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An Attempt to Characterize the Frequency, Health Impact, and Operational Costs of Oil in the Cabin and Flight Deck Supply Air on U.S. Commercial Aircraft

ABSTRACT: Industry, government, and labor representatives have all acknowledged that air supply systems on commercial aircraft sometimes get contaminated with pyrolyzed engine oil or hydraulic fluid, but efforts to define "sometimes" have been lacking. Despite the lack of attention it has received, the answer to this "how often" question is important because it will influence the willingness of industry, as well as regulators and legislators, to develop and implement control measures to prevent such air supply contamination. To address this data gap, an industrial hygienist collected reports of air supply contamination over an 18-month period (January 2006 through June 2007) from the following sources, all per defined inclusion criteria: (1) Service Difficulty Reports (SDR) and Accident and Incident Data System (AIDS) reports that airlines submitted to the Federal Aviation Administration (FAA); (2) incidents that flight attendants documented with one of 20 airlines and copied to one crewmember labor union; and (3) newspaper clips identified in online searches. A qualified airline mechanic reviewed each SDR and AIDS report with an oil or hydraulic fluid-related mechanical defect that did not explicitly mention oil or hydraulic fluid in combination with a specific word that indicated air supply contamination (i.e., "fume," "haze," "mist," "odor," "smell," or "smoke") to determine its eligibility. The resulting dataset of 470 air supply contamination events reported in the U.S. commercial fleet over an 18-month period translates into an average of 0.86 events per day and includes 350 incidents reported by airlines to the FAA, 115 reported flight attendants to their airline, and 37 incidents reported by at least one newspaper. There was limited overlap between sources. The data are discussed in detail along with commentary on whether and how the data are representative, the health and operational costs associated with air supply contamination, and some preventive measures.

KEYWORDS: aviation, aircraft, air supply contamination, engine oil, hydraulic fluid

Introduction

The potential for heated engine oil and hydraulic fluid to contaminate the aircraft air supply due to maintenance, operation, and design failures or deficiencies is an ongoing problem that has been documented in the aviation industry since the introduction of the "bleed air" air supply system in the 1950s [1,2]. With the bleed air design, outside air is compressed in the aircraft engines or auxiliary power unit and then conditioned and routed to the cabin and flight deck through ventilation ducting. The air compressors have a wet side that comes into contact with oil and a dry side that comes into contact with supply air, and the wet and dry sides are supposed to be kept separate from each other with tight fitting seals. The practice of bleeding high temperature compressed air off the aircraft engines (in-flight) or auxiliary power unit (APU) (on the ground) for ventilation is popular with aircraft manufacturers and their customers because it is more economical than the turbo compressor or ram air systems that it replaced.

However, shortly after the introduction of bleed air, the Committee on Aviation Toxicology of the Aero Medical Association acknowledged the potential for "toxic substances [to] arise in personnel compartments of an airplane [supplied with bleed air] from such sources as oil…and hydraulic fluids" [1]. Of particular concern was that pyrolyzed engine oil could leak or spill from the wet side of the compressors in the engines or APU into the dry side, coating the air conditioning system and ductwork with oil residue and contaminating the cabin and flight deck supply air. But despite this known hazard, bleed air had become the air supply system of choice on most military and commercial aircraft within ten years of its introduction, with the commercial market led by the Boeing 727 introduced in 1963. As the bleed air

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system became more widespread, so did information on the risk of air supply contamination with synthetic engine oil [3] and pilot ill-health and incapacitation in-flight as a result of exposure to such contaminants [4].

With the continued growth of the commercial and military fleets, there has been an increase in the frequency of investigations, recommendations, and reports of ill health and compromised aviation safety related to bleed air contamination [1–28]. Some of these investigations have been inconclusive because of the challenges involved in capturing irregular and sometimes transient/low-level exposures when oil (for example) contaminates the air supply, as well as the nonspecific nature of some of the symptoms. However, toxic constituents of vaporized or pyrolyzed oil include tricresylphosphates (TCPs), carbon monoxide, and N-phenyl-L-naphthylamine (PAN) [6]. TCPs are added to all major commercial aviation engine oils used on the U.S. fleet and at least one popular hydraulic fluid. The content of a total of ten possible isomers (TCPs) is reported as 1–5 % on the Material Safety Data Sheets of these products and their presence has been confirmed by chemical analysis, both at ambient and elevated temperatures [25–27].

Despite ongoing requests from crewmember associations, neither the acute nor the chronic health impact of inhalation exposure to heated engine oil and its breakdown products in a reduced pressure environment has been systematically tested, or at least the results of such testing have never been published. Still, crewmembers around the world continue to report chronic health effects consistent with exposure to TCPs, oil aerosols, and carbon monoxide [28]. The increase in the number of investigations and reports since the 1990s is likely a result of improved awareness-by researchers and government officials at least, as well as a greater likelihood that crew and passengers will detect oil in the air supply since cigarette smoking was banned on commercial flights.[3] The authors submit that the documented reports still represent only a small fraction of the actual number of reports because of widespread underreporting by airlines, crew, and passengers. Certainly, the Federal Aviation Administration (FAA) and others acknowledge that airlines underreport smoke and fume events [33–35]. Underreporting issues are addressed in the discussion section.

