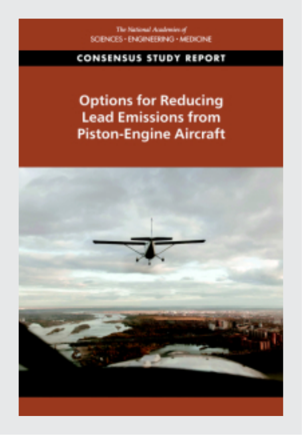

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Special Report 336

Options for Reducing Lead Emissions from Piston-Engine Aircraft

Committee on Lead Emissions from Piston-Powered General Aviation Aircraft

A Consensus Study Report of
The National Academies of
SCIENCES • ENGINEERING • MEDICINE

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COMMITTEE ON LEAD EMISSIONS FROM PISTON-POWERED GENERAL AVIATION AIRCRAFT

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Preface

In Section 177 of the FAA Reauthorization Act of 2018 (P.L. 115-254), Congress called on the Secretary of Transportation to arrange for a study of aviation gasoline by the National Academies of Sciences, Engineering, and Medicine (the National Academies). Congress indicated that the study should include assessment of:

> (1) Existing non-leaded fuel alternatives to the aviation gasoline used by piston-powered general aviation aircraft;
> (2) Ambient lead concentrations at and around airports where piston-powered general aviation aircraft are used; and
> (3) Mitigation measures to reduce ambient lead concentrations, including increasing the size of run-up areas, relocating run-up areas, imposing restrictions on aircraft using aviation gasoline, and increasing the use of motor gasoline in piston-powered general aviation aircraft.

Chapter 1 of this report provides additional information about the committee's Statement of Task.

To carry out that congressional request, the National Academies formed a committee of 10 members providing expertise in air pollution modeling and monitoring, airport planning and operations, regulation of aviation fuels and emissions, exposure and health risk assessment, statistics, mechanical and aviation engineering, transportation systems analysis, aviation fuel performance, and general aviation piloting. Six members are currently affiliated with academic institutions; four are currently with or retired from the private sector; two have held positions in government agencies. Several members are or have been active pilots. (Committee biographical information is provided in Appendix A.)

In the course of preparing its report, the committee held public information-gathering sessions on November 19-20, 2019, and February 18-19, 2020, to hear presentations from and have discussions with: Raymond Best, Textron Aviation; Elliott Black, Boyd Rodeman, Warren Gillette, Monica Merritt, and Mark Rumizen, Federal Aviation Administration; Christopher Cooper, Aircraft Owners and Pilots Association; Chris D'Acosta, Swift Fuels; Megan Eisenstein, National Air Transportation Association; Philip Fine, South Coast Air Quality Management District, CA; Walter Desrosier and Lowell Foster, General Aviation Manufacturers Association; Amanda Giang, University of British Columbia; Marion Hoyer, U.S. Environmental Protection Agency; Jeffrey Knutson, Cirrus Aircraft; Mike Kraft and Jennifer Miller, Lycoming Engines; Ryan Manor, Phillips 66; Doug Macnair, Experimental Aircraft Association; Jeremy Roesler, University of North Dakota; Tim Shea, Shell. (See Appendix B for meeting agendas.) In addition, the committee is grateful to the other individuals who provided written materials to the committee.

Amy R. Pritchett, *Chair*
Committee on Lead Emissions from
Piston-Powered General Aviation Aircraft

Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

FRED CORNFORTH, ConocoPhillips (retired)
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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **DAVID ALLEN (NAE),** The University of Texas at Austin, and **CHRIS HENDRICKSON (NAE),** Carnegie Mellon University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Appendixes

Abbreviations and Acronyms

100LL	100 octane low lead aviation gasoline
100VLL	100 octane very low lead aviation gasoline
AAAE	American Association of Airport Executives
AC	advisory circular
ACRP	Airport Cooperative Research Program
ADI	anti-detonation injection
AKI	anti-knock index
ANPRM	advance notice of proposed rulemaking
AOPA	Aircraft Owners and Pilots Association
ASTM	American Society for Testing and Materials
avgas	aviation gasoline
BLL	blood lead level
BMEP	brake mean effective pressure
CAA	Clean Air Act
CBOB	conventional gasoline for oxygenate blending
CDC	Centers for Disease Control and Prevention
CO	carbon dioxide
CRC	Coordinating Research Council
CWA	Clean Water Act
dL	deciliter
DOT	U.S. Department of Transportation
E0	ethanol free gasoline
EAA	Experimental Aircraft Association
EDB	ethylene dibromide
EIA	U.S. Energy Information Administration
EM	electron microscope
EPA	U.S. Environmental Protection Agency
ETBE	Ethyl tert-butyl ether
FAA	Federal Aviation Administration
FADEC	full authority digital engine control
FBO	fixed base operator
FOE	Friends of the Earth
GA	general aviation
GAMA	General Aviation Manufacturers Association

GAMI	General Aviation Modifications, Inc.
GHG	greenhouse gas
HC	hydrocarbon
LTO	landing and takeoff
MMT	Methylcyclopentadienyl manganese tricarbonyl
MOGAS	motor gasoline
MON	lean motor octane number
MSL	mean sea level
MTBE	Methyl tert-butyl ether
NAAQS	National Ambient Air Quality Standards
NAFI	National Association of Flight Instructors
NATA	National Air Transportation Association
NEI	EPA's National Emissions Inventory
NHANES	National Health and Nutrition Examination Survey
NIEHS	National Institute of Environmental Health Sciences
NIOSH	National Institute for Occupational Safety and Health
nm	nanometer
NPDES	National Pollutant Discharge Elimination System
NPIAS	National Plan of Integrated Airport Systems
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
OTM	OSHA Technical Manual
PAFI	Piston Aviation Fuels Initiative
PEL	permissible exposure limit
PEM	proton exchange membrane
PI	principal investigator
PPE	personal protective equipment
psi	pounds per square inch
RBOB	reformulated gasoline for oxygenate blending
RFS	Renewable Fuel Standard
RON	research octane number
RVP	Reid Vapor Pressure
SAB	Science Advisory Board
SAE	sampling and analysis error
SAFE	Society of Aviation and Flight Educators
SAIB	Special Airworthiness Information Bulletin
SAMA	Small Aircraft Manufacturers Association

STC	supplemental type certificate
TC	type certificate
TEL	tetraethyl lead
TSCA	Toxic Substances Control Act
TWA	time-weighted average
UAT ARC	Unleaded Avgas Transition Aviation Rulemaking Committee
UL	unleaded
UNC	University of North Carolina
VOC	volatile organic compound

Summary

The U.S. general aviation (GA) sector, with a fleet that consists mostly of piston-engine aircraft, serves many important functions. Aerial observation, medical airlift, pilot training, and business transport are examples of important GA functions that are applied across the country, while some functions, such as crop dusting, aerial firefighting, search and rescue, and air taxi service, have particular significance to communities in rural and remote locations. Piston-engine aircraft are critical to performing all of these functions, and they are also the predominant aircraft used for personal and recreational flying, typically in the smallest, most basic airplanes.

The vast majority of piston-engine airplanes and helicopters are powered by aviation gasoline (avgas). Nearly all of the country's approximately 170,000 active piston-engine aircraft burn a grade of avgas, designated "100LL," that contains lead. The number "100" refers to 100LLs octane rating and "LL" stands for "low lead." Lead is added in the form of tetraethyl lead to 100LL to achieve the octane rating needed for the safe operation of those high-performance aircraft with high-compression engines, which account for about one-third of the fleet and an even larger percentage of fleet fuel consumption. Because 100LL can be used by all kinds of piston-engine aircraft, this single grade is the only type of fuel consistently available to GA aircraft operators. Consequently, 100LL is also the only fuel that most existing piston-engine aircraft are certified to use by the Federal Aviation Administration (FAA).

A highly toxic substance, CDC concluded that there is no known safe level of lead in blood. Because of the susceptibility of the developing nervous systems, exposure to low concentrations of lead, including prenatal exposure, has been linked to decreased cognitive performance in children. Since the use of lead additives in automotive gasoline was banned in 1996, avgas has become the country's primary source of lead emissions. For more than 25 years, FAA, the GA industry, and fuel developers have been searching unsuccessfully for an unleaded "drop-in" replacement fuel for 100LL that can satisfy the performance requirements of the entire piston-engine fleet, including those high-performance aircraft that require avgas with an octane rating of 100 or higher.[1] During that time, the American Society for Testing and Materials (ASTM) adopted specifications for a second grade of leaded avgas, 100VLL ("very low lead"), which has the same octane rating as 100LL but nearly 20 percent less lead. In addition, ASTM issued specifications for unleaded (UL) avgas with lower octane ratings, which can be used by lower-performance aircraft. While only one fuel, UL94, that meets the ASTM specifications for unleaded avgas is currently produced, and is available at a select number of airports, 100VLL is not being produced.

Section 177 of the FAA Reauthorization Act of 2018, called on FAA to commission this study by a National Academies committee. The study was to consider (a) ambient lead concentrations at and around airports where piston-engine aircraft are used, (b) existing non-leaded fuel alternatives to avgas used by piston-engine general aviation aircraft; and (c) mitigation measures to reduce ambient lead concentrations, including increasing the size of run-up areas, relocating run-up areas, imposing restrictions on aircraft using avgas, and increasing the use of motor gasoline.

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[1] A full replacement for leaded avgas is sometimes referred to as a "drop-in" fuel because it would not require any changes to the existing piston-engine fleet, any FAA certification approvals for use in existing aircraft and engines, any modifications to future engines and aircraft, or any new investments in fuel storage and dispensing capacity.

Those mitigations could involve actions targeted at reducing lead emissions or reducing elevated concentrations of airborne lead in specific locations (hot spots). Findings with respect to each of these items in the study request are summarized next. The committee came to realize that currently there is no individual, certain solution to the aviation lead problem, and therefore a multi-pathway mitigation approach offers the greatest potential for tangible and sustained progress. The pathways that comprise this approach are described and recommendations are made for facilitating their pursuit.

AMBIENT LEAD CONCENTRATIONS AT AND NEAR AIRPORTS

Environmental health studies commonly rely on blood lead levels as a metric of exposure to the pollutant. Because lead does not appear to exhibit a minimum concentration in blood below which there are no health effects, there is a compelling reason to reduce or eliminate aviation lead emissions and sources of exposure.

Airborne lead, which is usually in the form of particulate matter, can be inhaled by people in communities surrounding airports. In addition, particles containing lead can deposit onto soil and other surfaces and be ingested through activities, such as hand-to-mouth contact with surfaces where the particles have deposited. Deposited lead also can be resuspended into the air as dust and inhaled. Therefore, past emissions from piston-engine aircraft that deposited to soil and other surfaces can contribute to present-day lead exposures within and near airports.

Lead exposures to workers at airports present another area of concern warranting mitigation. For example, the practices and protections of some airport personnel and aircraft technicians may need to be modified to reduce occupational and take-home exposures from lead deposits and residue in aircraft engines, oil, and spark plugs.

Assessing the feasibility and effectiveness of the airport-specific application of potential mitigations would benefit from an improved understanding of individual airport characteristics. Airports differ in traffic activity, layouts, meteorological and topographical conditions, and proximity to the local population. They serve as bases for different types and numbers of aircraft that provide different functions within the community. Therefore, additional analyses are needed to take into account airport-specific conditions and attributes, including the geographic distribution of lead around the airport. Such analyses would inform the selection, design, and effectiveness assessment of lead mitigations at individual airports.

EXISTING UNLEADED FUEL ALTERNATIVES

The only specified and available unleaded avgas, UL94, has the potential to be used in about half to two-thirds of existing piston-engine aircraft, although these are generally the lower-performance aircraft that account for less fuel burn and flight hours. Aircraft would need to acquire FAA certification approvals to use UL94, which many newly produced aircraft do not have. However, many low-performance models are technically capable of using this fuel and continued innovations in engine design could soon enable many future high-performance aircraft to use it as well. The potentially significant obstacle to the greatly expanded use of UL94 (or other unleaded lower-octane fuels meeting ASTM standards) is that thousands of small airports would need to invest more than $100,000 in a second avgas storage and dispensing system to accompany existing systems for supplying leaded avgas to aircraft that require fuel with enhanced octane. Because the piston-engine fleet has very low annual turnover, the supply of an avgas containing lead additives for higher performance aircraft will likely need to be supplied for many decades, unless a high-octane unleaded alternative can be developed and made widely available.

OTHER POTENTIAL LEAD MITIGATION MEASURES

Three specific potential lead mitigations are called out in the legislative request for this study: (a) imposing restrictions on aircraft using avgas, (b) increasing the use of motor gasoline in piston-engine aircraft, and (c) changing the locations within airports where pilots perform their engine run-ups during pre-takeoff checks.

Imposing Restrictions on Aircraft Using Avgas

The imposition of restrictions on aircraft using leaded avgas could take different forms, including limits on their use or on the fuels they burn, possibly by imposing costs (e.g., taxes or surcharges) on the use of leaded fuels, coupled with other measures, such as providing financial incentives for enabling private and public operators of aircraft and airports to change to lower-lead or unleaded fuels. Restricting the use of the high-performance piston-engine aircraft that require leaded avgas would have far-reaching ramifications for the many critical functions served by that portion of the fleet. Although it was not feasible to assess the ramifications on the industry, it is the judgment of the committee that restricting the use of this large and important component of the GA fleet would not be a viable mitigation. By comparison, restrictions on the fuel used by piston-engine aircraft, such as requirements for the use of UL94 by some or all low-performance aircraft that do not need to use high octane fuel, would require that substantial numbers of airports establish the requisite fuel storage and dispensing capacity to ensure the unleaded fuel's widespread availability sufficient that aircraft operators could be confident that the fuel will be available along their routes of flight. For thousands of small airports, including many that are privately owned or operated by municipalities or other entities with limited revenues and financial capability, the cost of adding this capacity is likely to be prohibitive.

Increasing the Use of Motor Gasoline

The use of automotive, or motor, gasoline is not a viable unleaded alternative to avgas for appreciable lead reduction. Supplies dispensed at just about all automotive filling stations are blended with ethanol, which is corrosive to aircraft components. The use of automotive gasoline prior to adding ethanol also is not viable because the octane levels of pre-blended supplies are formulated with the expectation that octane-enhancing ethanol will be added before dispensing the fuel. Therefore, octane ratings of fuels exiting refineries that are intended to be used by automobiles are too low for most aircraft including many that do not have high-compression engines.

Changing the Locations Within Airports Where Pilots Perform Engine Run-Ups

It is standard safety practice for pilots to stop on a ramp or a taxiway just before takeoff to conduct an engine "run-up" (i.e., confirm that the engine can safely attain full power to produce takeoff thrust. They do this in part by briefly advancing the throttle to confirm the engine operates properly at high power. Studies indicate that the exhaust from engine run-ups can create geographic areas with higher lead concentrations, such as when situated to combine with exhaust from aircraft taking off at full power. However, the magnitude, frequency, and dispersion of these concentrations and their proximity to people are airport- and context-specific, depending on factors such as the level of traffic activity, meteorological and topographical conditions, and the location and orientation of runways and areas where pilots perform their pre-takeoff checks in relation to buildings and people. Hence, to assess whether changing the location of run-up areas will achieve appreciable benefits in mitigating hot spots for ambient lead concentrations requires detailed information on specific conditions at individual airports, and particularly those that have moderate to high traffic activity, which number in the hundreds or more.

A MULTI-PATHWAY APPROACH FOR MITIGATING AVIATION LEAD

Achieving continuing, and potentially full, reductions of lead from aviation is a challenge for which there is currently no single known technical solution that is certain to be available in the near term. The advent of an unleaded drop-in fuel could greatly reduce or even eliminate aviation lead. However, the formidable technical challenges and associated uncertainties about whether and when such a fuel could be developed and deployed suggest that it should not be relied upon as the sole mitigation measure.

