respond to unusual odors. For these reasons, it is likely that this dataset underestimates the actual frequency of exposure to oil fumes. Mechanics described some references in pilot and maintenance logs to additional incidents of unusual odors in the aircraft cabin/flight deck that had necessitated maintenance action, although in most cases, too much time had passed to access the list of crew names, so these events were not included.

VI. Recommendations

Based on the data presented here and insights into the maintenance practices at this airline (which, anecdotally, are typical within the US aviation industry), the author recommends the following:

1. Airlines must replace engines, APUs, and ACMs on a hard-time schedule (e.g. every 15,000 operating hours or so) and not on the popular "on-condition" basis which waits for a component to fail before it is inspected and replaced. Some other preventive maintenance strategies include procedures to prevent overfilling the engine and APU oil reservoirs, resealing the APU compartment more often to prevent oil leakage, boroscoping engines for evidence of oil staining and doing so more frequently as engines age, and inspecting/monitoring to confirm APU and engine oil seal integrity. Additional preventive measures are described in the air quality standard for commercial aircraft published by ASHRAE;[24]

2. Airlines must train pilots and flight attendants to recognize when they may be exposed to oil fumes, including an overview of odors and acute/chronic symptoms associated with exposure. Any training must ensure that crewmembers understand that individuals may interpret the same odor differently, and some people may not smell anything. Training needs to emphasize the importance of not dispatching an aircraft until the source of unusual odors has been identified and remedied. Also, pilots must be reminded to don their oxygen masks if they suspect air supply contamination based on an unusual odor, symptoms, or both, even if there is no visible sign of exposure to airborne contaminants;

3. Airlines must train maintenance workers to inspect and address the three potential sources of oil fumes (APU, engines, and ACMs) for signs of contamination, especially when they find components that have been contaminated downstream. Also, after a significant contamination event (perhaps defined as one which requires medical care for any aircraft occupant), airlines must develop and enforce protocols to ensure that the metal ducting upstream of the mix manifold is cleaned, and that the porous ducting downstream of the mix manifold is inspected and, if it is soiled, replaced. Maintenance workers may benefit from ground-based contaminant detection instruments intended to provide an objective assessment of air supply contamination. One available unit concurrently measures various volatile compounds in real time and interprets the combined readings to notify the user of the type of contaminants (e.g., oil, hydraulic fluid, deicing fluid);[25] and

4. The current fleet should be retrofitted with bleed air cleaning and monitoring equipment to mitigate exposure, and also serviced with less toxic oils. At a minimum, for any newly manufactured aircraft, airlines must call upon manufacturers to provide either bleed air monitoring and cleaning equipment, or a non-bleed ventilation supply system. The only commercial aircraft with a non-bleed system is the B787 which is expected to enter service later this year.

Despite the growing body of evidence that exposure to oil fumes can compromise occupant health, flight safety, and operations, airlines continue to downplay these risks, generally claiming that, even if oil fumes contaminate the air supply, the concentration of contaminants is too low to explain crew or passenger symptoms. As well, airlines and manufacturers have ignored recommendations to install and operate bleed air monitoring/cleaning equipment, claiming that such equipment is neither necessary nor available. For these reasons, either the FAA or Congress need to mandate control measures to prevent exposure to oil fumes during commercial flights. Companies that manufacture and market necessary bleed air monitors and cleaners will not be motivated to develop aircraft systems until there is an assured market.

VII. Conclusion

These data demonstrate that the crew health, flight safety, and operational impact of exposure to contaminated bleed air is significant. Many of these events could have been prevented (or at least, their impact could have been mitigated) with appropriate crew and maintenance worker training. Protocols to monitor and replace components before they reach the end of their service life, and to install and operate suitable bleed air monitoring and cleaning equipment are also necessary.

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References

[1] Michaelis, S., "Chemicals Reported Found In Aircraft Cabins and Cockpits," *Aviation Contaminated Air Reference Manual*, London: ISBN 9780955567209, pp.555-561, 2007.

[2] Hanhela, P.J., Kibby, J., DeNola, G., et al., "Organophosphate and Amine Contamination of Cockpit Air In the Hawk, F-111, and Hercules C-130 Aircraft," DSTO-RR-0303, Australian Government Department of Defence, Defence Science and Technology Organisation, 2005.

[3] Bobb, A.J., and Still, K.R., "Known Harmful Effects of Constituents of Jet Oil Smoke," TOXDET-03-04, US Air Force, Naval Health Research Center Detachment (Toxicology), Wright-Patterson AFB, 2003.

[4] van Netten, C. and Leung, V., "Comparison of the Constituents of Two Jet Engine Lubricating Oils and Their Volatile Pyrolytic Degradation Products," *Applied Occupational and Environmental Hygiene*, Vol. 15, No. 3, pp.277-283, 2000.

[5] van Netten, C., "Analysis of Two Jet Engine Lubricating oils and a Hydraulic Fluid: Their Pyrolytic Breakdown Products and Their Implications on Aircraft Air Quality," *Air quality and comfort in airliner cabins ASTM STP 1393*, edited by N. Nagda, American Society for Testing and Materials, West Conshohockhen, PA, pp.61-75, 2000.