Despite the fact that pyrolyzed oil in the air supply has been recognized as an exposure hazard on aircraft equipped with bleed air systems for more than 50 years, and despite the prevalence of both anecdotal and official reports of short-term illness, long-term illness, and compromised flight safety, there is no official tally of the frequency of these events. This paper attempts to address that data gap.

There are few official sources of data that can be used to estimate the frequency of air supply contamination events involving engine oil or hydraulic fluid. The FAA does require that pilots enter any maintenance irregularity (including smoke/fume events) into the pilot log book (14 CFR 121.563) but these data are not publicly available. However, the FAA also requires all U.S. airlines that operate under Part 121 or 135 (defined as "common carriage," essentially commercial aircraft) to submit a Service Difficulty Report (SDR) for "each failure, malfunction, or defect concerning an aircraft component that causes accumulation or circulation of smoke, vapor, or toxic or noxious fumes in the crew compartment or passenger cabin *during flight*" (14 CFR 121.703(a)(5) and 14 CFR 135.415).[4] "During flight" is defined as "the period from the moment the aircraft leaves the surface of the earth on takeoff until it touches down on landing," so technically, smoke/fume events identified during ground operations need not be reported. However, airlines must also submit a SDR for any such failure, malfunction, or defect identified *at any time* if the airline considers that flight safety is or may be endangered (14 CFR 121.703(c) and 14 CFR 135.415(c)), and must submit a Mechanical Interruption Summary Report for "each interruption to a flight, unscheduled change of aircraft en route, or unscheduled stop or diversion from a route, caused by known or suspected mechanical difficulties or malfunctions that are not required to be reported under §121.703" (14 CFR 121.705). U.S. airlines must also report any "occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations" to the FAA's Accident and Incident Data System (AIDS). Finally, airlines are required to immediately report incidents that result in the "inability of any required flight crewmember to perform normal flight duties as a result of injury or illness" (49 CFR 830.5) to the nearest National Transportation Safety Board field office, although the definition of "flight crewmember" does not include flight attendants (14 CFR 1.1).

[3]The smoking ban was introduced on selected U.S. flights in 1988 and eventually expanded to all U.S. flights in 2000 [29–32].

[4]Part 121 of the Federal Aviation Regulations (FARs) is titled "Domestic, Flag, and Supplemental Operations," and includes aircraft with 20 seats or more. Part 135 of the FARs is titled "Commuter and On-Demand Operations" and includes aircraft with 10–30 seats. The SDR reporting rules also apply to privately-owned aircraft that are leased for business purposes (14 CFR 91.1415) but the focus of this paper is commercial aircraft.

Another source of smoke/fumes incident data is reports that crewmembers submit to their airlines, although airlines are not required to share these data with either the FAA or with crewmember representatives. Despite the fact that neither the health nor the safety of crewmembers are regulated by the U.S. Occupational Safety and Health Administration, a sample of airlines are required to report "recordable injuries and illnesses" (i.e., involves medical treatment, loss of consciousness, restriction of work or motion, or transfer to another job) to the Bureau of Labor Statistics' (BLS) occupational injury and illness reporting program (29 CFR 1904.21). These airline reports, however, are of little use in this analysis because they provide no information on cause and they typically describe the illness in only generic terms (e.g., "inhalation, chemical"). The majority of flight attendants in the United States are represented by labor unions and the largest of these is the Association of Flight Attendants–CWA, AFL-CIO (AFA), with approximately 55 000 members at 20 major and regional airlines. The majority of AFA airlines do not voluntarily share incident reports with the union, so the union learns about most documented incidents directly from its members, unless post-incident psychological support is required, in which case airlines will notify the union's Employee Assistance Program.

The media is another source of in-flight smoke/fume incidents, but typically only those events that are serious enough to require a diversion, emergency landing, or significant delay are reported.

Methods

An industrial hygienist employed by the AFA (primary author of this paper) built a dataset of air supply contamination reports covering an 18-month period (January 2006 through June 2007) from the following sources, all per defined inclusion criteria: (1) Service Difficulty Reports (SDR) and Accident and Incident Data System (AIDS) reports that airlines submitted to the FAA; (2) incidents that flight attendants documented with one of 20 U.S. airlines and copied to the central safety department of the AFA labor union; and (3) relevant newspaper clips identified in online searches. The focus of this data collection effort was engine oil contamination, but the industrial hygienist also included a cursory search for hydraulic fluid-related contamination.

