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Anatomy of an occupational hazard: Cabin air contamination in the air transportation industry
Part 6. The atmosphere

J.M. Lind[*]

CPCU ARM (USA)

This paper examines the overall environment in which exposure to cabin air contamination occurs, namely the atmosphere. The primary toxin is presumed to be carbon monoxide, as established in the preceding parts of this series, for which occupational exposure limits have been established to the terrestrial workplace, assumed to be at or close to sea level, with scant regard paid to altitude-specific modifications appropriate to the aircraft cabin working environment. Relevant features of that portion of the terrestrial atmosphere encountered in flight are reviewed. Given the dearth of data concerning carbon monoxide intoxication in large passenger aircraft (jetliners), work on similar hazards encountered by high mountain climbers is reviewed. Adventitious combustion in the engine, and salient features of air compression within it, are reviewed. The tabulated International Standard Atmosphere is used to estimate actual oxygen availability at flight cruise altitude. The degree of its diminution, relative to sea level, seems to have been hitherto disregarded. There are significant human health implications: CO production is greater than might have been expected, and the severity of the consequences of its inhalation under conditions of mild hypoxia, especially for those engaged in strenuous physical activity, appears to have been overlooked.

1. INTRODUCTION

So far in the series of articles that define the hazard, we have reviewed its history [1], the root cause of contaminated cabin air [2], proximate causes [3], the contaminants [4], and the hardware that causes the hazard [5]. The present Part 6 explores the overall environment where the exposure occurs.

2. THE ATMOSPHERIC ENVIRONMENT OF COMMERCIAL AIR TRANSPORTATION

Engine oil and related vapour leaks that foul cabin air while aircraft are parked or during taxi between gate and runway occur under the same ground level atmospheric conditions that exist for the local residential, industrial and commercial community (including the presence of, typically, much terrestrial pollution from vehicular traffic). If line maintenance personnel need to replicate the conditions that caused a recent, ground level, engine- or APU[1]-related cabin smoke or fume event, they can do so with reasonable certainty of success.

Climbing out from the airport, atmospheric conditions are constantly changing. Temperature, pressure and air density fall rapidly during the climb. Humidity, turbulence and high-level industrial pollutants all have an influence. And by the time a modern airliner reaches the top of its flight profile it is cruising above almost 80% of Earth's atmosphere (by mass)—over 80% of the air we need to breathe to stay alive. Therefore, in-flight fume event conditions *cannot be reliably duplicated on the ground*; hence it is futile to attempt line maintenance investigations; even an (emergency) C-check on the ground may fail to find anything; the condition must be dealt with at a more fundamental level of redesign.

3. THE TROPOSPHERE[2]

Aircraft fly within the troposphere, the lowest layer of the atmosphere (Fig. 1). The troposphere, or "trope" as meteorologists call it, rises from the surface to an average altitude of 10–11 km. It is the only level of our many-layered atmosphere containing moisture. Temperature and pressure decrease at rather uniform and unchanging rates up to the tropopause, an imaginary barrier between the two lower atmospheric layers, troposphere and stratosphere.

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[*] E-mail: crewadvoc8@yahoo.com

[1] Abbreviations: APU, auxiliary power unit; ECS, environmental control system; fasl, feet above (mean) sea level; HPC, high pressure compressor; ISA, international standard atmosphere; LPC, low pressure compressor; OPR, overall pressure ratio; SSC, single stage compression; TBO, time between overhaul; TCP, tricresyl phosphate.

[2] https://spaceplace.nasa.gov/troposphere/en/

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From the tropopause a short distance upward to the ozone layer the temperature remains the same at about –57 °C.

The tropopause is highest at the equator (almpst 20 km), lowest at the poles (~ 6.7 km).

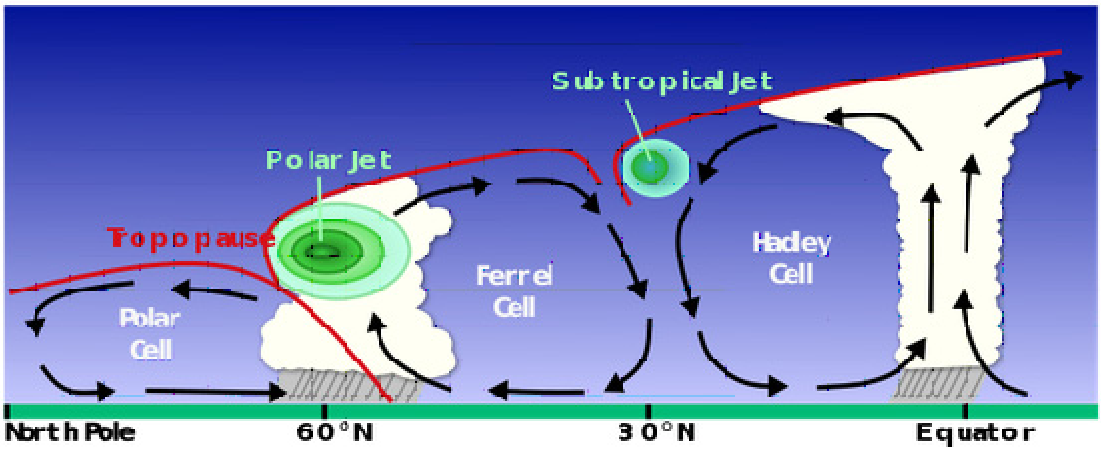

Figure 1. Various features of the troposphere.[3]

