~~60~~**Essay #10 in Aspen Fly Right's public-education series, 16 Mar 2023, revised 15 Dec 2023**
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Aspen Airport, air pollution, and public health

Executive Summary

On a busy fine day, up to 300 aircraft land or take off at Aspen Airport. Takeoff jet-blast points almost exactly toward the kids' ski-school building at the base of Buttermilk, 640 meters or 2100 feet south. The prevailing winds blow the same way. Yet any air pollutants carried to that heavily used area—or the X Games and World Cup zones, or the ski slopes and downtown areas beyond—*have never been measured*: the County's air-pollution consultant saw no need. Today's scientific understanding of what jet engines emit, how it travels, and how it can affect human health now invites reexamination based on actual data.

To stimulate and inform rigorous tests, over the Presidents' Day weekend on 17–21 February 2023, a 12-citizen volunteer team organized by Aspen Fly Right performed tens of thousands of air measurements. We used 14 inexpensive but surprisingly capable instruments to measure those jet plumes' dynamics and where they may have delivered five air pollutants during the main ski periods on five consecutive days. We're still analyzing a gigabyte of data, but some preliminary results look instructive. Of course, our training and instruments couldn't provide the scope or fidelity of a professional air study, but could (and we think did) credibly check whether a full, expert, and accurate study is warranted. It does seem to be.

Jet blasts are twisted by the rotating gas turbine into stable vortices that can carry pollutants for at least 700–1,000 meters. We tried to track specific takeoff pulses from near the airplane through a midpoint to the base of Buttermilk, and are checking if we succeeded. Such jet-plume travel is physically plausible: the pollutants are being powerfully blasted that way, even if errant breezes nudge them a little sideways.

Jet-engine pollutants include acrid nitrogen oxides and unburned hydrocarbons, but are mostly fine particles, far smaller than road-vehicle exhaust. We measured them at three sites in three size ranges (two are Federally regulated). They showed large, sharp spikes associated with specific causes like nearby autos or jet takeoffs. These fine particulate emissions grow and react as their plume travels and ages. Many get coated with highly reactive organic compounds (often carcinogenic) or metals. Inhaled, very fine particles can enter the bloodstream and travel throughout the body, potentially transporting toxins to every organ.

Even more mobile, penetrating, reactive, and concerning—as medical science is now finding—are "ultra-fine" particles, up to a hundred times smaller still. These invisible nanoparticles are harder to measure and too small for our inexpensive instruments to detect, but they make up almost all jet-engine emissions. Burning one kilogram of fuel at full throttle can emit up to hundreds of quadrillions of ultrafine particles, with immense surface area to deliver toxins. They've been measured at other airports and up to ten miles downwind. They're more toxic than bigger particles. Yet they're wholly unregulated. Medical evidence strongly suggests checking if they might be creating significant health risks to our community.

Our measurements found no violation of Federal air-quality standards—only because those use far longer measurement periods, and half the pollutants have no standards. But what's the basic cause? Burning fuel causes all these worrisome transport emissions. Next-generation cars, trucks, and planes burn nothing and are evolving swiftly. Public health is now another reason to bring them on sooner—and not to slow or preëmpt their arrival by mis-investing to sustain and expand obsolete fossil-fueled infrastructure instead.

In April 2020, Aspen Journalism[1] and *The Aspen Times*[2] published an important feature article, "Airport expansion may not resolve pollution and noise problems." It noted longstanding local "concerns about toxic smells, roaring engines and carbon emissions"—overridden in the ASE Vision process by "the threat of losing commercial [air] service" (an old threat debunked in our 5 January 2023 Essay #4 as fictitious). The authors set the stage, with three sets of italics added:

> Airplanes departing from the Aspen-Pitkin County Airport roll down the taxiway toward Aspen and then do an about-face to line up for takeoff. Once air control gives the go-ahead, pilots lay on the throttle and jet exhaust erupts from the engines, pointed right at the base of Buttermilk, where kids are learning to ski about a half-mile away on Panda Peak.
>
> "It's toxic — a thick smell in the air like something's partially burned. There's a sudden thrust when they rev the engine up, and you get these blasts of bad air," said Tim Mooney, an activist opposing the expansion who sat on various advisory committees.
>
> Mooney doesn't know what he's breathing downwind from the airport on a busy day, and neither do county officials as *no ground-level air quality measurements have ever been taken at or around the airport.*
>
> The 874-page EA [the 2018 Environmental Assessment], based on a Federal Aviation Administration modeling tool, uses a potential future fleet mix to extrapolate impacts to air pollution, carbon emissions, noise and traffic from 2015 to 2033.
>
> That is not uncommon, said Mary Vigilante, president of Synergy Consultants, which produced the EA. Ground-level measurements are significantly more expensive than modeling, she said, and "based on these results, *there was nothing to indicate warranting doing more detailed work*."
>
> But locals still complain of a stinging in their eyes and the burned, metallic taste of jet fuel at the Aspen Business Center and on the nordic ski tracks laid each winter on the city of Aspen golf course.
>
> "My guess is that people are making reference to exhaust associated with volatile organic compounds," Vigilante said, noting that it also could be nitrogen oxides, or NO_x, a family of poisonous, highly reactive gases that form when fuel is burned at high temperatures and help create smog.
>
> The research on the odors is hazy, and *there's no way to know for sure without taking an air sample.*

Let that sink in: downwind of the Airport, the community and its elected officials have long heard anecdotal reports of, and many have personally experienced, air pollution's signs—throat and eye irritation, fuel odor, respiratory symptoms—but no one has measured them. (We asked[3].)

In the public-comment period of an Airport Advisory Board meeting on 21 July 2022, two University of California/Davis professors politely but trenchantly criticized Ms. Vigilante's methodology and her overreliance on theoretical modeling inappropriate for this use and inadequately grounded in specific local measurements[4]. The second expert, a member of the National Academy of Sciences, was cut off after his three minutes had expired, but AAB members later usefully questioned him for another 13 minutes, and seemed surprised by and interested in what they learned. (The AAB's air agenda has mainly focused so far on greenhouse-

gas emissions—the *other* kind of air pollution, clearly distinguished by our County Commissioners[5] and vital to the fate of the Earth, but not immediately relevant to local public health.) As far as we know, this was the only occasion when AAB or previously ASE Vision members had directly received substantial and substantive technical information contradicting what they had been told by sources solely chosen and instructed by County Staff[6].

Being a scientific as well as an educational and charitable organization, Aspen Fly Right felt a duty and opportunity to start filling this air-pollution measurement gap. We assembled a talented and diverse team of a dozen local citizens (Appendix A), and bought or borrowed 14 instruments of three types (Appendix B) to measure many thousands of data points on five kinds of air pollution. Over the Presidents' Day long weekend, 16–21 February 2023, we conducted an intensive five-day measurement campaign to see if and how far we could answer three simple questions:

- What are our kids (and others) breathing near the ski school at the base of Buttermilk?
- Where does it come from?
- How much of it comes from airplanes?

The inherent limitations of a small nonprofit organization prevented our fully answering the second and third questions, though we did find evidence suggesting a causal connection between airplanes' jet exhaust and some unknown part of the air pollution we measured around the base of Buttermilk. But our intent fully recognized these obvious limitations. We did not attempt, and we were not enabled by instrument quality and specialized training, to conduct the sort of professional air-quality assessment that highly skilled and well-funded specialist organizations perform. We sought only to conduct an instrumented reconnaissance that could test whether observed air pollution in this specific health-critical site might indicate thorough expert study. We conducted simple but, we believe, valid and credible tests of Ms. Vigilante's hypothesis that a generic theoretical model showed no need for actual measurements and justified ignoring long and deep community experience. Our data imply the opposite conclusion. We are not sounding an alarm, but we are substituting facts for speculation. The facts we found do appear to warrant a significant public investment of time, money, skill, and attention in proper measurement. So although we don't know all the answers, we've established the validity of the questions.

Our rationale for measuring approximate air quality at the base of Buttermilk was simple. As we'll explain below, up to ~300 aircraft per day (on busy days in fine weather, otherwise fewer) spool up to full throttle at the south end of Runway 33 before taking off, or land in the opposite direction. Some departing aircraft take off immediately, while others stand at full throttle for a few to perhaps ten seconds, checking that all is well, before releasing the brakes for their takeoff roll. (ICAO's standard assumed operating cycle at sea level includes 0.7 minutes in takeoff mode at 100% thrust.) Either way, their jet exhaust points *directly*—within a few degrees—across a flat, smooth, snowy field and two parking lots to the front door of the Hideout, where Aspen's children gather for ski lessons on the slope behind that extensively used building complex. As we'll see, a special, invisibly small, hard-to-measure kind of air pollution that jet engines most prolifically produce is particularly worrisome—most of all when inhaled by young, exerting lungs[7]. Childhood exposure to such particulate pollution, especially in very small sizes[8], can compromise lung development and program a lifetime of respiratory and allergy problems.

To understand why jet aircraft emissions may be of health concern, we'll now review jet exhaust's health risks[9] and physical behavior, then the design and challenges of our observations, what we've learned so far, and what it may mean.

What's in jet exhaust?

Jet engines by far dominate the air pollution from airports' panoply of aircraft, ground equipment, buildings, fuel facilities, and internal and external traffic. (Just 0.3% of ASE's aviation fuel sales goes to piston engines, though their leaded aviation gasoline is a substantial health hazard and needs to be phased out[10].) Non-engine emissions from airplanes—tire, brake, and asphalt wear, and resuspension of dust stirred up by aircraft movements—can also be significant[11]. So can vapors from fuel and from de-icing and anti-icing fluids.

Jet engines are designed to burn kerosene-like aviation fuel efficiently, but their exhausts have no pollution-control systems as automobiles do, because those would interfere with the desired thrust. The engines are designed to blast out as much hot gas as they can, as fast as it can go, to propel the plane. Inevitably, the very hot combustion oxidizes nitrogen in the air, and "non-ideal combustion conditions…may lead to the production of by-products, including sulfur oxides [from traces of sulfur in the fuel], additional nitrogen oxides, [ammonia,] unburned hydrocarbons and particulate soot"—plus chemicals "from the combustion and release of lubricant oils[12] and from mechanical component wear."[13] Although such residual products typically total less than 1% of jet exhaust by weight, they are potent pollutants. Some may act as, or interact with soot particles to form, condensation nuclei whose complex chemistry forms many new compounds.

Most pollutants, especially carbon monoxide and unburned hydrocarbons, increase strongly at *low* engine power, such as when idling or taxiing: many species of hydrocarbon emissions rise by 20–50× or more when idling, while emitted particles get smaller. Increasing thrust to a mid-range typical of cruise conditions often reduces emissions. Then increasing jet-engine power to full takeoff and climb thrust can raise particle formation by 10–40× or more. The amounts and kinds of pollutants produced depend on many other conditions too, but are mainly of three kinds:

- Hydrocarbon mixtures can be very complex and are often of health concern—especially because as much as one-fourth of jet fuel is aromatic hydrocarbons (carbon-ring compounds akin to benzene). Many aromatics are known or suspected carcinogens. Major international airports like Schiphol, Heathrow, Atlanta, and Los Angeles that continuously measure their emissions often tend to emphasize hydrocarbons.
- Nitrogen oxides (chiefly NO_2, formed directly or from emitted NO within a few minutes) are well-known respiratory irritants, extensively studied in vehicular and industrial air pollution. They may turn into nitric or nitrous acid, and they can help to turn hydrocarbon vapors into photochemical smog containing toxic ozone.
- Of greatest concern, jet exhaust contains copious ultrafine particulate matter (100 nm[14] and smaller, but in some usages including PM_1) and fine particulates ($PM_{2.5}$). Both sizes penetrate deeply throughout the lungs. UFPs and much of PM_1 (plus the small fraction of $PM_{2.5}$ smaller than ~30 nm) can cross into the bloodstream, carrying toxicity to every organ and tissue in the body. The ~0.01–0.1 µm (10–100 nm) particles that dominate jet exhaust deposit very largely[15] in the region where alveolar sacs exchange gases with the

bloodstream. At full jet throttle, this dust is about three-fourths sootlike black carbon. "With regards to human health concerns, the ultra-fine particles (nanoparticles) at the 4–7% low power (idle) and high power (take-off) engine levels are clearly a health hazard and will not be filtered by normal [human] airway mechanisms….[T]hey do not tend to agglomerate nor deposit upon other particles, but instead remain separate and suspended. Thus the ambient air at and around airports will have periodic peaks in ultrafine PM during normal jet operations. From these observations engine specific conditions appear to govern not only particle formation but also its trajectory thereafter, with a broad range possible."[16]

Once created, these three classes of pollutants further react and combine. The soot particles, and any sulfate particles from residual sulfur in the fuel, nucleate condensation as they travel away from the engine. This process builds up diverse particles with complex forms and chemistries that rapidly evolve as the plume travels and ages. Burned and unburned organic compounds and traces of metals from the fuel or the engine often condense around the mainly-sooty particulates. Condensation and growth *can increase particulates of potential health concern by roughly 10–100*× over hundreds of meters' travel, especially in cold weather that speeds condensation[17].

The composition of jet-exhaust particle plumes is hard to measure and is very sensitive to sampling site, timing, weather, and other conditions. Some particles condense, others evaporate, and many react in a dizzying array of complex processes. These shifts in particles' size, form, and composition fuzz traditional distinctions between volatile and nonvolatile particles[18]. Synthetic biofuels like Sustainable Aviation Fuel (Essay #7) can reduce ultrafine particle emissions by ~50–70%[19], but those particles' production remains prolific: *a jet engine at high power directly emits from tens to hundreds of* quadrillion *ultrafine particles per kg of fuel*[20]. One General Aviation jet taking off from Aspen at full throttle can burn a kilogram of fuel in a second or two[21].

Those tiny particles' share is enormously higher than in road-vehicle or industrial emissions, whose typically larger particles were long found in many epidemiological studies to be strongly correlated with harm to human health. But the emergent threat isn't just in the *number* of ultrafine particles; it's also that the *smallest* jet-exhaust particles, far smaller than PM_1, *now appear even more dangerous*—even though they're far harder to measure, are not yet regulated, and are less well understood. *This suggests a special need for prudence to protect public health.*

The basic problem is geometry. As a BBC science journalist[22] and air-pollution author explained (with emphasis added), a soccer ball fills the same volume as 156 golf balls, but the golf balls have 464% or 6.9 m^2 more total surface area. "On a nano-scale, that difference is amplified. *A cloud of a billion 10-nm particles has the same mass as just one* PM_{10} *particle, but a combined surface area a million times larger*. And that surface area comes coated with toxic, unburnt fuel from vehicle [or jet] exhausts."