Thus, a multi-pathway approach that pursues lead emission and exposure reductions is needed in which the development of a drop-in fuel proceeds as a part of broader mitigation pathway focused on the development and deployment of lead-free fuels and new propulsion technologies, in combination with mitigation pathways focused on airport operations and practices and on existing fuels and aircraft. Implementation will require the participation of many across a diverse industry involving private, corporate and public entities, including pilots; airport managers and personnel; fuel suppliers; and aircraft engine, propulsion, and airframe manufacturers.

As illustrated in Table S-1, the pathways are complementary to one another and would be pursued simultaneously. However, they differ in their potential to yield near-term reductions in lead emissions and exposures, implementation complexities and requirements, and certainty of being effective. For some pathways, candidate policy options are easy to identify while, for others, the most suitable policies are difficult to define because they could involve combinations of financial assistance and incentives, regulatory requirements, support for technology research and development, and other potential interventions to motivate and enable the desired response. Some mitigations would confer ancillary benefits that would justify their pursuit, even where the lead reductions could be relatively modest, such as increasing awareness in the aviation industry about the degree of lead exposure that aviation causes to encourage widespread change. Pursuing them together would account collectively for reduced lead in aviation, and would increase the probability of significant technical breakthroughs sufficient to achieve the ultimate goal of no leaded avgas.

TABLE S-1 Candidate Pathways for Aviation Lead Mitigation Measures

	Airport Operations and Practices		**Existing Specified Fuels and Fleet**		**New Lead-Free Technologies (Fuels–Propulsion Systems)**		
Considerations	Aircraft Operations at Airports	Pilot and Airport Personnel Practices	100VLL Used by All Aircraft or with Some Using UL94	UL94 Used by Low-Performance Aircraft	UL94 in New Aircraft Including High-Performance Aircraft	100+UL in All Aircraft	New Propulsion Systems (new aircraft and retrofit some legacy aircraft)
Potential Reduction in Lead Exposures[a]	Small and variable, depends on individual airport conditions, activity, and hot spots[b]	Small and variable, but could be particularly important for aircraft technicians	Up to 20% reduction (could exceed 40% if combined with UL94 use by low-performance aircraft)	Up to 30% reduction (could exceed 40% if combined with 100VLL use by all other aircraft)	~0.5% reduction per year	100% reduction	~0.5% reduction per year
Time Frame for Lead Reduction Benefits If Started Soon	Near-term	Near-term	Near- to mid-term	Mid-term	Far-term for appreciable reductions and will require technical advances	Unknown, may require technical breakthrough	Far-term, pace of reduction depends on cost, rate of innovation, and extent of applicability to GA fleet
Focus of Implementation	Airport management	FAA flight standards, pilot instruction and training	Fuel supply chain, especially refiners	Fuel supply chain and airports, especially fuel storage and	Engine and aircraft makers	Fuel supply chain, especially fuel developers;	Technology developers, aircraft manufacturers, aircraft owners

		programs, GA community		dispensing capacity		engine and aircraft makers	
Possible Policy Actions for Facilitating Implementation	Provide data and tools for analysis and identifying operations changes	Provide training and education materials, engage in awareness campaigns	Directives and/or incentives, perhaps focused on refiners	Incentives and financial assistance for airports to add fueling capacity, eased FAA certification	Directives and/or incentives applicable to GA industry	Public–private collaborative (PAFI-like) for R&D, testing, and certification	R&D support, FAA certification, incentives for aircraft owners to incur expense
Main Sources of Uncertainty in Achieving Effective Implementation	Variability in airport-specific factors	Potential to affect practices	Refiner capacity to meet tighter lead specifications	Feasibility of adding fuel supply chain (refiners and airports), certification	Ability to design suitable engines for all high-performance aircraft	Potential to meet fuel performance requirements	Rate of innovation, certification challenge, cost and owner interest
Ancillary Benefits and Concerns	Greater lead awareness and interest in lead-free fuels and propulsion	Greater lead awareness and interest in lead-free fuels and propulsion				Environmental and health impacts related to other fuel components	Changes in pollutants, including greenhouse gases over life cycle

[a] Where percentages are given, they refer to estimates of reductions in lead from the total fuel consumed by the piston-engine fleet.

[b] Hot spots often refer to a spatial zone of emissions impact where the airborne lead concentration is significantly elevated above background.

RECOMMENDATIONS

Having evaluated these different, but complementary, pathways for reducing aviation lead, the committee concludes that concerted efforts are warranted to initiate and sustain progress across them all. The committee's recommendations are given next, grouped within each pathway with a summary of their desired outcomes.

Airport Operations and Practices

- FAA should coordinate its efforts to reduce lead pollution and exposures at airports with those of other federal agencies that have key responsibilities for protecting public health, safety, and the environment at airports, including the Occupational Safety and Health Administration (OSHA) as well as EPA. FAA should collaborate with these agencies to explore the regulatory and programmatic means within their respective jurisdictions that can be brought to bear and combined in a complementary manner to reduce lead emissions and exposures at airports (Recommendation 4.1).
- FAA, in partnership with prominent organizations within the GA community, should initiate an ongoing campaign for education, training, and awareness of avgas lead exposure that is targeted to GA pilots, aircraft technicians, and others who work at airports. Informed by research on the most effective approaches for reaching these audiences, the campaign should be multi-pronged by ensuring that information on lead risks and mitigation practices is prominent in relevant manuals, guidelines, training materials, and handbooks for pilots, airport management, and aircraft technicians. Where appropriate, it should also be covered in relevant certification and licensure examinations. In addition, the information should be featured on FAA and GA organization websites and included in written materials distributed at GA industry conferences, tradeshows, and fly-ins (Recommendation 4.2).
- FAA should update its guidance on the location of run-up areas to reflect the results of research since the latest interim guidance was issued in 2013, including the need to account for both the emissions of engine run-ups and of takeoffs when analyzing the geographic distribution of lead emissions at the airport. This analysis should support decisions of whether to move run-up areas to reduce people's exposure to lead emissions while also accounting for other concerns including safety and aircraft noise (Recommendation 4.3).

The outcomes envisioned from these recommendations will result from increasing awareness by the many individuals needed to effect change in everyday operations. Pilots and aircraft owners, airport managers and personnel, and aircraft technicians would understand the hazards created by leaded avgas to themselves and the local community, and would follow best practices for containment during refueling, locating and timing engine run-ups, proper disposal of inspected fuel samples, and exposure protections. Airports would purposefully move pre-takeoff run-up areas to reduce the proximity of lead concentration hot spots to people where airport location, traffic activity levels and exhaust interactions warrant such a response.

Existing Fuels and Fleet

- FAA should research public policy options, which could be implemented as quickly as possible at the federal and state levels as well as by Congress, for motivating refiners to produce and airports to supply 100VLL. The objective would be to reduce lead emissions from the entire piston-engine fleet while unleaded alternatives are being pursued for fleetwide use (Recommendation 5.1).
- FAA should research public policy options that will enable and encourage greater use of available unleaded avgas by the portion of the piston-engine fleet that can safely use it. Possible options include (a) issuing a Special Airworthiness Information Bulletin that will permit such use and (b) providing airports with incentives and means to supply unleaded fuel, particularly airports that are eligible for FAA-administered federal aid as part of the National Plan for Integrated Airport Systems (Recommendation 5.2).
- A mechanism should be established for facilitating the increased availability of existing grades of unleaded avgas across the fleet of piston-engine aircraft. Fulfilling that need would likely require congressional involvement, such as by providing incentives for pilots to use existing unleaded avgas and for more small airports to add requisite fuel storage and dispensing capacity (Recommendation 5.3).

The outcomes envisioned from these recommendations would motivate changes within the fuel supply chain to reduce lead in aviation fuels quickly. 100VLL would be made available for purchase and used by the entire piston-engine fleet, potentially leading to a 20 percent reduction in lead emissions after fully replacing 100LL without necessitating any changes in airport fueling capacity, aircraft or engines, and aircraft operations. Even as 100VLL would be made widely available, increasingly larger portions of the low-performance fleet would be certified to use a lead-free lower octane avgas, such as UL94, and many pilots of these aircraft motivated to use it. The fuel would be made available at many high- and medium-volume airports where supplemental fuel storage and dispensing capacity exists or can be economically added. This development has the potential to result in lead reductions that could exceed 40 percent when combined with 100VLL being used by legacy high-performance aircraft, although this full reduction may not be achieved due to expected limits on the availability of an unleaded grade at many lightly used airports where the cost of adding more fueling capacity may be prohibitive.

Future Lead-Free Fuels and Propulsion Systems

- FAA should continue to collaborate with the GA industry, aircraft users, airports, and fuel suppliers in the search for and deployment of an acceptable and universally usable unleaded replacement fuel. The collaboration should be carried out through the Piston Aviation Fuels Initiative (PAFI) or an alternate holistic process for evaluating all the properties and conditions necessary for production, distribution, and safe use of the fuel, including the use of common test protocols and procedures and by making available the needed testing facilities for the development of the data required to support FAA approvals for the fuel to be used by existing piston-engine aircraft (Recommendation 6.1).

- A clear goal should be established that all newly certified gasoline-powered aircraft after a certain point in time (e.g., within 10 years) are approved to operate with at least one ASTM-specified unleaded fuel. Also, an additional amount of time should be identified by which all newly produced gasoline-powered aircraft, including those currently produced with older type certificates, would attain that same goal. Congressional action to establish the goal and timeframes would ensure achievement of those important results. For example, that congressional action would promote the development of new engine variants compatible with existing unleaded fuels which could possibly yield prescriptions to support the eventual retrofit of some legacy aircraft and engines as they reach required overhaul milestones (Recommendation 6.2).
- FAA initiatives—including collaborations with industry and other government agencies such as the National Aeronautics and Space Administration—should be used to promote the development, testing, and certification of safe and environmentally desirable lead-free emerging propulsion systems (such as diesel, electric, and jet fuel turbine engine) for use in GA aircraft, including the requisite airport refueling and recharging infrastructure. Congressional encouragement and the provision of resources as required would ensure the success of those initiatives (Recommendation 6.3).

The outcomes of these recommendations have the longest time frame and some are uncertain as to when they can be realized and at what cost – but they lead to a full transition of the aviation industry from the use of leaded fuels. If the technical challenges in creating a safe, unleaded aviation fuel can be overcome, it would become widely available and the entire gasoline-powered GA fleet would be able to use unleaded fuels, either through the development and supply of a single high-octane unleaded grade (e.g., 100+UL) that can serve the entire fleet or a mix of higher- and lower-octane (e.g., UL94) unleaded grades that can serve different portions of the fleet. While the former outcome—a drop-in fuel— would enable economies of scale in fuel production and reduce the need for multiple fuel distribution, storage, and dispensing systems, either outcome would greatly reduce or even eliminate lead from the GA sector.

In parallel, within a decade or so, all newly produced gasoline- powered aircraft, including high-performance aircraft, would be certified to use an unleaded avgas grade, which may need to be a lower octane grade if a safe unleaded drop-in replacement for current 100LL is not established in time. Aircraft operators could choose to transition their aircraft systems to use this fuel once it is sufficiently available along their routes of flight and at their home base airports. The capability to use a lower octane grade, which currently exists for at least a few high-performance engines in production, would gradually increase the demand for unleaded fuel, and motivation for airports to install appropriate fueling systems to provide it, if coupled with many legacy, low-performance aircraft using the fuel. High-performance engines capable of using unleaded avgas might also transition into the legacy fleet as older aircraft undergo major engine retrofits.

Furthermore, the share of new aircraft using lead-free fuels, such as diesel and jet fuel, or non-petroleum propulsion systems, such as electric power, would be increasing steadily driven by innovation and consumer interest and uptake (to possibly include retrofits in some legacy aircraft) to yield appreciable lead reductions and also could confer other environmental benefits such as reduced greenhouse gas (GHG) emissions.

Over the coming decades, efforts to reduce GHG emissions from the production and use of transportation fuels may influence the availability and composition of petroleum-based aviation fuels and hasten the introduction of aviation propulsion systems that do not require petroleum. It will be important that the transition to using avgas with lower or no lead content also coordinate with efforts seeking to reduce or eliminate GHG emissions, given the shared concerns with developing and certifying new aircraft technology, the supply and distribution systems for GA aircraft fuels, and broad awareness within the GA community.

ONGOING NEED FOR RESEARCH, DATA, AND ANALYSIS

While ample evidence and knowledge exist about the harm caused by lead pollution to highlight the need to initiate a comprehensive set of aviation lead mitigations now, there also remains a compelling need for more research and data to inform the design and assessment of mitigations and to target them in the most effective manner. Recommendations for research to meet such needs are provided in Box S-1; for instance, mitigations can be better applied with better understanding of how environmental lead concentrations at and near airports vary according to differences in airport configuration, activity levels, and other characteristics. Additional recommendations and discussions are provided in Chapter 3 of this report. EPA has been at the forefront of efforts to further the needed research, data, and analysis largely within the context of its obligation to implement the CAA. Success in designing and implementing a lead mitigation strategy will require such an ongoing commitment to research, data collection, and analysis.

BOX S-1 Recommended Research on Aviation Lead Pollution and Its Effects

EPA should conduct more targeted monitoring and enhanced computational modeling of airborne lead concentrations at airports of potential concern, as indicated by its most recent screening study, to evaluate aircraft operations that are main contributors to lead hot spots and designing airport-specific mitigation measures. In addition to airports found to have airborne lead concentrations exceeding the concentration of the lead NAAQS, the additional monitoring and modeling should include airports found to have lead concentrations that are lower but approaching the NAAQS concentration (Recommendation 3.1).

EPA and the National Institute of Environmental Health Sciences should sponsor research to enhance the understanding of lead exposure routes and their relative importance for people living near airports and working at them. The research should include studies, such as observations of blood lead levels among children, in communities representing a variety of geographic settings and socioeconomic conditions that are designed to examine the effectiveness of the lead mitigation strategies over time (Recommendation 3.2).

CONCLUDING COMMENT

There are no known safe lead exposures as measured by blood lead levels; lead's adverse effects on human health, and particularly on the development of children, are well established. While the elimination of lead pollution has been a U.S. public policy goal for decades, the GA sector continues to be a major source of lead emissions, largely because of the complex challenge of eliminating those emissions that is documented in this report. However, the evidence of lead pollution's hazard demands that those challenges not become an excuse for inaction, but instead become the subject of concerted, sustained, and multipronged efforts to find and implement mitigations.

It is important to note that EPA, which sets National Ambient Air Quality Standards under authority of the Clean Air Act (CAA), has been studying airborne lead concentrations at airports for the past decade to determine whether lead emissions endanger public health or welfare. However, the agency has not yet proposed such a formal determination, positive or negative. Given the uncertainty of this development, CAA-specific regulatory tools were not considered in this study, but if they were to become available, they would almost certainly have a prominent role in a lead mitigation strategy.

A key message of this report is that a lead mitigation strategy focused almost entirely on developing an unleaded drop-in fuel that would eliminate aviation lead emissions has a high degree of uncertainty of success given the formidable technical challenges. Additional mitigation measures are available that could be applied in the near and mid-terms to make progress in reducing lead emissions and exposures while other approaches having the potential for much larger impacts are being pursued.

1
Introduction

In the 1970s, the aviation industry converged on a standard for the aviation gasoline (avgas) used in piston-engine aircraft that remains unchanged to this day, and is commonly called "100LL." The "100" refers to the octane level of avgas, which is even higher than the octane level of high-tier automotive gasoline. The "LL" stands for "low lead," reflecting the fact that avgas' higher octane is created by the addition of tetraethyl lead (TEL).[1] The addition of lead to boost octane enables the reliable operation of high-compression piston engines at the wide range of altitudes and climates in which small aircraft operate. An important function of the lead additive is to prevent early detonation of fuel in the cylinder. Detonation in a gasoline engine is often called "knock" because of its characteristic sound. Because knock can lead to the failure in flight of critical engine components, it must be avoided.