Relevant SDR and AIDS Reports that Airlines Submit to the FAA

The FAA provides public access to the reports that airlines submit to the SDR and AIDS reporting systems in online databases. The reports include the incident date, airline, aircraft type, phase of flight, a description of what happened, and sometimes information on "precautionary procedures" such as an aborted takeoff or a flight diversion. The industrial hygienist searched the "problem description" (SDR) or "problem narrative" (AIDS) fields in these databases for the specific search terms listed in Table 1 for the period January 1, 2006 through June 30, 2007 for all U.S. commercial operators and all aircraft models and makes. The databases do not allow wild card or proximity searches, and although the FAA classified the majority of the identified SDR reports under "smoke/fumes/odors/sparks" or "fluid loss" categories, for example, it was not possible to search for reports according to those terms. A certificated airline mechanic affiliated with the International Association of Machinists (secondary author of this paper) with 29 years of experience in heavy maintenance, line maintenance, and quality control inspections on a wide variety of aircraft types reviewed each SDR and AIDS report with an oil or hydraulic fluid-related mechanical defect that did not explicitly mention either oil or hydraulic fluid in combination with a word indicating air supply contamination (i.e., "fume," "haze," "mist," "odor," "smell," or "smoke") and rated it as "more than likely yes," "more than likely not," or "not enough information." Only the obvious candidates identified by the industrial hygienist and the "more than likely yes" reports identified by the mechanic were included in the final dataset.

Incidents that Crew Documented with Their Airline and Crewmember Union

Flight attendants may document an incident of smoke/fumes in the cabin with their airline, their union, or both. Many flight attendants choose not to report incidents, for reasons described later. For a report to be eligible for this analysis, the flight attendant had to be a member of the AFA labor union (about a 50 % chance in the United States) and had to have documented the event with his or her airline. In many cases, the flight attendant would also have had to independently provide AFA with a copy of the report submitted

TABLE 1—*Search terms applied in analysis of the FAA's SDR (n = 345) and AIDS (n = 6) databases.*

SDR or AIDS search term[a]	*N*
Smoke in (halation, cabin, into cabin, the cabin, cabin and cockpit, cockpit, the cockpit, flight deck, the flight deck, fwd cabin, aft cabin)	87
Oil smell/oily smell	42
Oil leak/leaking oil	40
Oil fumes/fumes	32
Haze	28
Oil odor	26
Bleed air	21
Dirty sock/pungent/foul/acrid	15
APU oil	12
Hydraulic fluid/skydrol	11
Burning smell	9
Oil mist/mist	6
Burning oil/burned oil	5
Pack burn	5
Oil contaminat*/contaminated air	4
Smoky oil/oily smoke	4
Cabin air	3
TOTAL	350[b]

[a]Additional search terms with zero hits were chemical smell, conditioned air, hazy, oil haze, oil smoke, oil spill, and smoking oil.
[b]One report was identified in both databases with the same search term.

to their airline because most airlines do not share their incident reports with the union. For a flight attendant report to be included in the dataset, either the airline had to have confirmed that there was oil or hydraulic fluid in the air supply system, or the industrial hygienist had to classify the report as "more than likely" to have involved oil or hydraulic fluid in the air supply system, based on an account of crewmember discussions with airline maintenance workers after the event, aircraft mechanical records when available, and an analysis of the defining characteristics of the event (e.g., odor of dirty socks or burning oil, any visible indication of air supply contamination, symptoms consistent with exposure to pyrolyzed engine oil, etc.). Incident reports that suggested other causes of symptoms (e.g., inadequate ventilation, pesticide exposure, deicing fluid, electrical smoke/fumes, pressurization problems, cleaning products, exhaust fumes, and fuel fumes) were excluded, as were reports where nonspecific symptoms were reported and there was no indication of cause.

Relevant Newspaper Clips Identified in Online Searches

AFA staff members, including the industrial hygienist conducting this analysis, receive a daily e-mail list of online newspaper stories on aviation safety, health, and security issues drawn from the yahoo.com news search engine for stories that contain one more of the following terms: "aviation," "airline," "airplane/aeroplane," "flight attendant," and "cabin crew." Stories that reported a fume, haze, mist, odor, or smoke in the cabin or flight deck, or both, were added to the dataset if they involved a domestic airline and did not reference another known cause (e.g., electrical malfunction, exhaust fumes, deicing fluid, carry on baggage, cargo fire, etc.). Typically, airline representatives are quoted as attributing in-flight smoke/fumes to an undefined mechanical problem, so the inclusion criteria are looser for this source than for the other two.