Nanoparticles are generally a very small fraction of the mass of particulate pollution, but are the majority of the particles. Yet "because government authorities monitor $PM_{2.5}$ (and other sizes) *by mass* (millions of nanoparticles may not even register a measurement by microgram)…their reports underrepresent the true risk." The one regulation for road vehicle emissions (Euro 6) that limits the number of very fine nonvolatile (at 300˚C) particles from diesel and direct-injection

gasoline engines to 0.6 trillion particles per km goes down to 23 nm (about the size of a typical jet-exhaust particle), but even that seemingly small diameter misses over 30% of urban nanoparticles[23]. US air-pollution rules apply to typically fewer than 10% of the total particles; the rest, including almost all jet exhaust particles, are too small to be included yet.[24]

In other words, measurements are reported and standards are set by *mass*, but health risks rise with particles' *number and surface area*, putting smaller particles' toxicity literally in touch with more tissues in your body. Millions of nanoparticles can give a low $PM_{2.5}$ reading, but the typical jet-exhaust particle is ≥50 times smaller still than the nominal 1-µm boundary between PM_1 and $PM_{2.5}$. "A low $PM_{2.5}$ reading on [a] government website or mobile phone app can therefore give a false impression of clean air when it is, in fact, swirling with particles entering our arteries" and capable of depositing toxins onto, say, plaque in a coronary artery within 24 hours[25].

Health effects of jet-engine particulate emissions

The Abstract of a 2016 review paper[26] by Chinese Academy of Sciences, UCLA, and SUNY experts, with emphasis added, summarizes thus the medical importance of particle size:

> Air pollution is a severe threat to public health globally, affecting everyone in developed and developing countries alike. Among different air pollutants, particulate matter (PM), particularly combustion-produced fine PM ($PM_{2.5}$)[,] has been shown to play a major role in inducing various adverse health effects. Strong associations have been demonstrated by epidemiological and toxicological studies between increases in $PM_{2.5}$ concentrations and premature mortality, cardiopulmonary diseases, asthma and allergic sensitization, and lung cancer. The mechanisms of PM-induced toxicological effects are related to their size, chemical composition, lung clearance and retention, cellular oxidative stress responses and pro-inflammatory effects locally and systemically. *Particles in the ultrafine [particle or UFP] range (<100 nm), although they have the highest number counts, surface area and organic chemical content, are often overlooked due to insufficient monitoring and risk assessment. Yet, ample studies have demonstrated that ambient ultrafine particles have higher toxic potential compared with $PM_{2.5}$.*

That's because of their larger surface area and their greater transport of organic chemicals and metals[27]. Many of those contaminants, as the article documents, can generate reactive oxygen species that are particularly damaging at the cellular level. The text continues, with emphasis added:

> …[A]mong the PM fractions, UFPs [<100 nm in diameter] possess the highest particle number and surface area, carrying higher chemical contents than $PM_{2.5}$….Studies have shown that UFPs have detrimental effects on both the respiratory and cardiovascular systems, and exacerbation of asthma….However, our understanding of UFPs is still incomplete because of a deficiency in extensive UFP-monitoring networks, rapid physicochemical characterization techniques, and limited epidemiological and toxicological studies….Given the health concerns related to UFPs…, further research is needed to evaluate the health risks associated with these tiny particles.*** Emerging evidence has shown that, *among different particles, UFPs are potentially the most dangerous owing to their small size, deep penetration, large surface area/volume ratio, high content of redox-cycling organic chemicals, alveolar deposition[,] and high rates of retention in the lung.***Convincing evidence has established the association between PM and many pulmonary diseases that contribute to early mortality and reduced life expectancy.* However, for ambient UFPs…, although much progress has been made in understanding their toxicological effects and mechanisms of toxicity, there are still many knowledge gaps on their impact on human health…. *Available evidence strongly suggests that UFPs… may be more potent in causing adverse health*

effects in humans because of their high deposition rate in the alveolar region, impaired clearance by alveolar macrophages and higher surface reactivity, pro-oxidative and pro-inflammatory effects than their larger counterparts. Thus, it is imperative to focus future research on the health effects of nano-scale pollutants so that preventive strategies and regulatory guidelines can be developed to reduce exposure and improve human health.

Its cited epidemiological evidence found that in 2010, "outdoor air pollution, mostly by $PM_{2.5}$, [led]…to 3.3 million premature deaths per year worldwide…" (nearly 4 million in 2020[28]). It's sobering, therefore, that the ultrafine particles making up "nearly all" jet exhaust *appear to be even more toxic but are not yet regulated*. Those particles are often collected, and their effects aggregated, along with PM_{10} and $PM_{2.5}$—each size category can subsume smaller ones too—and may turn out to be responsible for some significant part of the risk ascribed to larger particles[29]. The article's Figure 2 (our Fig. 1) summarizes these risks:

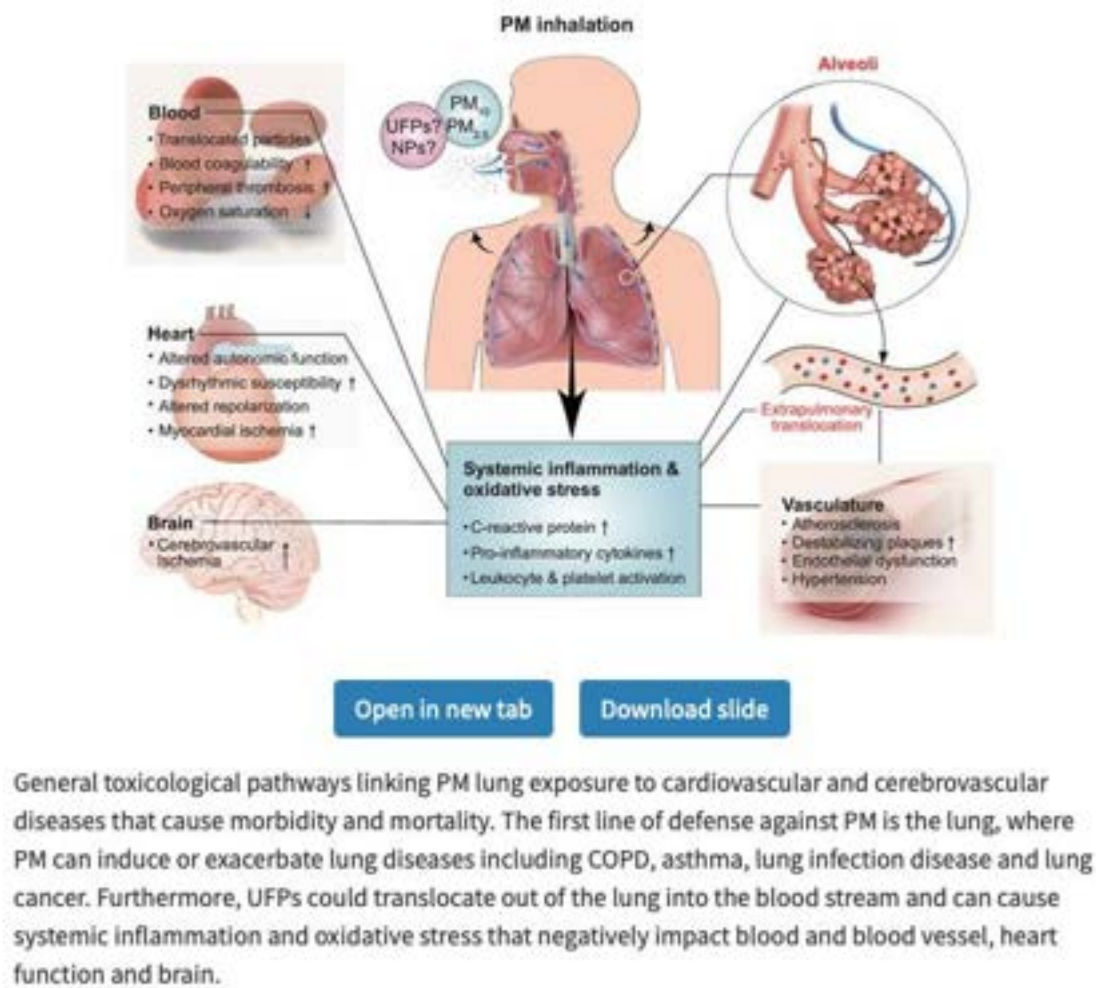

Fig. 1. An authoritative graphic summary[30] of how inhaling particulate air pollution can harm human health. According to Ref. 22, the Global Burden of Diseases study[31] estimated that 21% of all deaths from stroke, and 24% of all deaths from ischemic heart disease, could be ascribed to air pollution, now thought[32] to implicate chiefly fine and ultrafine particles. If true, this would make epidemiological evidence hard to find because those deaths have many other causes too.

Or to emphasize how finer particles penetrate into more of the human body (Fig. 2):

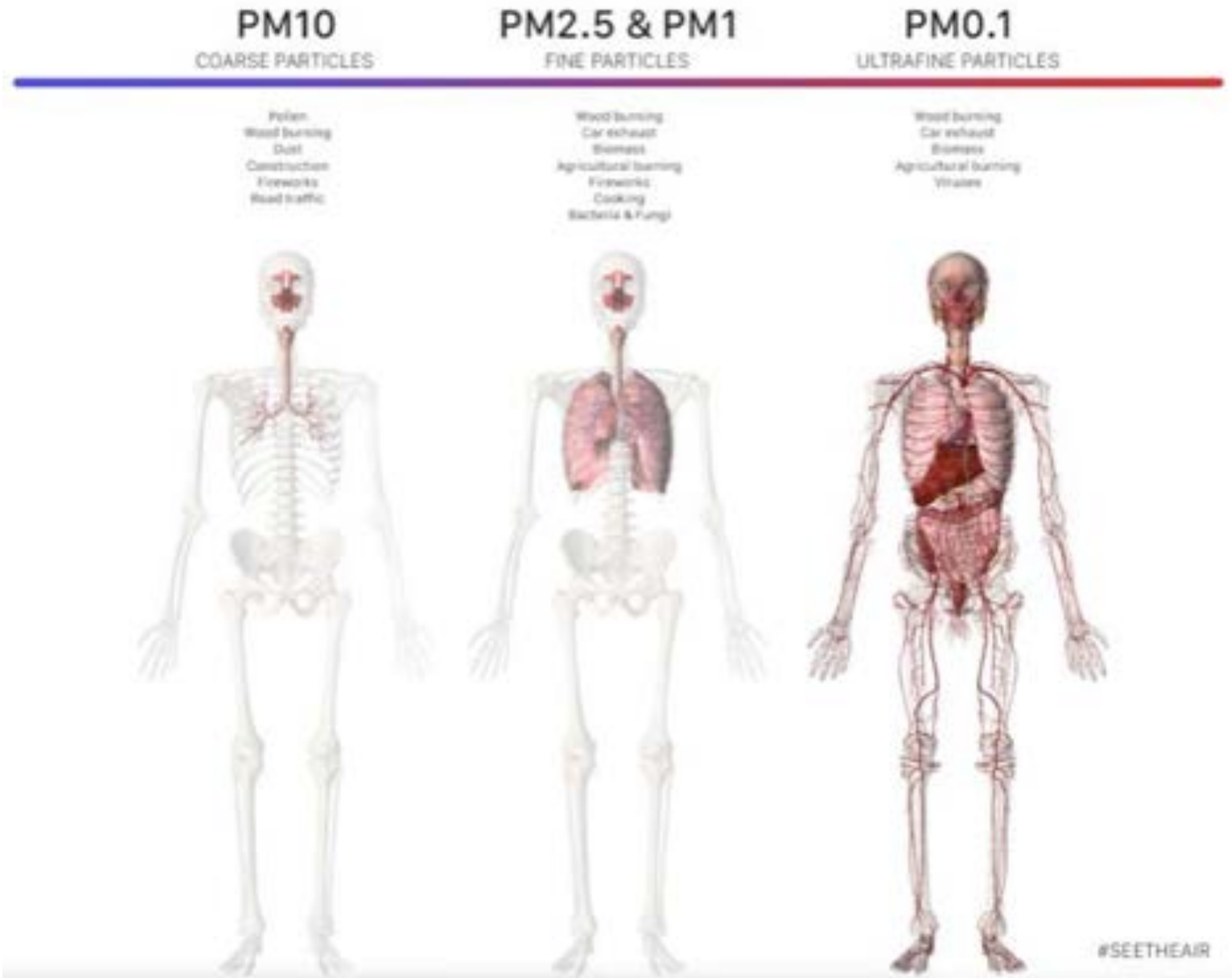

Fig. 2. Penetration of particles into the body, distinguished by particle size[33].

Particulate matter (PM) varies widely in size (Fig. 3). Jet-exhaust particulates are predominantly "ultrafine" particles (UFP)—typically smaller than 0.1 micrometers (µm or microns) or 100 nanometers (nm). That's at or below the lower detection limit of most inexpensive instruments; Aspen Fly Right's instruments could measure only down to 0.3 µm (300 nm), while typical jet-exhaust ultrafine particles are around 10–15 nm. Their large surface area helps them "potentially contain high proportions of organic material such as polycyclic aromatic hydrocarbons"—noxious coatings that the nanoparticles can transport via blood throughout the body. Indeed, "the total surface area of the deposited nanoparticles has been suggested to be predictive of toxicological potential in the lung."[34] It has been understood for more than two decades that *the size, numbers, and surface area of particles are more important to health than the mass of particles inhaled*[35].