4. FACTORS PERTINENT TO HUMAN HEALTH

Aircraft occupants, specifically flight and cabin crewmembers and passengers, are directly exposed to residual contamination the moment they enter an aircraft. Particulate matter derived from oil vapour that has been subjected to high temperatures in the lubricating system [5] may be found in residual quantities on walls and other surfaces in the cabin. These deposits are in equilibrium with the cabin atmosphere and may be presumed to account for the characteristic smell of many aircraft cabins, noticed especially when entering from a fresh air external environment. This phenomenon has not so far been adequately investigated.[4]

The APU provides electricity to power demands on or near the ground when the main engines are not running, and likewise compressed air for the cabin (if air conditioning is necessary) and main engine starting. When the APU is running, potential exposure to hazardous substances increases from possible oil smoke, haze and odoriferous substances leaking into the compressed air. When the main powerplants are started, in preparation for taxi-out from the apron, potential exposure increases. That is not to say that contamination from these units is always present. Not so. The potential for air contamination depends upon various factors. First, equipment condition, which can be inferred from aircraft maintenance history. APU and main engine age, assessed in operating hours and/or cycles since new or since major overhaul (SMOH), gives a good indication of reliability (i.e., of operating within specifications). Second, any pilot entries in the aircraft logbook noting system irregularities should lead to specific maintenance investigation. Third, the minimum equipment list (MEL) names inoperative systems unnecessary for flight safety; they can be repaired during the next scheduled maintenance period, but an extensive list may reflect inefficiency of overall maintenance and repair procedures.

This occupational safety hazard series (refs 1–5 and the present paper) is very critical of the state of aircraft maintenance since the advent of deregulation [1,2]. Maintenance contracts are often awarded to the lowest bidder, which in itself is a questionable procedure. No one make or model of aircraft or its engine type is singled out for particular criticism. Aircraft makes and models and their powerplants are generally well designed and dependable. Inefficiency of equipment repair and utilization beyond reasonable hours recommended by manufacturers (as TBO) abuses the equipment and, notably, increases the potential for contamination causing health problems among travelers.

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[3] https://www.chegg.com/homework-help/questions-and-answers/subtropical-jet-polar-jet-tropopause-hadley-cell-ferrel-cell-polar-cell-north-pole-60-n-30-q48092659

[4] Swab testing of cabin interior surfaces [6] and ECS ducting [7–9] have revealed extensive deposits of TCP and other materials consistent with the pyrolysis products of engine oil.

4.1 Degree of exposure at altitude as a health factor

Degree of exposure can mean many things. At this point we mean, simply, differences in the way aircraft occupants receive the air they breathe during a standard flight. In the following, we highlight how the different groups of aircraft occupants interact with contamination.

(i) *Flight attendants* are the most exposed aircraft occupants during cabin air contamination events. Up and working, they take in air at much higher rates for longer periods of time than others (mostly seated) on the aircraft. Busy and concentrating on passenger requests, they may not notice their own symptoms of declining performance. CO occurring alone is colourless and odourless. Fumes comprising visible haze or smoke, or odour, offer warning so that pilots can be informed and take remedial action.[5] Without visual or olfactory warning, contamination is undetectable until cumulative exposure to CO is sufficient to engender symptoms. Low-level exposures that last for the duration of a flight will result in accumulation of bound CO in muscle myoglobin (including in the heart) and in the brain. Such accumulation may exacerbate the adverse effects of greater concentrations of CO, at altitude, compromising the long-term health outlook for flight attendants; adverse effects may not manifest themselves until well after the exposure.

(ii) *Pilots* are next in line of severity of exposure. They are usually physically, and also mentally during the long intervals of flying on autopilot, at rest, respiring lightly at their workstations on the flight deck.[7] If exposed to air contamination, they can and occasionally do use aviator's breathing oxygen. They must make emergency decisions recognizing that cabin crew and passengers are exposed to essentially the same toxic contamination,[8] which they must endure without access to adequate supplies of oxygen. Passengers are unprotected against contamination toxicities.

Pilots are not trained by the employer (the airline) to respond consistently when fumes and insidious health symptoms are detected. Throughout the history of cabin air contamination, the airline industry has not advised or prepared pilots to respond to the hazard. Standard procedures are needed.

(iii) *Passengers* are supposed to be seated with seatbelts secured against possible turbulence. Their respiration rates are the lowest of all occupants. They occasionally do become ill from poor air quality [11]. Passengers are never advised of the possibility of cabin air contamination. Confused when they see flight attendants become incapacitated, they wonder why, but are never told. Even when they ask for medical treatment after landing, they are not told or they are offered a misleading excuse. More and more, hospital emergency personnel located near airports are learning from experience, but the airline industry does not educate or offer guidance that could make treatment more effective. In practice, airline and industry authorities try to cover up the incident. The present author knows of a nurse with persistent symptoms of CO exposure that could have been treated using hyperbaric oxygen if a word or two of guidance had been offered, but could not be diagnosed by her hospital associates because the airline responsible for her injury would not coöperate. He knows of a marketing professional so ill from a contaminated flight that she needed many months of recovery, during which she could no longer execute her duties, and in consequence lost her executive position. Most of these cases are anecdotal, never even reported, let alone investigated.

