Anatomy of an occupational hazard: Cabin air contamination in the air transportation industry
Part 5. Carbon monoxide—how it forms in aircraft engines

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This paper outlines the production of carbon monoxide in jet aircraft. Given that CO is a product of incomplete combustion of carbonaceous material, the obvious sources would appear to be the gas turbines—the main engines and the auxiliary power unit. Nevertheless, leakage of CO from the planned combustion of jet fuel in its chamber seems unlikely. On the other hand the route from turbine lubricating oil into the bleed air pressurizing the flight deck and passenger cabin is already established. We look in detail at the lubricating system. High temperatures, otherwise harsh conditions and the not infrequent occurrence of transient fires within the sumps favour the production of CO from the oil.

1. INTRODUCTION

We have identified carbon monoxide, some would say prematurely, as the cabin air toxin of most concern [1]. Nothing in society in general or in the aircraft cabin in particular comes close to CO in its combination of likelihood of occurrence, concentration and toxicity—hence potential danger—as carbon monoxide. Naturally then, as a next step we wish to examine how CO forms in the engine bearing sumps and how it may contribute to the cause and effect of toxicity in the cabin.

Carbon monoxide (CO) is a poison [2]. It kills and disables more people than any other toxic compound. It is, therefore, the most studied. As long as a victim's feet are on the ground, someone, somewhere has studied it; peer-reviewed literature addresses every instance of its occurrence from every angle imaginable. But once a person leaves the ground on an airplane, the literature stops. No information exists to help us understand the why and how of CO at high flying altitudes. We must sort it out for ourselves.[1]

CO poisoning is hypoxic, not anoxic. The affinity of haemoglobin in red blood cells to bind with CO is about 240 times stronger than for oxygen (O_2). When a person becomes surrounded by and breathes into the lungs the odorless, tasteless and colourless poison, O_2, which continues to be inhaled, is shunted aside in favour of CO. Until the victim escapes from the toxic environment, blood carries the poison throughout the body, depositing it in skeletal muscle, the heart muscle, the brain and the nervous system. CO binds to myoglobin [3], the oxygen storage protein in muscle; myoglobin has a similarly higher affinity for CO than for oxygen.[2]

When a flight attendant closes the door prior to departure in a commercial airliner, the aircraft becomes an air-conditioned pressure vessel. Arguably, clean air can be expected on most flights; it is, after all, the #1 requirement for a safe and enjoyable trip. Nevertheless, the past thirty years of experience of crew members and passengers indicate that clean air is not always available.

2. HOW IS CARBON MONOXIDE PRODUCED IN JET AIRCRAFT?

Until now, investigators from outside the airline industry have never written about *production* of CO on aircraft. If engineers within the industry have investigated this phenomenon, they have kept the data confidential.[3] They (and their managers) have not, apparently, acted to bring the process under control. Complete combustion of flammable carbonaceous material produces nontoxic carbon dioxide and water. When temperatures are high enough to begin the combustion process but not high enough to assure complete combustion, or when oxygen is relatively lacking (including the case of inadequate mixing of fuel and air [3]), CO is formed.

Two systems exist on aircraft where CO can be produced: the auxiliary power unit (APU) and the main engines that provide thrust to propel the aircraft. The

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[1] The US Federal Aviation Administration, at least, has been aware of the potential occurrence of CO in general aviation, having issued Advisory Circular 20-32B, "Carbon monoxide (CO) contamination in aircraft—detection and prevention", in 1972. This replaced the earlier Advisory Circular 20-32A from 1968. Strangely, CO contamination never appears to have been considered a problem in commercial jet aviation.

[2] Haemoglobin is, essentially, a tetramer of myoglobin. Binding of oxygen to the latter is not, however, coöperative.

[3] Hung (1993) investigated the matter in stationary gas turbines [4]. We also note more recent studies [5,6].

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latter are usually wing-mounted engines.[4] The tail-mounted APU is a turbine engine-driven system that uses the same oil and supplies compressed air in much the same fashion as the main engines.[5] The APU is used primarily on the ground to provide air conditioning, electric power and compressed air for starting the main engines. Located high above the tarmac in the tail of most aircraft, the APU is not in a handy place for regular maintenance inspection.

When not inspected for extended periods of time oil leaks can occur unnoticed. Ducting leading from the APU into the main distribution duct can become fouled. When this occurs,which may be more common than we know, oil residues in the main duct can continue to taint cabin air while airborne. It is unlikely that this type of contamination includes carbon monoxide.