Since 100LL became the universal grade of avgas, the harmful health consequences of lead pollution have become better understood. A highly toxic substance, lead is known to have profound adverse effects on the development of infants and children, and it can remain in the human body for decades to cause lasting harm. Furthermore, it is a persistent pollutant. As a mineral naturally found underground, once lead is extracted and released by human activity it stays in the environment and its levels accumulate with additional emissions.

Compared to other historic sources—heavy industry, early military aviation, and automobiles before their transition to unleaded gasoline 40 years ago—piston-engine aircraft have not been the largest contributor of the lead that has persisted in the environment. However, these other sources have been eliminated or greatly reduced, making avgas one of the few major sources of a pollutant whose environmental concentrations are not naturally dissipating over time. Thus, continued emissions from aircraft engines can add to lead concentrations that may already be presenting concerns in some locations, particularly at and near the roughly 13,100 airports where most piston-engine aircraft operate. The lead in avgas can also present an occupational health hazard to those who refuel and maintain piston-engine aircraft. Thus, "low-lead" is a misnomer in the sense that any amount of lead in fuel can be too high from a human health standpoint, prompting interest in reducing aviation's reliance on leaded gasoline.

The Clean Air Act (CAA) requires the U.S. Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQS) for principal air pollutants (known as criteria pollutants), which are widespread ambient air pollutants that are reasonably expected to present a danger to public health or welfare (see 42 USC 7408-7409).[2] Lead is one of the criteria pollutants subject to regulation.[3] In cases where a regulated pollutant may reasonably be anticipated to endanger public health or welfare, the EPA can propose standards that apply to aircraft engine emissions; however, it must consult with and obtain approval from the Federal

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[1] 100LL is specified to have a maximum of 0.56 grams of lead (0.875 grams of TEL) per liter and a minimum of 0.28 grams (0.437 grams of TEL) per liter.

[2] Within the context of the CAA, welfare effects include effects on soils, water, agriculture, forests, wildlife, fabricated materials, atmospheric visibility, and climate.

[3] In 1976, EPA listed lead under CAA section 108, making it what is called a "criteria pollutant." As part of the listing decision, the agency determined that lead was an air pollutant, judged to have an adverse effect on public health or welfare. In 1978, EPA [under section 109(b)] issued primary and secondary lead NAAQS to protect public health and welfare. The lead NAAQS level is now 0.15 $\mu g/m^3$, averaged over a 3-month averaging period.

Aviation Administration (FAA) to issue any proposed standard that may affect aviation safety. Moreover, EPA does not have regulatory authority over which fuels may be used by aircraft. The fuels used in specific engine and aircraft types are defined by the engine and aircraft manufacturers and by American Society for Testing and Materials (ASTM) specifications controlling the composition and physical properties of purchased fuel. FAA is responsible for certifying engine and aircraft types based on the manufacturer's testing of the engine and aircraft when using a defined ASTM fuel specification. Thus, even FAA does not directly approve the fuels used, but rather certifies that a given type of engine or aircraft is permitted to operate on a fuel defined by the manufacturer based on its testing. Aircraft owners are not permitted to use fuels that are not specified in an aircraft type certificate (TC) approved by FAA. More details on relevant FAA and EPA statutory and regulatory authorities and their interconnections are provided in Box 1-1.

BOX 1-1 EPA and FAA Authorities Pertaining to Aircraft Emissions and Aviation Fuel Properties

Endangerment Finding

Section 231 (a)(2)(A) of the CAA requires the EPA Administrator to "issue proposed emission standards applicable to the emission of any air pollutant from any class or classes of aircraft engines which, in [the Administrator's] judgment, causes or contributes to air pollution which may reasonably be anticipated to endanger public health or welfare." According to a 2010 advance notice of proposed rulemaking from EPA, the term endangerment finding is often used as a shorthand reference to such a judgment. It is notable that in instructing the Administrator to consider whether emissions of an air pollutant cause or contribute to air pollution, the law does not require the Administrator to find that emissions from any one sector or group of sources are the sole or even the major part of an air pollution problem. Moreover, the requirement does not contain a modifier such as "significant" or "major" to the term "contribute" and thus does not appear to set the magnitude of the contribution as a criterion for an endangerment finding. Thus, EPA has broad authority in exercising its judgment regarding whether emissions from certain sources cause or contribute to air pollution, which may reasonably be anticipated to endanger public health or welfare.[a]

Emission Standards

Section 231(a)(2)(A) of the CAA grants EPA authority to propose standards applicable to the emission of any air pollutant from any class or classes of aircraft engines judged to cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare. EPA is given discretion to issue the standard over a period of time that permits the development and application of the requisite technology, considering the cost of compliance within that period. In doing so, however, the agency must consult with the Secretary of Transportation. In addition, Section 231(c) states that EPA's regulations regarding aircraft "shall not apply if disapproved by the President, after notice and opportunity for public hearing, on the basis of a finding by the Secretary of Transportation that any such regulation would create a hazard to aircraft safety." If a proposed emission standard is finalized by EPA, Section 232(a) of the CAA directs the Secretary of Transportation to issue and implement regulations to ensure compliance with the emissions standards, including aviation fuel standards.

Fuel Standards

CAA section 216 defines "motor vehicle," "nonroad engine," and "nonroad vehicle." Section 211(c)(1) allows EPA to regulate any fuel or fuel additive used in motor vehicles and nonroad vehicles or engines where emission products of the fuel of fuel additive either: (A) cause or contribute to air pollution or water pollution that reasonably may be anticipated to endanger public health or welfare, or (B) will impair to a significant degree the performance of any emission control device or system in general use, or which the Administrator finds has been developed to a point where in a reasonable time it will be in general use were such a regulation to be promulgated. This section of the CAA was used as basis for eliminating lead from fuel used in motor vehicles. However, in the Act, aircraft are not defined as nonroad vehicles and aircraft engines are not defined as nonroad engines. Accordingly, EPA's authority to regulate fuels under section 211 does not extend to fuels used exclusively in aircraft, such as leaded avgas.[a]

Fuels used in aircraft engines are regulated by FAA under section 232 of the CAA and 49 U.S.C. § 44714 (Aviation Fuel Standards). Under section 232, the Secretary of Transportation is to consult with the administrator of EPA regarding implementation of EPA standards and is to modify aircraft TCs as appropriate and necessary. In linking back to the CAA provisions governing emissions standards, 49 U.S.C. § 44714 requires FAA to prescribe standards for the composition or chemical or physical properties of an aircraft fuel or fuel additive to control or eliminate aircraft emissions EPA decides under Section 231 of the Clean Air Act endanger the public health and welfare and to issue regulations providing for carrying out and enforcing those standards.

An addition to 49 U.S.C. § 44714 (from section 565 of the FAA Reauthorization Act of 2018) gives FAA authority to allow the use of a unleaded aviation gasoline in aircraft as a replacement for leaded aviation gasoline if the agency: (1) qualifies the unleaded gasoline as a replacement for approved leaded gasoline, (2) identifies the aircraft and aircraft engines eligible to use the unleaded gasoline, and (3) adopts a process, other than the traditional means of certification, to allow eligible aircraft and aircraft engines to operate using the qualified replacement unleaded gasoline in a manner that ensures safety. (The law creating this addition states that existing regulatory mechanisms by which an unleaded aviation gasoline can be approved for use in an engine or aircraft will also remain in effect.) See Appendix C for additional details.

[a] 75 Federal Register 22440-22468. April 28, 2010. Advance Notice of Proposed Rulemaking on Lead Emissions From Piston-Engine Aircraft Using Leaded Aviation Gasoline; Proposed Rule. See https://www.govinfo.gov/content/pkg/FR-2010-04-28/pdf/2010-9603.pdf.

The U.S. active piston-engine fleet totals some 170,000 airplanes and helicopters. Unfortunately, no unleaded replacement fuel exists for aircraft that require high octane levels to operate safely, which comprise the roughly one-quarter of the fleet with the highest-performance engines that are used the most intensely and thus are estimated to consume more than half of all avgas. The remaining aircraft that are candidates for using lower octane grades of fuel are those with lower performance and that operate at lower altitudes, many of which were originally designed to allow for the use of avgas with lower octane before 100LL became the industry standard about 50 years ago.

Thus, one possible approach for achieving early reductions in leaded avgas consumption is to transition the fleet to use two gasoline grades—a lower octane unleaded grade for those aircraft that can safely perform with it, and 100LL for those that require higher octane fuel to resist knock and ensure safe performance. This approach would lower overall lead emissions by the piston-engine fleet, depending on how many aircraft could operate with the lower octane fuel and how often those aircraft are used. However, the transition would potentially require the testing and recertification of a large number of aircraft and engines, some of which were designed and built decades ago, and whose manufacturers may no longer exist. Aircraft owners interested in switching to unleaded fuels may find this recertification option prohibitively expensive, except in cases where a supplemental TC (STC) is already available at moderate cost. Moreover, fuel consumption by aircraft in the piston-engine fleet varies widely because aircraft serve a range of general aviation (GA) purposes, such as pilot training, transport for small and remote communities, emergency medical transport (medevac), aerial surveying, and crop dusting. The higher performance aircraft, which are used disproportionately for such non-recreational purposes, consume high quantities of fuel, but cannot be satisfied by existing lower octane unleaded avgas.

The primary challenge associated with the two-fuel option is that it would require investments in a second supply chain for an unleaded fuel, including refinery and distribution capacity. Inasmuch as the supply of avgas is already a highly specialized element of the total gasoline market, accounting for roughly 0.1 percent of the total volume of gasoline refined each year in the United States, splitting its market in two could be problematic from an economic standpoint. In addition, many airports across the country, including thousands of very small facilities that are privately owned or operated by municipalities, counties, and other entities, would need to establish a second fuel storage and dispensing system to accommodate a second fuel, at significant and potentially prohibitive expense.

Because unleaded automotive gasoline is widely available and relatively inexpensive it is sometimes proposed as an option for reducing lead use by the portion of the piston-engine fleet that can use lower octane fuel. Indeed, thousands of piston-engine aircraft were granted STCs during the 1980s that allowed them to use “MOGAS,” which presumably referred to the unleaded automotive gasoline being produced and dispensed at automobile filling stations at that time. Many of these aircraft remain in the fleet; however, current formulations and properties of unleaded automotive gasoline do not resemble those earlier supplies. Gasoline containing ethanol cannot be used in aircraft because of its corrosive effects. Moreover, automotive gasoline delivered from refineries does not achieve designated octane levels until after ethanol, which boosts octane, is added at gasoline storage and distribution terminals prior to delivery to filling stations. Absent the addition of ethanol, the octane levels of the automotive gasoline exiting refineries would be too low for use in most aircraft, including many lower performance aircraft.

In recognition of the many challenges associated with having multiple grades of avgas, FAA has been working with fuel suppliers and aircraft manufacturers and operators to develop a higher-octane unleaded “drop-in” fuel that can safely be used by all piston-engine aircraft currently using 100LL without requiring any modifications to engines or operations. Most recently, the Piston Aviation Fuels Initiative (PAFI), a collaborative formed by FAA and the GA industry in 2013, has established testing standards for new fuels, as well as a qualification test program to confirm that compliant fuels work in a broad range of existing aircraft gasoline engines. Furthermore, PAFI has established mechanisms for public-private cooperation to help overcome the logistical, economic, and policy challenges to transitioning to a drop-in fuel. The aim of the collaborative, which is ongoing, is to provide a solution that would allow the current piston-engine fleet and fuel supply chain to transition to unleaded fuels without prohibitive costs. PAFI's efforts build on prior FAA and industry work to identify fuel additives to replace TEL (see, for example, CRC, 2010). While this earlier work was unsuccessful in finding a replacement additive, it shed light on the many important factors that must be considered for a drop-in fuel. Low toxicity and prevention of knock and engine shutdowns are essential requirements, but so too are compatibility with a wide range of engine and fuel system materials and high performance with respect to many other capabilities such as freeze resistance, hot and cold starting, and transport and storage stability.

Of course, a longer-term strategy to reduce aviation lead could include the development and introduction of small, GA-type aircraft that do not need gasoline. Diesel and turbine engines, whose use has traditionally been limited to larger, more complex aircraft, have been demonstrated in smaller airplanes. Furthermore, battery electric aircraft are now being developed, as are hybrid-electric aircraft in which a small onboard generator supplements the electricity stored in a battery to power an electric motor. However, these latter propulsion systems are, at this time, generally limited to single flight demonstrators operated as experimental rather than fully certified aircraft. While technology developments under way in electric ground vehicles may have application to small aircraft (e.g., the improved storage capacity and decreased cost of batteries), the aviation sector has unique demands for very low-weight technologies and very high reliability and safety assurance. Moreover, the very slow annual turnover of the piston-engine fleet means that it could take decades for the introduction of new, lead-free technologies to have an appreciable effect on aviation lead emissions.

The challenge in reducing aviation lead emissions is therefore complex and multi-faceted. Meeting the challenge may require approaches that go beyond the development and introduction of new fuels and aviation technologies to include a nearer-term focus on the way piston-engine aircraft are used and operated at airports where lead emissions can be more concentrated and where pilots, aircraft technicians, and aircraft and airport maintenance personnel may have greater exposure to lead. Therefore, in addition to sponsoring research to evaluate and find possible drop-in fuels, FAA has sponsored a number of studies, including several by the Airport Cooperative Research Program (see, for example, NASEM, 2015, 2016), to better understand how the lead emitted from the burning and vaporization of avgas disperses and concentrates at airports and contributes to human exposure. The studies have also examined potential mitigation measures at airports, including reconfiguring and relocating where pilots perform their engine run-ups during pre-takeoff checks, and changes in practices to ensure that avgas liquid and vapor are contained during refueling and after pilots inspect the quality of sampled fuel prior to flight (TRB, 2014). Although not sponsored by FAA, a small number of studies have also been undertaken to gain a better understanding of how aircraft technicians and airport maintenance personnel can be exposed to the lead from avgas, and how such exposures may be mitigated. (See Chapter 4.)

EPA has also studied lead emissions and concentrations at airports, starting in 2010 when it began an assessment as part of a rulemaking activity to determine whether lead emissions endanger public health or welfare.[4] The assessments have included air quality monitoring at and near airports and demographic analyses of the population residing near airports. In addition, because it would be impracticable in terms of time and resources to obtain monitored data for every airport, EPA used computational modeling to estimate airborne lead concentrations at other unmonitored airports. Following the release of its latest modeling and monitoring data in February 2020, EPA concluded that the results indicate that lead concentrations at and near airports are typically well below the lead NAAQS (EPA, 2020). Nevertheless, the monitoring did find some airports where lead concentrations exceeded the NAAQS in locations in close proximity to where pre-takeoff engine checks take place. Moreover, the agency has continued to express concern about aggregate exposures from all sources of lead, including low concentrations in air from piston-engine aircraft operations, and has therefore pointed to the importance of working to reduce lead emissions from aviation.[5]

At the time this committee's report was authored, EPA had not proposed a formal determination, positive or negative, of whether lead emissions from the use of leaded avgas cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare. Further updates on the status of EPA's deliberations could provide data and analyses that inform mitigation strategies and point to where more research and assessments are needed. While a formal EPA determination is not a prerequisite for introducing measures to mitigate aviation lead, it would add more clarity about the array of regulatory and non-regulatory means available for this purpose.

STUDY REQUEST AND CHARGE

Section 177 of the FAA Reauthorization Act of 2018 (P.L. 115-254) calls on the Secretary of Transportation, acting through FAA, to make appropriate arrangements with the National Academies of Sciences, Engineering, and Medicine (the National Academies) to convene an expert study committee to examine:

> (a) existing non-leaded fuel alternatives to the aviation gasoline used by piston-powered general aviation aircraft; (b) ambient lead concentrations at and around airports where piston-powered general aviation aircraft are used; and (c) mitigation measures to reduce ambient lead concentrations, including increasing the size of run-up areas, relocating run-up areas, imposing restrictions on aircraft using aviation gasoline, and increasing the use of motor gasoline in piston-powered general aviation aircraft.