4.2 The mountain climber experience

The technical literature on CO contamination in jet aviation is so scanty as to be almost nonexistent. When an aircraft arrives at destination with ill and incapacitated travelers aboard, usually only local news media might respond. Industry observers of the issue tend to be sceptical. That carbon monoxide poisoning is involved is even more unbelievable to the public.[9]

Turning to other experiences for guidance, mountain climbers have for decades dealt with carbon monoxide exposures in their tents. The literature is still scanty but informative. At altitude, combustion is more likely to be

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[5] Carbon monoxide sensors could (in principle), and should, be installed in every aircraft to warn of this danger. Around the globe, aircraft operated by major air carriers of all countries do not have installed CO sensors, despite the major regulatory agencies (FAA, CAA, EASA etc.) mandating that CO shall not exceed ppm.[6] The reasons are many, not least the technical suitability of presently commercially available sensors. But the most important reason concerns the expectation that CO will be detected too often. False positive alerts would cause unnecessary and expensive emergency diversions from the intended flight schedule. In fact, whatever the precise reasons, they can all be reduced to excessive cost (including of further research and development as needed) as the deciding factor against the installation of CO sensors.

[6] In all likelihood this limit is too low (cf. the terrestrial workplace exposure limits of 20 ppm (8 h) and 100 ppm (15 min) [10]), but establishing a more appropriate limit is still work in progress.

[7] They must, of course, be instantly ready to switch to a state of high mental activity, not only in the event of any unexpected emergency but also during takeoff and landing, especially in difficult meteorological conditions.

[8] Cabin, but not cockpit, air is typically partly recirculated, hence bleed air contamination might be slightly less.

[9] The literature of carbon monoxide poisoning well attests to its low profile, a fact that might merit an anthropological investigation.

incomplete, and hence produce relatively more CO, than at sea level due to the lower oxygen pressure [12]. And altitude has been found to promote CO uptake into the human bloodstream, and the formation of carboxyhaemoglobin [12];[10] the increased severity of the consequences of exposure at altitude is corroborated by ref. 13. We recall that common symptoms of carbon monoxide exposure are headache, nausea, rapid breathing, weakness, exhaustion, dizziness and confusion.[11] Many of these are also symptoms of acute mountain sickness (flu-like symptoms—headache, nausea, weakness, dizziness), and severe CO intoxication can resemble high-altitude cerebral oedema with progressive confusion, ataxia and, ultimately, loss of consciousness [14].[12] Hypoxia (severe oxygen deficiency)—already present at high altitude (and in the aircraft cabin)—due to acute carbon monoxide poisoning may result in reversible neurological effects, or it may result in long-term (and possibly delayed) irreversible neurological (brain damage) or cardiological (heart damage) effects.[11]

Mountain climbers camping at elevations up to last camp before the summit sometimes breathe exhaust fumes from propane- or similarly fueled heaters and camp stoves along with the available oxygen at altitude. Air pressure and density variation with altitude is given in the International Standard Atmosphere (ISA) table (Appendix A). This is the data used to evaluate environmental health issues that affect mountain climbers and air travelers. The highest base camp elevation on Mount Everest in Nepal is 5364 m. Standard day pressure of air at this altitude is *c.* 51.7 kPa. The partial pressure of the oxygen in the air (pO_2) is diminished *pro rata*.[13]

Density also diminishes at altitude. From the ISA table, average standard density at the Mount Everest base camp in Nepal is 0.5796 relative to sea level.[14] When a mountain climber's air is polluted by combustion fumes from burnt hydrocarbon fuel exhaust, the climber is exposed to carbon monoxide within air at the ambient density. Regardless of their actual altitude, high-flying air travelers breathe air similar to that breathed by mountain climbers at 6000–8000 fasl: the sealed airplane fuselage is supplied with pressurized (i.e., compressed, to correspond to that altitude[15]) and heated ambient air by the engines. Fumes, including CO, emanating from partial combustion of synthetic turbine engine lubricating oil [5],[16] are mixed into the engine-supplied air prior to its distribution throughout the aircraft cabin, Unlike the mountain climber, who can quickly move out of the tent, aircraft cabin occupants who suspect exposure to carbon monoxide (e.g., by monitoring a personal gas sensor), cannot escape exposure; at best they can don a personal mask equipped with CO-absorbing material (e.g., activated carbon).

5. COMBUSTION

5.1 Complete combustion[17]

Complete combustion occurs when heating releases enough energy to initiate sustainable oxidation of fuel (an exothermic reaction). The oxidizing agent is usually atmospheric oxygen. Complete combustion occurs when sufficient oxygen is present and enough time for combustion is available to assure all combustible matter is consumed.[18] Complete combustion of a hydrocarbon fuel produces carbon dioxide and water.