Results

Overall Dataset

After removing duplicate entries and consolidating data from multiple sources for a given event, the final dataset included 470 incidents over an 18-month period (January 1, 2006 through June 30, 2007) that involved oil or hydraulic fluid, translating into an average of 0.86 incidents per day. The mechanic

TABLE 2—*Source of 470 incident reports, including airline reports to FAA, flight attendant reports to airlines, and online newspaper stories.*

Source	Number of Events
Total number of events identified in one or more FAA database (of these, 119 were from AFA airlines)	350
Events identified in FAA database only	328
Events identified in FAA database and in a flight attendant report to airline	11
Events identified in FAA database and in media story	6
Events identified in FAA database, flight attendant report to airline, and media story	5
Total number of events documented by at least one flight attendant report to AFA airline	115
Events identified in flight attendant report only	94
Events identified in flight attendant report to airline and media story	5
Events identified in media stories (of these, 15 were from AFA airlines)	37
Events identified in media story only	21

identified an additional 94 reports in the FAA databases with insufficient information in the narratives to determine whether oil had contaminated the air supply. For example, a typical narrative reads: "Station employee reports smoke in cabin. Check APU oil level, within limits. Corrective action: removed and replaced air conditioning sock per MM 21-20-2." These reports were not included in the final dataset.

The majority of air supply contamination events (74 %) were identified in the FAA databases, with 24 % reported by AFA flight attendants to their airlines, and 7.9 % reported by the media (Table 2). The percentages add up to more than 100 % because of some overlap between sources.

A total of 47 aircraft types were cited in 462 of the 470 incidents, ranging from small turboprop aircraft to wide-body jets (Table 3). Aircraft type was not reported in eight of the incidents. The aircraft types most frequently cited were the CL600 (11 %), DC9 (11 %), MD80 (8.9 %), and the ERJ145 (8.1 %), followed by the B737 (6.2 %), B757 (6.0 %), and the Cessna 750 (5.5 %). Compared to the

TABLE 3—*Aircraft type listed in documented events (N = 470).*

Airbus 300	6	Bombardier BD700	1	Embraer RJ-145	38
Airbus 310	3	Bombardier CRJ700	1	Embraer RJ-170	2
Airbus 319	8	Bombardier Dash 8	17	Embraer RJ-190	2
Airbus 320	8	Canadair CL600	54	Falcon 2000[(a)]	2
Airbus 321	4	Canadair CRJ200	2	Gulfstream GV[(a)]	1
Airbus 330	6	Cessna 402	1	Gulfstream 200[(a)]	1
ATR-72	2	Cessna 525	2	Hawker 800XP	4
Beech 400[a]	6	Cessna 560	13	McDonnell Douglas MD10	1
Beech 1900	10	Cessna 650	3	McDonnell Douglas MD11	1
Bell 407	1	Cessna 680	1	McDonnell Douglas MD80	42
Boeing 717	1	Cessna 750	26	McDonnell Douglas MD88	18
Boeing 727-200	2	Convair CVAC580	2	Saab 340	3
Boeing 737[b]	29	Douglas DC8	1	Skrsky 576	2
Boeing 747[c]	9	Douglas DC9	53	Not reported	8
Boeing 757[d]	28	Embraer RJ-120	5		
Boeing 767[e]	13	Embraer RJ-135	19	TOTAL	470
Boeing 777-200	7	Embraer RJ-140	1		

[a]Aircraft operated under 14 CFR 135, otherwise operated under 14 CFR 121.

[b]The model was specified for 23 of the 29 B737 aircraft as follows: three B737-300, ten B737-400, two B737-500, two B737-700, four B737-800, and two B737-900.

[c]The model was specified for eight of the nine B747 aircraft as follows: one B747-200 and seven B747-400.

[d]The model was specified for 16 of the 28 B757 aircraft as follows: 16 B757-200.

[e]The model was specified for ten of the 13 B767 aircraft as follows: two B767-200, five B767-300, and three B767-400.

TABLE 4—*Assessment of whether "top ten" aircraft types in the incident dataset are over or under represented as a function of the percentage of those aircraft types certificated in the United States.*

Aircraft Type	Number and Percentage of 470 Incident Reports	Number and Percentage of U.S. Certificated Aircraft (N=7524; BTS, 2005)	Aircraft Type Over or Under Represented in Incident Dataset[a]
Canadair CL600	54 (11 %)	data not reported (n/a)	n/a
Douglas DC9	53 (11 %)	257 (3.4 %)	over
McDonnell Douglas MD80	42 (8.9 %)	570 (7.6 %)	over
Embraer RJ145	38 (8.1 %)	675 (9.0 %)	under
Boeing 737	29 (6.2 %)	1299 (17 %)	under
Boeing 757	28 (6.0 %)	633 (8.4 %)	under
Cessna 750	26 (5.5 %)	n/a	n/a
Embraer RJ135	19 (4.0 %)	93 (1.2 %)	over
Bombardier Dash 8	17 (3.6 %)	88 (1.2 %)	over
McDonnell Douglas MD88	18 (3.8 %)	n/a	n/a

[a]Difference may not be significant

inventory data for U.S. certificated aircraft per the reporting requirement under 14 CFR 241.22 [36], the DC9, MD80, ERJ135, and Dash 8 aircraft types are overrepresented in the incident dataset, while the ERJ145, B737, and B757 aircraft types are underrepresented (Table 4).