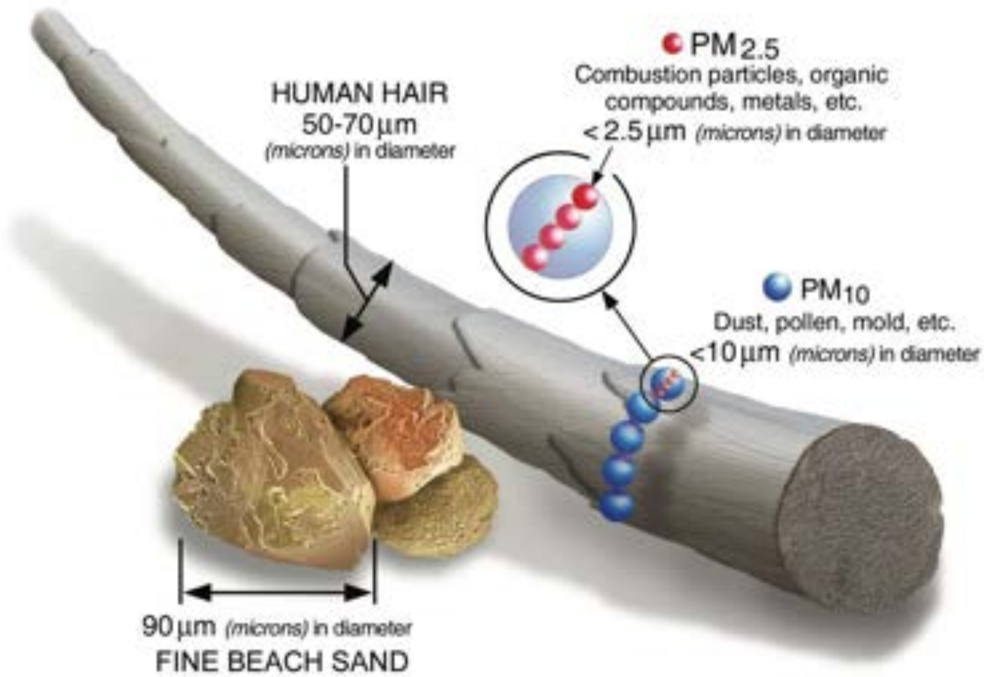

Fig. 3. A popular graphic comparison[36] *of particulate size with a typical 70-µm-diameter human hair (70 microns or millionths of a meter, or 2.8 thousandths of an inch). Our instruments reported particles with diameters from 0.3 µm (300 nm) to 1 µm as part of the ~0.1–1-µm class of particles called* PM_1*. Those are far smaller than the better-understood and -regulated* $PM_{2.5}$ *(≤2.5 µm, called "fine particles") and* PM_{10} *(2.5–10 µm "thoracic* coarse *particles," which also subsume* $PM_{2.5}$*) shown in the graphic. But our instruments could* not *observe particles smaller than 0.3 µm (300 nm), let alone smokelike nanoparticles that "represent almost all particles emitted by [jet] aircraft…[and] with a small fraction ranging in size between 100–250 nanometers"*[37]*. Nanoparticles are normally defined as 1–100 nm—similar to or smaller than a virus (~10–100 nm), far smaller than a red blood cell (~7,000 nm), and vastly smaller than the thickness of a sheet of paper (~100,000 nm). Traditional aviation-air-quality analyses lumped those nanoparticles into* $PM_{2.5}$*, but those nanoparticles are so much smaller that they have very different properties, now becoming widely recognized: they are typically more than 25 and often 50+ times smaller than* $PM_{2.5}$*, 10,000–100,000+ times lighter-weight, and fully able to travel throughout the lungs and into the bloodstream. They require special equipment to detect, yet appear to be the riskiest kind of particulate matter for human health.*

The emerging importance of nanoparticles

It is long and well established that particulate matter like PM_{10} and $PM_{2.5}$ is unhealthful to inhale. Thousands of scientific studies underpin their US and EU regulation, though efforts continue to tighten standards as more evidence of harm emerges. The three-decade Children's Health Study of thousands of schoolchildren in 12 Los Angeles communities, begun in 1992, rang the alarm bell on chronic underdevelopment of young lungs. Its findings led to many health-promoting policy shifts and stopped irreversible harm[38]. Colorado has also hosted similar research at altitude: the Director of Pulmonary Research at National Jewish Health in Denver, Prof. Nathan

Rabinovitch MD, found in 2006 that fine particulates worsened childhood asthma[39], then in 2016 that GPS-equipped personal monitors found substantial increases in asthmatic symptoms with *transient* exposures of ≥5 µg/m^3 (levels we found often far exceeded at Aspen Airport)[40]; and by 2022, that $PM_{2.5}$ exposure was set to cause tens, then hundreds, of thousands of additional US asthma cases[41]. There's no shortage of distinguished medical expertise on the importance of clean air for children's lungs and everyone's general health.

Collisions between that expertise and industrial interests have led to decades of regulatory fights. On 6 January 2023, the US Environmental Protection Agency was finally able to propose tightening $PM_{2.5}$ annual exposure standards[42] from 12 to 9–10 µg/m^3. (Short-term US exposure limits are severalfold larger.) EPA also invited public comment on lowering the annual standard further to 8—the current Australian standard. The case is strong. Environmental Defense Fund commissioned a study[43] finding that tightening the standard to 8 would prevent more than four times as many premature deaths as a standard of 10. The latest 3.7-million cohort study[44] found that 10 was associated with substantially more heart attacks and heart disease than 8, so the looser standard of 10 is not protective enough (let alone the 24-hour standard of 35 µg/m^3). The World Health Organization's 2021 guideline for $PM_{2.5}$ is just 5 µg/m^3, or 15 µg/m^3 for 24 hours. No doubt the EPA's final ruling will be litigated, and interested legislators may jump in too.

EPA also adopted in January 2023 an ICAO-matching standard[45] for jet-engine nonvolatile ultrafine particulate emissions only (because the volatile ones are so hard to measure), and has posted a memo[46] documenting their health effects, building on the Integrated Science Assessment finished in 2019[47].

While the fine-particle ($PM_{2.5}$) debate continues—that science is over but the shouting is not—increasing evidence is suggesting that exposure to *ultra*fine particles may especially harm human health. For example, a 2020 Dutch study exposed 21 healthy nonsmoking volunteers aged 18–35 to 2–5 doses of UFP (averaging 53,500 particles/cm^3) during 5 hours of cycling. Relatively small but clear lung and cardiac effects were observed[48] from *single* exposures to particle sizes <20 nm (from aviation) but not to particle sizes >50 nm (from road traffic)—a potentially important finding for susceptible sub-populations, including children. A 2021 review of animal and test-tube studies[49] amply confirmed cytotoxicity, inflammation, and other concerning effects, and concluded[50]: "Taken together, these results suggest that the exposure to aircraft emissions induce pulmonary and systemic inflammation, which potentially contributes to cancer, asthma, respiratory and coronary heart disease." So what does this imply for airports and public health?

Ultrafine particles and airports

A 2015 synthesis[51] by the Transportation Research Board of the National Academies found that $PM_{2.5}$ around US airports dominates airport emissions' health risks, with concentrations ranging from relatively low to near or above Federally permitted standards. Ultrafine particulate concentrations at airports, it found, can be orders of magnitude (factors of ten) above background with some persistence many, e.g. 600, meters downwind (p 40). That later proved to be understated.

Measurements near the Santa Monica regional airport found takeoff spikes 440× above background 100 m downwind, reaching 2.2 million particles per cm^3, with elevated ultrafine particles

extending beyond 660 m downwind (2.5× above background) and 250 m crosswind[52]. At the LAX blast fence, particle counts exceeded 10 million per cm^3 during takeoffs[53], >10× the count at lower engine power. Air monitoring up-wind of LAX found mainly ~90-nm particles; downwind, ~10–15 nm (matching many engines' main emissions, and 167–250× smaller than 2.5 μm); and 2–3 km downwind, intermediate in size, with "significant exposure and possible health implications for people living near the airport."[54] At 500 m downwind from LAX, average ultrafine particle counts of 50,000 particles/cm^3 were observed, peaking with aircraft operations, and covarying with soot, particle-bound polycyclic hydrocarbons, and NO_x. UPF concentrations were nearly as large 500 m as 250 m downwind from the departure end[55].

Even in 2007, when ultrafine particle "levels from aircraft were measured to persist up to 900 m from the runways, indicating potential risks to the nearby communities,[56]" it seemed that "airport operations are associated with elevated levels of UFP much further downwind in the neighboring community than would have been predicted by prior studies of UFP from roadway-traffic." In 2014, jet-engine nanoparticle emissions were found to spread *~16 km (10 miles)* downwind from such major airports[57]. Their potential drift into downtown Aspen has apparently not been measured, but would seem prudent to check and to contrast with traffic-related emissions.

A first-rate review in 2021[58], emphasizing occupational exposures, found that especially due to the nano-sized particles that dominate jet exhaust, "Proximity to running jet engines or to the airport as such for residential areas is associated with increased exposure and with increased risk of disease, increased hospital admission and self-reported lung symptoms. We conclude that though the literature is scarce and with low consistency in methods and measured biomarkers, there is evidence that jet engine emissions have physicochemical properties similar to diesel exhaust particles, and that exposure to jet engine emissions is associated with similar adverse health effects as exposure to diesel exhaust particles and other traffic emissions." Diesel exhaust's particulates are mutagenic, carcinogenic[59], and in mouse models genotoxic[60]. But jet exhaust particles, though similar to diesel exhaust particles in "inflammatory potency and… ability to induce DNA damage," are generally smaller, more penetrating, and even more reactive.

The health risks of ultrafine particles are an emergent area of medicine, subject to much uncertainty, but in general, more research is revealing greater risks. In summary, the 2021 review[61] raises significant concern about the potential effects of both occupational and downwind community exposure to jet-exhaust emissions, based on multiple lines of evidence and numerous human, animal, and cellular studies. More research is needed because measuring such fine particles is difficult, but "Based on the accumulated knowledge so far, measures to reduce occupational exposure and emission levels at airports should be increased." This heightens the strategic importance of the aviation innovation revolution that will move society far beyond fossil-fueled airplanes, as described in our Essay #5 (12 January 2023) and its underlying technical brief (invited by the Airport Director for himself and his lead aviation consultants).

Physical behavior of jet-engine exhaust plumes

The ultrafine particles that jet engines emit in astronomical numbers can thus drift for many miles downwind at ground level, and have been measured at other airports to travel in coherent high-concentration plumes for well over a half-mile. Aspen Fly Right therefore became con-

cerned that jets waiting to take off from Aspen Airport are pointing their exhaust plumes almost exactly toward the Powder Pandas' Hideout—the children's ski school at the base of Buttermilk.

As the Google Earth image in Fig. 4 shows, the air distance from the jet exhaust of airplanes at their nominal start-of-takeoff site to the front of the Hideout is ~640 m (~2,100′). It was 305 m or 1,000′ longer than that until 2011, when a $13-million County project extended the runway toward Buttermilk to raise airlines' summer capacity by letting their planes carry more load on hot days. During planning, citizen queries about potential unintended consequences—such as airplanes' greater air pollution at Buttermilk and increased accident risk in a densely populated area like the X Games zone—were dismissed without discussion or analysis, on the grounds that a longer runway was obviously a safer runway, so its other possible effects need not be considered[62]. The Public Safety Council wasn't allowed to assess its health-and-safety implications[63]. It was handled solely as a land-use issue by the Planning and Zoning Commission. The County's Emergency Management Coordinator was rebuked for giving the Board of County Commissioners at First Reading her professional opinion that risks like plane crash and air pollution should be analyzed and considered. In hindsight, greater prudence would seem warranted. The air-quality issue was not so much ignored as deferred. Now it's back, at one-third closer range.

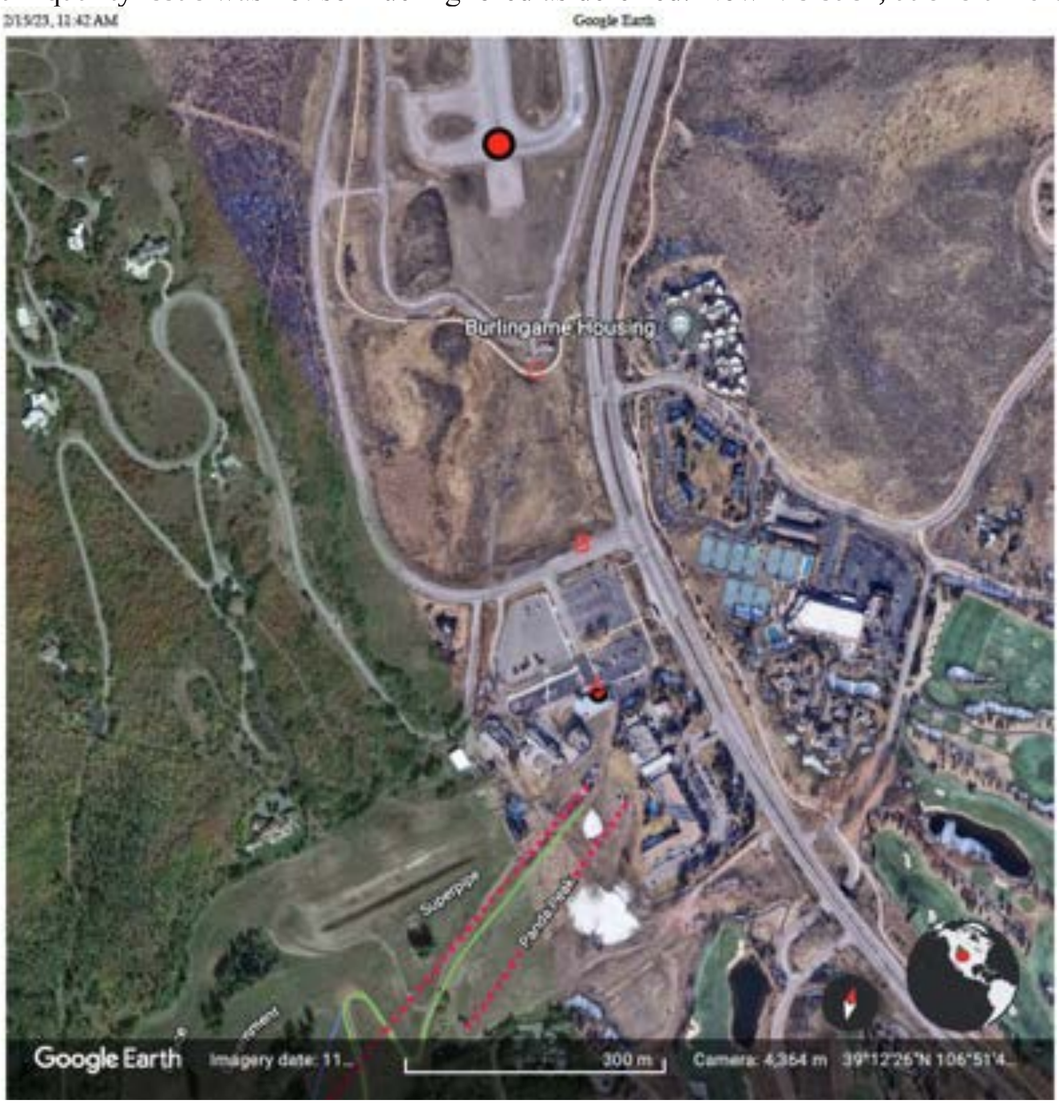

Fig. 4. Google Earth image[64] showing the south end of takeoff Runway 33, which points north (towards the top) on a true bearing of 330.7˚. The large black-rimmed red dot is about where planes apply full thrust to take off. The runway's centerline points south to just a few degrees west of the light-blue-gray building (small black-rimmed red dot), now called the Hideout, where the Powder Pandas children's ski school marshals. The children then walk SSE to the Panda Peak small lift (the lower dotted red line) for their ski lessons. Our approximate main air-quality measurement sites were at C, B, and A, seeking to track jet pulses in that sequence.

The telephoto rear view of an airplane taking off as seen from the Buttermilk access road on the axis from the takeoff site to the ski school, or (peering through trees) from farther away near the front of the ski school, looks more or less like Fig. 5:

Fig. 5. A relatively dirty jet takeoff seen through a telephoto lens from the direction of the children's ski school at Buttermilk. The turbidity is due to particles, including probably quintillions of nanoparticles, being jet-propelled toward Buttermilk. Aviation air-pollution models seldom distinguish these smoke-like, mainly sooty particles from the merely "fine" $PM_{2.5}$ or smaller PM_1 particles that Aspen Fly Right used as a surrogate to see if jet pulses could be tracked from plane to ski school despite interfering winds, plume buoyancy, topography, and dispersion.