2.1 The engine lubricating system

In the schematic diagram (Fig. 1), imagine a molecule of oil as it travels from the bottom of the oil tank along the ochre route through the oil pump and supply filter directly to the compressor bearings, turbine bearings, and the accessory gearbox (within the black engine silhouette). After the lubricating job is done, oil is scavenged (brown route) through boost pumps, a filter, the fuel/oil heat exchanger, and back to the tank (reservoir).

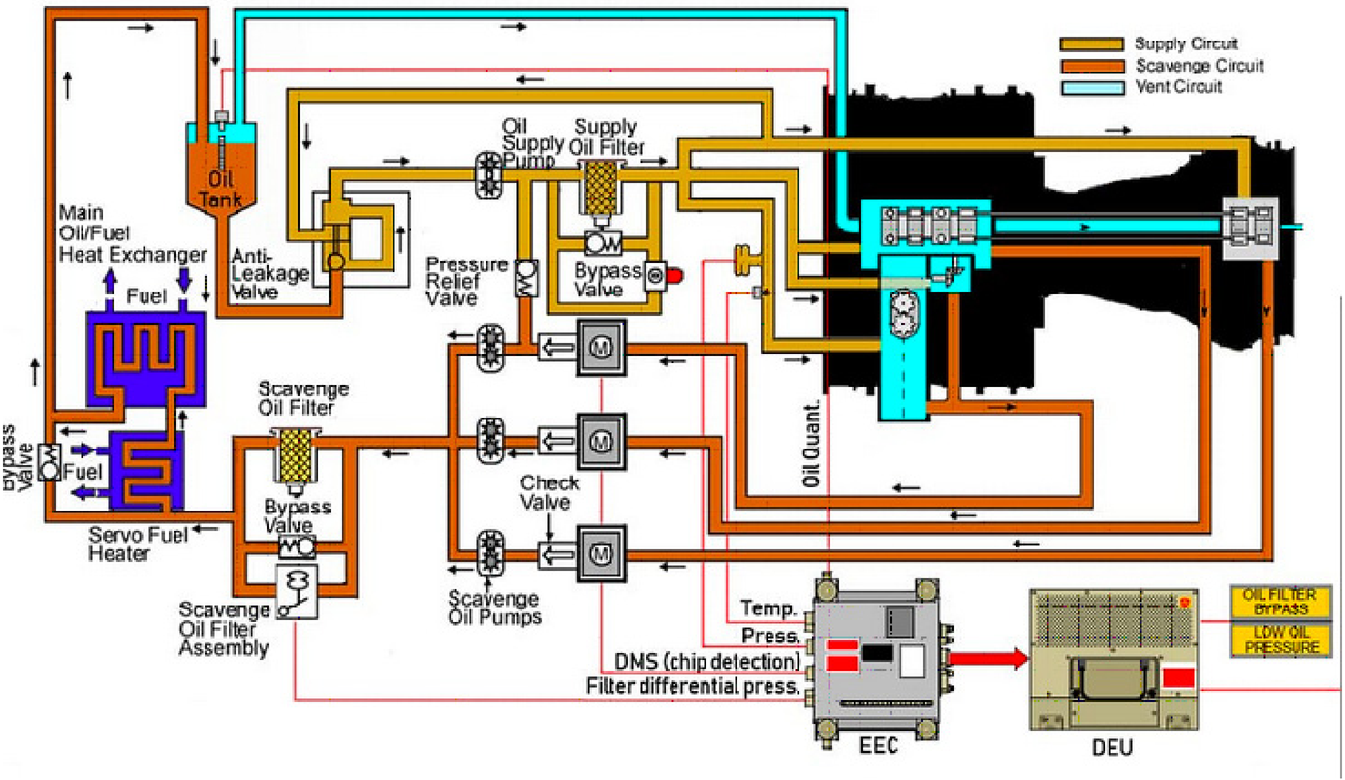

Figure 1. Jet engine lubricating system (see text; colour online). EEC denotes electronic engine control.

2.2 Basic configuration of an aircraft turbine engine

The heavy rotating central shaft or shafts (double-hashed lines in Fig. 2) carry multiple stages of compressor and turbine assemblies at speeds varying by engine model, but typically 13,000 rpm; foreword fan speeds are typically 3,500 rpm.[6] Bearing assemblies are arranged along the central shaft, each located within housings (i.e., sumps) designed to contain lubricating oil at a system pressure of about 45 psi.[7] Depending upon engine model, one or several sumps contain bearings for the aft turbine shaft, one or more for the compressor shaft(s).