5.2 Incomplete combustion[17]

Incomplete combustion is a chemical reaction that involves *partial oxidation* of a fuel. It occurs when insufficient O_2 is available to oxidize the fuel completely. Energy released from this combustion is lower than from complete combustion. Carbon particles (in the form of soot, tar etc.), water and carbon monoxide are products resulting from this process.

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[10] While ref. 12 belongs to the "grey" literature, sponsorship of the reported work by the US National Fire Protection Association (NFPA) lends it credibility.

[11] https://www.cdc.gov/niosh/topics/co-comp/default.html

[12] Note that "flu-like symptoms" is a common complaint of passengers after fume events.An office worker at the University of Maryland School of Public Health was stricken by "the flu" after recent air travel and spent three days at home recovering. On the first day of her return to work, she did not appear to be suffering from the weakened aftermath that usually follows actual flu.

[13] The composition of (dry) air is nitrogen (N_2) *c.* 78%, oxygen (O_2) *c.* 21%, argon (A) *c.* 1%, along with trace amounts of other elements, and compounds like CO_2 *c.* 0.04%. This composition remains essentially unchanged up to an altitude of well over 50 km.

[14] Air at sea level (standard density = 1.000) has a mass/volume ratio of *c.* 1.225 g cm^{-3}.

[15] Federal Aviation Regulations, §25.841. PRESSURIZED CABINS. (a).

[16] This same compressed air is the source pressure used to retain oil within the "wet" (oil) side of the bearing sump seals [5]. When the seals are faulty, excessively worn, or momentarily back-pressured, some of the air can leak out from the seals. Part of the air, now laden with CO, travels across the compressor air stream and leaves the engine through the low-pressure bleed valve before being ducted into the cabin [4].

[17] https://pediaa.com/difference-between-complete-combustion-and-incomplete-combustion/

[18] An example [15]: Candle wax burns completely in a carefully arranged placement. The flame melts wax at a slow rate to match oxygen supply and burning is at the exact rate to assure fully consumed wax vapour. At end of the process nothing remains in the candleholder base.

5.3 Causes of oil fires leading to incomplete combustion in the aircraft lubrication system[19]

Possible causes are discussed in detail in §3 of ref. 5:
- Blocked bearing sump ventilation system
- Vapour pressure of oil (which depends on temperature) is too high (or too low)—a high ratio of oil vapour pressure to pO_2 favours incomplete combustion, and pO_2 decreases as altitude increases
- Accumulated scale of flakes, soot or tar
- Turbulence in combustion chamber
- Small combustion zone (sump is small, much of the volume is occupied by oil spray).

Bearing sump temperatures are constantly changing. Atmospheric factors (temperature, pressure, humidity) vary as altitude changes and as weather systems (in which great differences of pressure may prevail) are transited. Power changes imply that engine rpm varies, which in turn changes internal pressures and flow rates of air and oil, making it less likely that optimal combustion conditions will obtain, resulting in more CO production than otherwise (under completely uniform altitude, meteorological conditions and engine power). Relevant parameters are:
- Temperature range of circulating oil: –40 ~ 20 °C [16]
- Occasional sump temperature of as much as 1700 °C [17]
- Flash Point of oil: 246 °C [16]
- Bleed temperatures at low-pressure (~275 kPa) exit port: 200–250 °C.[20]

6. ENGINE COMPRESSOR AND PRESSURIZATION

Although scholarly articles exist that explain the technical engineering and operation of the environmental control system (ECS), none discuss issues that will help us understand the unhealthful exposures in the cabin that can arise from the pressurized lubrication system. At risk of faulty interpretation of the conseqeunces of fume events, that challenge must be faced head-on if we are to begin to understand [18–20].

For each make and model of turbine engine, its specification may include the overall pressure developed by a compressor after all stages of operation. To know the pressure of the bleed air at any point within these stages, some method must be used. This will comprise the air pressure used for the cabin, bearing sumps, and other purposes. For example, the CFM56 engine has a two-stage compressor (comprising LPC and HPC—three stages if the fan is counted)—here we mean overall stages, which themselves may comprise (sub)stages. The low-pressure bleed valve is placed at Stage 5 of the HPC, which is Stage 10 of the entire compression section of the engine.[21] Air density ρ (in effect air pressure P modified to include air temperature T effects[22]) must be used when evaluating standard oxygen *partial* pressure for CO creation.

Compressed density is expected to be a function of the mean distance between like molecules (e.g., oxygen) in the ambient air. Considering *standard density* instead of *standard pressure* will enable us to find an expression for *compressed density* up to 36 000 fasl. Air density is the key factor in our quest to identify CO creation and its effects at altitude.

The diminishing density of Stage 10 bleed air as the aircraft climbs past 8000 fasl implies increasing production of CO due to increasingly incomplete combustion of oil vapours. However, when the bearing sumps are performing as designed and the sump environment is clean and efficient, escape of CO through the seals shouild be negligible; harmless venting out of the sump of CO along with sump sealing air is expected.

6.1 Pressurization—assumptions to be considered

(a) Does cabin pressurization begin immediately after takeoff?