So can the powerful jet plume transport mass, especially ultrafine particles, from the taking-off aircraft to the ski school? How far do jet plumes travel from planes still on the ground? We were surprised by what the literature disclosed. First, a ramp-crew safety diagram[65] (provided by the maker of every aircraft type) shows that each of a CRJ700's jet engines, though not the most powerful used at ASE, produces at full throttle a 60-mph (97 km/h) plume velocity 88 m or 290′ behind the plane (Fig. 6):

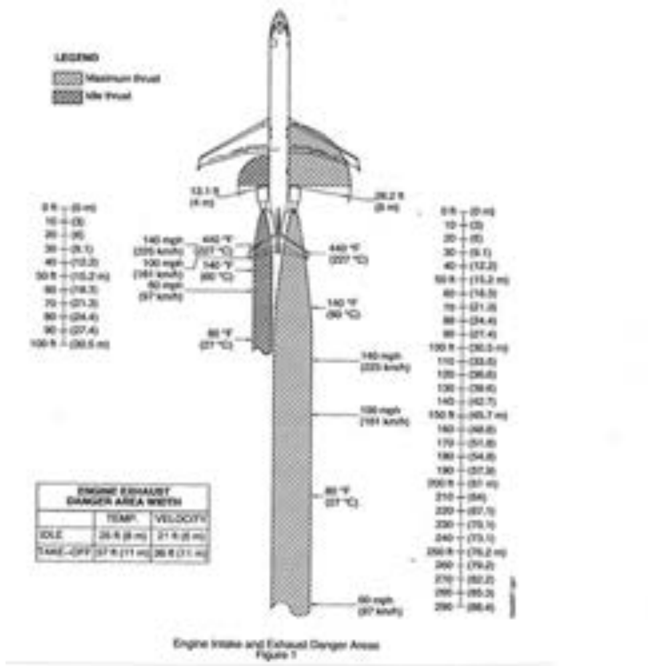

Fig. 6. The CRJ-700's twin engines each produce 56 kN of nominal thrust. Some General Aviation airplanes at ASE have more powerful engines; for example, a G600's twin engines each produce 71 kN (27% more); Fig. 5's, 66–67 kN.

The plumes from twin fuselage-mounted jet engines quickly merge into a single plume. As it goes back, it can become somewhat broader. It tends to hug the ground, but ultimately will rise from its warmth's buoyancy and will begin to diffuse.
Its fine and especially ultrafine particulates, volatile organic compounds (VOCs) like unburned fuel residues, and NO_x linger.

Jet-blast diagram courtesy of Bombardier.

The jet engine's gas turbine, emitting that fast stream of hot gas to produce thrust, is a rotating machine, so its exhaust plume twists. This vortex gives the plume enough spatial coherence to transport pollutants for at least 700–1000+ m (some literature even mentions 1,200 m). Elegant 2010 lidar scans[66] directly imaged jet plumes from planes on the ground at two British airports for up to 800 m range, though NO_x measurements got fuzzy[67] at 1000–1570 m. NASA's pioneering 2010 experiments with alternative aviation fuel physically measured[68] combustion products and emissions in net plumes not only 145 m (p 57) and nearly 200 m (p 59) behind a DC-8 but also occasionally at >500 m, using a mobile analytic van. Physically observed plume length[69] can thus exceed the ~640 m from ASE's takeoff site to the Hideout, especially since Aspen's altitude reduces the air density that resists the plume's propagation.

These findings encouraged us to try to measure transits of takeoff jet-plume pulses from location C to B to A in Fig. 5: from sites along the north side of Open Space and Trails' public bike path ~300 m from the jet exhaust at start-of-takeoff position, to sites along the north pulloff on the public Buttermilk access road ~500 m from the plane, to several locations in the public parking lot a few tens of meters or less from the Hideout's front door. All three points fall in nearly in a straight line from the jets' takeoff position, taking account of the likely widening of jet pulses' path as they moved south. We explored the effects of different positions across the runway axis.

Why jet plumes are hard to measure

Of course, it's not that simple. Each actual plume trajectory is also influenced by wind, which near Aspen Airport can be quite erratic: it's not unusual for pilots to see multiple windsocks all pointing in different directions. As the plume loses momentum, it becomes more easily deflected and diffused. Although the field from the runway to the Buttermilk access road is smooth, north of the center and the west end of the pullout it also ends in a low rounded swell covering some infrastructure. That topography might shift some plume flow eastward and upward.

February prevailing winds at the Aspen Airport are out of the north or slightly west of north, plus a daily up-/down-valley cycle from the SSE that occurred almost entirely outside our measurement hours. The actual winds during our 16–21 February 2023 measurement campaign followed this normal pattern and were mostly light[70], but for a brief snowsquall.

However, a gradually slowing jet plume's actual path over a range of ~640 m is very sensitive to even light winds that it may encounter along the way. Visualize the beam of a powerful flashlight held in a shaky hand: at such a distance, it will only occasionally flash across its distant target (and traverse the two waypoints with most of our instruments). Moreover, the initially hot jet plume's buoyancy, competing with a ground-hugging tendency from the Coanda effect[71], could cause much of the "beam" to rise above our heads so we couldn't detect or measure it, though it could still transport the same particles and gases into the Buttermilk complex and beyond.

For these reasons, we might reasonably expect to see only a few rare events where the plume could be measured successively and unambiguously by our ground stations at locations C, B, and A. Subject to check by closer data analysis, we do have the preliminary impression that we saw some such signatures, which would establish that the jet plume can indeed transport its PM_1 and $PM_{2.5}$ pollutants from plane to ski school. This three-site correlation remains to be checked and compared with actual flight departure times from our logs and online data.

However, this doesn't mean *we* could measure the ultrafine particles thereby transported: they were simply too small for our inexpensive instruments to detect. Rather, it means that experts with lab- or regulatory-grade equipment[72] fit for this purpose should do those measurements. They should also expand our limited "transect" measurements at our sites C and B to test the effects of distance from Highway 82, whose interfering effects are discussed below. Perhaps they could deploy a fuller array of fine-time-resolution sensors on a transect, to try to detect jet-plume signatures traversing the array under the influence of varying winds. Most importantly, they should measure the <10–200+-nm particles we couldn't detect, and should collect particle samples for a lab study to distinguish jet-engine from road-vehicle emissions as discussed below.

To help interpret our downwind measurements and inform optimal real-time relocation of our instruments, we installed at site C, near the Airport boundary and together with our air-pollution instruments, a Kestrel 5500L miniature digital weather station[73] that recorded timestamped wind-speed, direction, and other meteorological parameters every two seconds. Our tripod-mounted instruments blew over several times, partly due to strong gusts from the jet blast itself.

What happens when wind makes the jet plume's "beam" wander off the exact target where our instruments stand, as it usually will? Its pollutants are simply transported by momentum and prevailing winds *into other places in the same general area*. There they diffuse into an invisible miasma, meandering around and through the building complex to its south side and onto the ski slope behind, then presumably further upvalley[74]. (Pollution gets diluted and dispersed but not destroyed.) Concentrations on the slopes may vary widely with wind and topography: some skiers and hikers anecdotally report pockets of stiller air where throat-burning or fuel-like vapors seem stronger. We didn't try to find or record such situations, but in all three of our measurement locations, we did smell strong whiffs of jet fuel, throat- and eye-irritating gases (probably NO_x), and other pollutants when a plane was taking off and the wind came from the runway.

What could our instruments measure?

Instruments to measure various kinds of air pollution come in many degrees of accuracy (how close they are to showing the correct values), precision (how exactly they show their results), stability, simplicity, ruggedness, cold-tolerance, portability, and cost. A 2020 report to Pitkin County[75] explained, just as we would, why that contractor had used low-cost sensors to measure particulates at the North Forty fire station in 2020:

> Reference monitors are used in regulatory monitoring of criteria air pollutants. These monitors are located at a fixed site, are expensive to operate, and require highly trained specialists. They provide known and consistent quality data under a variety of ambient conditions.
>
> Low cost sensors, such as those deployed in this study by [contractor] APIS, are relatively inexpensive, portable and require little to no training to operate. The accuracy of data may vary from sensor to sensor. This is one reason why sensors are not currently suitable for regulatory monitoring. However, they do provide information about local air quality that help determine areas where air quality may be a concern and require more robust and accurate monitoring.
>
> Several sensors, including the models of those used in this study, were co-located with reference monitors in a comparison study conducted by California South Coast Air Quality Management District. See http://www.aqmd.gov/aq-spec/sensors.
>
> Correlations with reference monitors indicate that the [specific] sensors used in the [APIS] airport air quality study tend to overestimate pollutant concentrations. [Ours variously read high or low in SCAQMD lab and field tests, according to pollutants, concentrations, durations, and other details.]

According to the same evaluations by the SCAQMD—the world-class California agency mentioned (Appendix B)—our instruments are broadly comparable to the County contractor's $5k APIS instrument and $229 Purple Air sensor (widely used to measure wildfire smoke). We entirely agree with Pitkin County's study that low-cost sensors "help determine areas where air quality may be a concern and require more robust and accurate monitoring." That was our purpose. Of course, governments' regulatory-grade-or-equivalent instruments are far more elaborate and costly. A County consultant, apparently assuming top quality, said a single instrument could cost $50,000. Instead, Aspen Fly Right bought ($3.2k) or borrowed 15 instruments (including the weather station) worth ~$14k, chosen not for regulatory-grade accuracy but for an "optimal degree of sloppiness" to check whether there's a real problem needing better tools.

Of course, any instrument is useless if not properly set up and operated. Guided by a helpful EPA handbook[76] and other materials published to support "citizen scientists," we acquired factory-calibrated equipment, used pre- and post-campaign collocation to confirm that different instruments at the same place and time showed similar readings, and synchronized their and our clocks to make timestamps comparable[77]. We also noted local events that could distort our readings, such as a passing heavy vehicle, or an adjacent car starting up. We downloaded and examined the data each evening to inform next day's deployments. We're still analyzing our data, so different or further conclusions may emerge. And to re-emphasize, we do not hold ourselves out as air-pollution experts or as obtaining definitive data from lab- or regulatory-grade equipment. We're simply trying to fill a major measurement gap by doing affordable basic measurements just good enough to check if an air-quality issue needs careful study.

What are our kids breathing at the base of Buttermilk?

Perhaps our simplest and most important measurements explored what Aspen kids are breathing around the base of Buttermilk. More than 10,000 data points measured near location A (very close to the front of the Hideout) over 17–21 February 2023, typically from late morning to late afternoon, examined PM_{10} and $PM_{2.5}$ particulates with high precision and fairly high accuracy, PM_1 (only down to 0.3 µm in diameter, not 0.1) less exactly, and nitrogen oxides and total volatile organic compounds with lower accuracy and precision. Our instruments' varying capabilities and performance metrics are summarized in Appendix B below.

Most of our measurements agreed reasonably between different instruments, with significant differences between days and between different times at single days (such as the big burst of air pollution as cars arrived to pick up kids after ski school each midafternoon). We often saw pronounced spikes in pollutant concentrations, some from vehicles passing or idling nearby in the parking lot (including their exhausts and road dust), and some, if confirmed by further study, seemingly from airplanes taking off. All particulate records were quite spiky, with numerous, sharp, and prominent transient events, as we'll publish in timeseries graphics being prepared. Concentrations were generally higher at location B, on the access road, and far higher at location C, on the bike path nearest the departing airplanes, than at location A by the ski school. This is consistent with the hypothesis that airplanes are substantially contributing to air pollution.

Maximum observed values were tens to hundreds of times the minimum or, often, the average values. In general, we saw more total PM_{10} than $PM_{2.5}$, which in turn exceeded PM_1, but that's all measured by *mass* concentration ($\mu g/m^3$), so the particle counts, surface area, and hence health risks would show the opposite. We typically measured volatile organics in the hundreds of parts ~~of~~per billion (>10,000 ppb near the ramp), and nitrogen oxides averaging tens to >100 parts per billion, with maxima of hundreds. Some basic measurements are tabulated on p 18 below.

We also measured air pollutants in the Elk Parking Lot near the de-icing pad[78] to check emissions from idling jet engines and often APUs (plus the spray trucks) and at a private plane parked near the FAA control tower. These two sets of readings, each spanning several days, found some significant concentrations, particularly for hydrocarbons. This suggests the need for more exact and detailed monitoring for specific hydrocarbons, NO_x, fine and ultrafine particulates, and nanoparticles, to protect the health of airport workers and users. It also lends credence to passenger complaints of fuel odors near the Terminal, unchecked by any measurements there. It would be easy and useful to hang cheap portable monitors like the ones we used in and around buildings of interest, and from workers' clothing, to improve air-quality situational awareness.

Comparing our measurements with regulatory standards

Although one member of our team is a public-health physician and medical toxicologist, we think it best for independent experts on air pollution and health to assess the health implications of our findings as they emerge from our data analysis. A widely used point of reference meanwhile might be the Federal government's set of primary National Ambient Air Quality Standards (NAAQS)[79] under the Clean Air Act. Those regulatory standards are meant to protect public health—including for "sensitive" populations such as asthmatics, children, and elders—from six

“criteria air pollutants.” Those are ground-level ozone, carbon monoxide, lead, and sulfur dioxide (none of which we measured[80]), plus the two kinds relevant here—nitrogen dioxide and particulate matter (PM). Those standards, copied from EPA’s 5 April 2022 NAAQS Table, are:

Pollutant [links to historical tables of NAAQS reviews]		Primary/ Secondary	Averaging Time	Level	Form
Nitrogen Dioxide (NO_2)		primary	1 hour	100 ppb	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		primary and secondary	1 year	53 ppb (2)	Annual Mean
Particle Pollution (PM)	$PM_{2.5}$	primary	1 year	12.0 μg/m^3	annual mean, averaged over 3 years
		secondary	1 year	15.0 μg/m^3	annual mean, averaged over 3 years
		primary and secondary	24 hours	35 μg/m^3	98th percentile, averaged over 3 years
	PM_{10}	primary and secondary	24 hours	150 μg/m^3	Not to be exceeded more than once per year on average over 3 years

(2) The level of the annual NO_2 standard is 0.053 ppm. It is shown here in terms of ppb for the purposes of clearer comparison to the 1-hour standard level.

OSHA has a 500 ppm Permissible Exposure Limit for *occupational* exposure to petroleum hydrocarbons during an 8-hour workday and 40-hour workweek, plus numerous standards for specific hydrocarbon species[81], but no *public* VOC standards[82], which are stricter because only workers are deemed to “accept” higher risk in return for their jobs. NO_x is hard to measure accurately with low-cost instruments, but is a well-understood air toxin and a useful proxy to help track the travel of fine particulates.