[4] A video showing how bleed air works and how contaminants from engine oil can invade the cabin can be found at https://www.youtube.com/watch?v=ETRZDsgjEvE

[5] https://www.aviationmatters.co/what-is-aircraft-auxiliary-power-unit-apu/ is a useful guide.

[6] For shaft speeds, see https://simpleflying.com/aircraft-engines-rpm-guide/

[7] For oil pressure, see https://www.aircraftsystemstech.com/p/turbine-engine-oil-system-maintenance_97.html

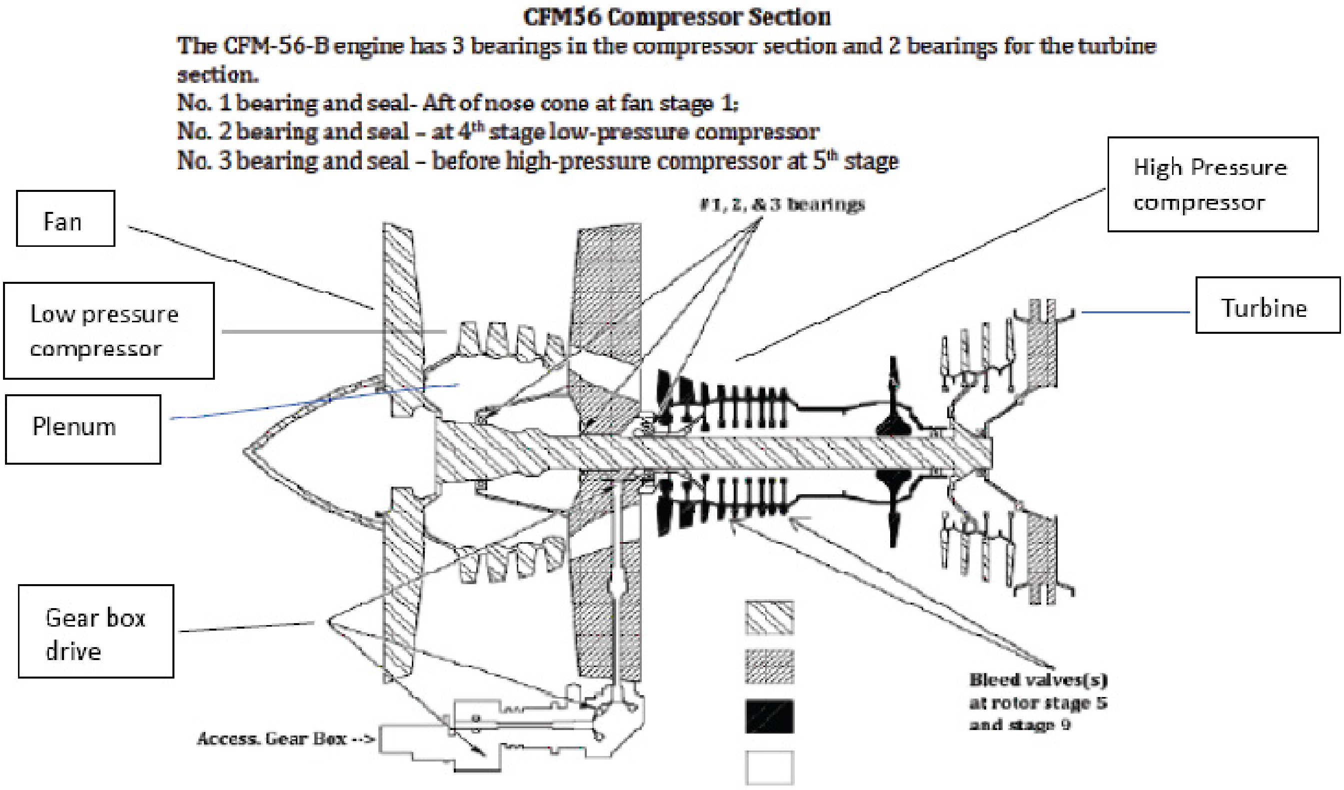

Figure 2. Cross-section of the single-shaft CFM56 high-bypass turbofan engine, showing bleed valve configuration with respect to the forward bearings and bearing seals.[8] See also main text for further explanation.