Ambient air is quite breathable up to an elevation of 3000 or 4000 fasl. Most humans will remain comfortable enough sitting quietly at 8000 feet. Does it matter, then, whether the compressor is operating up to an aircraft altitude of 8000 feet? Probably not; passengers and crewmembers probably would not notice any difference between ambient air at 8000 feet and aircraft cabin pressurization via bleed air at 8000 feet.[23]

(b) But, considering the mechanism of the compressor, a reasoned answer is that it must be functioning to some degree starting from takeoff. Ambient air pressure even below 8000 fasl is being compressed for producing thrust. This compressed ambient air is used to ensure that lubricating oil remains in the sumps, and presumably some is providing pressurized air to the cabin, into which ambient air cannot normally

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[19] https://aeroenginesafety.tugraz.at/doku.php?id=9:92:92

[20] https://blog.metcar.com/how-gas-turbines-in-jet-engines-use-air-bleed-valves

[21] This is the compressed air used for cabin pressurization.

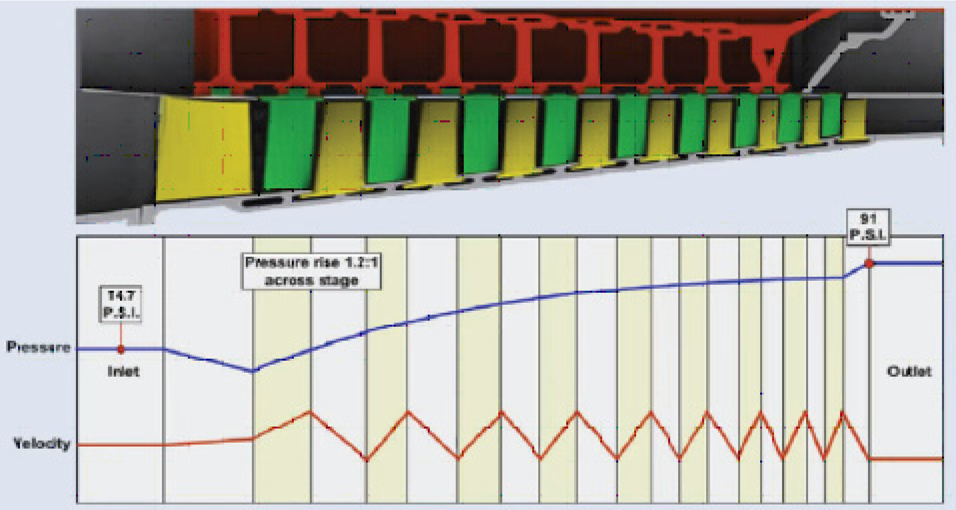
[22] This can be seen by writing the Boyle–Charles law, $PV = nRT$, V being volume, n being the number of moles and R the universal gas constant, as $\rho = M_r P / (RT)$, where M_r is the molar mass.

[23] Actual in-flight barometric measurements show that after take off from near sea level the cabin pressure decreases linearly (with sidereal time) until cruise pressure is attained (corresponding to an altitude of 6000–8000 fasl), whereafter it remains constant until descent; from 6000–8000 fasl to landing the pressure increases linearly (J.J. Ramsden, personal communication).

enter (but outflow valves permit egress)—the flight deck and cabin are sealed tightly against their environment—but up to 8000 fasl the compressor needn't work hard.

(c) Air density is a key factor in our quest to pinpoint CO creation and its effects at altitude. During climb, up to 8000 fasl, nothing in the cabin needs to change except the pressure—ostensibly it suffices to simply allow suffient air to escape to maintain identity between interior and exterior air pressures.[24] In the engine, pressurized bleed air will simply seal the bearing chambers as usual. Hence, we consider the flight phase of climb up to 8000 fasl as inconsequential to our CO at altitude investigation.[25]

(d) The 1:1 ratio of external to cabin pressure ends at 8000 fasl. From this point upward, compressors on the (usually nowadays) two engines are on their own to hold cabin differential pressure at that corresponding to 8000 fasl, while supplying the mandatory fresh air (Fig. 2).[24] Stage 10 bleed air must do all the work. Cabin differential pressurization between the aircraft altitude and the cabin altitude will be maintained by the position of the outflow valves.[26]



Compressors Part 1—Aircraft Gas Turbine Engines #05

Fig. 2. Engine high pressure compressor (schematic diagram)—HPC stage—showing its 10 stages.[27]

6.2 Compressor operation—a pressure v. density exercise[28]

The object here is to determine pO_2 relative to sea level. As an example we use the CFM56 engine, the compressor stages of which are: 1 fan stage + 4 LPC stages + 9 HPC stages = 14 in total. Fan and LPC are boosters for the HPC. The high-pressure bleed port in Stage 14 is used only during taxi and descent [21,22]. (Relatively) low-pressure compression bleed air (stage 10 overall) is used during climb & cruise. Differential compression at each individual stage of a compressor (single stage compression (ratio) or SSC) approximates to 1.2875 (may be less in actuality). OPR is calculated as:

$$\mathrm{OPR} = (\mathrm{SSC})^c \qquad (1)$$

where c is the number of compression stages. Relative compressed density is given by

$$\mathrm{RCD} = \mathrm{OPR} \times \rho \,. \qquad (2)$$

To clearly demonstrate the relative dearth of oxygen at altitude, pO_2, which follows *pari passu* the overall air density, is then normalized to sea level. Results are given in Table 1.