Of the 470 incidents, 319 (68 %) were reported in-flight only, 116 (25 %) were reported during ground operations only, and 5 (1 %) were reported both in-flight and on the ground (Table 5). Phase of flight was not reported for the remaining 30 incidents (6.4 %).

Of the 324 in-flight incidents, the majority were reported during climb (42 %) or cruise (26 %) (Table 5). The operational impact of the in-flight incidents was considerable, with 57 % of the flights getting diverted to another airport (Table 6). An additional 6 % reported aborted takeoffs or emergency landings. There is insufficient information to determine the impact on flight scheduling for the remaining aircraft, but it not unreasonable to assume that many of the subsequent flights would have been delayed for maintenance staff to investigate the source of smoke/fumes.

Of the 121 ground-based incidents, the majority were reported during taxi (60 %) (Table 5). The majority of these flights either returned to the gate or never left the gate, and were reported as either delayed or canceled (Table 7).

Relevant SDR and AIDS Reports that Airlines Submit to the FAA

The industrial hygienist identified 1787 reports in the SDR and AIDS databases that included one or more of the search terms listed in Table 1. Of these 1787 reports, 300 met the inclusion criteria for air supply

TABLE 5—*Phase of flight when incidents were identified (N = 470).*

Ground Versus Inflight	Phase of Flight	Number of Events reported
Ground operations	At the gate	36
Ground operations	Inspection/maintenance	4
In-flight	Take off	36
In-flight	Climb	136
In-flight	Cruise	83
In-flight	Descent	31
In-flight	Approach	13
In-flight	Not specified	30
Ground operations	Landing	8
Ground operations	Taxi (in or out)	73
Not reported		30
TOTAL[a]		480

[a]Total exceeds 470 because six events were reported during two phases of flight and two events were reported during three phases of flight. There were 319 events that were only reported in-flight, 116 that were only reported during ground operations, five events that were reported both during ground operations and in-flight, and 30 events without any information on phase of flight.

TABLE 6—*Operational impact of events reported in-flight (N = 324).*

Operational Impact	Number of Flights
Diversion to another airport (including departure airport)	184 (57 %)
No reported change in flight plan and no reported emergency descent/landing (but typically maintenance-related delay for subsequent flight)	95 (29 %)
Aborted takeoff	11 (3.4 %)
No reported change in flight plan, but emergency descent/landing at arrival airport	9 (2.8 %)
Not reported	25 (7.7 %)
TOTAL	324

contamination (289 with oil and 11 with hydraulic fluid), 1226 did not, and 261 reports were forwarded to the mechanic for review. Of the 261 reports, 50 met the inclusion criteria for air supply contamination with oil and 94 reports were too generic to determine cause. In total, 350 events that airlines documented with the FAA from January 1, 2006 through June 2007 met the inclusion criteria for air supply contamination with oil or hydraulic fluid, and of these, 345 were identified in the SDR database and 6 in the AIDS database, with one of these being identified in both (Table 1).

In all, 119 of the 350 events reported to the FAA (34 %) involved AFA airlines, but AFA flight attendants only reported 16 of these events (13 %) to their airlines (per available documentation) (Table 2). A total of 11 of the 350 events reported to the FAA (3.1 %) were reported in the media (Table 2).

Flight attendant reporting to airlines and airline reporting to the FAA varies. Here is a comparison between reporting practices during this 18-month period at two major AFA-member airlines that voluntarily notify the union of events that either pilots or flight attendants report in writing to the airline.

- At “Airline A,” there were 33 documented events identified in one or more sources. Of the 33 events, the airline reported 13 to the FAA, the flight attendants reported 25 in writing to the airline, and the media reported on 4. Of the 20 events that the airline did not report to the FAA, 5 clearly met the SDR reporting requirements and all were diverted, indicating that the pilots were aware of the problem. In addition, 5 of the 20 unreported events met the SDR “all flights” reporting requirements involved smoke and either returned to the gate or never left the gate, suggesting the potential for compromised safety. It appears then that a total of 10 of 33 (30 %) reports met the SDR reporting requirements, although the airline failed to report them.
- At “Airline B,” there were 55 documented events identified in one or more sources. Of these 55 events, the airline reported 3 to the FAA, flight attendants reported 53 in writing to the airline, and the media reported on 4. Of the 52 that the airline did not report to the FAA, 6 clearly met the SDR inflight reporting requirements (involved smoke), and of these, 4 were diverted, indicating that the pilots were aware of the problem. In addition, 14 unreported ground–based events involved smoke and of these, 8 aircraft either returned to the gate or never left the gate, suggesting the potential for compromised safety, thereby meeting the “all flights” SDR reporting requirements. It appears then

TABLE 7—*Operational impact of events reported during ground operations (N = 121).*

Operational Impact	Number of Flights
Return to gate and delayed or canceled	62 (51 %)
No information provided on impact on flight plan or subsequent flights	47 (39 %)
Never left the gate and delayed or canceled	8 (6.6 %)
Emergency evacuation (some of these flights may have been canceled)	3 (2.5 %)
Emergency landing (event reported on the ground and inflight)	1 (0.08 %)
TOTAL	121

that at a minimum, a total of 14 of the 52 (27 %) reports met the SDR reporting requirements, although the airline failed to report them.