While oil, gases and particulate matter can leak from any sump, the compressor shaft bearings located upstream from the compressor bleed valve are of most concern; these are the locations whence contaminants can most easily find their way into the aircraft cabin. Fig. 2 indicates that there are two and possibly three bearings upstream from the low- and high-pressure bleed valves.[9]

When the occasional seal or bearing failure occurs, or a seal wears out because of utilization beyond its designed useful life [8], we can imagine carbon monoxide formed by incomplete combustion leaking outward through faulty or worn seals into the plenum outside the sump. We might also imagine oil creeping upstream of air entering the inner sump compartment when the pilot reduces power at the start of descent. In addition, oil can escape through seals located within the lubricated central shaft.

Once outside the sump, contaminant-laden air will leave the plenum (essentially an "empty", i.e. air-filled, compartment, shown above and before the #1 bearing in Fig. 2). CO will enter the empty plenum and escape from between the compressor rotor-retaining disks into the front stages of the compressor airstream, which is flowing very fast, accelerating, and being compressed through the 9-stage compressor. From the location of the first four, low-pressure compressor stages (hash-lined blades in Fig. 2) to the location of the intermediate (5th stage) bleed valve located half-way through the high-pressure compressor stages, some of the contaminants, including CO, must cross the gap from the inside (the compressor core) to the outside (the compressor shroud or casing), where the bleed valves are located. Hence some CO, having crossed the airstream, will be extracted through the bleed valve. Once extracted, the route to the cabin and flight deck is assured; cabin occupant exposure to CO gas will be assured.[10]

2.3 Anatomy of the bearing sumps

Air, oil and high temperature first become combined in the bearing sumps. Although seals located throughout the engines can wear, crack, otherwise fail and hence leak oil, we are concerned only with the foremost bearing sump(s) of the forward-located compressor section.

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8 Regarding turbine engine bearing seals, see https://www.aviationpros.com/engines-components/aircraft-engines/turbine-engines-parts/article/10252336/turbine-technology-turbine-engine-seal-applications

9 See also ref. 7.

10 See https://www.youtube.com/watch?v=xknOx-6_zqU (compressor rotor assembly).

Depending upon the specific engine design, this sump and any other sumps closest to the air intake and upstream from the bleed valves can compromise the quality of cabin air. This is where sump air seal integrity is essential.

Referring to Fig. 3, oil is sprayed through the oil jet directly onto the spinning roller and ball bearings that support the rotating core shaft. Temperatures are said to be less that 1700 °C in this, the #1 (front) bearing sump. Oil temperature averages 220 °C. Sealing air, indicated by X in Fig. 3, will have the temperature of the 5th stage bleed valve, about midway along the 9-stage compressor (for the CFM56 engine). The air moving inward across the seals meets the oil spray in the bearing inner compartment. This establishes the first (and most favourable) point where combustion of carbonaceous material can occur. Considering the continuous, very dynamic oil and air flows transiting in and out of this small chamber, combustion time will be very short. Weighing the combined temperatures of bearing sump, oil spray, sealing air and the seconds available for combustion before air is vented out at the top of the sump and oil is scavenged from the bottom, production of carbon monoxide would seem to be possibly continuous and certainly reasonably likely to occur at times.[11] Oil is required expressly for the purposes of lubricating and removing heat from the few mechanical parts of the engine. The sumps contain the highest temperatures and pressures in the engine except for the combustion section itself.