The study committee's Statement of Task (see Box 1-2) reflects the legislative request, and emphasizes the importance of being as quantitative as possible, particularly when considering how candidate mitigation measures could potentially improve air quality near airports in relation to EPA's lead NAAQS. Those mitigations could involve actions targeted at reducing lead emissions or reducing elevated concentrations of airborne lead in specific locations (hot spots). While not obligated to make recommendations on the adoption of one or more of the

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[4] 75 Federal Register 22440-22468. April 28, 2010. Advance Notice of Proposed Rulemaking on Lead Emissions From Piston-Engine Aircraft Using Leaded Aviation Gasoline; Proposed Rule. See https://www.govinfo.gov/content/pkg/FR-2010-04-28/pdf/2010-9603.pdf.
[5] See https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YG46.pdf.

mitigations identified in the legislative request, the study committee is nevertheless given the latitude to recommend near- and longer-term lead reduction mitigations that warrant further consideration, including recommendations on priority research needs for reducing future piston-engine aircraft lead emissions.

BOX 1-2 Statement of Task

The study of lead emissions from the consumption of aviation gasoline by piston-powered general aviation aircraft shall include an assessment of:

— Existing non-leaded fuel alternatives to the aviation gasoline used by piston-powered general aviation aircraft;
—Ambient lead concentrations at and around airports where piston-powered general aviation aircraft are used; and
—Mitigation measures to reduce ambient lead concentrations, including increasing the size of run-up areas, relocating run-up areas, imposing restrictions on aircraft using aviation gasoline, and increasing the use of motor gasoline in piston-powered general aviation aircraft.

As part of assessing mitigation measures, the committee will consider potential improvements in air quality near specific airports in relation to the maximum allowable lead concentration established for the National Ambient Air Quality Standards. The evaluation methods should be quantitative to the extent possible. The committee is not asked to recommend the adoption of one or more mitigation measures. As appropriate and based on available scientific and technical information, the committee will recommend near- and longer-term mitigation measures that warrant further consideration by federal agencies. In addition, it will identify priority research needs for reducing future lead emissions from piston-engine aircraft.

STUDY APPROACH

To fulfill its charge, the study committee reviewed the literature on the health impacts of lead in the environment and the many research reports on the contribution of piston-engine aircraft to lead concentrations, including the Airport Cooperative Research Program (ACRP) and EPA reports noted above. Federal ambient air and water quality standards, as well as standards pertaining to workplace health and safety, were reviewed to obtain a better understanding of how lead emissions and exposures are regulated. In considering the history of the use of leaded fuels for piston-engine aircraft, the committee examined reports on past technical research to find replacements for leaded avgas, some dating back decades, along with documents and articles on websites from the aviation industry, fuel suppliers, and the GA community. To find any references to best practices for controlling aviation lead emissions and exposures, the committee reviewed the many manuals, handbooks, and other procedural and instructional documents that are commonly used by GA pilots, airport operators, and aircraft technicians, including relevant FAA publications, circulars, and bulletins.

During two meetings open to the public, the committee invited briefings from officials and representatives from FAA and EPA. They discussed the obligations and regulatory authorities of their agencies related to lead emissions from aircraft in the context of the CAA, including subjects such as EPA and FAA cooperation. EPA reported on the agency's evaluation of the air quality impact of lead emissions from aircraft using leaded avgas and the status of rulemaking and endangerment assessments under the CAA. These briefings, and follow-on correspondence, provided the committee with both background and highly detailed information on the challenges associated with reducing and potentially eliminating lead from avgas and with controlling lead concentrations and exposures resulting from aircraft and airport operations.

The committee also invited briefings from representatives of aircraft and engine manufacturers, airports, fixed base operators who dispense aviation fuel, small airplane operators, and suppliers and developers of aviation fuel. Along with FAA officials, they explained the technical demands of aviation fuel in providing sufficient octane and other properties essential for ensuring the safe operation of piston-engine aircraft. They provided information on the role of piston-engine aircraft in the national transportation infrastructure, the means by which engines and aircraft are certified and their fuels defined, and the operations and varied activities that take place at the thousands of small airports that serve most of the aircraft in the piston-engine fleet including their refueling. They also discussed the progress being made in the development of unleaded fuels and in aircraft gasoline engines and alternative propulsions systems. Numerous committee member questions were fielded during these briefings, and they were often followed by more specific information requests handled through email correspondence.

PAFI was the subject of several briefings by FAA and the program's GA industry collaborators. Briefers' explanations of the purpose, structure, accomplishments, and status of the collaborative were valuable to the committee. Not only did they provide a fuller picture of the many technical hurdles that must be overcome to develop a safe and effective drop-in fuel, but also insights into practical issues will need to be addressed if such a fuel is developed and promoted as a general replacement for leaded avgas. One can expect, for instance, that in addition to a candidate fuel's technical properties, questions about its eventual price, availability, proprietary control, and impact on fueling infrastructure would be concerns in a GA industry experiencing declining demand and activity levels. Indeed, because of PAFI's emphasis on spurring private-sector fuel development, the proprietary formulations of the fuels being evaluated under the program and their specific behaviors and performance when tested have remained confidential, and thus unknown to the study committee. The information on PAFI that is provided in this report, therefore, is essentially the same information contained on FAA's public website.[6]

So informed, the study committee addressed specific aspects of the Statement of Task. It examined the lead emission rates from piston-engine aircraft, the chemical and physical states of the lead emitted by the aircraft, lead environmental transport and deposition, routes of lead exposure, and potential environmental and human health impacts related to lead emissions. These reviews included the consideration of completed studies on environmental lead concentrations from emissions at and around airports. The committee then identified a number of gaps in understanding of environmental dynamics, exposures, and potential health effects, and considered how they might be filled by research, monitoring, education, and other means. The committee also considered how airport-related activities and operations, including refueling, pre-flight checks, and aircraft maintenance, could contribute to aviation lead emissions and

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[6] See https://www.faa.gov/about/initiatives/avgas.

exposures. Based on these reviews, it identified some potential ways to reduce their contributions.

In addition, the committee considered the unleaded and lower-lead fuels approved for use by all or portions of the existing piston-engine fleet. The committee estimated the potential to reduce lead emissions by replacing 100LL with one or more of these fuels. It also examined the potential for MOGAS to play a meaningful role in reducing aviation lead. Finally, the committee focused on the promise of an unleaded drop-in fuel and lead-free propulsion technologies for application to aircraft in the existing and future fleets. As part of this focus, the committee reviewed the history, structure, and accomplishments of PAFI and considered the status—as much possible given information restrictions—of the fuels being tested under the collaborative as well as outside of it by fuel suppliers.

Having considered the challenges and opportunities for reducing aviation lead from multiple pathways (airport operations and practices, fuel availability and development, the characteristics and use of the existing piston-engine fleet, and aircraft engines and lead-free propulsion systems), the committee came to view the goal of fully eliminating aviation lead as being complex, multi-dimensional, and having uncertain potential to be attained soon, or at all, by focusing on a single approach such as the advent of an unleaded drop-in fuel. As a result of this conclusion, the committee considered combinations of pathways that can be taken to curb lead emissions and exposures along with initiatives aimed at developing lead-free fuels and technologies. While in many cases the relative advantages and disadvantages of choosing specific policy measures (such as, relative benefits and costs of regulations, taxes, or subsidies) to facilitate progress along each pathway could not be fully assessed in this study, such assessments would be needed to decide on the most appropriate mitigations to pursue.

Additionally, with respect to the Statement of Task's expectation that possible mitigations would be assessed with regard to their impact on meeting the lead NAAQS, EPA's finding that lead concentrations are typically well below the lead NAAQS at airports suggested that such mitigation-specific quantification would not be fruitful, and probably not possible. In requesting this study, Congress did not ask for lead mitigation options to be considered in relation to the NAAQS or with the CAA's jurisdiction and mitigation tools directly in mind. The study committee, nevertheless, notes EPA's continuing concern about aggregate exposures from all sources of lead, and recognizes that key agency decisions, such as a formal endangerment determination, positive or negative, could have an important bearing on the prioritization and implementation of public policies that align with the mitigation pathways considered in this study.

REPORT ORGANIZATION

The remainder of the report is organized into six chapters. The next chapter (Chapter 2) provides background on the U.S. piston-engine aircraft fleet, its use characteristics, and the airports where the aircraft operate from and are based. Chapter 3 addresses the Statement of Task's call for an assessment of ambient lead concentrations at airports where piston-engine aircraft are used. The chapter also includes an examination of the potential health effects of lead exposure and various aspects of aviation lead emissions. Chapter 4 considers how airport-related activities and operations may be contributing to lead emissions and exposures. It also discusses mitigation measures that may apply to those activities and operations, such as changes to engine run-up areas.

The Statement of Task's request for an assessment of existing lead-free fuel alternatives, including motor gasoline (MOGAS), is addressed in Chapter 5 as part of a review of existing unleaded and lower-lead fuels to replace 100LL fully or partially. Chapter 6 reviews the potential for an unleaded drop-in fuel, and considers PAFI and its progress. The chapter also considers the prospects for converting some of the existing fleet to lead-free technologies and of future lead-free propulsion systems making in-roads into the GA sector.

In Chapter 7, the report concludes with a summary assessment of the findings and recommendations from the previous chapters.

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2

Background on the Piston-Engine Aircraft Fleet and Airports

The U.S. active piston-engine fleet consists of approximately 144,000 aircraft in civilian use (FAA, 2020a). Adding in the roughly 27,000 experimental aircraft without Federal Aviation Administration (FAA) type certifications, the piston-engine fleet has about 170,000 active aircraft in total. Nearly all of these aircraft, which consist of airplanes and helicopters, are the basis of most general aviation (GA) operations, which encompasses a diverse range of functions including transportation, recreation, pilot training, emergency services, and other commercial, sport, and government purposes.

This chapter begins with an overview of the basic types of aircraft in the piston-engine GA fleet and their varied GA uses. Background is then provided on some of the characteristics of the approximately 13,100 airports from which most piston-engine aircraft are based and operate. These airports vary widely in size, activity levels, features, and function. On one end of the spectrum are heavily used, state-, county- or municipally-owned airports that accommodate both turbine and piston-engine aircraft, often with intensive operations such as pilot training and business aviation. On the other end are airfields that may be privately owned and consist of grass, water, and sand landing strips that may have highly specialized and seasonal applications such as crop spraying, fire protection, and sightseeing and sport flying. In some rural and remote parts of the country, and particularly in Alaska, the small airfields and aircraft that operate from them are the principal means of transportation for residents and visitors and for access to critical supplies and services.

Consideration is also given to aircraft operations at airports. As defined by FAA, an aircraft "operation" is either a takeoff or landing. Each operation involves pilots taxiing to and from the runway and performing checks, including engine "run-ups" while stopped before takeoff to confirm that the engine can safely attain full power with normal indications. Run-ups may also be performed during aircraft maintenance and repair. So as not to interfere with the operations of other aircraft and to orient propeller wash away from people and structures, airports will sometimes designate special areas for these pre-takeoff checks, often just before the aircraft turns onto the runway for takeoff. All but the smallest and most specialized airports will also have areas and facilities designated for aircraft repair, maintenance, and refueling. Background is provided on some of these features because their wide variability across the many airports that serve piston-engine aircraft can have important implications on the opportunities available to reduce emissions and concentrations from leaded aviation gasoline (avgas) through measures such as adding an unleaded fuel choice and relocating run-up areas.

U.S. PISTON-ENGINE FLEET

As noted above, the active GA fleet includes about 144,000 piston-engine aircraft with type certifications, and a further 27,000 experimental aircraft, a large portion of which are amateur built but also include the country's more than 2,000 show and vintage airplanes (e.g., warbirds) (FAA, 2020a). While data on the engine types of experimental aircraft are not readily available—and therefore not included in the following description of the piston-engine fleet—it is reasonable to assume the vast majority have piston-engines, for a total of about 170,000 aircraft that burn gasoline.

While the country's 144,000 type-certified piston-engine aircraft can be grouped in many ways, the most common groupings are by type of wing (fixed- and rotary-wing, or airplane and helicopter) and number of engines (single- and multi-engine). Most of these airplanes—nearly 90 percent—have a single, gasoline-powered reciprocating engine, and are small (e.g., they have six or fewer seats, weigh less than 5,000 pounds when fully loaded, and require only 750- to 2,500-foot runways). They are seldom flown higher than 10,000 to 15,000 feet (because few are pressurized or designed for efficient operations at higher altitudes), further than 1,200 miles, or faster than 175 mph; however, some high-performance single-engine piston aircraft can operate at higher speeds and altitudes. In the piston-engine fleet, the large number of single-engine airplanes is accompanied by about 12,500 multi-engine airplanes and about 3,000 rotary-wing aircraft. These latter aircraft are flown more hours on average than the single-engine planes, as they are more likely to be used for commercial purposes (see Table 2-1).

TABLE 2-1 U.S. Active Type-Certified Piston-Engine Aircraft Fleet Size and Hours Flown, 2019

Aircraft Type	**Number of Aircraft**	**Percent of Total Fleet**	**Hours Flown During a Year**	**Percent of Total Fleet Hours Flown**	**Average Hours Flown per Year**
Single-engine, Fixed-wing	128,470	89	12,700,000	84	93
Multi-engine Fixed-wing,	12,470	9	1,731,000	12	139
Rotary-wing	3,082	2	628,000	4	204
Total	144,485		15,059,000		104[a]

[a] Based on total values shown in the table.
NOTE: The table does not include the approximately 27,000 experimental aircraft, most of which are likely to have gasoline engines.
SOURCE: FAA, 2020a.

Over the past several decades, the demand for new piston-engine airplanes has been trending down, especially among the most basic small aircraft. Domestic deliveries of new airplanes declined from more than 10,000 units in 1980 to about 900 in 2019 (GAMA, 2020, 9-10, 16). There has been much speculation about the causes of this decline, from product liability costs that have increased new aircraft prices to a shrinking population of private pilots. The average price of a new piston-engine aircraft in 2019 was more than $550,000 (GAMA, 2020, 9). While these new aircraft tend to have increasingly more advanced avionics and other sophisticated features, the needs of many private pilots can be met by the large selection of well-maintained and reconditioned used airplanes already in the fleet. Flown an average of about 100 hours per year, piston-engine airplanes have long service lives, as the average age of the large number of single-engine airplanes in the fleet is nearly 50 years (FAA, 2020a). The combination of fewer pilots and highly durable aircraft is reflected in low annual fleet turnover rates and modest aircraft resale prices. FAA has estimated that the average market value of a single-engine GA aircraft (based on the 2017 fleet in 2018 dollars) was approximately $60,000, while the average value an aircraft manufactured before 1984 was less than $45,000 (FAA, 2020b).

USES OF PISTON-ENGINE AIRCRAFT

To better understand the characteristics of the GA sector, and resulting demands on airport and air traffic control systems, FAA conducts annual surveys of GA pilots and aircraft owners. Respondents are asked to report on the number of hours flown, basic type of aircraft used (e.g., number of engines), and reasons for flying. The 2019 survey data indicates the piston-engine fleet logged more than 15 million hours of flying that year, with single- and multi-engine airplanes accounting for about 96 percent of the hours and rotary-wing aircraft accounting for the remainder (see Table 2-2). While some of this flying was for transporting people and goods from point to point, most of it was for other purposes. For reasons explained below, because the FAA survey data are aggregated nationally, they can mask considerable geographic variation in how often and for what purposes piston-engine aircraft are flown, particularly in remote and rural communities lacking good roads, commercial airline service, and other means of access.