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[24] Federal Aviation Regulations, §25.831 Ventilation. (a) mandates the provision of "at least 0.55 pounds of fresh air per minute" to each occupant. Depending on the duration of climb, it may not suffice to simply exhaust the excess air from the cabin.

[25] Tacitly, we ignore the possibility that the APU was used on the ground to ensure supply of fresh air to the cabin after closing the doors.

[26] https://www.cfinotebook.net/notebook/operation-of-aircraft-systems/pressurization

[27] See https://www.youtube.com/watch?v=NfrcJRHs4Fc for a good elementary exposition of the workings of the compressors. OPR varies among the many models of engines that have been and are being produced; some have an OPR of 35.5 OPR, some less.

[28] See also p. 3 of ref. 20.

Table 1. Variation of air density and oxygen content with altitude.

Pressure increase per stage (SSC)	*c*	Altitude/fasl	Air density ρ normalized to sea level[a]	RCD[b]	pO_2 relative to sea level
~ 1.287	14	0	1.0	34.3923	100.00%
~ 1.287	10	8 000	0.7860	9.8377	28.76%
~ 1.287	10	12 000	0.6932	8.6762	25.36%
~ 1.287	10	18 000	0.5699	7.1330	20.85%
~ 1.287	10	30 000	0.3741	4.6823	13.69%
~ 1.287	10	36 000	0.2981	3.7311	10.91%

[a] From the ISA table (Appendix A).
[b] Calculated from eqn (2).

6.3 Density evaluation exercise—comments on §6.2 and assessment

1. Temperature decreases with altitude. Between 8000 and 36 000 fasl, temperature drops from –0.8 to –56.3 °C.

2. Intermolecule distance diminishes with compression. From the moment of ingestion into the engine, compression mechanically concentrates the molecules within the bleed air used for cabin supply and to ensure containment of the oil behind the seals of the small bearing sumps (housings).

3. Compressed air mixes with oil vapours in the already hot sump. We can imagine sump temperatures rising and falling with engine power changes, meteorological conditions and lubricating system cooling. Sumps will run warmer after many hours and cycles because of the accumulation of soot on the walls and other physical features within the sump, and building up restrictions in the air ventilation and oil scavenge lines. A new or recently cleaned sump will run cooler and more efficiently than a highly utilized or older system compromised by deferred scheduled maintenance.

4. Restricted flow out from the sumps will increase pressure within them, which increases the probability of leakage through the sump seals into the cabin. Internal sump pressure rises with increasing temperature. The likelihood of cabin contamination will increase when temperature and the presence of oil vapour and oxygen are in just the right combination. Actual fire in the sump is possible [5].[19] Incoming sealing air pressure may be overcome, allowing flow of combustion products out of the sump and ultimately into cabin air. Crewmember illness provides corroborating evidence that this condition can be present throughout the flight on fume-compromised aircraft.

5. "Dwell time". Manufacturers advertise their aircraft cabin air replacement rates, intending to assure customers that air conditioning systems provide a steady stream of fresh, clean air. Cabin air turnover rates of 10 to 15 times per hour paint a picture of rapidly repeating aerial refreshment throughout a flight.[29] Could this be true?

All aircraft ECS maintain cabins between 6000 and 8000 fasl pressure altitude. This is managed primarily by outflow valves slowly closing as the aircraft climbs with minor adjustments of differential pressure made by the cabin pressure regulator.[30] The OPR (Table 1) determines the setting of the outflow valves at any given altitude. We can visualize reasonably well the outflow valves continuously moving toward the closed position until reaching cruise altitude, typically 36 000 fasl.

As readily seen from the ISA table (Appendix A), atmospheric pressure at 36 000 fasl is only 22% of the value at sea level. Outflow valves must mostly be kept closed, but the cabin pressure regulator will periodically modulate the outflow valve, letting some cabin air escape, to maintain cabin pressurization at 8000 fasl.

Since flow of air out of the cabin has been slowed down or stopped, the "dwell time" (the time of replacement of cabin air at high altitude) will be lengthened; from about 4 to 6 minutes.[29] The restricted airflow implies that air contamination will be retained for longer intervals. CO will accumulate until inflow (from bleed air) and outflow become balanced.

Under such conditions it is highly pertinent that the oxygen content is only just over 10% of its value at sea level (Table 1). Not only does this exacerbate the adverse health effects of CO (cf. §4.2), but it also increases the likelihood of carbon monoxide formation due to incomplete combustion (cf. §5.3). The well-nigh ineluctable conclusion is that some carbon monoxide is present in turbofan engines of every airline aircraft at some time during every flight. Those who breathe most—cabin crew, because of their almost ceaseless physical activity—will be exposed to the dangers most.

6. Local density variations. The ISA table gives pressure at altitude only for standard conditions. Local

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[29] https://aviation.stackexchange.com/questions/8841/how-do-big-planes-like-737-manage-fresh-air-for-passengers-during-flight.
[30] Ref. 20, p. 6.

temperatures and pressures, which are not standard, and humidity, all of which depend on meteorological phenomena, will also affect density. This suggests concomitant fluctuation of the dependent phenomena, notably degree of incomplete combustion, degree of ingress of CO and odoriferous compounds into the cabin. Humidity exacerbates both.