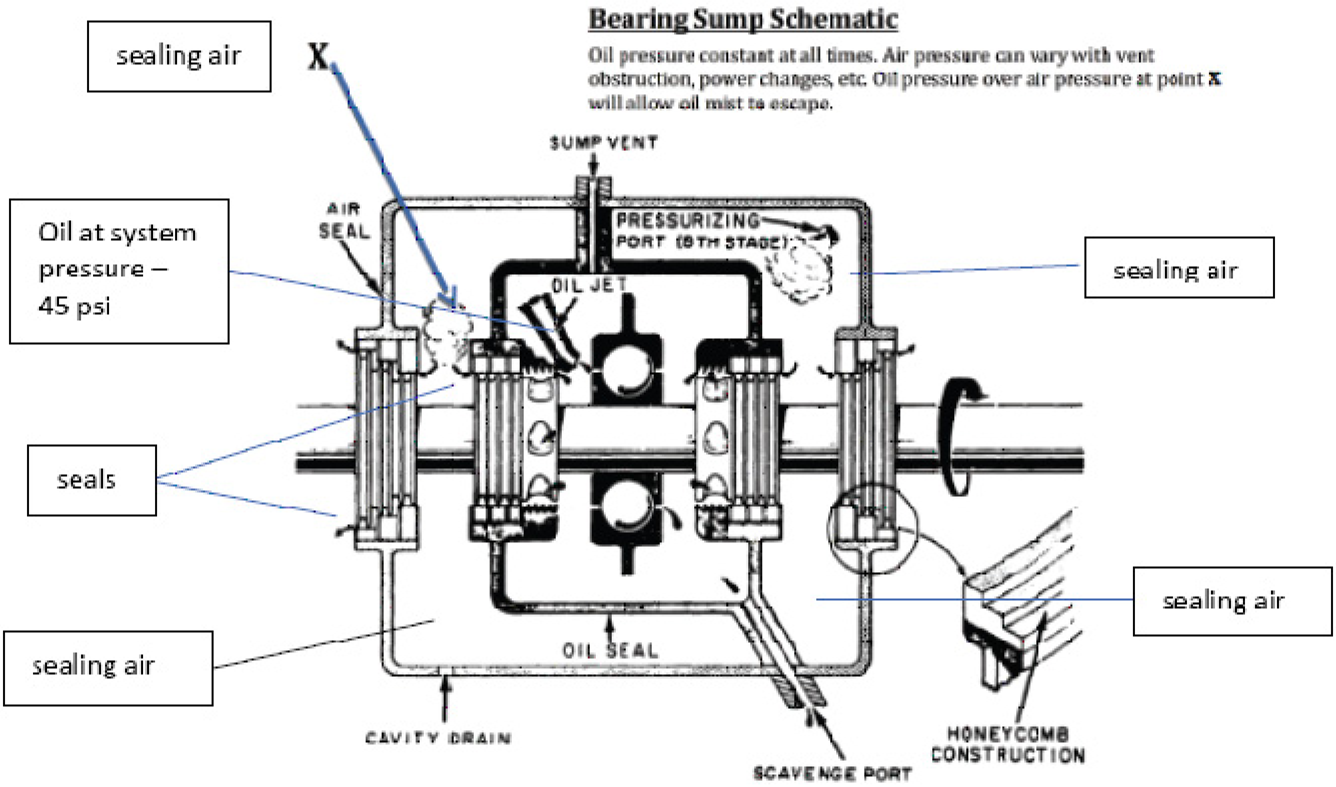

Figure 3. Schematic diagram of a bearing sump (see text).[12]

3. ENGINE FIRES

Circumstantial evidence—symptomology—from flight attendants and pilots before 2017 made the case for carbon monoxide as the toxic substance emanating from engine oil most affecting air travelers; speculation, but little actual research from scientific institutions, could be found to support the proposition; confidence in the identification of CO as the main causal agent subsequently emerged. In the 2020s, a university institute researching modern turbine engines, not for human health and safety purposes but to better understand engine performance limits in supersonic military applications and other scenarios pertinent to civilian use, provided the missing evidence incidentally relating to human health and flying safety.[13] In the following sections, heavy reliance is put on that work.

[11] See §A1 concerning the frequency and severity of seal wear.
[12] For a similar diagram, see T.W. Wild, *Aircraft Powerplants* (9th edn), Fig. 14-11. New York: McGraw-Hill (2018).
[13] Graz University of Technology (Austria), "Aeroengine safety". See https://aeroenginesafety.tugraz.at/doku.php?id=9:92:92, updated to January 2023. The Table of Contents lists 25 separate sections covering many individual issues and components of

3.1 Oil fires

Over the last several decades the vast majority, if not every, turbine engine research and investigation project failed to consider that an "unfriendly fire"[14] could occur within turbojet and turbofan engines. It is a wonder that professionals who were examining smoke, odours and fumes on aircraft did not recognize that where there is smoke there is likely to be fire. It is actual fire that creates products of combustion, also created by partial combustion of carbonaceous oil. These products (soot, sludge and adherent deposits at and around bearings) accumulating within the lubricating system clog the filters and degrade efficient engine performance. Their accumulation accounts for the increasing frequency and severity of occurrence of smoke, odours and fumes in cabins and on flight decks on all bleed air-served aircraft. If ever a reason for manufacturers to build more bleed-free aircraft was recognized, this is it!