TABLE 2-2 Uses of the U.S. Piston-Engine Aircraft Fleet, 2019

			Percent of Total Hours Flown by Purpose					
	Number of Aircraft	**Total Hours Flown**	**For-Hire Transport**	**Business Transport**	**Personal and Recreation**	**Pilot Training**	**Aerial Observation and Agriculture**	**Other**
Single-engine, fixed-wing	128,470	12,700,000	1.6	7.4	42.7	39.8	3.4	5.1
Multi-engine, fixed-wing	12,470	1,731,000	10.1	15.4	24.1	42.4	2.8	5.3
Rotary-wing	3,082	628,000	2.2	2.5	9.2	50.0	18.3	18.2
Total	144,485	15,059,000	2.6	8.1	39.2	40.5	4.0	5.6

NOTE: The table does not include uses of the approximately 27,000 experimental aircraft.
SOURCE: FAA, 2020a.

For-Hire Transportation (Air Taxi)

In regulating air transport operations and flight standards, FAA has long distinguished between for-hire and private transportation. The rationale for making this distinction is that customers of for-hire carriers do not have direct control over their own flying safety; and therefore the government must assume a more prominent role in ensuring airworthiness and safe operation. Piston-engine aircraft are more common among providers of for-hire air taxi services, and are rarely used by commercial airlines. Operating much like short-distance air charter services, these carriers typically fly aircraft with fewer than 10 seats, but sometimes more. Because they are often used for purposes in addition to for-hire transportation, the aircraft are usually counted as part of the GA fleet. According to the FAA survey, about 1,400 piston-engine aircraft provided air taxi service in 2019 (FAA, 2020a). They accounted for about 2 percent of hours flown by the fleet that year, with the multi-engine, high-performance airplanes accounting for a disproportionately high share of their hours (see Table 2-2).

Business Transportation

From a regulatory standpoint, private aircraft that are used for business transportation are treated like other kinds of private GA aircraft because they are used for in-house transportation incidental to the owner's main line of business. Nevertheless, many of these GA aircraft are flown by professional pilots. While most corporations that operate business aircraft use turbine airplanes, about 12,000 piston-engine airplanes are also used for GA business transportation (FAA, 2020a). They are usually (about 90 percent of the time) self-piloted by the person conducting the business rather than by a hired crew. In total, business aviation accounts for about 8 percent of the 15 million hours flown by piston-engine aircraft annually (see Table 2-2).

Personal and Recreational Use

About three-quarters of the aircraft in the piston-engine fleet, consisting of about 108,000 airplanes and helicopters, are used exclusively for personal and recreational flying, often by private pilots who are not instrument-rated (FAA, 2020a). Often weather- and daylight-dependent for operations, much of this fleet sits idle for long periods. Thus, despite accounting for a large majority of piston-engine aircraft, the personal and recreational fleet accounts for less than 45 percent of total fleet hours flown (see Table 2-2). Most of the smallest, low-performance airplanes in the piston-engine fleet are used for these private purposes, and much of the flying is local in nature operating at relatively low altitude and low speeds.

Pilot Training

The piston-engine fleet used for pilot training totals to more than 15,000 aircraft, or about 10 percent of the fleet (FAA, 2020a). Because these aircraft are used intensely, they account for more than 40 percent of fleet hours flown (see Table 2-2). What's more, these flying hours are often logged by multiple training sessions in a single day, and as such, the flying hours of these aircraft can be accompanied by a significant amount of additional time spent with engines running while on the ground practicing procedures, taxiing, and performing pre-takeoff checks.

Aerial Observation and Agricultural Services

Aerial observation and agricultural services are important local uses of piston-engine aircraft—for instance, for ensuring that utility rights-of-way are clear, photographing land uses, and treating crops. While only less than 2 percent of the piston-engine fleet is used mainly for these purposes, these activities account for about 6 percent of fleet hours flown (see Table 2-2 and FAA, 2020a).

Other Uses

Fixed- and rotary-wing piston-engine aircraft are used for a wide range of public and commercial purposes. Public purposes include search and rescue, aerial firefighting, police aviation, traffic reporting, and emergency medical airlifts (medevac) (FAA, 2020a). Examples of commercial uses are entertainment and sport applications such as air tours and sightseeing, airshows, air racing, and parachute jumping. About 4 percent of the piston-engine fleet is used primarily for these purposes, and these aircraft account for about 6 percent of hours flown (see Table 2-2 and FAA, 2020a).

AIRPORTS WHERE PISTON AIRCRAFT OPERATE

Excluding about 6,000 heliports and seaplane bases, FAA has identified 13,117 airports in the United States, including 4,815 public-use and 8,302 private-use airports (see Table 2-3). Among these 4,815 public-use airports (which are mostly owned by cities, counties, and states), FAA has designated 3,249 to be part of the national airport system, known as the National Plan of Integrated Airport Systems (NPIAS). Another 72 private-use airports are included in the NPIAS, bringing the total to 3,321 public- and private-use airports in the national system. These airports are eligible for federal funding assistance for infrastructure improvements.

TABLE 2-3 Percentage of the U.S. GA Fleet Based at Airports by Category

Airports	**Number of Airports**	**Percent of GA Aircraft Based (includes mostly piston-engine aircraft but also some turbine-engine aircraft)**
NPIAS Primary	380	16.7
NPIAS Non-primary	2,941	58.5
National	*88*	*10.5*
Regional	*492*	*22.4*
Local	*1,278*	*21.3*
Basic/Unclassed	*1,083*	*4.3*
Public and Private Airports Not in NPIAS	9,790	24.8
TOTAL	**13,117**	**100**

NOTES: NPIAS = National Plan of Integrated Airport Systems eligible for federal grants. The GA fleet consists of mostly piston-engine aircraft but some turbine-engine aircraft as well.
SOURCE: FAA, 2019b.

The 3,321 airports in the NPIAS consist of 380 “primary” airports and 2,941 “non-primary” airports. The primary airports account for nearly all scheduled airline enplanements and freight loadings and serve as bases for nearly all of the commercial passenger and cargo airline fleet. The 30 busiest primary airports, referred to as large hubs, house few piston-engine or other GA aircraft, but there are some exceptions such as Honolulu (HON), Las Vegas (LAS), and Salt Lake City (SLC). By comparison, most of the country’s approximately 30 medium- and 70 small-hub airports have sufficient capacity to accommodate both airline operations and GA users. Together with the other 260 primary airports that are classified as “nonhubs” because they have little or no commercial service, the 380 primary airports serve as the bases for about 17 percent of the total GA fleet.

The vast majority of GA aircraft—nearly 60 percent of the fleet—are based at the country’s 2,941 non-primary airports that are used only for GA. This large grouping of airports is further subdivided into "national," "regional," "local," and "basic/unclassed" facilities. The 88 national airports are usually located in metropolitan areas, often near major business centers, and therefore they accommodate large amounts of business aviation, often with significant operations by jets and multi-engine airplanes in GA service. Comprised of the country's busiest GA airports, they serve as bases for about 11 percent of the GA fleet.

By far the largest segment of the GA fleet, about 43 percent, is based at the country's nearly 1,800 regional and local non-primary airports. Typically, these airports are located near population centers but not necessarily in major metropolitan areas. While they support some longer-distance flying (especially the regional airports), they are mostly used for local flying, flight training, and emergency services and the GA fleet they serve consists almost entirely of piston-engine aircraft. By comparison, the 1,083 "basic/unclassified" airports in the NPIAS are mostly located in rural areas. About 3 percent of the GA fleet is based at these airports, which receive some federal funding because of their roles in keeping remote communities connected to the country's aviation system. The remaining 25 percent of the GA fleet, consisting almost entirely of piston-engine aircraft, is based at the nearly 10,000 other small airports that are not part of the NPIAS.

Geographic Variability in GA Uses and Airports

The national-level data presented above do not convey the geographic variability that exists in GA aircraft uses and airports. The national data can be particularly misleading when considering GA's role in vast, sparsely populated states such as Montana, Nevada, and other western states, but especially Alaska, whose communities are scattered across more than 580,000 square miles of land and on islands who inhabitants that have no or limited access to roads, airline service, or other long-distance transport modes. For most of Alaska's communities—more than 80 percent of which are inaccessible to a state or long-distance highway—GA flights are the only option for year-round passenger and cargo transportation (ADTPF, 2009). Likewise, GA is essential for medical airlifts, search and rescue, and other emergency services. Alaska has about 400 public use airports and seaplane bases, or nearly 10 percent of country's total. Moreover, the state has hundreds of other private airfields, and pilots routinely operate from many of the state's thousands of lakes and gravel bars where there are no constructed facilities (FAA, 2016). The state of Alaska estimates that about 40 percent of the state's economic output and 25 percent of its jobs depend on access to aviation, most of it provided at rural airports and airfields by GA aircraft (ADTPF, 2009).

GA's critical importance to Alaska, as well as many other rural states and remote locations across in the country, means that measures aimed at reducing aviation lead use need to be carefully considered so as not to create undesirable side effects, the distribution and magnitude of which could differ significantly by region.

Airport Facilities and On-Airport Operations

General Characteristics

An airport has both airside and landside features. Airside features consist of runways, taxiways, apron areas, aircraft parking positions and maintenance buildings, hangars, refueling stations, air traffic control facilities, and navigational aids. Landside features include terminal and cargo buildings, access roads, automobile parking lots, and other facilities for airport employees and users. The airside and landside features of airports can vary greatly. Some airports have control towers, instrumented landing systems, aircraft maintenance services, and multiple runways of varying length and orientation. They may also have terminal and cargo facilities. Other airports can have little more than a short landing strip or sea lane, sometimes with aircraft parking, maintenance, and refueling areas, but seldom many landside facilities.

A review of certain airside features, including the presence of paved and lighted runways, reveals the wide variability in the country's airports that serve primarily GA traffic. Table 2-4 shows that most private airports do not have a paved or lighted runway, and that the situation is similar for about 25 percent of public-use airports. More than two-thirds of airports do not have a runway longer than 4,000 feet, including nearly half of all public-use airports. It is reasonable to assume that the other airside facilities at these small airports are also limited, including traffic control and aircraft maintenance and fueling services.

TABLE 2-4 Runway Characteristics of U.S. Civilian Airports[a]

	Airport Type		
Characteristic	**Public Use**	**Private Use**	**Total**
Total number of airports	4,776	8,266	13,042
Airports without a paved runway	24%	86%	63%
Airports without a lighted runway	28%	90%	67%
Airports without paved or lighted runway	48%	90%	64%
Airports with longest runway length less than 4,000 feet	48%	84%	71%

[a] Only operational airports in the United States are included.
NOTE: Airport totals do not align with those in Table 2-3 because of differences in survey periods.
SOURCE: Data available from the Airport Planning and Programming Office, Federal Aviation Administration. Personal communication, Boyd Rodeman, FAA, October 28, 2020.

Fueling Facilities and Operations

The variability among airports in fueling services is an important consideration for this study because one option for reducing lead from avgas is to ensure that both unleaded and leaded avgas grades are available for pilots depending on the requirements of their aircraft. There is currently considerable variability in the fueling services available at airports in accordance with variability in airport size, types of aircraft served, and levels of traffic activity (NASEM, 2019). Because all piston-engine aircraft can use 100LL, most airports that serve only gasoline-powered aircraft have a common fueling system that dispenses this grade only.

By selling only one universally usable grade of avgas, the airport can reduce its investment in fueling infrastructure and avoid concerns about having to ensure that different types of fuels are physically separated during storage and dispensing to avoid co-mingling or misfueling by pilots. According to data from the National Air Transportation Association (NATA), the average installation cost of a 5,000 gallon fuel storage tank is $110,000 while the cost of a 10,000 gallon tank is $150,000.[1] Thus, the added cost of having to invest in two smaller tanks (one for leaded avgas and another for unleaded avgas) to hold the same total volume of fuel as one larger tank containing a single grade of avgas can be significant for an airport with limited revenues and financial capability. It also merits noting that over the past 20 years, the consumption of avgas has declined by about one third, reflecting the downward trend in GA flying (GAMA, 2020, 24). Hence, as avgas demand has declined, most small airports have had little incentive to expand their fueling infrastructure.

While data could not be found on the total number of airports that only have multiple tanks and dispensing systems for avgas, it is reasonable to assume that a large majority of the smallest facilities have no more than one. As reported in Table 2-3, the smallest 70 percent of the 3,321 NPIAS airports (1,278 local and 1,083 basic/unclassed) serve as the bases for 25 percent of the GA fleet, thus averaging about 15 to 20 aircraft each. One would not expect these airports to have multiple avgas storage and dispensing systems. Additionally, the nearly 9,800 non-NPIAS airports serve as the bases for an average of about 5 aircraft each, suggesting that the vast majority of these airports have no more than one system, if any at all. While data are not available on the financial capacity of these small airports to add refueling facilities or to initiate other lead mitigation assessments and measures, it is reasonable to assume this capacity is limited given the small number of aircraft these airports house.

FINDINGS

The U.S. piston-engine fleet, which consumes most of the leaded gasoline used in aviation, numbers about 170,000 aircraft, including about 27,000 experimental aircraft (Finding 2.1).

Piston-engine aircraft serve many different purposes, some with particular significance to specific regions. Typically, the smallest, most basic aircraft are used for personal and recreational flying, while another important purpose is pilot flight training. Aerial observation, medical airlift, and business transport are examples of important GA functions across the country, while some functions, such as crop dusting, aerial firefighting, search and rescue, and air taxi service, have particular significance to communities in rural and remote locations (Finding 2.2).

The different GA functions affect flight hours and fuel consumption by segments of the piston-engine fleet. Personal and recreational flying accounts for about half of all hours flown, and involves about 75 percent of the piston-engine fleet. The aircraft in the remaining one-quarter of the fleet, flown for business, government, and commercial purposes, are used most intensely and account for about half of all hours flown. Because this "working" segment of the piston-engine fleet consists disproportionately of multi-engine and high-performance airplanes and helicopters that burn fuel at higher rates, it is likely to consume more than half of all the avgas used by the fleet (Finding 2.3).

The size of the piston-engine fleet has been fairly stable for decades, consisting of many older well-maintained and reconditioned aircraft that are augmented by about 900 new aircraft per year. Annual turnover of the piston-engine fleet is therefore very low, resulting in average aircraft age approaching 50 years. Aircraft piston engines are carefully monitored for maintenance issues and regularly overhauled. Retrofits of aircraft systems, including installing new engines on current airframes, can require extensive and expensive testing and FAA certification (Finding 2.4).

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[1] Presentation to the committee, M. Eisenstein, NATA, February 18, 2020.

The piston-engine fleet operates from about 13,100 airports, consisting of a combination of publicly (municipal, county, and state) and privately owned facilities having wide range of traffic activity and financial capability. About 3,300 airports—mostly publicly owned—are eligible to receive federal assistance for certain types of infrastructure improvements because they are part of the national airport system (NPIAS). While about three quarters of the piston-engine fleet is based at these NPIAS airports, the remaining 25 percent of the fleet is spread across the remaining 9,800 other airports, many of which are very small with limited financial or technical capability to add more fueling infrastructure or to perform assessments of lead impacts for mitigations such as changing airport layouts (Finding 2.5).

The findings presented above are referenced in the chapters that follow when examining options for reducing aviation lead emissions at airports through changes in the operations of aircraft at airports, to the fuels available to GA pilots, and in the aircraft themselves. They indicate that GA's critically important functions, particularly in (but not exclusive to) rural and remote communities, mean that measures aimed at reducing aviation lead need to be carefully considered so as not to create undesirable side effects. The distribution and magnitude of those potential effects may differ significantly by region. The relatively low value of most existing piston-engine aircraft and the fleet's low annual turnover warrant consideration when considering lead mitigation measures focused on changing the mix and types of aircraft in the fleet as a means of reducing reliance on leaded avgas. The disproportionately large portion of avgas consumed by the working segment of the fleet has implications on the extent to which the supply of an unleaded avgas can impact total lead emissions, especially if that supply cannot be used by this segment. The findings are also important for assessing the potential for making changes in airport layouts as a lead mitigation strategy or for making unleaded avgas widely available for use by portions of the piston-engine fleet, which operates across thousands of airports, including many with limited capacity to invest in new fueling infrastructure or airport modifications.