7. Sump temperatures. Throughout this investigation (the results of which are presented in this paper and its five predecessors), temperatures within the bearing sumps have been difficult to define. Nothing about the atmosphere is stationary—air density and humidity vary, especially as the aircraft transits different flight levels, and these influence sump temperature (§5.3). When we think about the range of temperatures conducive to the formation of CO, the risk can jump from nil to acute in a very brief interval of time.

In the absence of CO sensors, odour (from burnt oil) is a marker of combustion, complete or incomplete, and hence of CO. Since CO itself is odourless, it can never be assumed that the absence of a burnt oil smell indicates the absence of CO. Crewmembers should be aware of the symptoms of CO poisoning at various levels and be alert to their presence among their colleagues.

8. Descending from altitude. Engine power will be at or near idle. This will slow compressor rpm, reducing compression throughout. To assure sufficient compressed air for the cabin, the Stage 14 bleed valve will open. If necessary, compressed air from both engines will assure that the 8000 fasl cabin altitude is maintained. Humidity may increase, with an effect on air density. Driven via the accessory gearbox, oil pump rpm will have slowed proportionately. Oil pressure within the sump should remain at system-recommended pressure but rate of flow will diminish. Bleed air pressure, and temperature in the sumps, should diminish, causing the sealing pressure differential to dwindle, making leakage more likely. On the other hand, dwell time of contaminants in the cabin should decrease as the altitude decreases (cf. ¶5).

It is notable that during throttling back at the start of descent, flight attendants repeatedly report odour. Illness symptoms intensify. An explanation is elusive, but under these circumstances incoming sealing air pressure at the idle power setting may be insufficient. If internal sump pressure increases during descent, escape of contamination from the sumps is further favoured.

7. SUMMARY AND CONCLUSION

This paper has investigated the immediate environment where carbon monoxide is created in turbine aircraft engines high above 80% of Earth's atmosphere. Ambient air is there so thin and cold that in most respects pO_2 is too low to sustain an ordinary flame. However, to provide air sufficient to sustain human life (at the engineered 8000 fasl cabin altitude), the air and all it contains must be compressed.

Compressed low-pressure air from a mid-point of the high pressure compressor on most engines is sufficient to provide this sustaining air at a comfortable enough level. However, the oxygen in this compressed air is now dense enough) to support incomplete combustion of oil vapours in the small bearing compartments (sumps) along the core shaft of the engine. Of most concern are the bearing sumps located upstream of the high-pressure compressor. From these sumps leak the by-products of incomplete combustion, including carbon monoxide. Leakage crosses the compressor airstream and some of it is extracted through the low-pressure bleed valve along with new compressed air. From here it is directed through the air conditioning system and into the cabin.

We assume the process occurs in this way because temperatures conducive to CO formation appear to be present within the compressor bearing sumps [5]. We assume that oil vapours under pressure are turbulent in the confines of the sump, and that compressed sealing air from the compressor is usually insufficient to support *complete* combustion of oil vapours, but *is* sufficient to support *incomplete* combustion most of the time while the aircraft is airborne. This implies that cabin occupants might be breathing low levels of carbon monoxide most of the time.

We assume the amount of carbon monoxide created fluctuates. Power changes vary temperatures and pressures in the sumps. Meteorological conditions change ambient pressures, temperatures and humidity. Turbulence changes *g*-forces, engine wear and momentary clearances between moving parts; the environment aloft is always in flux, always changing. CO creation increases and decreases accordingly. The US Airways flight 1041 (16 January 2010) crew experienced these fluctuations directly (personal communication to the author). They were disabled partially and permanently by the experience.

We stand firmly by these assumptions and implications because we understand:

(a) the limits, and the state of the art, of the aircraft systems involved;

(b) the time, place and degree of human illnesses, incapacitations and disabilities suffered by aircraft occupants; we understand why they experience their impairments the way they do;

(c) Our investigation surrounding the issue of cabin air contamination finds no other reasonable causes that could engender similarly deleterious consequences among airline employees and the traveling public.

Borrowing the legal phrase *res ipsa loquitur*, we embrace the following assertions:

- It is a rule of evidence whereby the negligence of an alleged wrongdoer can be inferred from the fact that the accident happened;
- It is a maxim where the very improbable facts of an accident imply the negligence of the defendant. It effectively shifts the burden of proof to the defendant.

We welcome the shift of burden of proof from the victim to the creator or perpetuator of the hazard. Suggesting negligence on the part of the airline industry is not, however, the intent of this paper and its predecessors [1–5]. After all, proving negligence lies within the purview of the law. We are not lawyers. Significantly, where negligence might be suspected, the airline industry is not alone. If negligence be established, the airline industry has associates that should stand up in fact and principle alongside it.