Incidents that Crew Documented with Their Airline and Crewmember Union

The industrial hygienist collected a total of 115 smoke/fume incidents involving oil or hydraulic fluid that AFA member flight attendants documented with their airlines (Table 2). Airlines reported 16 of these events to the FAA and the media reported on 10 of these events.

Relevant Newspaper Clips Identified in Online Searches

A total of 37 events were identified in newspaper clips identified in yahoo.com aviation news clips circulated by e-mail to AFA employees during the 18-month period (Table 2). Of these 37 events, 11 were also identified in a FAA database and classified as oil in the air supply events. Also, of the 37 events, 15 involved AFA airlines, and of those 15, 10 were reported by AFA members to their airlines.

Discussion

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

There are no national or international reporting systems to monitor the frequency with which oil or hydraulic fluid contaminates the air supply systems on commercial aircraft. Also, there are no published air quality data collected during air supply contamination events on commercial aircraft, and it is challenging for researchers to do so. For example, no U.S. airline would agree to allow its crewmembers to collect samples of airborne chemical contaminants as part of a recent Congressionally-mandated and FAA-funded research project [38]. This dearth of available data has limited the abilities of researchers to define the health impact of exposure.

The possible exception to the absence of unpublished air supply data involves an industry investigation into a series of BAe146 aircraft with a history of oil odors [39], although the supply air was passed through a charcoal filter before it was sampled which is highly atypical. During another air sampling survey, the APU manufacturer measured airborne TCPs at four times their limit for “APU acceptability,” although this detail was not reported publicly [40]. Some additional unpublished industry data refer to a passenger aircraft with a reported oil leak event in-flight that resulted in pilot incapacitation [17], identifying TCP isomers and triphenylphosphate [41].

There are some limited published bleed air sampling data for military aircraft. For example, TCPs have been identified on recirculating air filters [22] and airborne TCPs and PAN have been identified in flight decks [8]. These military aircraft were serviced with Exxon 2380 and Mobil Jet Oil II engine oils, both products used widely on the commercial fleet, and the bleed air design is the same on commercial aircraft.

The isomeric mixture of TCPs may vary between oil products and even between batches of the same product. It is proprietary, although it may contain as many as ten isomers, six of which contain mono- or di-ortho isomers that have been rated five to ten times more toxic than even the tri-ortho isomer of TCP [42,43]. The tri-ortho isomer is regularly mistaken as being the most toxic and is the only isomer with a published exposure limit, perhaps because of its high profile history, including an outbreak of paralysis caused by widespread ingestion of adulterated alcohol [44]. The only published studies that attempt to measure the health impact of exposure to these oils under controlled conditions assess the impact of ingestion or dermal exposure at sea level pressure on test animals’ motor function [42,45–47]. Controlled studies that assess the impact of inhalation exposure on acute and chronic neurological functions have not been published, despite the neurological symptoms reported by crew and passengers [10,48,49] and the recognized potential for this exposure on aircraft.

Without comprehensive or enforceable recordkeeping regulations, it is challenging to estimate the frequency of these events:

- Based on data from 3 airlines in the United Kingdom, members of the UK Committee on Toxicity recently estimated that pilots report smoke/fume events on 1 % of flight segments, and maintenance workers conduct engineering investigations into smoke/fume events on 0.05 % of flight segments, noting that the frequency of events may vary by airframe, engine type, and maintenance practices [37].
- A representative from the U.S. Flight Safety Foundation (FSF) recently estimated that five to ten aircraft per day are diverted around the world due to smoke/fume/fire events, most of them smoke [50]. This estimate was based on accident/incident research and discussions during international meetings with airlines and manufacturers, but the FSF could not estimate how many of these were caused by oil or hydraulic fluid. Other sources of smoke/fumes in the cabin/flight deck include in-flight fires, electrical faults, aerosolized deicing fluid, exhaust fumes, and carry on baggage. The presence of smoke/fumes from any source in the cabin/flight deck creates a potential health and safety hazard, but the focus of this discussion and analysis is fumes that contain engine oils or hydraulic fluids because of their inherent toxicity, as previously noted.
- In 2002, the U.S. National Research Council published the following frequency estimates for air supply contamination with engine oil or hydraulic fluid for a small selection of aircraft types, all presented as number of events per 1000 flight cycles: 3.88 for the BAe146; 1.29 for the A320; 1.25 for the B747; 1.04 for the DC-10, 1.02 for the MD80, 0.63 for the B767, and 0.09 for the B737 [5]. These estimates were based on several years of data from 3 airlines. To put these numbers in context, there were an estimated 10 556 000 departures on U.S. airlines in 2006 [51], so applying even the lowest frequency estimate of 0.09 events per 1000 flight cycles fleet-wide, for example, translates into 950 events per year in the U.S. fleet or an average of 2.6 events each day.