Our observations in front of the ski school (location A in Fig. 5) measured these values during 3–6½-hour periods each day on 17–21 February 2023, using sensors described in Appendix B:

Pollutant, units	*Instrument*	*Mean Absolute Error*	*Averaging Time*	*5-day range of daily means*	*Overall range*
NO_x, ppb	Egg	21 to 32	5 seconds	20 to 40	0 to 193
NO_x, ppb	fobs	11 to 18	1 minute	8 to 158	0 to 377
Total VOC, ppb	fobs	unknown	1 minute	101 to 340	1 to 3,598
PM_1, μg/m^3	Egg	unknown	5 seconds	0.1 to 0.6	0 to 29
$PM_{2.5}$, μg/m^3	Egg	6 to 7	~~1minute~~5s	0.5 to 1.5	0 to 42
$PM_{2.5}$, μg/m^3	fobs	7 to 11	1 minute	2.7 to 54	1 to 306
$PM_{2.5}$, μg/m^3	ECM (19–21 Feb)	6.9 (3.6 to 10.4), p 27	10 seconds	3-day sensor median 4.4; gravimetric filter 4.4	1.2 to 182
PM_{10}, μg/m^3	Egg	18 to 21	5 seconds	0.7 to 1.5	20 to 42
PM_{10}, μg/m^3	fobs	19 to 28	1 minute	4 to 116	2 to 853
Particles ≤100 nm	—	—	—	—	—

Comparing all those readings with the NAAQS standards shows:

- Maximum observed NO_x values were several times the EPA 1-hour standard, but for much shorter periods; daily average concentrations averaged modestly below EPA's annual-mean standard, but each day's peaks exceeded it (by manyfold on most sensors).
- For volatile organics (VOCs), there is only an occupational standard, so no meaningful comparison is possible for general public exposure.
- For PM_{10}, some readings exceeded EPA's 24-hour once-a-year maximum by severalfold, but averages were below it (by large margins on two days).
- For $PM_{2.5}$, some peaks were manyfold above, but averages well below, EPA's proposed 8–10 μg/m^3 standard[83]; our particle filter found 4.4 μg/m^3, just below WHO's 5 standard.
- For PM_1, there is no regulatory standard—only convincing scientific evidence of greater risk than for $PM_{2.5}$—but our measurements near the ski school repeatedly peaked at just over 5 μg/m^3, which at a nominal jet-takeoff density[84] would imply a substantial >35k ultrafine particles per cm^3 (comparable to the LAX results discussed on p 11). Moreover, our instruments' 0.3 μm detection limit meant they couldn't see the important 0.1–0.3 μm size range that PM_1 includes, so they understated its total; and the small *mass* shown for PM_1 conceals an immense *number and surface area* of ultrafine and reactive particles.
- That's even more true and important for ultrafine particulates, where regulation hasn't caught up with the science, there is no standard, and establishing one will be very hard[85].

We found no evidence of a public-health emergency. (For completeness, though: being unable to measure nanoparticles, we can't assess their concentrations or health implications. Absence of evidence is not evidence of absence.) There's time to figure this out—with, we respectfully suggest, due deliberate speed.

These comparisons could be strictly construed as showing that measured air pollution at the base of Buttermilk complex doesn't exceed Federal standards. That's literally true but misleading, for two reasons: (a) those standards are measured for far longer periods than our five days' campaign (even the 1-hour NO_x standard is to be measured daily for three years), and (b) there are no Federal public standards for three of the six pollutants. Neither reason is reassuring or dispositive. They leave us in some unease—increased by the many strong and briefly standard-exceeding transient spikes we observed, some potentially significant for health.

Taken as a whole, our observations would seem to suggest the value of professional measurement with lab-grade or regulatory-equivalent sensors, for longer periods in each day, and for more days. Our measurement periods strongly overlapped the main skiing hours, especially for children. However, long-term EPA standards designed for cities and industry need careful interpretation, because skiers are not on the slopes 24 hours a day or throughout 1–3 years, so extrapolating between their briefer exposures and long-term exposure limits could be misleading. Exposures relevant to public health but *not* related to aircraft emissions can also occur in road vehicles, in buildings, and during other parts of the day and night; such confounding exposures should be taken into account and distinguished from exposures attributable to aircraft emissions.

The overriding concern to keep front-of-mind is that the hard-to-measure nanoparticles that make up almost all of jet exhaust particulate emissions are increasingly the most concerning type of

aviation-related air pollution. Standards lag the science, probably by one or more decades. The absence of a Federal standard does not mean exposure is safe. Assessing potential risks to public health from not-yet-regulated emissions requires prudent judgment informed by expert measurement. Guesswork about the unknown no longer suffices to ensure public health and safety.

Where does the observed air pollution come from, and how much comes from airplanes?

Many sources of air pollution can interfere with the aircraft pollution we sought to measure. Buildings at the base of Buttermilk may have boilers or furnaces, kitchens may use combustion appliances, so we stayed upwind of these sources and, where possible, of motor vehicles. Perhaps most importantly, vehicles in the typically-full Buttermilk parking lots and on the access roads emit NO_x and particulates and raise road dust. Even skiers walking by can kick up dust.

Those autos may turn out to be the biggest source of air pollution at the ski school. If they proved sufficiently worrisome, then one class of potential solution might encourage or require electric-only vehicles at Buttermilk, so polluting vehicles would park at, say, the park-and-ride and skiers would shuttle by electric bus or van. Or perhaps preferential parking or a fee discount, plus rapid electrification of rental fleets, might speed the shift away from internal-combustion vehicles. There are many potential ways to reduce vehicular pollution. Perhaps our measurements may help to inform their choice and urgency. But such policy musings get ahead of the evidence. First let's measure who's emitting how much of what.

We don't even know yet whether those road vehicles and their movements around the parking lots produce more or less health risk at, say, the kids' ski school than Highway 82 traffic does. That major road traffic, modulated by traffic lights that cause frequent idling of stopped vehicles east of our site B, is clearly a very important source of particulate and gaseous emissions. It can be reduced by better land-use, housing, transit, parking, and other policies. And it will soon be slashed by the rapidly accelerating transition to electric cars and trucks, then airplanes.

Some assert that Highway 82 road-vehicle emissions cannot be distinguished from aircraft emissions. That's a proper and very important analytic concern, but we don't share the conclusion, because there are at least four potential ways to distinguish these two sources:

- They have severalfold different particle size distributions (as observed e.g. at Heathrow[86] to distinguish jets' emissions from road traffic's, and in five further literature citations[87]). That difference should be readily observable with instruments more sophisticated than we could afford but available to air-pollution experts[88].
- Perhaps we could observe distinctive changes in emissions as the overnight curfew ended at 0700 and morning flights began. Unfortunately, at least on the one day we tried this (17 February 2023), there were too few early flights for a clear aviation signal to emerge, or winds were unfavorable, or both. Takeoffs between 0700 and ~1000 are officially said to be relatively few, especially for General Aviation, but the cluster of early-morning airline departures in high season may make this experiment worth repeating.
- When the Airport next closes for maintenance in May 2023, it should be easier to study the daily profile of pure highway emissions in various winds with no aircraft emissions.

- We hoped to be able to observe the signature of a jet-exhaust pulse traveling from near an airplane taking off through an intermediate point to the base of Buttermilk, i.e. from locations C to B to A in Fig. 5. In that quest we suspect we may have succeeded. We are still examining a gigabyte of detailed data to ensure that what look like distinctive emission spikes at those successive waypoints (measured with five-second resolution) actually are, cannot reasonably be ascribed to some other cause, and do match known takeoffs.

In summary, neither we nor anyone else knows how much of what kinds of air pollution is emitted by Aspen aviation and is reaching sensitive areas like the kids' ski school and the X Games and World Cup zones. Our initial rough measurements suggest, consistent with common sense, that *some* air pollution does come from planes—especially the unmeasured nanoparticles that are the most worrisome kind—but we have insufficient evidence to guess how much. Aviation emissions should therefore be measured, and distinguished by particle size from road-vehicle emissions and traffic dust. Much good scientific literature does that, and our local, state, or Federal government should do it too.

Nanoparticles' potential contribution to our community's public-health risks, especially for the most vulnerable (young and exerting) lungs, is unknown and merits independent assessment by multiple experts. We hope our findings will stimulate a thoughtful mix of higher-fidelity local measurements and well-designed, strongly measurement-based and -validated pollution-transport modeling, using tools Prof. Tony Tyson suggested to the Airport Advisory Board[89].

The basic solution: access and mobility without burning fuels

Whatever our snapshot of present air pollution shows, we can be confident that pollution *from both road vehicles and planes* will decline over the next decade, and may virtually disappear over the next 2+ decades, as fossil-fueled fleets are replaced by better and cheaper electrically propelled (and, we hope, superefficient) versions. Our progressive electric grids already deliver all-renewable electricity to run those vehicles (Aspen), or soon will (Holy Cross Energy).

To speed that clean-air era, our community needs a decision process that doesn't prematurely divert this transition or delay its benefits by investing to expand, rather than transform, today's polluting air and ground transportation systems. There are many compelling reasons to accelerate the transition. Unexpectedly worrisome air pollution, and the potential consequences of guessing wrong about emergent science as jet traffic keeps growing, may add another.

What should be done next?

So summarizing what we've learned so far from Aspen Fly Right's citizen-science effort to replace old assumptions with modern data:

- The longstanding but empirically unsupported official claim that Aspen air pollution in sensitive areas particularly prone to airport emissions is theoretically minor and thus needn't actually be measured is implausible and should be abandoned.
- Aspen Fly Right needs to complete and publish its data analysis (delayed, with our apologies, by some personal circumstances among our team). We appreciate the community's patience, and will proceed as briskly as we can, consistent with care and clarity.

- Careful field measurements designed by independent outside experts, using at least lab-grade if not regulatory-equivalent instruments and informed by prospecting with low-cost ones, should specifically include nanoparticles in the 10–100 nm range typical of jet exhaust. These measurements should be long enough, in appropriate sites, to draw a convincing picture of what is in our community's air, and roughly what sources emit it. This study should be designed under the direction of the Airport Advisory Committee with a steering group of distinguished, independent, disinterested experts; promptly reported; and transparently published in full. Funding should be led by our local governments, but may be augmented by the Colorado or Federal government or by the private sector. It's in everyone's interest to resolve air-quality questions professionally, independently, definitively, and impeccably.
- It seems likely that most of the air pollution thus measured will turn out to come from road and air vehicles. City, County, private-sector, civil-society, and individual efforts to reduce that traffic, *and* to switch to vehicles that don't burn fuel and don't pollute the air, should be accelerated. Mobility (or, more precisely, access) without fuel should form the core of public policy for our community's air and road transport—with added urgency.
- Sustainable Aviation Fuel (Essay #7) should be sped to halve ultrafine particle emissions.
- If jet-plume pollution proves worrisome, airport design experts should explore whether a downwind berm or ramp might help diffuse it and still meet FAA airfield design rules.
- Nearly everyone, directly and indirectly, uses today's polluting land and air vehicles. Our community owns that problem and its solutions. Finger-pointing is unhelpful; we're all in this together, we all breathe the same air, and we all need to focus on shared solutions.
- Any air issues found to be caused by aviation are the responsibility of the Airport's operators and policymakers—not of affected businesses, residents, and guests. Whatever turns out to be entering Buttermilk air from the Airport was put there not by ski operators, but mostly by airplanes whose owners and operators serve or are part of the community, under policies set by our elected officials and the FAA.
- Local businesses may well find that adding a new dimension and intensity to this community's longstanding environmental leadership can strengthen its brand. If Aspen doesn't turn out to have an air-quality problem, that could be because it prudently and accurately checked before competing resorts did. If it does turn out to have a problem, that's because it took responsibility for finding and fixing it before others did. Either way, community leaders' decisive and evidence-based choices could confirm the quality, safety, and healthfulness of the Aspen experience.
- Some past policies may not have been fully informed or have thought through all their unintended consequences. Let's fix that together, collaboratively and without blame, and move on to our other challenges, conscious of lessons learned from this one.
- This path reinforces the importance of transparent public processes that hear diverse views and are informed by current science to craft sound, adaptable, and farsighted policies. These are the aims of Aspen Fly Right, and are why we undertook this work.

Aspen Fly Right's volunteer citizen-science effort will evolve and yield further public insights as our data analysis proceeds. It's only the first step in a substantial, inclusive, and durable process for improving how Airport (and other) community decisions are made. Our goal remains a safer, cleaner, quieter, better Aspen Airport. We're honored to have taken this first step, and hope it may encourage others to support, extend, and emulate our work.

Appendix A
Aspen Fly Right's volunteer air-quality measurement team, 16–21 February 2023

Aspen Fly Right and its supporters are deeply grateful to the dozen local citizens who have given generously of their time and talent to make possible this intensive citizen-science effort:

Ellen W. Anderson, BA (Brown) plus UC/Denver graduate studies, was a Pitkin County Deputy Sheriff from 1981 to 2011. In addition to all patrol officer duties with advanced training, she was also Airport Liaison, founding director of Aspen's Tipsy Taxi, Special Projects Coordinator, and Public Information Officer. She co-authored "Colorado Validation of the Standardized Field Sobriety Tests", published by NHTSA in 1996. As a consultant, she wrote successful proposals for Pitkin and two other County Airports and the 2003 XGames and was an armed security guard. From 2003 to 2011 she was Emergency Management Coordinator, and developed and coordinated emergency plans across 27 first-responder agencies. She has received recognition from the International Association of Chiefs of Police, National Commission Against Drunk Driving, Colorado Task Force on Drunk/Impaired Driving, Centers for Disease Control, Colorado Department of Transportation, and Town of Basalt. Her public service has included Aspen City Council, Planning and Zoning, Pitkin Clean Air Advisory Board, County Election Commission, and more than a dozen other organizations. She has lived in Aspen since 1976, and is cofounder and Treasurer of Aspen Fly Right.

Ginny Bultman earned a BS in Education at North Texas University in 1986, then moved to Snowmass Village to build costumes for Snowmass Repertory Theater and never left. She was a public-safety dispatcher at Pitkin County Regional Emergency Dispatch Center 1994–2020, becoming a dispatch supervisor, training program director, and Communication Unit Leader. She served on the Pitkin County Incident Management Team, the Triad Critical Incident Debrief Team board, the National Emergency Number Association, and the Association of Public Safety Communications Officials, and was a Colorado Training Standards Institute instructor. She now supports her family's local locksmith business, designs costumes for local theatres, and spends time with her husband and 19-year-old son.

Walter Chi has worked with airlines since 1985 and at Aspen Airport for more than three decades. He has a degree in Aviation Management and Flight Operations, was a longtime flight instructor and tow-plane pilot, and is a commercial-rated pilot for powered aircraft and gliders, with his own twin-engine Cessna 320 at ASE since 2000. He also had a 27-year City of Aspen Police Department career as a patrolman, field trainer, and investigator, and is a property manager.