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3

General Aviation Lead Emissions and Their Potential Health Impacts

This chapter addresses the portion of the committee's Statement of Task that calls for an assessment of ambient lead concentrations at and around airports where piston-engine general aviation (GA) aircraft are used. The chapter begins with a general overview of environmental lead dynamics, routes of human exposures, and human health risks attributable to lead exposures. The chapter then considers lead emissions resulting from the combustion of leaded avgas by GA aircraft and aircraft activities at airports that contribute to those emissions and nearby ambient lead concentrations. In addition, the chapter discusses various issues related to lead exposures to people in communities around airports as well as worker exposures at those airports. The chapter concludes with findings and recommendations.

ENVIRONMENTAL DYNAMICS AND ROUTES OF LEAD EXPOSURE

Although lead is present in the environment naturally, most elevated concentrations in air, water, and soil result from the past and current societal uses of lead (e.g., for transportation fuel additives, plumbing pipes, and paint). According to the World Health Organization, the widespread use of lead has resulted in extensive environmental contamination, human exposure and substantial public health problems in many parts of the world.[1] Lead can be released to the environment at any point in the sequence from ore mining to the use of finished products containing lead, and recycling processes (e.g., recovery of lead from discarded lead-acid batteries).

As discussed in EPA (2013), airborne lead is usually released to the environment in an inorganic form and as a component of particulate matter. Lead can deposit in soil, water, and other surfaces at various distances from an emission source. After deposition, lead particles can be resuspended and redeposited multiple times. The deposition patterns differ by size fractions.

Combustion of leaded fuel by piston-engine GA aircraft is a major source of lead released into the environment. Weathered or chipped lead-based paint from buildings and other structures contribute lead to soils. Lead can be released from lead pipe or solder that comes into contact with acidic water.

Lead compounds in the environment can be transformed biologically and chemically, and those changes affect transport in soil and uptake by vegetation. Lead may move from soil into surface water or groundwater, depending on the type of lead compound and the characteristics of the soil. In locations with large amounts of precipitation, lead tends to leach from soils to water. Organic matter in soils tends to retain lead by adsorption and hinder its release to water. After entering surface waters, lead can deposit to sediments and perhaps become resuspended into the water column.

Amounts of lead that come into contact with humans are influenced by rates of transport within and between air, surface water, soil, and sediment. The possible routes of human exposure to lead are through inhalation, ingestion, and dermal absorption (see Figure 3-1). In addition to

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[1] See https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health.

exposure to airborne lead through inhalation, lead deposited from air on plant materials or in water becomes available for human consumption. Lead exposures that do not originate from atmospheric deposition include ingestion from lead-containing consumer goods, contact with dust or chips of lead-containing paint, and ingestion of drinking water contaminated by lead leaching from water pipes or lead-containing solder. In addition to exposure to inorganic forms of lead, workers can be exposed to lead in its organic form (e.g., tetraethyl lead [TEL] in aviation gasoline [avgas]).

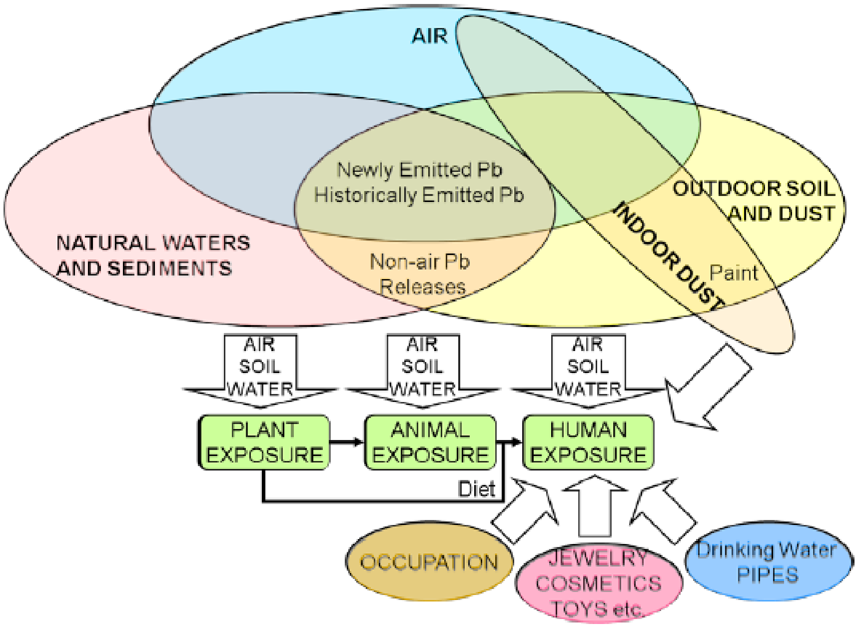

FIGURE 3-1 Conceptual model of multimedia lead exposure representing the movement of lead through various environmental pathways and routes of exposure.
SOURCE: EPA, 2013, xxx.

NATIONAL TRENDS IN AIRBORNE LEAD CONCENTRATIONS AND EMISSIONS

For decades, lead in gasoline for on-road motor vehicles had been the primary source of environmental lead. In 1975, the U.S. Environmental Protection Agency (EPA) began to phase out the use of TEL as a gasoline additive. The phaseout culminated with a ban in 1996 on the sale of gasoline with added lead for on-road vehicles. EPA allowed the continued sale of leaded gasoline for piston-engine GA aircraft.

Between 1970 and 2014, estimated nationwide lead emissions decreased by 99.7 percent (about 220,000 tons), mostly due to elimination of lead additives for gasoline.[2]

Sharp declines in annual nationwide lead emissions from 1990 to 2014 are illustrated in Figure 3-2. Between 1999 and 2014, lead emissions from metals industrial processing, fuel combustion, and other sources all decreased by approximately 90 percent. The largest remaining source category is nonroad vehicles and engines, which accounted for 63 percent of the anthropogenic (human-induced) lead emissions in 2014. Lead emissions from piston-engine GA aircraft is the primary source within the nonroad category.[3]

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[2] See https://www.epa.gov/air-emissions-inventories.

[3] See https://www.epa.gov/air-emissions-inventories.

The percentage contribution of aviation-related lead emissions has increased because of dramatic reductions in other sectors, as illustrated in Figure 3-2. EPA reports that in 2017 piston-engine GA aircraft comprised the largest single source of lead air emissions in the United States (see Figure 3-3). Those aircraft accounted for 468 tons of emissions, which was roughly 70 percent of total lead emissions to air in the United States.[4,5] The estimate includes lead emissions from aircraft on the ground and in-flight.

Although requirements for unleaded gasoline do not allow for lead additives, federal regulations allow unleaded gasoline to contain up to 0.05 grams of lead per gallon (40 CFR 80.2). Because lead occurs naturally in crude oil, trace amounts might be present after the refining process.

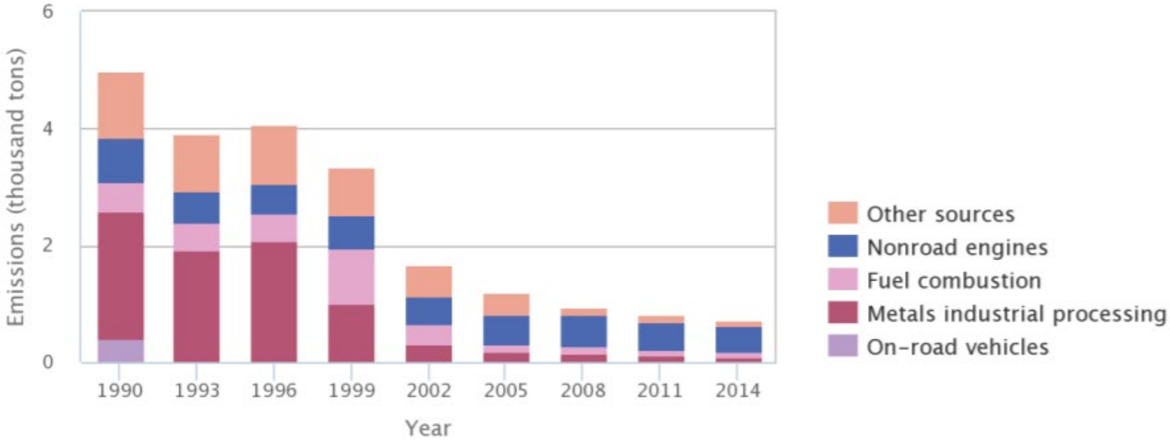

FIGURE 3-2 Anthropogenic lead emissions in the United States by source category, 1990-2014.
NOTES: EPA notes that the trend shown in the figure from 1990 to 2014 reflects changes in the methods used to develop emission estimates as well as actual changes in the emissions over time. Therefore, real-world changes in emissions from year to year could have been larger or smaller than those illustrated in the figure. EPA obtained the data from the 2014 National Emissions Inventory, Version 2. Accessed 2018.
SOURCE: https://www.epa.gov/report-environment/outdoor-air-quality.

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[4] See https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data.

[5] The EPA emissions inventory uses 2.12 grams Pb per gallon which is 3.3 grams TEL per gallon.

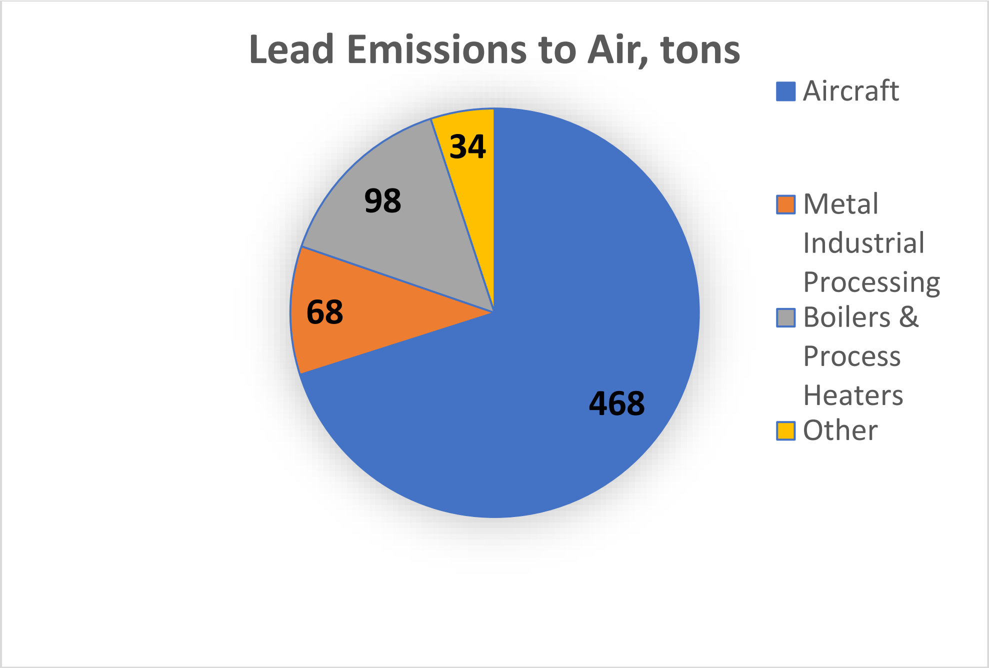

FIGURE 3-3 2017 U.S. Emissions Inventory for Lead.
NOTE: Other sources include chemical production and petroleum refining.
SOURCE: https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data.

Responding to the phaseout of lead in gasoline, average airborne lead concentrations decreased 99 percent from 1980 and 2016 (see Figure 3-4). EPA used monitoring data from seven sites in seven counties to illustrate the trend shown in the figure, as they were the only monitoring sites that provided sufficient data to assess trends from 1980. None of those sites reported annual maximum 3-month average lead concentrations greater than the 2008 National Ambient Air Quality Standard (NAAQS).

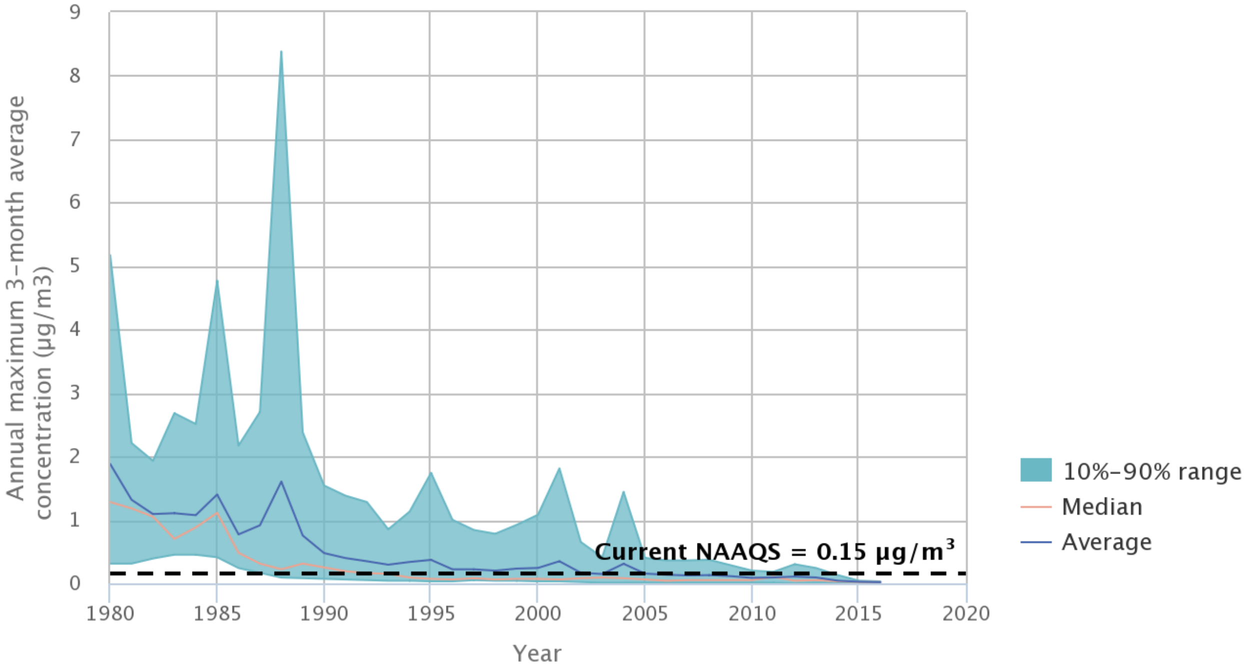

FIGURE 3-4 U.S. ambient lead concentrations; 3-month averages; 1980 to 2016.
NOTES: The current lead NAAQS provides context for the magnitude of the concentrations. Measurements were collected from 7 monitoring sites in 7 counties. EPA obtained the data from EPA's Air Quality System. Accessed 2017.
SOURCE: https://www.epa.gov/report-environment/outdoor-air-quality.

HEALTH EFFECTS FROM LEAD EXPOSURES

Lead serves no biological function and has been understood to be a powerful toxicant since ancient times (Daley et al., 2018). Australian pediatricians Gibson and Turner described health effects resulting from childhood exposure to lead in paint at the end of the 19th century (Gibson et al., 1892). Despite the awareness of its toxicity, the physical and chemical qualities of lead made it attractive for a variety of applications. As an example, despite known toxicities documented well before, it was not until 1978 that lead-based paints were banned for residential use in the United States.

While it is beyond the scope of this report to provide an exhaustive compilation of the health effects associated with lead exposure, this section provides a broad overview of lead's profound and negative health impacts. Adverse health effects of lead have been observed in multiple organ systems because the mechanisms that induce lead toxicity are common to all cell types and because lead is widely distributed throughout the body through blood (ATSDR, 2020; EPA, 1986, 2013; NTP, 2012).