3.2 Oil sump fires

During operation (i.e., flight), temperature and thus the risk of an oil fire in an engine increases. In other words, the risk of oil sump fires is increased by the high operating temperatures in flight. The shaft seals of the main bearing chambers are critical components; fires consume ignitable oil–air mixtures in the bearing chambers. As oil temperature rises generally, a small, sudden temperature increase may be sufficient to initiate an oil sump fire. Synthetic aviation oils self-ignite above 260 °C.[15] The oil can be present as either vapour, mist or larger drops. Oil fires can have a variety of appearances and temporal progression (both short and prolonged fires have been observed in bearing chambers). The burning of oil typically results in intensive fire that can overheat large cross-sections in short interval. It can generate coke deposits that can cause blockages of return oil tubes and filters and damage bearing tracks.[16]

3.3 Metal fires

Metals can burn in the presence of aerial oxygen, albeit with wide variation of facility of burning across metals. Due to the high pressure and/or high air speeds in engines, the rear compressor region and labyrinths (seals) contain enough oxygen to ignite and sustain a metal fire. The most commonly encountered relatively ignitable materials in engines are titanium alloys (Fig. 4), albeit little investigated until recently.

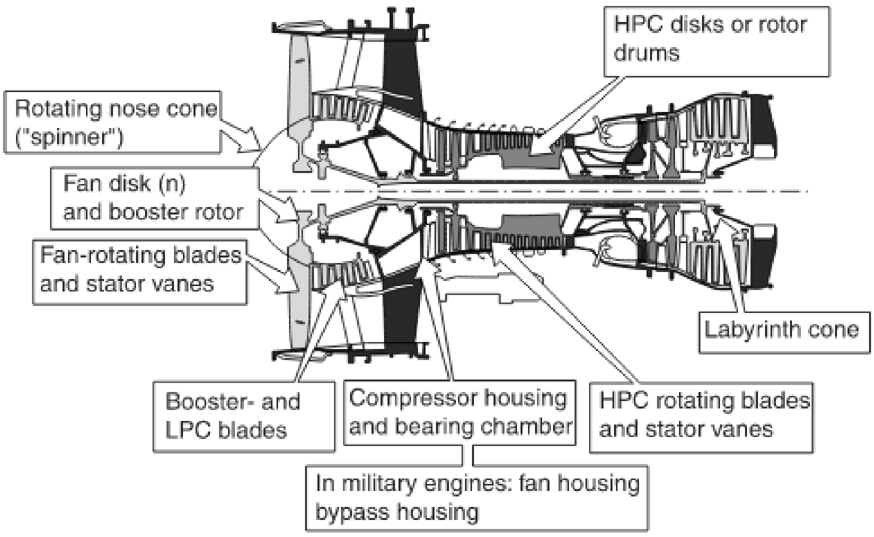

Figure 4. Typical titanium structural parts in a large commercial turbofan engine with a high bypass ratio (from §9.1.1[13]).

modern turbojet engines used in civilian and military operations. Those of the greatest present interest are: §§9.0 "Fires and explosions" (especially subsections 9.1 "Metal fires" and 9.2 "Oil fires"); 7.0 "Rubbing and maintaining clearances"; and 19 "Maintenance", which should be referred to for more detail.

[14] Defined as a fire occurring within a contained area that can occur occasionally, intermittently and without warning. The fire itself will usually remain safely contained while toxic products of combustion may escape to endanger locally exposed individuals or populations. It contrasts with "friendly fire" (in insurance and military contexts), which is fire deliberately set and remaining contained, as in a fireplace or boiler, from which any resulting loss cannot be claimed as an insurance liability. Friendly fire also denotes action by one's own forces during military combat, causing damage near or casualties to one's own troops, and therefore hostile by effect if not by intent.

[15] See "Aeroengine safety" (where it is called self-ignition).[13] The estimate given in Part 4 (pp. 65–80 of this issue), §A2.1.1 is presumed to have come from oil manufacturer testing.

[16] See §A2 concerning the question how often bearing sump fires occur.

3.4 Titanium fires

In order to ignite a titanium alloy, abundant oxygen must be present and the metal temperature must reach about 1600 °C. The initiating factor may be mechanical rubbing due to clearance losses (e.g., from thermal expansion). Bearing damage can lead to serious rubbing occurrences. The fairly stringent requirements of sufficient temperature and air pressure and/or flow speed with suitable flow conditions at the point of ignition ensure that subsequent burning does not usually exceed a few seconds in duration. Nevertheless, the intense heat generated by a titanium fire (oxidation is highly exothermic) even if of this short duration at a labyrinth seal location in the presence of oily substances fed by sealing air under pressure has the potential to wreak considerable damage on the seal and its immediate environment.