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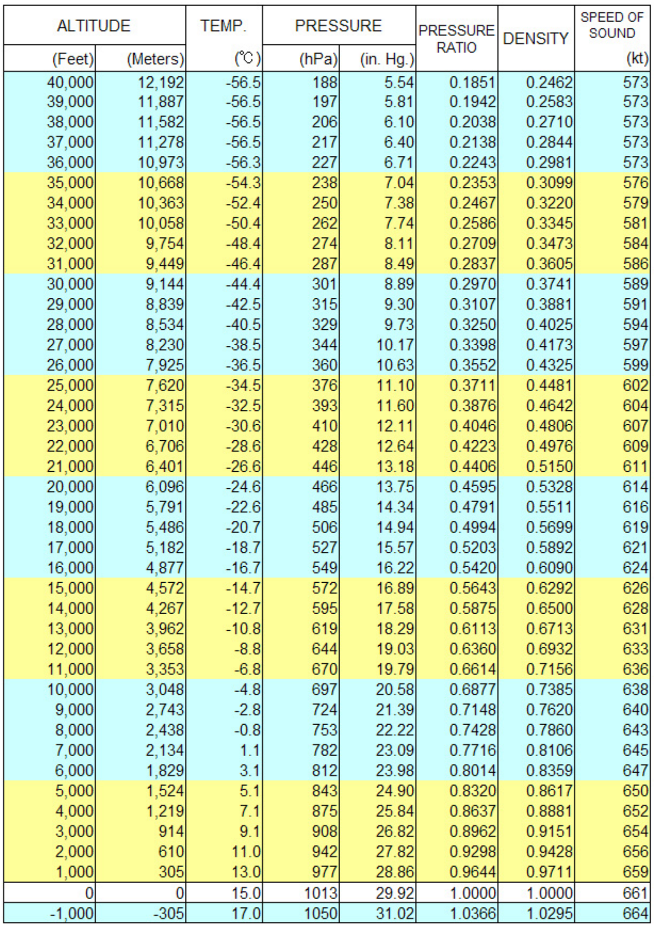
APPENDIX A

International Standard Atmosphere (ISA) table.



ALTITUDE		TEMP.	PRESSURE		PRESSURE RATIO	DENSITY	SPEED OF SOUND
(Feet)	(Meters)	(℃)	(hPa)	(in. Hg.)			(kt)
40,000	12,192	-56.5	188	5.54	0.1851	0.2462	573
39,000	11,887	-56.5	197	5.81	0.1942	0.2583	573
38,000	11,582	-56.5	206	6.10	0.2038	0.2710	573
37,000	11,278	-56.5	217	6.40	0.2138	0.2844	573
36,000	10,973	-56.3	227	6.71	0.2243	0.2981	573
35,000	10,668	-54.3	238	7.04	0.2353	0.3099	576
34,000	10,363	-52.4	250	7.38	0.2467	0.3220	579
33,000	10,058	-50.4	262	7.74	0.2586	0.3345	581
32,000	9,754	-48.4	274	8.11	0.2709	0.3473	584
31,000	9,449	-46.4	287	8.49	0.2837	0.3605	586
30,000	9,144	-44.4	301	8.89	0.2970	0.3741	589
29,000	8,839	-42.5	315	9.30	0.3107	0.3881	591
28,000	8,534	-40.5	329	9.73	0.3250	0.4025	594
27,000	8,230	-38.5	344	10.17	0.3398	0.4173	597
26,000	7,925	-36.5	360	10.63	0.3552	0.4325	599
25,000	7,620	-34.5	376	11.10	0.3711	0.4481	602
24,000	7,315	-32.5	393	11.60	0.3876	0.4642	604
23,000	7,010	-30.6	410	12.11	0.4046	0.4806	607
22,000	6,706	-28.6	428	12.64	0.4223	0.4976	609
21,000	6,401	-26.6	446	13.18	0.4406	0.5150	611
20,000	6,096	-24.6	466	13.75	0.4595	0.5328	614
19,000	5,791	-22.6	485	14.34	0.4791	0.5511	616
18,000	5,486	-20.7	506	14.94	0.4994	0.5699	619
17,000	5,182	-18.7	527	15.57	0.5203	0.5892	621
16,000	4,877	-16.7	549	16.22	0.5420	0.6090	624
15,000	4,572	-14.7	572	16.89	0.5643	0.6292	626
14,000	4,267	-12.7	595	17.58	0.5875	0.6500	628
13,000	3,962	-10.8	619	18.29	0.6113	0.6713	631
12,000	3,658	-8.8	644	19.03	0.6360	0.6932	633
11,000	3,353	-6.8	670	19.79	0.6614	0.7156	636
10,000	3,048	-4.8	697	20.58	0.6877	0.7385	638
9,000	2,743	-2.8	724	21.39	0.7148	0.7620	640
8,000	2,438	-0.8	753	22.22	0.7428	0.7860	643
7,000	2,134	1.1	782	23.09	0.7716	0.8106	645
6,000	1,829	3.1	812	23.98	0.8014	0.8359	647
5,000	1,524	5.1	843	24.90	0.8320	0.8617	650
4,000	1,219	7.1	875	25.84	0.8637	0.8881	652
3,000	914	9.1	908	26.82	0.8962	0.9151	654
2,000	610	11.0	942	27.82	0.9298	0.9428	656
1,000	305	13.0	977	28.86	0.9644	0.9711	659
0	0	15.0	1013	29.92	1.0000	1.0000	661
-1,000	-305	17.0	1050	31.02	1.0366	1.0295	664