Much of what is known about the health effects of lead exposure to humans comes from extensive work carried out since 1970, when studies of exposures to airborne lead from motor vehicle exhaust were being vigorously pursued through EPA, National Institute of Environmental Health Sciences (NIEHS), and other organizations. That effort was prompted by the realization that airborne lead concentrations, especially in large metropolitan cities, were especially problematic for young children. Atmospheric lead concentrations exceeded 8 µg/m^3 in the late 1980s (see Figure 3-4), while pre-industrial concentrations of airborne lead from natural origins are estimated at 0.0006 μg/m^3 (Patterson, 1965).

In cellular based studies, lead was found to disrupt mitochondrial function and cellular metabolism. The most extensively studied health outcomes are neurological, renal, hematological, immunological, reproductive, and developmental effects for children (ATSDR, 2020). In addition, lead and lead compounds have been listed as a potential carcinogen, although few if any direct links in humans have been reported (NTP, 2016).

Research suggests that significant adverse health effects occur at blood lead levels (BLLs) below the current reference level (level of concern) set by the Centers for Disease Control and Prevention (CDC) (Gatsonis and Needleman, 1992; Lanphear et al., 2005; Schwartz, 1993, 1994). Typically expressed in units of μg/deciliter (dL), BLLs reflect recent exposures to lead in the environment or workplace and releases from bone (which is a major reservoir for lead in the body). Learning and behavioral deficits may occur at BLLs lower than 5-10 μg/dL, including attention-related behavioral problems (Canfield et al., 2003; Froehlich, 2009; Nigg, 2008). Exposure to low concentrations of lead, including prenatal exposure, has been linked to decreased performance on standardized IQ tests for school-aged children (ATSDR, 2020). Bellinger (2012) estimates that lead exposure accounts for up to 23 million lost IQ points in a six-year birth cohort of U.S. children. Lead exposure has also been linked with higher levels of aggression, delinquent behavior, and criminal behavior (e.g., Beckley et al., 2018). Some investigators observed that criminal behavior in urban cities has dropped in parallel with the reduction of airborne lead following the elimination of leaded fuels for motor vehicles (Nriagu, 1990, Wakefield, 2002). In addition, in a New Zealand cohort, lead exposure during childhood was associated with lower socioeconomic status in adulthood (Rueben et al., 2017).

Lead is taken up in developing children through metabolic pathways normally dedicated to calcium uptake. Because their blood-brain barrier is not fully developed, much of the lead is concentrated in the brain where it can interfere with nerve function and development of neuronal pathways. Lead exposure in children has been documented in brain scans (Rueben, 2020). In contrast, approximately 95 percent of the lead that enters the body tissues of adults is deposited in bone at equilibrium. Lead deposits in the bones of pregnant women can be transferred to the fetus during the normal process of supplying calcium from the mother's bones for fetal development (ATSDR, 2020). Whether through ongoing exposure or through release of lead from bone, higher lead levels during pregnancy result in increases in preterm birth and lower birthweight (Taylor et al., 2014).

There are various subgroups of adults that exhibit increased susceptibility to lead-related health effects. Lead exposure has been linked to pregnancy-induced hypertension and hypertension and cardiovascular disease among other adults, particularly among post-menopausal women, when the process of calcium loss from bone also causes the release of bone lead (ATSDR, 2020). Thus, increases in BLLs due to release from bone could exacerbate the normal loss of neurons during the aging process. In a meta-analysis, Chowdhury et al. (2018) found that exposure to lead was associated with increased risk for cardiovascular and coronary heart disease. In general, because health effects associated with lead exposure have been observed in every organ system, any pre-existing condition that compromises physiological functions could render a person more susceptible to lead's effects.

Although much progress has been made in reducing lead exposures to humans, childhood lead poisoning remains a critical environmental health concern. Epidemiological studies commonly rely on BLLs as a metric of exposure. Since the late 1970s, mounting evidence has demonstrated that lead causes irreversible, asymptomatic effects at BLLs far below those previously considered safe. Thus, CDC incrementally lowered its level of concern for BLLs from 60 to 5 µg/dL over the last 40 years (CDC, 2020). Because lead does not appear to exhibit a threshold concentration for health effects, CDC concluded that there is no known safe level of lead in blood and refers to 5 µg/dL as a reference level. That level was determined by examining the data on children, ages 1-5 years, in the National Health and Nutrition Examination Survey (NHANES) and selecting the BLL at the 97.5 percentile (CDC, 2020).

In response to the committee's Statement of Task, the remainder of this chapter focuses on environmental and occupational aspects related to lead emissions from the use of avgas by piston-engine GA aircraft.

LEAD EMISSIONS FROM GA AIRCRAFT

Lead emissions from piston-engine GA aircraft at and near airports arise from numerous aircraft activities that can have different contributions to airborne particulate matter containing lead. Ground-level activities include idling at hangars, taxiing, run-up, takeoff roll, after-landing roll, and maintenance operations. Aloft activities include climb-out, local flying, and approach. These activities occur under different engine load and different times in mode, and differentially contribute to total lead emissions. A special type of landing and takeoff (LTO) cycle is a touch-and-go; it is a common flight training practice and involves a landing, ground roll, and takeoff without the other activity modes common to a conventional LTO cycle (e.g., no taxiing and run-up).

Understanding the impacts of leaded fuel combustion requires estimating emissions and ideally also resulting airborne concentrations. EPA (2010, 2020a) describes the development of emission inventories for specific airports by using:

- Piston-engine aircraft activity data;
- Aircraft-specific fuel consumption rates during the various modes of a landing and LTO cycle;
- Time spent in each mode (run-up, taxi/idle-out, takeoff, climb-out, approach, and taxi/idle-in); and
- Assigned values for the lead content in the fuel, and the retention of lead in the engine and oil.

In-flight lead emissions are estimated by taking the difference between the total nationwide emissions (based on avgas sales) and the sum of emissions estimated for each airport (EPA, 2010). National and airport-specific estimates are updated every 3 years as part of EPA's National Emissions Inventory (NEI). The documentation of changes to the emissions estimation methodology informs examinations of trends over time.

The development of specific emission inventories for each airport in the nation involves the use of assumptions and approximations that add uncertainties to the inventories. For some airports, LTO data are not available and they are estimated using equations that include the number of based aircraft at the airport and county population with adjustments for airports located in Alaska. Because many airports have both jet-engine and piston-engine aircraft operations and only the latter type emits lead, a fraction of LTOs attributable to piston-engine aircraft is assigned. That fraction is estimated using the numbers of aircraft based at an airport.

However, actual operations can vary dramatically, such that a small number of aircraft conduct a disproportionately large number of LTOs, as is often the case at airports with flight schools.

Emission factors (grams of lead emitted per piston-engine LTO) are estimated from fuel burn rates which vary by aircraft with large differences for single-engine versus twin-engine aircraft. Again, these splits are estimated using the number of based aircraft and this may not reflect actual activity. Five percent of lead in the burned fuel is assumed to be retained in the engine and oil. Time-in-mode can differ from the assumed national defaults, depending on the airport configuration, how operations are managed, and pilot behavior. Finally, the lead content of fuel is estimated using national sales volume for each grade of aviation gasoline (with sales now dominated by 100LL) and assuming the lead content for each grade is at its maximum allowable concentration (e.g., 2.12 grams per gallon for 100LL) (EPA, 2010). The cumulative impact of these assumptions and approximations on airport-specific emission inventories is not clear.

NASEM (2015a) provides a methodology and spreadsheet tool to prepare refined airport-specific lead emission inventories. Table 3-1 shows the activity-specific contributions to total lead-bearing particulate matter emissions for three airports using a refined emission inventory methodology with on-site data collection. These estimates exclude emissions during local flying, which is an important aspect because of the environmental persistence of lead. While the percentage contributions from some activities are relatively constant (e.g., taxiing and takeoff), for other activities there are large airport-to-airport differences (e.g., run-up and touch-and-go)**.**

TABLE 3-1 Estimated Contributions of Piston-Engine GA Aircraft Activities to Particulate Matter Lead Emissions at Three Airports

	Percentage of Total Emissions (%)[a]		
Source Group	**RVS**	**APA**	**SMO**
Run-up	22%	12%	13%
Taxiways	12%	12%	15%
Takeoff	5%	7%	6%
Climb-out	26%	21%	29%
Approach	17%	12%	27%
Landing	1%	1%	2%
Touch and Go[b]	11%	29%	1%
Hangars[c]	6%	6%	6%
Helicopters[d]	1%	0%	1%

[a] RVS is Richard Lloyd Jones Jr. Airport in Tulsa, Oklahoma; APA is Centennial Airport in Denver, Colorado; SMO is Santa Monica Municipal Airport in Santa Monica, California.
[b] Touch-and-go operations for fixed-wing aircraft consist of an approach, brief ground roll (landing), an immediate takeoff, and a climb-out—all of which occur without exiting the runway.
[c] Includes all emission activities within a hangar area, such as taxiing and idling.
[d] Includes all phases of helicopter operation.
NOTES: On-site data were collected for nominally 1 month at each airport in 2013. Estimates do not add up to 100 percent for each airport.
SOURCE: NASEM, 2015b.

The EPA 2017 NEI includes more than 19,000 airports that are estimated to have lead emissions.[6] The total amount of lead emissions from those airports was estimated to be 224 tons. Approximately 25 percent of the airport lead emissions is attributed to about 178 airports (less than 1 percent). About 50 percent of the lead emissions is attributed to 587 airports (approximately 3 percent). Those airport emissions estimates are based on aircraft fleet and activity information, rather than the volume of avgas combusted, which is the basis used for the aircraft lead emission estimate in Figure 3-3.

AIRBORNE LEAD CONCENTRATIONS FROM EMISSIONS AT AIRPORTS

Estimates of airport-specific lead emissions provide general estimates of lead released to the nearby environment. Airport-specific estimates can also be used to identify lead hot spots, which are localized, relatively high concentrations of airborne lead relative to background concentrations. Mitigation efforts can seek to reduce hot spots, reduce total emissions, or both. Hot spots can occur distant from the public, such as in restricted access zones within the airport boundaries. The airborne lead concentration is dispersed as it travels downwind. Hot spots can also occur at locations where people are present on or near to the airport footprint. For example, emissions near an airport boundary can cause hot spots that extend beyond the footprint. For airports in densely populated areas, modeling results suggest these localized, relatively high concentrations can extend into residential neighborhoods (NASEM, 2016).

Hot spots tend to arise at locations where multiple activities contribute lead emissions, such as downwind of run-up areas near the end of a runway with taxiing/idling and ground rolls before takeoff. Figure 3-5 shows contours of modeled airborne lead concentrations at Richard Lloyd Jones Jr. Airport in Tulsa, Oklahoma. The top-left panel presents total lead concentrations while the other three panels are the contributions from taxiways, run-up areas, and takeoffs. Hot spots are located at the ends of runways and an aircraft maintenance area (although the latter is likely ill-characterized and possibly biased high). Run-up areas tend to be important contributors to hot spots. Taxiing and idling while awaiting clearance for takeoff can also be significant.

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[6] See https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data.

(a) Total

(b) Taxiways

(c) Runup Areas

(d) Takeoffs

FIGURE 3-5 Modeled airborne lead concentrations at Richard Lloyd Jones Jr. Airport in Tulsa, Oklahoma for a nominally 1-month period in 2013 using on-site activity data collection.
NOTES: Airport property boundaries are designated by a thick black line; dark interior lines indicate runways. 1,000 ng/m^3 equals 1 µg/m^3.
SOURCE: NASEM, 2015b.

Building on the observation that hot spots tend to occur near run-up areas (not just because of run-up operations but because of the confluence of emissions from run-ups, queuing before takeoff, and takeoff operations), EPA modeled one airport and developed empirical relationships to estimate near-field lead concentrations using aircraft class (single versus multi-engine) and operations cycle activity (landing and takeoff versus touch-and-go) as the predictor variables (EPA, 2020a). Model-extrapolated estimates of lead concentrations were generated for hot spots at more than 13,000 airports nationwide. (EPA refers to hot spots as zones of maximum impact.) Numerous assumptions were made to conduct the nationwide analysis because airport-specific activity data are limited. Therefore, for those airports with model-extrapolated lead concentrations greater than or within 10 percent of the lead NAAQS concentration (0.15 μg/m^3), sensitivity analyses were conducted by varying key influential parameters to constrain the estimate concentrations. According to EPA (2020a), this screening analysis identified four airports having "model-extrapolated lead concentrations potentially greater than the lead NAAQS at the maximum impact area with unrestricted areas [to public access] within 50 meters."

It is important to note the exposure to airborne lead at concentrations less than the NAAQS can result in health effects depending on the susceptibility of the individual at any given time and the magnitude, duration, and frequency of the exposures (EPA, 2013). EPA (2020a) focused mainly on possible NAAQS exceedances. Nationwide results were presented as model-extrapolated lead concentrations stratified by LTO ranges across the 13,000 airports, without also identifying how many and which airports fall into each of the LTO ranges.

AIRBORNE LEAD PARTICLE SIZES FROM PISTON-ENGINE GA AIRCRAFT EMISSIONS

The exhaust of engines burning gasoline consists of gases including carbon monoxide, nitrogen oxide, and carbon dioxide, carbon in the form of soot, and carbonyl hydrocarbons (such as formaldehyde, a known carcinogen) (Rindlisbacher, 2007). In addition, if the fuel is leaded, the exhaust will contain lead dibromide particles. The addition of TEL to avgas would result in lead deposits that foul engines, unless the lead is scavenged following combustion. This is accomplished by adding organohalides (such as ethylene dibromide [EDB]) to gasoline, which react with the volatilized lead to form lead halide particles (EPA, 1986, 2013; Nriagu, 1990). When TEL and EDB are added to gasoline, lead dibromide particles are formed in the exhaust gas.

In prior studies of motor vehicle exhaust, lead dibromide particles were shown to range in size from about 20 to 100 nanometers (nm) in diameter with a mean near 50 nm (for example, Little and Wiffen, 1977). Griffith (2020) confirmed this size distribution (mean size found to be 38 nm) in exhaust from a motor vehicle engine burning 100LL fuel and further demonstrated that these particles consist primarily of collections of 5 to 10 (or more) lead dibromide beads (4 nm diameter per bead) embedded in a hydrocarbon matrix (see Figures 3-6 and 3-7). Biological studies (Button et al., 2012; Kesimer et al., 2013) of the ability of nanoparticles of different size to penetrate the lung defenses have demonstrated that particles of greater than 40 nm are for the most part unable to pass the mucus barrier in the lung to gain access to the epithelial cells. Thus, it might be expected that most of the lead dibromide particles inhaled in the past from motor vehicle exhaust would have been flushed from the lungs by the mucosal system. However, if the 4 nm lead-dibromide beads were easily released from the larger assemblies, the smaller lead beads would rapidly transit the lung defenses and gain access to the epithelial cells. Griffith (2020) reports that exhaust particles collected in flight from a single piston-engine aircraft burning 100LL fuel were found also to consist of 4 nm lead-dibromide beads embedded in a hydrocarbon matrix. However, the particles in the aircraft exhaust were found to be much smaller (13 nm average diameter) and each particle contained only 1 or 2 lead dibromide beads. Such particles have the potential of rapidly penetrating the lung defenses either as the 13 nm particles or 4 nm beads. In addition, in the nasal passage, such small particles could gain direct access to the brain. Based on grams of lead emitted into the air for the particle size range considered by Griffith (2020), there may be 5 to 10 times more single lead-containing particles than from legacy motor-vehicle emissions.

Whether this translates to a higher relative toxicity is unclear and further research would be valuable. Although larger particles may be unable to pass through the mucus barrier of the lung, lead absorption can occur through other mechanisms. Particles larger than 2.5 μm that are deposited into nasopharyngeal and tracheobronchial regions can be moved to the esophagus by mucociliary transport and swallowed. Particles smaller than 2.5 μm can deposit in the alveolar region and be absorbed following extracellular dissolution or ingestion by phagocytic cells (ATSDR, 2020).