4. FUME EVENTS IN PERSPECTIVE

Temperature variations within the sump determine the probability of ignition of the oil, in combination with its concentration and that of oxygen (i.e., its pressure). The conditions found during flight at altitude are significantly different from those at ground level, which accounts for the failure of maintenance troubleshooting teams to duplicate the combustion process when a fume-compromised aircraft returns to its starting airport soon after takeoff, or diverts to an unscheduled emergency landing, or arrives at destination. Hence, compromised aircraft are consistently cleared for flight, with the best of intentions, and return to revenue service, where more and more human occupant health is placed in jeopardy since in flight the conditions for small engine fires and CO generation recur.

If starting time, place, ending time, air pressure, meteorological conditions and aircraft configuration during a fume event were carefully recorded, one might avoid a recurrence by avoiding the particular combination associated with an event; changing the parameters would seem to offer some control over the situation. This is an unlikely proposition for the following reasons:

(a) Under conditions engendering cabin air contamination, sometimes odorless carbon monoxide will occur alone, without accompanying telltale smoke, haze or odour from the (partial) combustion of oil constituents. Overcoming this issue will require accurate air quality sensors targeting CO placed throughout the cabin and flight deck.

(b) Meteorological conditions are hardly ever identical from place to place and from epoch to epoch. Often this variability will not be significant, but sometimes it will.

(c) Without exact knowledge of all relevant parameters, creation of carbon monoxide is unpredictable. Similar, but not identical, conditions can occur to create CO within differing environments.

(d) The aging process and diverse maintenance protocols for aircraft systems creates a constantly changing set of conditions affecting, *inter alia*, cabin air purity.[17] Investigators suspect small, undetectable amounts of contamination exist most of the time on aircraft. Whether they are below threshold for triggering adverse health effects is a presently unresolved question.

[17] See also §A3.

5. CONCLUSIONS

Taking cognizance of strong evidence of carbon monoxide poisoning suffered by many ill and disabled airline crew members and some passengers, investigators have been confronted with the inference that the air in human occupied areas of commercial aircraft is at times unsafe. Nevertheless, many have failed to believe, and some still disbelieve, that such a condition can occur in aircraft, a view seemingly encouraged by airline authorities, which everywhere have receded into a background of self-protectionism to avoid public disclosure.

Meanwhile, investigators and researchers sought facts to demonstrate or refute the unsafe condition. More than two decades have been necessary to accomplish this feat. The story is now told with confidence. We understand how oil and pressurized bleed air come together to create toxic fumes in the very hot bearing compartments of modern, high-bypass turbofan engines.

Carbon monoxide production is in itself a thoroughly studied, chemically simple process that long ago—since the time of Prometheus—became the most dangerous cause of chemical pollution death in society. Now the challenge is to find and implement a practical solution for the benefit of air travelers, whether pilot, cabin crew or passenger, everywhere.

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APPENDIX

A. SOME OPEN QUESTIONS

A1. What is the frequency and severity of seal wear?

Have investigators found reliable statistics to enable a failure rate for bearing sump seals to be established? With deregulatory loss of official oversight went statistics, statistics of any nature. Perhaps they still exist somewhere within the proprietary files of airlines.

From previous investigations and reference materials, it can be deduced that complete oil seal failure ultimately leads to bearing failure. This condition seldom occurs but when it does will require replacement of either the main engine or the APU [9]. Shabbir et al. advocate the creation of an open-source database to monitor seal failures and replacement [10]. This will be an exercise in frustration.

Airline managers check oil periodically during stops along the way each day. If the oil level is low, they are supposed to record the amount of new oil used to top up the reservoir. I am personally aware that the maximum daily oil loss for the B737 was 6 quarts per day at one airline. After 6 quarts the aircraft was supposed to be removed from service, but I doubt that ever happened. Oil depletion is strictly an internal exercise that will not be dependably recorded.[18]

MRO (maintenance, repair & overhaul) requires aircraft downtime for an engine change. Overhaul is estimated to cost more than $3,000,000 for a high-bypass engine. Overhaul or tear-down to replace just the seals is unlikely because the effort may leave the engine with other time-sensitive parts remaining in place. Inspections that may lead to engine disassembly may simply not be accomplished. Apart from the engineering cost, there is also the cost in lost revenue—of the order of $100,000 per flight on average in North America.