Asa DeHaan holds a CMC BS in Sustainability, has a strong interest in the sciences, and aspires to pursue graduate degrees at CU/Boulder. As a contractor to, then an employee of, the Aspen Global Change Institute (which is not affiliated with this project), for the past seven years he has maintained the hardware and data of the iRON network of ten meteorological monitoring devices tracking climate change from Independence Pass to Glenwood Springs. He also builds sensor arrays for use around his downvalley farm.

Brandon Gonzales is a data and machine learning consultant based in Aspen. He holds three honors degrees: a double BS from UC/Boulder in Civil Engineering and Applied Math, and an MS in Computer Science from Johns Hopkins. A ten-year Ajax Labs consultant specializing in natural language processing and graph theory, his experience spans vision recognition systems, data and financial analysis, and cybersecurity. He and his family live in the North Forty and his children attend a nearby ski school.

Michael Kendrick, a retired 52-year Valley resident married to a 6th-generation local, grew up in Texas and attended UT Austin with interests in math, science, computers, and Emergency Medicine. A 37-year Pitkin County Deputy Sheriff and instructor, he's been an EMT, a 30+-year paramedic, Database Manager for four local Police agencies, and in Buttermilk Ski Patrol, Basalt Ambulance (Director), and Aspen Ambulance. He was Medical Group Leader for ten years at the X Games and worked security/medical at the 1996 and 2001 Olympics.

Dr. Tom Kurt, MD, MPH, has six medical specialty fellowship designations: FACPM, FACMT, FAACT, FACOEM, FCP and FACE. Tom is a medical toxicologist and public health physician, and was formerly an active

pilot. He served during Viet Nam at the Air Force Academy Hospital and Wyoming ANG, being honorably discharged as Major, Flight Surgeon, USAF. He then founded The Airport Clinic at Stapleton International Airport in Denver, where he was a designated FAA Senior Aviation Medical Examiner and Accident Investigator. During that period he was also medical director for Aspen Airways and Rocky Mountain Airways and a member of the Aerospace Medical Association. Tom has been a first responder at two major airline crashes and provided input for the medical kit components now required on all scheduled airline aircraft. He served on the ASE Vision's Airport Experience Working group, and was present during two ASE Mock Disaster Drills. Tom also serves on the Pitkin County Board of Health, and on the clinical faculties at the Colorado School of Public Health (Clinical Assistant Professor) and the University of Texas Southwestern Medical Center (Adjunct Professor).

Amory B. Lovins, originally a consultant experimental physicist, is a leading authority and advisor on energy and a wide range of scientific and technological subjects. Author of 31 books and 850+ papers, he has received many of the world's top energy and environmental awards, received 12 honorary doctorates (seven in science), advised many leading firms and governments worldwide, and taught at ten universities. He is currently Adjunct Professor of Civil and Environmental Engineering (Atmosphere and Energy) at Stanford. He has lived in Old Snowmass since 1982, and is cofounder and President of Aspen Fly Right.

Tim McFlynn attended the US Air Force Academy, was an Air Force Reservist, and earned Stanford BA and JD degrees. He cofounded the Manaus Fund, and is Founder and Executive Director of Public Counsel of the Rockies, Director and former Board President of Wilderness Workshop, and cofounder, Trustee, and former Board Chair of Pitkin County Open Space and Trails Program. He has lived in the Valley since 1987.

Xinyu ("CC") Teng, from Beijing, earned a BS in Civil and Environmental Engineering at the University of Illinois, where she has conducted laboratory and field studies on climate, aerosols, and other scientific problems including air pollution. She is pursuing a Master's degree in Atmosphere and Energy at Stanford University, where she is working on landfill greenhouse gas emissions removal through single cell protein production.

Chris Trautner, with a lifelong interest and aptitude in physics, has a half-century of experience as a tool user and maker of unusual Aspen homes and other challenging building projects. He is founder and President of Trautner-Long Construction.

Aspen Fly Right also greatly appreciates the advice and help of the many experts at government agencies, universities, research institutes, and private firms (in the US, France, and Poland) who helped us choose and procure the right equipment, use it properly, and interpret its results. Responsibility for any errors or omissions is ours alone, and we would appreciate their being called specifically to our attention via info@aspenflyright.org.

Appendix B
Aspen Fly Right's Air Quality Measurement Instruments, 16–21 February 2023

This campaign used three kinds of low-cost but surprisingly sophisticated portable instruments using modern miniaturized sensors, air-handling, onboard computation, and telecommunications. All are rugged, cold-tolerant, and easily powered by 5-VDC internal or external batteries. The first two types are designed for citizen-science and educational use, with Cloud-based tools for data analysis and graphing. All three produce timestamped .CSV data files. The first two devices also have onboard GPS and add geolocation data to their data files.

Aspen Fly Right bought three $768 Air Quality Eggs, 2022 model (left image), from the Ithaca maker Wicked Device LLC (airqualityegg.com)—book-sized monitors configured to measure

PM_1, $PM_{2.5}$, PM_{10}, and NO_2. They also monitor temperature, relative humidity, and barometric pressure. They ingest air through holes in the bottom, display real-time readings on an LCD panel, and export their data files by WiFi or USB cable (also providing setup interface and 5VDC power source). They aggregate two Plantower PMS5003 laser scattering cells (nephalometers), with 0–500 μg/m^3 range and 1 μg/m^3 resolution, 1-second time resolution, and ±10% $PM_{2.5}$ consistency. The Eggs measure NO_x with a Winsen ZE12 electrochemical cell specified for ≤10 ppb resolution, 0–2 ppb detection range, and 30-second response. We configured our Eggs for their minimum 5-second time resolution to detect takeoff-related transient events.

Our data recovery appears to be over 90%, and for nearly all sensors 99–100%. This would generally be considered excellent sensor performance. With minor exceptions, we fully deployed all our sensors to maximize data-capture and analytic opportunities in a variety of sites. Our data analysis continues at this writing.

We borrowed from Stanford University eight €199, 70-gram (2.5-ounce) Flow fobs (middle image) made by the French firm PlumeLabs.com for largely urban network use. They can be hung from clothing, neck, pack, etc., or placed in a stationary site. Their silent 5-mm, 15,000-rpm fan draws in air from holes all around. Each fob measures ~~PM_1,~~ $PM_{2.5}$, PM_{10}, NO_2, and VOCs with 1-minute time resolution. The latter two measurements decompose the incoming gas with a tiny 250˚C membrane for analysis by metal-oxide sensors. Particulates are measured by a miniature laser scattering cell. Each fob communicates real-time data, color-coded Air Quality Index maps of the fob's daily travels, and .CSV files, all via low-energy Bluetooth to a paired smartphone. Onboard artificial intelligence keeps the sensors calibrated. Version 2, which we didn't have, can reportedly detect nanoscale particulates too.

We also borrowed three ECM sensors (right image)—successors to the widely used[90], roughly deck-of-cards-sized ~$2k MicroPEM wearable air-quality sensor for children. The ECMs are far costlier than our low-cost sensors, and are closer to research-grade. Deployed 19–21 February 2022, they were collocated with the Eggs to cross-check their $PM_{2.5}$ measurements every 10 seconds. They also provided gravimetric data from post-campaign analysis of a 2.5-cm pre-

weighed Teflon collection filter with 0.3 L/min flow (preadjusted to Aspen altitude). The 10-s data were expertly renormalized (~0.8–1.2×) to calibrate their medians to the filtrate-mass µg/m³.

Each make and model of sensor has strengths and weaknesses. For comparison, the APIS sensor[91] used in Pitkin County's study at the ABC measures 0–1,000 ppm CO, 0–20 ppm NO, NO_2, and O_3, and 0–100 ppm total VOC. Its maker claims r^2 (how well its measurements match a reference instrument—1 means perfect correlation, 0 means none) of >0.9 for NO and 0.7 for NO_2; accuracy is not specified. That's a $5k instrument; those used for Federal regulation or its equivalent normally start around $20–25k, with a few nearer $15k.

The authoritative [California] South Coast Air Quality Management District's independent online assessments[92] show two key metrics, each backed by a detailed field and lab report for each model assessed: the field and laboratory r^2 measurements, and the field and lab MAE (Mean Absolute Error), which shows the absolute measurement error in µg/m³ (determined in side-by-side comparisons with reference instruments on various timescales) and is typically a more important metric than r^2 for getting the right answer:

SCAQMD tests	*Pollutant*	*Field r^2*	*Lab r^2*	*Field MAE*	*Lab MAE*
Particulates					
Air Quality Egg (2022)	PM_1	0.88[93]–0.89		2.9–3.9	
	$PM_{2.5}$	0.88–0.90	0.99	6.0–7.1	5.0–8.0
	PM_{10}	0.29–0.52		18.5–20.8	
PlumeLabs (Flow 2 not 1)	PM_1	0.01–0.14			
	$PM_{2.5}$	0.01–0.13		7.3–10.6	
	PM_{10}	0.00–0.04		19.3–28.3	
RTI MicroPEM (ECM predecessor)	$PM_{2.5}$	0.65–0.90	0.99	6.4–8.3	
PurpleAir (PA-II)	PM_1	0.96–0.98	0.99		11.7–15.9
	$PM_{2.5}$	0.93–0.97	0.99		1.7–4.2
	PM_{10}	0.66–0.70	0.95		15.6–20.5
Nitrogen oxides					
Air Quality Egg (2022)	NO_2	0.39–0.55		20.8–32	
PlumeLabs (Flow 2 not 1)	NO_x	0.04–0.14		11.2–17.6	
APIS	NO	0.87–0.97		1.3–2.6	
	NO_2	0.30–0.44		6.1–9.4	

In addition, Plume Labs reports these French lab-test results[94] for our Flow 1 fobs, tested soon after their 2019 release, and thinks all the sensors tend to underestimate the reference values. We cannot explain why the PM r^2, summarized as ~0.90–0.95, is far higher than SCQMD's for the Flow 2 model. The more critical MAEs below are also comparable or better. The reported French inter-Flow-unit correlations are also excellent: respectively >0.95, >0.99, 0.89, 0.91, and 0.83.

CNRS/LISA (France) tests	*Pollutant*	*Number of fobs tested*	*Lab r^2 median (range)*	*Lab MAE median (range), µg/m^3*
PlumeLabs Flow 1	PM_1	5	0.93 (0.94–0.98)	5.45 (3.07–10.8)
	$PM_{2.5}$	5	0.92 (0.87–0.97)	6.91 (3.63–10.38)
	PM_{10}	5	0.88 (0.67–0.98)	8.16 (4.98–17.61)
	NO_2	8	0.96 (0.83–0.98)	36.4 (29.2–42.3)
	VOC (EtOH-equivalent)	4	0.69 (0.68–0.72)	meaningless because VOC mix undefined

Thus our Eggs are far more accurate (MAE) than Purple Air for PM_1, worse for $PM_{2.5}$, and comparable for PM_{10} (but with worse correlation); for the PM_1 of greatest interest to our study, the Eggs were the most accurate sensor of all types shown. The Eggs are also more accurate for particulates than the Flow 2 fobs (SCAQMD didn't test our older Flow 1 fobs), and the Flow 2 fobs showed poor correlations, though their internal battery, three-variable measurements, and extreme portability give them offsetting value, and they performed quite well on particulates. If the French tests for our actual model, then the Flow fobs are more comparable with the Eggs. The Eggs are less accurate on nitrogen oxides than the $5k APIS instrument but are better correlated, and are much better correlated but less accurate than the Flow fobs according to SCAQMD (but not the French tests). The Eggs were found highly precise for $PM_{2.5}$. All sensors in the table, except the Flow fobs, tended to overestimate the actual pollution, but within MAE constraints. We used our Eggs as our primary full-campaign monitoring instruments and the Flow 1 fobs as confirmatory and indicative (and as VOC sensors), though they merit greater credence if the French Flow 1 tests are more valid than the SCAQMD tests of Flow 2 fobs.

The predecessor of our ECMs, with similar optics, has a $PM_{2.5}$ r^2 of 0.65–0.90 (or, according to another posting of an early-version 2015 test[95], 0.80–0.87) field and 0.99 lab, with a field MAE of 6.4–8.3 µg/m^3. Those metrics are both comparable to our cheaper but five years' newer Eggs' performance. However, the ECMs' added physical calibration by real-time gravimetry gives them special value by providing an unambiguous physical metric to calibrate all our particulate sensors. (A two-stage impactor at the input prevents particles >2.5 µm from entering the ECM.) While all low-cost particle sensors merit less confidence than regulatory-equivalent units, it's reassuring that our ECMs' three-day *physical* particle capture at location A, for example, found average $PM_{2.5}$ of 4.4 µg/m^3—well *above* our Eggs' three-day sensor average of 0.8, though the disparity is within the Eggs' Mean Absolute Error field range of 2.9–3.9 (4.4 – 0.8 = 3.6).

These test data all illustrate the remarkable progress made in the past few years with smart, miniaturized, surprisingly sophisticated air monitors at low cost. They could be very useful to our local governments in prospecting for the potential presence or absence of problems warranting closer study, just as we have attempted here, and in rapidly detecting any issues and evaluating any complaints or concerns. Their low cost, easy downloads, and Cloud-based data-Lab interfaces (simple enough for schoolchildren to use) could enable a lending library, such as Los Angeles and some other cities and the USEPA offer. Their deployment could quickly make our community air-aware, scientifically informed, and mutually accountable for measured performance. Substituting real measurements for speculation and rhetoric could help clear the air.

[1] E. Stewart-Severy & S. Miller, "Airport expansion may not resolve pollution and noise problems," 8 Apr 2020, https://aspenjournalism.org/airport-expansion-not-expected-to-fix-pollution-and-noise-problems/.

[2] E. Stewart-Severy & S. Miller, "Airport expansion not expected to fix pollution, noise," 8 Apr 2020, https://www.aspentimes.com/news/airport-expansion-not-expected-to-fix-pollution-noise/.

[3] On 29 Nov 2022, Amory Lovins filed a Colorado Open Records Act request for any fine-particulates or NO_x air-pollution measurements made within two miles of the Airport since 2000. Pitkin County provided two reports: (1) "Air Quality Monitoring Summary, Pitkin County Airport, June and September, 2020," prepared by Andrea Holland for the Pitkin County Community Development Department (measuring NO, NO_2, NO_x, O_3, and total VOCs with APIS sensors and $PM_{2.5}$ and PM_{10} with Purple Air sensor(s), all taken on the roof of Aspen Fire Protection District Station 62 at 43 Sage Way Rd. at the ABC), and for the same client, (2) Air Resource Specialists (Ft. Collins)'s 2020 report of VOC measurements by EPA method TO-15 (lab analysis of air collected in canisters) at the same fire-station site (across Hwy 82 from, but strangely not *at*, the Airport's passenger terminal where the fuel odors complained of were actually reported). Lovins had criticized the latter study's design as irrelevant to its stated question (footnote on p 4 of 19 Apr 2022 letter to BOCC). Separately, the City of Aspen also had Air Resource Specialists measure VOCs by method TO-15 near Mountain Rescue Aspen in Feb–Mar 2022, including a winter inversion: "Air Monitoring Data Report, City of Aspen," April 2022, kindly provided by Chris Everson. None of these studies was done at Buttermilk or anywhere downwind of the Airport.