[6] Harrison, R., Murawski, J., McNeely, E., et al., "Exposure To Aircraft Bleed Air Contaminants Among Airline Workers: A Guide For Health Care Providers," Occupational Health Research Consortium in Aviation, Report to the US Federal Aviation Administration, Washington, DC, 2008.

[7] Michaelis, S., "A Survey of Health Symptoms in BALPA Boeing 757 pilots," *Journal of Occupational Health and Safety, Australia & New Zealand,* Vol. 19, No. 3, pp. 253-61, 2003.

[8] Harper, A., "A Survey of Health Effects in Aircrew Exposed to Airborne Contaminants," *Journal of Occupational Health and Safety, Australia and New Zealand*, Vol. 21, No. 5, pp.433-439, 2001.

[9]AAIB, "Bulletin No. 4/2/07, Bombardier DHC-8-400, G-JECE," EW/C2005/08/10, UK Air Accidents Investigation Branch, UK Department for Transport, 2007.

[10] SAAIB, "Investigation Report Concerning the Serious Incident to Aircraft AVRO 146-RJ 100, HB-IXN Operated By Swiss International Air Lines Ltd. Under Flight Number LX1103 on 19 April 2005 on Approach to Zurich-Kloten Airport," No. u1884, Swiss Accident Investigation Bureau, 2006.

[11] AAIB, "Aircraft Accident Report No. 1/2004, BAe146, G-JEAK," Report No. EW/C2000/11/4, UK Air Accidents Investigation Branch, UK Department for Transport, 2004.

[12] FAA, "Airworthiness Directive 2004-12-05: BAE Systems (Operations) Limited Model BAe 146 Series Airplanes," Docket No. 2003-NR-94-AD. Federal Aviation Administration, 2004.

[13] BAe, "Air Conditioning: To Inspect Engine Oil Seals, APU and ECS Jet Pump and Air Conditioning Pack For Signs of Oil Contamination," Inspection Service Bulletin No. 21-150, British Aerospace Operations Ltd., Prestwick International Airport, Scotland, issued 2001, revised 2002.

[14] PCA, "Technical Report on Air Safety and Cabin Air Quality in the BAe146 Aircraft," Parliament of the Commonwealth of Australia, Senate Rural and Regional Affairs and Transport Legislation Committee, Canberra, Australia, Senate Printing Unit, pp.83-96, 2000.

[15] ATSB, "British Aerospace Plc BAe 146-300, VH-NJF, Occurrence Brief No. 199702276," Australian Transport Safety Bureau, 1999.

[16] Montgomery, M.R., Wier, G.T., Zieve, F.J., et al., "Human intoxication following inhalation exposure to synthetic jet lubricating oil," *Clinical Toxicology*, Vol. 11, No. 4, pp. 423-426, 1977.

[17] Treon, J.F., Cleveland, F.P., and Cappel, J. "The Toxicity of Certain Lubricants, Engine Oils, and Certain of Their Constituents, With Particular Reference to the Production of Their Thermal Decomposition Products," Aeromedical Laboratory

Contract No. AF33(038)-26456. Kettering Laboratories, Univ. Cincinnati, for the Wright Air Development Center, USAF, Wright-Patterson Air Force Base, 1954.

[18] Reddall, H.A., "Elimination of Engine Bleed Air Contamination," *North American Aviation Incorporated for SAE Golden Aeronautic Meeting*, Los Angeles, California: Oct. 11-15, 1955.

[19] Boeing, "Smoke in the Cabin. Maintenance Actions For Environmental Systems. Best Practices," Service Letter DC9-SL-21-101, MD-80-SL-21-101, MD-90-SL-21-73, Boeing Commercial Airplanes, Commercial Aviation Services, Seattle, WA, 2003.

[20] FAA, "Proposed Implementation of Cabin Air Quality Recommendations. FAA Response to Recommendation 1 (Air Quality and Ventilation) of the US National Research Council Committee Report on Commercial Airliner Cabin Air Quality and the Health of Passengers and Crew," US Federal Aviation Administration, 2002. Available online at: http://www.faa.gov/about/initiatives/cabin_safety/rec_impl/

[21] FAA, "Guidance For Smoke/Fumes in the Cockpit/Cabin: Order 8300.10," Flight Standards Information Bulletin For Airworthiness 06-05A, US Federal Aviation Administration, 2006.

[22] FAA, "Response to FOIA Request 2011-3502" (List of Smoke/Fume Reports Received by the FAA Office of Aviation Accident Investigation and Prevention From US Airlines, 2009-10), US Federal Aviation Administration, 2011.

[23] PCA, "Technical Report on Air Safety and Cabin Air Quality in the BAe146 Aircraft," Parliament of the Commonwealth of Australia, Senate Rural and Regional Affairs and Transport Legislation Committee, Canberra, Australia, Senate Printing Unit, p.100, 2000.

[24]ASHRAE, "Standard 161-2007: Air Quality Within Commercial Aircraft," American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 2007.

[25] Aerosense Analytics, "Aerotracer." URL: http://www.airsense.com/media///airsense/downloads/aerotracer-engl.pdf [cited 26 May 2011].