The present author has repeatedly asked manufacturers and their customers, the air carriers, to put fume and smoke sensors in aircraft systems and the cabin and flight deck. They refuse to do so. This is probably because of fear of customer backlash—refusal to fly.[19] The cost of aircraft diversion to an emergency landing each time a pilot responds to the sensor warning comes off the asset bottom line. Keeping the aircraft flying is the call from on high. That pilots do not have early warning of a pending threat to flying safety does not appear to executives to be a problem. Money always drowns out common sense.[20]

A2. How often do bearing sump fires occur?

One might suppose that the engine fails, but ordinarily it does not. Sump oil fires usually remain within, or mostly within, the very small compartment containing the high-speed rotating shaft bearings. We can call these fires "unfriendly". They do create products of combustion in the sump that over time reduces engine performance. Without honest opinions from powerplant engineers, however, we cannot say for certain whether these fires are precursors to "hostile" fires, which escape their secure confines and threaten surrounding areas.

[18] See also ref. 11.
[19] Cf. ref. 12.
[20] The US Civil Aeronautics Board, now disbanded after having been considered to have become obsolete [13], considered these things and covered them using carefully constructed and then dictated ticket prices. These prices covered all essential operating costs, including thorough maintenance.

As recently as February 2023 Delta Airlines, and in April or May 2023 American Airlines (AA), have had fires that escaped the turbine sections of the engines during takeoff or in flight.[21] The fires in these occurrences might have originated from turbine section bearing sumps. From corroborating pictures taken from passenger windows on each of the aircraft, the flames apparently entered and were ushered overboard within the exhaust emissions. This seems apparent because they appear to be localized just under the trailing edge of the wing. The wings were not on fire, therefore I suppose the actual fire did not escape from the engines to threaten the rest of the aircraft. In February 2021, United Airlines Flight 538 had a "hostile" fire.[22]

How often does this happen? No one outside the airline industry knows; perhaps the FAA knows. We surmise that unfriendly fires are not rare occurrences. But they rarely become hostile while nevertheless creating toxic fumes and smoke. Accident statistics are readily available; fatal accidents within commercial operations are statistically rare. The hottest part of a turbine engine is the burner section. Here, ignition of a fuel–air mixture is deliberate, necessary for the production of thrust that makes flying possible. Such fires rarely escape the burner section. The second hottest area (other than the turbine section airstream) is found within the bearing sumps (housings). Air seals that contain oil at each of two to four turbine bearing sumps and one to three compressor bearing sumps (estimated numbers of sumps over many engine makes and models) may emit fire after catastrophic failure of the seals or bearings. This will compel an emergency response from pilots.

Contained sump fires nevertheless create toxic emissions. If seals are sound and within designed tolerances nearly all toxic fumes will be vented harmlessly overboard. If gradual degradation of the seals over excessive flight hours and cycles of use has occurred, then these toxic emissions can find their way into the environmental control system that supplies the cabin and flight deck with air to breathe.

Note that aircraft have engine fire control systems. Typically when an engine overheat occurs within an operating engine, temperature sensors immediately send a blinking light signal to the fire control 'T' handle or button at the pilot stations. If an *engine fire*, the warning light comes on steadily. A loud audio signal accompanies the light.

A3. Surely there is correlation between engine maintenance and fume events?

If correlation exists, it is not officially available from inside the industry. Air carriers, manufacturers, maintenance contractors and government regulators are presumably aware of the possibility, but consequential investigation is absent.Indeed, crew members report that the FAA has never investigated a fume event.[23] Academic researchers and independent investigators have observed and investigated and the situation can be summarized as follows. The airline industry operates under existential threat, fearful of authoritative public disclosure of unflattering facts that could lead to a collapse of passenger traffic.[24] Due to the ferocity of ticket price competition, industry leaders engage in relentless, systemic cost-cutting in order to assure low airfares. This leads to inadequate operating revenue that creates continual operational uncertainty. This uncertainty in turn begets unintended consequences, which takes our story back to the root and proximate causes of contamination in aircraft that were originally imposed by uninformed, unwitting lawmakers when they deregulated the airlines [13].

[21] My son-in-law was scheduled to fly on the AA flight. He is now a believer in the financial plight that seems be hamstringing the industry.

[22] These fires are rarely lethal. I cannot think of a catastrophic engine fire-related accident since United Airlines Flight 232, Sioux City, Iowa in 1989. See https://www.youtube.com/watch?v=dCTrs9mKmhc

[23] For example, I am aware that senior FAA officials refused to investigate a serious case of two-pilot incapacitation that nearly ended in disaster. They simply grounded the pilots and walked away.

[24] Cf. the bovine spongiform encephalopathy (BSE) epidemic that caused the collapse of the beef market [14].