To date, investigations have highlighted the increased risk of air supply contamination on the BAe146 [5,14,19], B757 [12], MD80 [5], and A320 [19] aircraft types. Compared to the aircraft inventory data reported by U.S. carriers [36], the DC9, MD80, ERJ135, and Dash 8 aircraft types are overrepresented in the incident dataset, while the ERJ145, B737, and B757 aircraft types are underrepresented (Table 4). This comparison assumes that the number of operating hours for a given aircraft is comparable between aircraft types and, for the sake of simplicity, that a given aircraft is only involved in one reported incident (even though there are some instances of multiple reports on a single aircraft). Underreporting [34,35] is likely to influence the proportion of documented reports for a given aircraft type, especially if it involves a carrier with a particularly large and homogenous fleet. For example, underreporting by a single carrier that operates a large fleet of B757 aircraft may skew the data. As well, some of the documented investigations refer to aircraft certificated in countries other than the United States [12,14,19], and some of those aircraft may have different components (e.g., B757 aircraft in the United Kingdom are equipped with a different engine than B757 aircraft in the United States) and may be subject to different maintenance practices, for better or worse. For example, a collection of 1050 incident reports collected by a pilot union in the United Kingdom between 1985 and 2001 is dominated by the B757 and BAe146 aircraft, followed by the ERJ145 and the A320 [33].

Collecting reports from FAA databases, flight attendant reports, and newspaper clips is a starting point, but the total is guaranteed to underestimate reality for the following reasons:

- Limited access to FAA reports: The online searches of the SDR and AIDS databases are likely incomplete because of the inability to perform proximity searches, the wide variety of descriptors that airlines use to describe events, and the number of reports with insufficient information to determine cause. In addition, FAA mechanical interruption reports could not be reviewed for this analysis because the data are not publicly available.
- Airlines underreport events to the FAA: In 2006, the FAA distributed a bulletin to its inspectors stating that "it appears as though there are numerous air carriers/operators who may not have reported these [smoke/fumes in the flight deck/cabin] events as required by regulation" [35]. The bulletin directed FAA inspectors to improve airline compliance with SDR reporting, but there is no published evidence of improved reporting since then.
- Limited access to flight attendant reports: AFA only represents about half of the flight attendants in the United States so, at most, half of the contamination events reported by U.S. flight attendants

could be captured, assuming that that these events are neither more nor less common at AFA airlines. Further, this analysis relied on AFA members to send a copy of any incident report to their union because the majority of AFA airlines do not voluntarily share the reports with the union; however, AFA members are not required to report to their union.

- Flight attendants underreport events to their airlines: Underreporting by crewmembers can be intentional or unintentional. AFA members only reported 16 of the 119 incidents (13 %) that their airlines reported to the FAA (per available documentation, Table 2), even though the majority of the FAA reports (74 %) involved a visible indication of contamination or an odor (Table 1). If these data are representative, then approximately one-quarter of events are not characterized by a detectable odor or smoke/fume, and it may be a much higher percentage since those events without a detectable odor or smoke/fume are less likely to be reported in the absence of air monitoring. AFA members describe a high probability that the airline will not provide information on the cause of an air supply contamination event, and associated workers' compensation claims are typically denied and difficult to appeal in the absence of objective exposure data; all of these factors discourage reporting. It is also possible that some airlines either identified and addressed or reported events early enough that the degree of contamination was either not detectable in the cabin or was not serious enough to be associated with symptoms, such that there would be no need or motivation for flight attendants to report them.

Despite the limitations of the FAA databases, the data provide some important insights into contamination events:

- In many cases when smoke/fumes are reported, the cause is not identified until later, such that the source of the problem is not fixed, more passengers and crew are exposed, and a costly diversion may be necessary. For example, the crew on a B757 aircraft described "poor air quality in the forward and aft cabin [and] an extremely foul odor from packs after liftoff" but extensive maintenance troubleshooting found no evidence of oil leakage [52]. On that same aircraft, eight days (and 41 hours of flight) later, "very strong fumes" entered the flight deck from takeoff throughout climb [53]. Maintenance did finally identify three oil leaks and replaced the engine, but the second event could have been prevented had there been some objective indication of oil leaking into the cabin air supply on the earlier flight coupled with standard maintenance procedures to locate and fix the leak. Air scrubbers could have prevented the initial exposure and an automated alert system could have enabled maintenance to identify the problem before it got worse.
- Without monitoring equipment to assist in identifying the cause of smoke/fumes, maintenance workers cannot only take too long to identify the cause, but can miss a problem altogether. For example, the crew on a B747 aircraft "experienced thick smoke in the cockpit shortly after takeoff" and performed an emergency landing, but "could not duplicate smoke or determine a reasonable cause for the condition" [54]. Similarly, on an ERJ145 aircraft, "the flight crew noticed an unusual odor on takeoff" and donned their oxygen masks [55]. The odor dissipated but, during cruise, smoke entered the flight deck and cabin. The captain declared an emergency and diverted the aircraft. Maintenance spent three hours troubleshooting but "could not duplicate the problem" so the aircraft was released for service. Again, on climb out, a "distinct burning smell, and much stronger" entered the flight deck. The crew diverted back to the airport, but again, maintenance could not identify the cause.
- In other cases, maintenance workers are able to identify oil in the air supply immediately. A B757 crew described how after a "return to gate for smoke in cabin, [maintenance] found and cleaned oil in ducts as far as the APU fire bottle access door" and reported "oil puddling in lower sections of ducts and in flanges" [56]. The report notes that all ducts were checked and cleaned, presumably by performing a pack burnout.
- Currently, crewmembers' eyes and noses are the only sensors on board, but as this example illustrates, sense of smell is unreliable. The crew on an ERJ145 aircraft reported "smoke in the cabin that had an electrical smell," but upon inspection, the source turned out to be "a bad oil bearing on the number one engine" [57].
- Occasionally, SDRs will describe symptoms reported by crew and passengers. A report on a MD80 aircraft describes how the "flight attendants and passengers reported chemical smell/fumes in the aft cabin while en route [and] occupants complained about numbness in hands and arms and

shortness of breath" [58]. The crew performed an unscheduled landing, the system was inspected for "evidence of oil leaks" and the coalescer bags were replaced, but "no trouble was found at any location and the aircraft was returned to service."

- Finally, SDRs highlight some humorous and unusual causes of smoke such as a melting captain's hat hung on a map light that had been left on in the flight deck [59] and an air intake screen full of cicadas [60].

Despite the number of reports it receives, the FAA has few regulations in place to prevent air supply contamination with engine oil and there is limited, if any, enforcement of the regulations that do exist, in part because they are open to interpretation. For example, the FAA requires that aircraft systems be *designed* to "provide a sufficient amount of uncontaminated air to enable crewmembers to perform their duties without undue discomfort or fatigue and to provide reasonable passenger comfort" (14 CFR 25.831(a)), that the air be "free of harmful or hazardous concentrations of gases or vapors" (14 CFR 25.831(b)), and that any maintenance work restore the aircraft to its original (i.e., design) condition (14 CFR 43.13 (b) and (c)). The FAA also requires that systems be designed and operated to maintain ambient carbon monoxide levels below 50 ppm (14 CFR 25.831(b)(1), 14 CFR 121.219), and that, during operation, each passenger or crew compartment be "suitably ventilated" (14 CFR 121.219). The spirit of the regulations is clear: the air supply must be clean and plentiful enough to not adversely affect either the health or comfort of the aircraft occupants. The regulations do not distinguish between "normal" and "failure" conditions or how foreseeable a given event may be. However, the regulations include subjective words like "sufficient amount," "undue discomfort," and "harmful or hazardous concentrations." Presumably, diverting a flight or donning oxygen masks implies undue discomfort or unacceptable hazard, as does airline occupants needing to be taken to hospital upon arrival. More difficult to define or prove, however, may be an unpleasant odor inflight accompanied by discomfort that is not "undue" but is unpleasant, or chronic neurological symptoms with a delayed onset. Ultimately, no objective criteria for aircraft air quality have been defined, either in the regulations or elsewhere.

The fact that 57 % of the events reported in-flight resulted in diversions (Table 6) and the majority of the ground-based events resulted in delayed or canceled flights (Table 7) is important because it suggests a business case for preventing these events with improved maintenance practices, air cleaning equipment, and investment in sensor equipment designed to identify an event in its early stages. The average cost of a diversion has been estimated between $22 000 and $207 000, varying by size of aircraft, the need for an overnight stay for grounded passengers/crew, and necessary ground time to troubleshoot and fix any mechanical failure [61,62].

Various technologies have been considered for cleaning the outside air supplied to commercial aircraft, including disposable carbon adsorbent filters, photocatalytic oxidation, catalytic converters, nonthermal plasma oxidation, and high temperature particulate filtration [63,64]. Additional control measures to prevent air supply contamination have been recommended, in conjuction with continuous monitoring for a chemical compound indicative of air supply contamination with immediate feedback to the flight deck [65].

Conclusion

The outside air supplied to the cabin and flight deck is first processed in the engines or APU where it can be contaminated with pyrolyzed engine oil or hydraulic fluid. The only exception to this rule is the B787 that is scheduled to enter service in 2009 and will rely on a nonbleed air system, both on the ground and in flight. This analysis identified an average of 0.86 events per day over an 18-month period, which is certain to be an underestimate for the reasons stated above. To this end, the frequency and potential severity of air supply contamination events present both an obligation and a business case for industry and regulators to develop and enforce preventive and remedial measures.

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