[4] In the AAB's video recording (https://drive.google.com/file/d/1dqYQ1OBOsw4Lgu1qoJ0fFy1ceAEFFMQu/view) at 18:05–20:34, and 20:42–24:21, then the AAB's discussion with Prof. Tyson at 32:40–45:40. He emphasized human health, the unsuitability of the air model the County is using, the importance of using the right model, and the absolute necessity—but low cost—of using the right locally measured data, which have not been gathered. He did not accept Ms. Vigilante's view that the required measurements and analysis would be costly or difficult.

[5] The BOCC's Resolution 105-2020 (https://aspenflyright.org/wp-content/uploads/2022/12/BoCC-revision-adoption_bocc.res_.105.2020-2-1.pdf), §12, addresses "greenhouse and other emissions," not lumping them together as many other public references and news stories still do.

[6] The official description at https://aspenflyright.org/wp-content/uploads/2022/12/ASE-Vision—Official-View_14-Dec-2022.pdf is contrasted with an alternative view at https://aspenflyright.org/wp-content/uploads/2022/12/ASE-Vision—The-Rest-of-the-Story_14-Dec-2022r.pdf.

[7] Finer particles are associated with greater decreases in children's lung function, implying greater health hazard: M. Yang *et al.*, "Is PM_1 similar to $PM_{2.5}$? A new insight into the association of PM_1 and $PM_{2.5}$ with children's lung function," *Envt. Intl.* **145**:106092 (2020), https://doi.org/10.1016/j.envint.2020.106092.

[8] These effects were initially studied for PM_{10} (which can be inhaled but can't penetrate the lungs' gas-exchange region), e.g. in the classic European study by G. Hoek *et al.*, "PM_{10}, and children's respiratory symptoms and lung function in the PATY study," *Eur. Respir. J.* **40**:538–547 (2012), https://doi.org/10.1183/09031936.00002611. Fundamental causes emerged, e.g. R. Wright & K. Brunst, "Programming of respiratory health in childhood: influence of outdoor air pollution," *Current Opinion in Pediatrics* **25**(2):232–239 (2013), https://doi.org/10.1097/MOP.0b013e32835378cc, and M. Soto-Martinez & P. Sly, "Relationship between environmental exposures in children and adult lung disease: The case for outdoor exposures," *Chronic Respir. Disease* **7**(3):173-186 (2010), https://doi.org/10.1177/1479972309345929. By 2016, a review found that "A substantial portion of the global burden of disease is directly or indirectly attributable to exposure to air pollution," especially in children: F. Goldizen, P. Sly, & L. Knibbs, "Respiratory effects of air pollution on children," *Pediatric Pulmonology* **51**(1):94–108 (2015), https://doi.org/10./1002/ppul.23262. Now avoiding $PM_{2.5}$ through cleaner indoor cooking has emerged as a global public-health opportunity: N. Seltenrich, "Breathing Room: Cleaner Fuels for Home Cooking in LMICs," *Env. Health Persp.* **131**(2) (2023), https://doi.org/10.1289/EHP12232.

[9] A recent estimate that global aviation's emissions kill ~26,000 people per year—far more than plane crashes—uses rather old health-effects literature and appears to understate the toxicity of nanoparticles, but remains informative: C. Grobler *et al.*, "Marginal climate and air quality costs of aviation emissions," *Env. Res. Ltrs.* **14**(11): 114031, https://doi.org/10.1088/1748-9326/ab4942.

[10] MIT Laboratory for Aviation and the Environment, "Piston Engine Aircraft Pose a Health Risk," https://lae.mit.edu/2016/08/26/piston-engine-aircraft-pose-a-health-risk/.

[11] M. Masiol & R. Harrison, "Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review," *Atmos. Environ.* **95**:409–455 (2014) (a broad, deep, and useful primer), http://dx.doi.org/10.1016/j.atmosenv.2014.05.070/.

[12] Unburned jet-engine lubrication oil has emerged as a major source of emissions from aircraft, including toxic organophosphate esters: A. Fushimi *et al.*, "Identification of jet lubrication oil as a major component of aircraft

exhaust nanoparticles," *Atmos. Chem.Phys.* **19**(9):6389–99 (2019), https://doi.org/10.5194/acp-19-6389-2019; F. Ungeheuer *et al.*, "Nucleation of jet engine oil vapours is large source of aviation-related ultrafine particles," *Nature Commns. Earth & Envt.* **3**:319 (2022), https://doi.org/10.1038/s43247-022-00653-w. The latter paper asks why "Large airports are a large source of ultrafine particles, which spread across densely populated residential areas, affecting air quality and human health," and finds "jet oil nucleation is an important mechanism that can explain the abundant observations of high number concentrations of non-refractory ultrafine particles near airports."

[13] Ref. 11.

[14] Nanometers or billionths of a meter.

[15] Ref. 26, Fig. 4.

[16] R. Vander Wal, V. Bryg, C.-H. Huang, "Aircraft engine particulate matter: Macro- micro- and nanostructure by HRTEM and chemistry by XPS," *Combustion and Flame* **161**(2):602–611 (2014), https://doi.org/10.1016/j.combustflame.2013.09.003.

[17] Conversely, cold weather's denser air can cause a jet plume to form a "jet wall"—a roiling mass of emissions that builds up vertically before the jet breaks through and propagates far beyond. We think we observed such behavior.

[18] EPA says "PM emitted from the [jet] engine is known as non-volatile PM…, and PM formed from transformation of an engine's gaseous emissions are [*sic*] defined volatile PM." It adds: "These particles can remain in the atmosphere for days to weeks and travel through the atmosphere hundreds to thousands of kilometers." Ref. 45, §III(A), printed p 6330.

[19] R. Moore *et al.*, "Biofuel blending reduces particle emissions from aircraft engines at cruise conditions," *Nature* **543**(7645):411–415 (2017), https://doi.org/10.1038/nature21420.

[20] For example, ~100 m downwind for idle/taxi and ~300 m for takeoffs from an active taxi-/runway at Oakland International Airport, emission intensities were 7×10^{15} – 3×10^{17} particles per kg of fuel in idle/taxi, and 4×10^{15} – 2×10^{17} in takeoff: L. Lobo, D. Hagen & P. Whitefield, "Measurement and analysis of aircraft engine PM emissions downwind of an active runway at the Oakland International Airport," *Atmos. Environ.* **61**:114–123 (2012), https://doi.org/10.1016/j.atmosenv.2012.07.028. The taxi plume at 4–7% of engine power was typically smaller in particle volume but larger in particle number than the takeoff plume, for mainly 737 aircraft. Engine-specific particle size distributions are given for, among others, the CF34-3B (41 kN but in the CRJ700's engine family).

[21] For calibration, a ~100-seat Boeing 717-200 at 113,000 lb GTOW (just above ASE's 100,000 current landing limit) burns ~1,800 kg of fuel for takeoff and climb from sea level; ASE takeoffs typically burn more to climb in the thinner air (https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_08/article_05_3.html).

[22] T. Smedley (author of *Clearing the Air*), "The toxic killers in our air too small to see," 15 Nov 2019, https://www.bbc.com/future/article/20191113-the-toxic-killers-in-our-air-too-small-to-see (a fine summary).

[23] Air Quality Expert Group report to UK Department for Environment, Food and Rural Affairs, "Ultrafine Particles (UFP) in the UK," 2018, https://uk-air.defra.gov.uk/library/reports.php?report_id=968. This report says "current measurement strategy…is insufficient to determine exposure from poorly understood UFP emission sources such as airports…," and recommends setting up "at least one permanent site monitoring in the vicinity of a major airport." P 34 notes that aviation emitted nearly half in 2020, and is expected to emit over half in 2030, of UK transport's particle *numbers*, which exceed 5×10^{25} particles per year.

[24] We ask specialists to forgive that we have oversimplified some of the metrics about particle size, which strictly speaking is an aerodynamic or other indirect form of effective diameter. Some particles also have irregular shapes.

[25] Ref. 22.

[26] T. Xia *et al.*, "Pulmonary diseases induced by ambient ultrafine and engineered nanoparticles in twenty-first century," *Natl. Sci. Rev.* **3**:416–419 (2016) (Oxford U. Press on behalf of China Science Publishing & Media Ltd.), https://doi.org/10.1093/nsr/nww064. This research was supported by NIH, NSF, EPA, and the Chinese government.

[27] C. Wiseman & F. Zereini, "Characterizing metal(loid) solubility in airborne PM_{10}, $PM_{2.5}$ and PM_1 in Frankfurt, Germany using simulated lung fluids," *Atmos. Envt.* **89**:282–289 (2014), https://doi.org/10.1016/j.atmosenv.2014.02.055.

[28] Ref. 7.

[29] Some sources of definitional and measurement confusion are discussed in Ref. 23 at p 14 and p 23.

[30] Ref. 26.

[31] "Global, regional, and national life expectancy, all-cause mortality, and cause-specific mortality for 249 causes of death, 1980–2015: a systematic analysis for the Global Burden of Disease Study 2015," *Lancet* **388**(10053):1459–1544 (2016), https://doi.org/10.1016/S0140-6736(16)31012-1, PMID: 27733281.

[32] Ref. 22.

[33] Gratefully reproduced from https://seetheair.org/2022/05/16/particulate-matter-pm2-5-mega-guide/.

[34] Ref. 58 p 6, citing O. Schmid & T. Stoeger, "c," "Surface area is the biologically most effective dose metric for acute nanoparticle toxicity in the lung," *J. Aerosol Sci*. **99**:133–43 (2016), https://doi.org/10.1016/j.jaerosci.2015.12.006.
[35] K. Donaldson *et al.*, "Ultrafine particles," *Occup. Environ. Med.* **58**:211–216 (2001), https://doi.org/10.1136/oem.58.3.211.
[36] Courtesy of USEPA, https://www.epa.gov/pm-pollution/particulate-matter-pm-basics.
[37] National Academy of Sciences, "Dispersion Modeling Guidance for Airports Addressing Local Air Quality Issues," 24881, 2017, p 27, http://nap.nationalacademies.org/24881.
[38] N. Künzli *et al.*, "Breathless in Los Angeles: The Exhausting Search for Clean Air," *Am. J. Public Health* **93**:1494–1499 (2003), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1447999/pdf/0931494.pdf. This exceptionally comprehensive, long-term, and influential study was founded by John Peters MD—the late Harvard School of Public Health mentor of our team member Dr. Tom Kurt. Its history includes the piquant detail that when the School Board resolved not to site schools within 500´ of a freeway, that was a threefold error—the research had shown harm to children's health within 500 meters, not feet—but the researchers felt it was a win because there were no previous siting rules based on air pollution (L. Hopper, "USC Children's Health Study, now 30 years old, raises nationwide awareness of pollution's harms," *USC News*, 4 May 2022, https://news.usc.edu/199179/usc-childrens-health-study-now-30-years-old-raises-nationwide-awareness-of-pollutions-harms/).
[39] N. Rabinovitch, M. Strand, & E. Gelfand, "Particulate levels are associated with early asthma worsening in children with persistent disease," *Am. J. Respir. Crit. Care Med.* 173(10):1098–1105 (2006), https://doi.org/10.1164/rccm.200509-1393OC, PMID 16484676.
[40] N. Rabinovitch *et al.*, "Within-microenvironment exposure to particulate matter and health effects in children with asthma: a pilot study utilizing personal monitoring with GPS interface," *Environ. Health* **15**(96) (2016), https://doi.org/10.1186/s12940-016-0181-5.
[41] N. Nassikas *et al.*, "Modeling future asthma attributable to fine particulate matter ($PM_{2.5}$) in a changing climate: a health impact assessment," *Air Qual. Atmos. Health* **15**:311–319 (2022), https://doi.org/10.1007/s11869-022-01155-6, PMID 35173822.
[42] https://www.epa.gov/newsreleases/epa-proposes-strengthen-air-quality-standards-protect-public-harmful-effects-soot.
[43] Industrial Economics, Inc., *Analysis of $PM_{2.5}$-Related Health Burdens Under Current and Alternative NAAQS*, 15 Apr 2022, https://globalcleanair.org/files/2022/05/Analysis-of-PM2.5-Related-Health-Burdens-Under-Current-and-Alternative-NAAQS.pdf. The study finds ~110,000 excess US deaths per year from $PM_{2.5}$ exposure, with a strong environmental justice component, finding that US Black populations aged 65+ experience three times the $PM_{2.5}$-attributable deaths per capita compared with all other races.
[44] S. Alexeeff *et al.*, "Association of Long-Term Exposure to Particulate Air Pollution With Cardiovascular Events in California," *JAMA Network Open* **6**(2):e230561 (24 Feb 2023), https://doi.org/10.1001/jamanetworkopen.2023.0561.
[45] At https://www.federalregister.gov/documents/2022/02/03/2022-01150/control-of-air-pollution-from-aircraft-engines-emission-standards-and-test-procedures.
[46] Cook, R. Memorandum to Docket EPA-HQ-OAR-2019-0660, "Health and environmental effects of non-GHG pollutants emitted by turbine engine aircraft," 23 Aug 2021.
[47] USEPA, *Integrated Science Assessment (ISA) for Particulate Matter* (Final Report, 2019). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-19/188, 2019, https://www.epa.gov/isa/integrated-science-assessment-isa-particulate-matter.
[48] A. Lammers *et al.*, "Effects of short-term exposures to ultrafine particles near an airport in healthy subjects," *Environ. Intl.* **141**:105779 (2020), https://doi.org/10.1016/j.envint.2020.105779.
[49] A typically suggestive modern *in vitro* study is H. Jonsdottir *et al.*, "Non-volatile article emissions from aircraft turbine engines at ground-idle induce oxidative stress in bronchial cells," *Nature Commns. Biol.* **2**:90 (2019), https://doi.org/10.1038/s42003-019-0332-7. This study "demonstrates acute bronchial epithelial cell injury after 1-h exposures to [nonvolatile particulate matter]…with the most pronounced response observed after exposure to PM from conventional Jet A-1 base fuel at ground-idle conditions."
[50] Ref. 58, p 16.
[51] B. Kim *et al., "*Understanding Airport Air Quality and Public Health Studies Related to Airports," Airport Cooperative Research Program, ACRP Report 135, pp 39–40, https://trid.trb.org/view/1364659. Ref. 45 gives a useful summary in §3(D) starting at printed page 6332.
[52] S. Hu *et al.*, "Aircraft emission impacts in a neighborhood adjacent to a General Aviation Airport in Southern California," *Environ. Sci. Technol.* **43**(21):8039–8045 (2009), https://doi.org/10.1021/es900975f.

[53] Ref. 58, p 3, based on a review's jet-takeoff data, notes that 7.7 million particles per cm^3 nominally weighs 1,086 $\mu g/m^3$, so 1 $\mu g/m^3$ corresponds to ~7,090 particles/cm^3—a ratio very sensitive to the particle size distribution.
[54] Ref. 11, with citations on p 441.
[55] H. Hsu *et al.*, "Contributions of aircraft arrivals and departures to ultrafine particle counts near Los Angeles International Airport," *Sci. Tot. Environ.* **444:**347–355 (2013), https://doi.org/10.1016/j.scitotenv.2012.12.020, PMID 23280292.
[56] D. Westerdahl *et al.*, "The Los Angeles International Airport as a source of ultrafine particles and other pollutants to nearby communities," *Atmos. Environ*. **42**(13):3143–55 (2008), https://doi.org/10.1016/j.atmosenv.2007.09.006.
[57] N. Hudda *et al.*, "Emissions from an International Airport Increase Particle Number Concentrations 4-fold at 10 km Downwind," *Environ. Sci. Technol.* **48**(12):6628–6635 (2014), https://doi.org/10.1021/es5001566.
[58] K Bendtsen *et al.*, "A review of health effects associated with exposure to jet engine emissions in and around airports," *Environmental Health* **20**:10 (2021), https://doi.org/10.1186/s12940-020-00690-y/ (an exceptionally clear review).
[59] Diesel particulate matter contains over 40 known organic carcinogens (https://ww2.arb.ca.gov/resources/overview-diesel-exhaust-and-health), and was classified as "carcinogenic to humans" in 2012 by the World Health Organization's International Agency for Research on Cancer: https://www.iarc.who.int/wp-content/uploads/2018/07/pr213_E.pdf.
[60] Ref. 58 provides a pithy literature review on p 6.
[61] Ref. 58.
[62] A main source of those queries was Pitkin County's then Emergency Management Coordinator, Ellen Anderson (now a cofounding officer and Director of Aspen Fly Right), whose responsibility and expertise was in issues like preventing mass casualties and other public hazards. Years earlier, her requests for radon testing in the Sheriff's Department's underground offices were likewise dismissed but then proven valid, leading to belated remediation after some employees' long exposure to the carcinogen. Apparently memories of her foresight then were short.
[63] The Aspen Chamber's factsheet emphasized that the runway extension "is not a 'growth inducement' project," "will not allow larger aircraft (greater wingspan) to operate at the Airport that can not operate today" because "The wingspan and weight limits are actually 'set in concrete' and cannot be changed," and the extension is approved by FAA as the national safety authority, implying it considered all public health-and-safety issues ("Summary of Runway Extension Facts," https://aspenchamber.org/sites/default/files/files/Runway-Ext-Fact-Sheet_0.pdf).
[64] 1142 MT 15 Feb 2023, https://earth.google.com/web/@39.20740232,-106.86169909,2392.88082927a,1971.38536179d,35y,346.71216468h,0t,0r.
[65] Jet blast merits respectful attention. In 2020, an American Eagle CRJ's jet blast during a post-maintenance engine run was filmed demolishing a sheetmetal hangar and overturning a smaller aircraft at San Luis Obispo Airport: https://twitter.com/jacdecnew/status/1243948984403668995?lang=eu.
[66] M. Bennett *et al.*, "Lidar Observations of Aircraft Exhaust Plumes," *J. Atmos. Oceanic Technol.* **27**:1638–1651 (2010), https://doi.org/ 10.1175/2010JTECHA1412.1.
[67] O. Zaporozhets & K. Synylo, "Modelling and measurement of aircraft engine emissions inside the airport area," *Procs. National Aviation U.* (Kiev) **N 2**(63):65–72 (2015), https://jrnl.nau.edu.ua/index.php/visnik/article/view/8862/10952.
[68] B.E. Anderson *et al.*, *Alternative Aviation Fuel Experiment (AAFEX)*, NASA/TM-2011-217059, https://ntrs.nasa.gov/api/citations/20110007202/downloads/20110007202.pdf; see pp 17, 56–59, 136, 212–3, 283–4. At high engine power, the plume could be analyzed even at >500-m range.
[69] Just the APU of a Tupolev-154 trijet had enough plume power to transmit its emissions for 700 m (O. Zaporozhets & K. Synylo, "PM Emissions Produced by Aircraft Under the Operations at the Airport," 2016, https://doi.org/10.18372/2306-1472.69.11059)—but the APU is designed to make electricity, not thrust. Of course, plume length is far greater aloft: modeling showed (K. Tait *et al.*, "Aircraft Emissions, Their Plume-Scale Effects, and the Spatio-Temporal Sensitivity of the Atmospheric Response: A Review," *Aerospace* **9**:355 (2022), https://doi.org/10.3390/aerospace9070355) that jet plumes emitted at altitude could spread 1–10 km horizontally and reach as far as 100–200 km downwind toward the end of their lives at ~10–15 hours—a tribute to their vortex heritage and spatial coherence.
[70] As can be seen in general terms from websites like https://windalert.com/spot/1084.
[71] O. Zaporozhets & K. Synylo, "Modeling of Air Pollution at Airports," in R. Agarwal, ed., *Environmental Impact of Aviation and Sustainable Solutions*, 2019, https://doi.org/10.5772/intechopen.84172 or https://www.intechopen.com/chapters/68002; —, "Estimation of buoyancy effect and penetration length of jet from aircraft engine by large eddy simulation method," *Intl. J. Sust. Aviation* **2**(1) (2016),

https://doi.org/10.1504/IJSA/2016.076070. The Coanda effect is the tendency of a jet or a smooth fluid stream to hug a convex surface it is traversing, the way a tangent stream of water seems to stick to the back of a spoon.
[72] Common options and challenges are described in Ch 3 of Ref. 23. The importance of measuring around airports is again emphasized at p 51, with examples (also in our text here) on pp 67–69.
[73] https://kestrelmeters.com/products/kestrel-5500-weather-meter. The specifications (https://kestrelmeters.com/pages/specifications-for-kestrel-pocket-weather-meters) show 0.1 m/s resolution, and accuracy as the larger of 3% of reading or least significant digit, for 0.6–40.0 m/s (1.3–89.5 mph, 1.2–7.8 kt).
[74] Such drift depends on wind regimes, which our topography makes complex. See e.g. R. Henry, S. Mohan, & S. Yazdani, "Estimating potential air quality impact of airports on children attending the surrounding schools," *Atmos. Envt.* **212**:128–135 (2019), https://doi.org/10.1016/j.atmosenv.2019.05.046.
[75] "Air Quality Monitoring Summary, Pitkin County Airport," June and September 2020, prepared for Pitkin County Community Development Department by Andrea Holland (Retired US Forest Service Air Resource Manager), provided to Amory Lovins by Pitkin County 2 Dec 2022 and 5 Jan 2023 in response to his 29 Nov 2022 Colorado Open Records Act request for all particulate or NO_x measurements made within two miles of the Airport since 2000. Thus there appear to be no other such measurements.
[76] USEPA, *The Enhanced Air Sensor Guidebook*, EPA/600/R-22/213, Sep 2022, https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=356426&Lab=CEMM. Another useful guide is R. Duvail *et al.*, "Performance Testing Protocols, Metrics, and Target Values for Fine Particulate Matter Air Sensors," EPA/600/R-20/280, Feb 2021, https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=350785&Lab=CEMM.
[77] The Flow fobs came set on French time and the EPC sensors on Eastern Standard Time, but the Eggs were set on Mountain Standard Time, all requiring care in synchronizing their timestamped data.
[78] We don't know whether any of the de- or anti-icing sprays might spoof our NO_x or hydrocarbon sensors, much as ozone from a home printer or photocopier can cause a spuriously high NO_x reading: our instruments' electro-chemical cells for detecting gaseous pollutants cannot perfectly discriminate between different molecules.
[79] See https://www.epa.gov/criteria-air-pollutants and https://www.epa.gov/criteria-air-pollutants/naaqs-table.
[80] Actually, our ECM device at location A was capable of measuring NO_x and CO, but didn't exceed their detection thresholds, respectively ~25 and ~200 ppb. The low CO is consistent with the modernity of the autos present. The NO_x result is consistent with all the Egg readings and with all but four fob-days, and the latter discrepancy may be due to the ECM's reporting every 10 seconds while the fobs average over one minute.
[81] https://www.osha.gov/annotated-pels/table-z-1 (which says many OSHA standards are outdated and inadequately protective). California's even more extensive table is at https://www.dir.ca.gov/title8/5155table_ac1.html#_blank; an overview is at https://www.osha.gov/annotated-pels.
[82] However, EPA is said to have adopted <200 µg/m^3 inside its own new building (which building is unspecified]: https://www7.nau.edu/itep/main/eeop/docs/airqlty/AkIAQ_VolatileOrganicCompounds.pdf.
[83] The $PM_{2.5}$ averages we observed at location A were not far from averages for the same days at the regulatory-equivalent GRIMM EDM180 sensor in central Aspen (also providing, and dominated by, high PM_{10} readings with only informational fidelity). Such comparisons are unlikely to be meaningful because of different airsheds, winds, topographies, surroundings, source terms, and other factors, and because the downtown readings are taken over 24 hours, with heavy daytime but little nighttime road traffic and no flights, while the airfield measurements span ~18% as many hours, all with medium traffic (but under an hour of high parking-lot travel) and generally high flight departures. Also, importantly, the sources of the downtown $PM_{2.5}$ could well include, and augment from local sources, particulates drifting in from the Airport, along with an unknown amount of low-mass but medically significant ultrafine particles. Microscopic examination of PM samples could illuminate these differences.
[84] Ref. 58.
[85] R. MacPhail, E. Grulke, & R. Yokel, "Assessing nanoparticle risk poses prodigious challenges," *WIREs Nanomedicine and Nanobiotechnology*, https://doi.org/10.1002/wnan.1216 (2013). OSHA has temporized with recommended average worker exposures not over 1.0 µg/m^3 for carbon nanofibers and nanotubes, and not over 0.3 µg/m^3 for nanoscale titanium dioxide (one-eighth the fine-sized TiO_2 particle standard), and acknowledges that since "[c]ertain nanoparticles may be more hazardous than larger particles of the same substance…existing occupational exposure limits for a substance may not provide adequate protection from nanoparticles of that substance." OSHA FactSheet, "Working Safely with Nanomaterials," DTSEM FS-3634, Apr 2013, https://www.osha.gov/sites/default/files/publications/OSHA_FS-3634.pdf. WHO in 2017 provided further interim guidance on manufactured nanomaterials (https://apps.who.int/iris/bitstream/handle/10665/259671/9789241550048-eng.pdf), and a European Commission 2006 paper provides still-useful details (https://ec.europa.eu/health/scientific_committees/opinions_layman/en/nanotechnologies/l-2/7-exposure-

nanoparticles.htm); even at that time, instruments could detect down to 3 nm, with 1-nm capability emerging. A 2022 review suggested potential ways forward (M. Visser *et al.*, “Towards health-based nano reference values (HNRVs) for occupational exposure: Recommendations from an expert panel,” *NanoImpact* **26**:100396 (2022), https://doi.org/10.1016/j.impact.2022.100396.

[86] B. Stacey, R. Harrison, & F. Pope, “Evaluation of ultrafine particle concentrations and size distributions at London Heathrow Airport,” *Atmos. Environ*. **222**:117148 (2019), https://doi.org/10.1016/j.atmosenv.2019.117148.

[87] “The number-size distributions of particles emitted by jet engines are dominated by a mode diameter smaller than ~30 nm, which is significantly smaller compared to particles from road traffic emissions,” citing M. Pirhadi *et al*., “Relative contributions of a major international airport activities and other urban sources to the particle number concentrations (PNCs) at a nearby monitoring site,” *Environ. Pollut.* **260**:114027 (2020), https://doi.org/10.1016/j.envpol.2020.114027; E. Riley *et al*., “Ultrafine particle size as a tracer for aircraft turbine emissions,” *Atmos. Environ.* **139**:20–29 (2016), https://doi.org/10.1016/j.atmosenv.2016.05.016, citing >8–20 km drift of ultrafine particles from major airports; M. Masiol *et al.*, “Sources of sub-micrometre particles near a major international airport,” *Atmos. Chem. Phys.* **17**:12379–12403 (2017), https://doi.org/10.5194/acp-17-12379-2017; F. Shirmohammadi *et al*., “Emission rates of particle number, mass and black carbon by the Los Angeles International Airport (LAX) and its impact on air quality in Los Angeles,” *Atmos. Environ.* **151**: 82–93 (2017), https://doi.org/10.5194/acp-17-12379-2017; and B. Stacey, “Measurement of ultrafine particles at airports: a review,” *Atmos. Environ.* **198**: 463–477 (2019), https://doi.org/10.1016/j.atmosenv.2018.10.041. The science distinguishing jet engines’ typically <20 nm, commonly ~10—15-nm, particles from road vehicles’ typically 30–50 or 60–80 nm particles seems beyond dispute.

[88] One of the types of instruments we borrowed (the ECM) captures particulates on a special filter that we hoped could be microscopically examined to distinguish particulates by physical size and form. Unfortunately, that turned out to require a far costlier type of instrument and analysis. Any good air-quality lab could do better.

[89] Ref. 37, specifically the EPA AERMOD model.

[90] T. Zhang *et al.*, “Development of an approach to correcting MicroPEM baseline drift,” *Environ. Res.* **164**:39–44 (2018), https://doi.org/10.1016/j.envres.2018.01.045. A newer comparison of the ECM to some other devices is at https://www.ncbi.nim.nih.gov/pmc/articles/PMC7217081.

[91] https://www.apis-aq.com/product-information/#specs.

[92] http://www.aqmd.gov/aq-spec/evaluations. All the evaluations quoted here are marked “preliminary,” more likely for bureaucratic than for technical reasons, and they are the industry’s gold standard for independent assessments.

[93] From the field report at http://www.aqmd.gov/docs/default-source/aq-spec/field-evaluations/air-quality-egg-2022-model---co-and-pm---field-evaluation.pdf?sfvrsn=16; the summary table incorrectly, perhaps earlier, shows a low-range value of 0.84. The field test found 0.92–0.93 over 24 hours.

[94] “Evaluation of Flow, a personal air quality sensor,” 25 Oct 2019, https://drive.google.com/file/d/1KLe72CT1bPLIYIfo74y2hN5Mca7bGose/view, describing seemingly capable tests by unstated author(s) using the CNRS’s public Laboratoire Interuniversitaire des Systèmes Atmosphériques.

[95] http://www.aqmd.gov/docs/default-source/aq-spec/field-evaluations/rti-micropem---field-evaluation.pdf?sfvrsn=2.