In addition to observing a high relative abundance of lead-bearing particles with a diameter less than 20 nm, Griffith (2020) also noted the presence of larger lead-bearing particles (35 nm or greater) at less frequency. Although those larger particles were fewer in number, they would likely dominate measurements of lead mass concentration, because mass scales with the cube of the diameter. However, smaller sized particles dominate particle number concentrations. Therefore, particle number concentrations may be a more meaningful metric than mass concentration for health studies of particle exposures less than 100 nm.

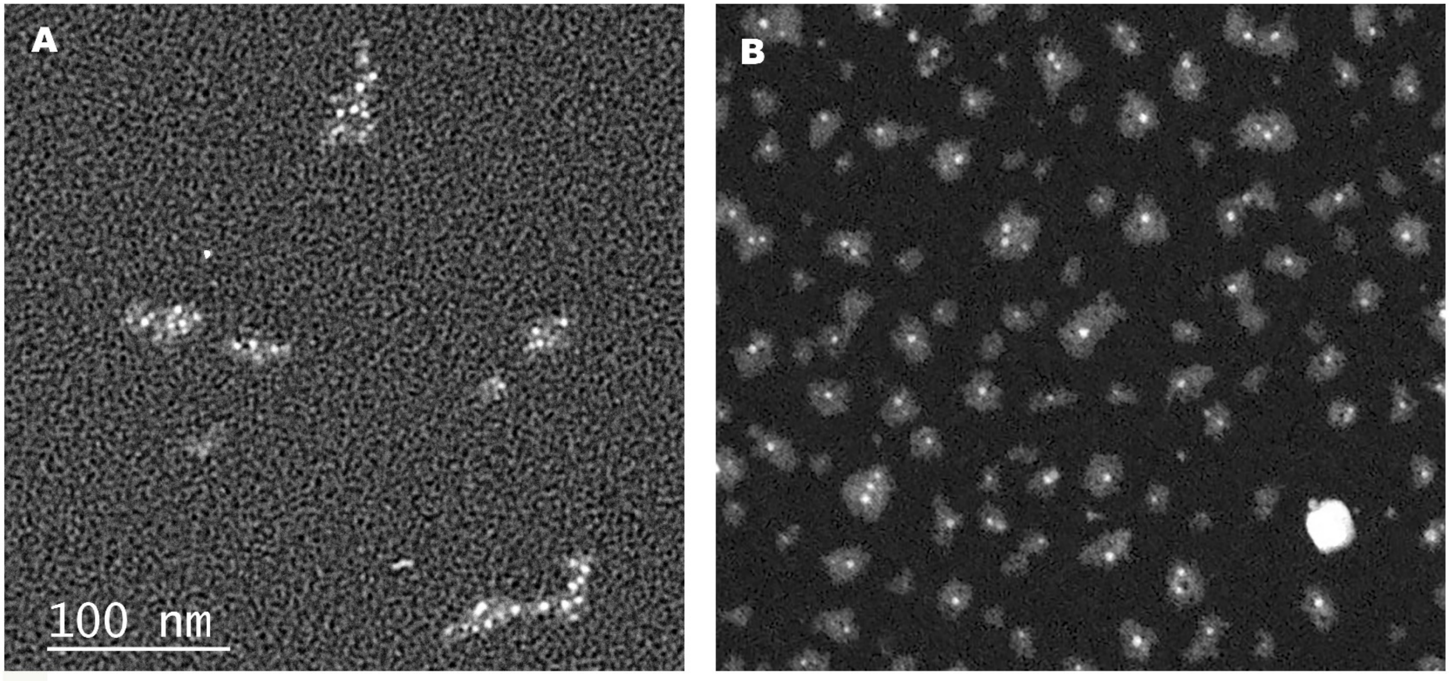

FIGURE 3-6 Images of exhaust particles from aircraft and automotive engines burning 100LL fuel.
NOTES: In a recent study (Griffith, 2020), exhaust particles from automotive and aircraft engines burning 100LL fuel and operated at 2400-2500 rpm were captured directly on electron microscopic supports and imaged without further contrast enhancement. (Left). Field of exhaust particles from a 1957 V-8 automobile engine burning 100LL gasoline. Particles consist of large irregular shaped aggregates of burned hydrocarbon matrix (light halo) containing many 4 nm lead beads (small white particles). Imaging by transmission electron microscopy and shown in inverted contrast. (Right). Field of exhaust particles captured in flight from an aircraft engine (O-320) burning 100LL fuel. Particles also consist of a burned hydrocarbon matrix but contain only 1 or a few lead beads. The large white particle is a single large lead containing particle. Imaging by high angle annular dark field electron microscopy. Magnification for both panels is the same.
SOURCE: Image courtesy of Jack Griffith, committee member.

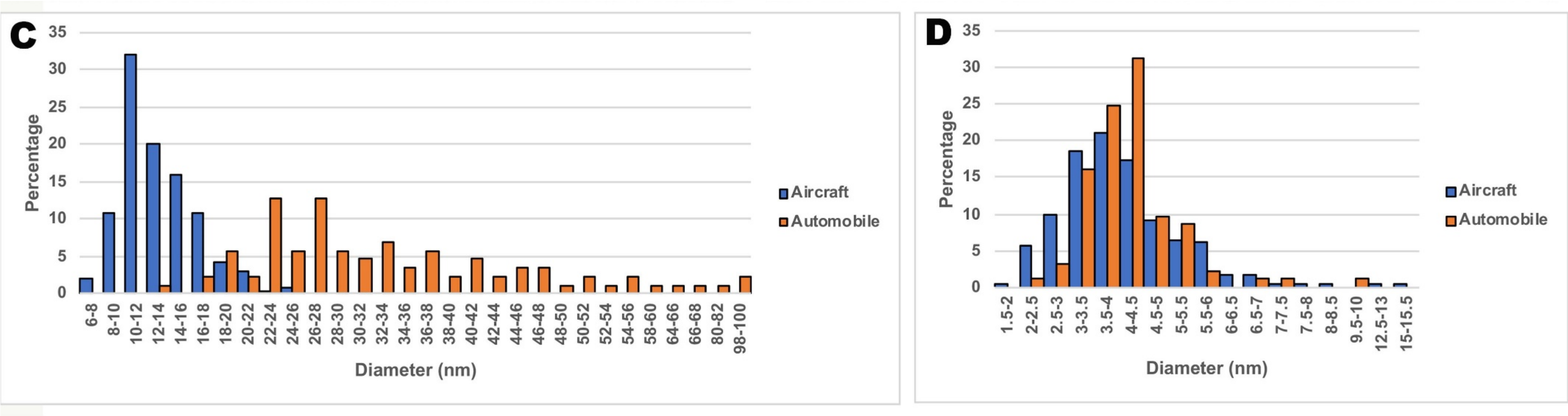

FIGURE 3-7 Size distributions of particle sizes in aircraft and automobile exhaust (C) and lead beads (D).
(C) Size distribution of automotive and aircraft particles showing the much smaller size of the aircraft exhaust particles. (D) Size distribution of the lead beads from automotive and aircraft emissions showing the same ~4 nm diameter. See Griffith (2020) for details.
SOURCE: Griffith, 2020.

ENVIRONMENTAL DYNAMICS OF PARTICULATE MATTER LEAD EMISSIONS

Both airborne concentrations and particle deposition locations depend on the emission height and particle size. The lead-bearing exhaust particles emitted close to the ground (such as, ground-based aircraft operations) have higher deposition rates and are transported over shorter distances in the atmosphere relative to particles emitted from aircraft aloft. Regarding particle size, particles with diameters less than about 100 nm have deposition velocities that increase as particle size decreases. In contrast, particles with diameters greater than about 500 nm have deposition velocities that increase with increasing size because of gravitational settling (Kruppa et al., 2019). As discussed in this chapter, lead-bearing particles in aircraft exhaust that are less than 20 nm in diameter have been observed to be in greater abundance than particles with larger diameters.

Particles deposited onto surfaces, such as soil, can be resuspended by wind or mechanical action (e.g., traffic on paved and unpaved roads, agricultural tilling). In many cases, the resuspended particles will be agglomerates of the deposited particles and these larger particles have different transport properties and lung deposition patterns. Deposited particles can also undergo chemical or biological transformations. These processes do not affect the lead burden in the environment, but the chemical form can influence transport within soil matrices and uptake by vegetation. Lejano and Ericson (2005) found soil lead content to be markedly higher in areas close to major highways.

Human exposure to lead particles from GA aircraft exhaust can occur via inhalation of airborne particles, inhalation of particles that deposit onto surfaces and are later resuspended, or ingestion through hand-to-mouth contact with surfaces where the particles have deposited (e.g., soil or locally grown fruits and vegetables). Further study of the complex processes involved in the environmental dynamics of lead will improve understanding of relationships between piston-engine aircraft emissions and human exposures.

PAST STUDIES OF COMMUNITIES NEAR AIRPORTS

Based on 2010 Census data, EPA (2020b) estimated that roughly 5.2 million people reside in a census block that intersects with a 500-meter buffer around an airport runway or a 50-meter buffer around a heliport.[1] Of those people, 363,000 are children age 5 years and under. In addition, 573 public and private schools that enroll about 163,000 students (grades K-12) are located near an airport runway or heliport.

The agency chose a distance of 500 meters because at that distance EPA estimated that airborne lead concentrations, averaged over 3 months (the averaging time used for the lead NAAQS) diminished to local background concentrations. EPA defined local background concentrations as the airborne lead concentrations that would be expected in the absence of a localized source, such as aircraft emissions (EPA, 2020c). However, because the estimated numbers of people are based on distance from airport runways, rather than distance from airport property boundaries (see Miranda et al., 2011), they likely underestimate the number of people living in residences or attending schools where relatively higher exposures are occurring. EPA

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[1] A census block is the smallest geographic area for which the U.S. Bureau of the Census collects and compiles census data, Populations were about 10 percent lower when restricting the analysis to end-of-runway buffers, instead of whole-perimeter runway buffers.

(2020b) acknowledged that on individual days, the impact of aircraft lead emissions can extend to almost 1,000 meters downwind from the runway of a highly active airport.

Miranda et al. (2011) compared BLL surveillance data for children (ages 9 months to 7 years) to place of residence in six counties in North Carolina to examine associations between BLLs and proximity of the residence to an airport. Controlling for potential confounding by exposure to deteriorating lead-based paint, the authors found that children living within 1,000 meters of the property boundary of airports at which planes use leaded avgas have statistically higher BLLs than other children do. The estimated effect on BLLs exhibited a monotonically decreasing dose–response pattern, with the largest change in BLL (4.4 percent higher) on children living within 500 meters of an airport boundary.

Two different studies based on BLLs lower than 10 µg/dl have estimated economic impacts associated with children exposed to lead from aviation gasoline emissions. Wolfe et al. (2016) estimated the nationwide annual costs of IQ losses from aircraft lead emissions. The authors developed a general aviation emissions inventory, including emissions from aircraft aloft, for the continental United States and modeled changes in atmospheric concentrations of lead. They used those concentrations to quantify the impacts of annual aviation lead emissions on the U.S. population. The authors found that aircraft lead emissions contribute to $1.06 billion 2006 USD ($0.01−$11.6) in annual damages from lifetime earnings reductions.

Zahran et al. (2017) studied time and space relationships between BLL data from more than one million children and their proximity to 448 airports in Michigan. The authors found consistent evidence that avgas use is significantly linked to elevated BLLs in children residing near airports. They estimate the social damages (IQ point loss and IQ point loss to future earnings) attributable to leaded avgas consumption to be at least $10 per gallon.

WORKER EXPOSURES AT AIRPORTS

In occupational settings at airports, workers can be exposed to inorganic lead through inhalation and ingestion of dibromide particles emitted from the combustion of leaded avgas. Workers can also be exposed to organic lead in the form of TEL in evaporative and refueling emissions from uncombusted avgas. TEL can be absorbed through the skin, eyes, and mucous membrane. Uncombusted avgas has additional toxic components of concern, including volatile organic compounds (VOCs) and the fuel additive EDB. Calculated estimates of evaporative emissions of those compounds at airports are presented below. Later, this section considers industrial hygiene and occupational health requirements that cover worker exposures to inorganic lead, TEL, and other hazardous components.

Evaporative and Refueling Emissions

Avgas is a volatile liquid fuel under EPA definitions for motor vehicle fuel.[2] Under ASTM D910, its vapor pressure range is 38-49 kPa at 38°C; this is normally referred to as Reid Vapor Pressure (RVP). In many publications, this is presented in pounds per square inch (psi), with a range of 5.5-7.1 psi. Except at the high end, RVPs in this range are below that normally seen in automotive gasoline. The only exception would be gasolines used in the summer ozone months in California, areas where federal regulations require the use of reformulated gasoline, and a few

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[2] See U.S. EPA definition at 40 CFR § 86.1803-01.

counties where the RVP is 7.0 psi.[3,4] As a volatile liquid fuel stored in a rigid or even semi-rigid container such as an aircraft fuel tank, it is the basic nature of the fuel to evaporate into the air in any ullage volume (unoccupied usable volume in the tank). These volumes taken together are commonly referred to as the tank headspace and will vary by tank design and the tank fill amount at any given time.

The various compounds in the avgas will evaporate into the headspace until it is saturated. This evaporative process depends on temperature, the vapor pressure, the mass fraction of the compounds in the fuel, and to a lesser degree elevation (i.e., atmospheric pressure). The evaporation continues until a liquid-vapor equilibrium occurs between the compounds in the liquid fuel and corresponding compounds in the headspace. These evaporative processes are relatively rapid, so most of the time the headspace will be saturated (Gauss, 1973). Table 3-2 below shows calculated headspace percent concentrations for VOCs at 25°C for sea level for 5.5 and 7.1 psi RVP aviation gasoline.

Grade 100LL avgas contains two other additive compounds (TEL and EDB) with relatively lower vapor pressures, which evaporate during handling and storage.

Using the ideal gas law and a molecular weight of 68 g/mole for the fuel vapor at 5.5-7 psi, the hydrocarbon concentration in the headspace ranges from 2.6-3.35 grams VOC per gallon headspace. The vapor pressure of TEL at 25°C is 0.00387 psi and for EDB it is 0.2322 psi (NIOSH, 2007).[5] As mentioned above, the concentration in the headspace depends on the mass fraction in the liquid. According to Table 1 of ASTM D910, for Grade 100LL, the allowable range for the TEL dose in the liquid is 0.27-0.53 ml TEL/liter avgas (0.28-0.56 g Pb/liter avgas). Using the high end of this D910 range, this calculates to a dosing rate of 3.31 g TEL per gallon of Grade 100LL avgas. Taking the TEL vapor pressure at 25°C and the high end of this dosing rate, the headspace concentration is 0.036 mg/gallon for Grade 100LL avgas.[6] Using a 1:1 molar ratio dosing rate for TEL and EDB, the ppm concentration of EDB in avgas would be the same as for TEL (3.31 g/gal), but due to the higher vapor pressure, the headspace concentration is 2.05 mg/gal.

TABLE 3-2 Calculated Headspace Concentrations

RVP (psi)	VOC Percent Concentration in Headspace at Saturation	VOC in Headspace (g/gallon) at Saturation	TEL in Headspace (mg/gallon) at Saturation	EDB in Headspace (mg/gallon) at Saturation
5.5	24.7%	2.60	0.036	2.05
7.1	31.9%	3.35	0.036	2.05

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[3] Reid Vapor Pressure (RVP) Control Periods for California Air Basins and Counties are provided at: https://ww3.arb.ca.gov/fuels/gasoline/rvp/rvp_controlperiod.pdf.

[4] EPA provides information on gasoline Reid Vapor Pressure at https://www.epa.gov/gasoline-standards/gasoline-reid-vapor-pressure.

[5] See pp. 136 and 302 of NIOSH (2007).

[6] While aviation gasoline related hydrocarbon emptying and breathing loss emissions from storage tanks should already be incorporated into local emission inventories, the 0.0365 mg/gallon concentration value for TEL and the 2.05 mg/gallon value for EDB may be useful in calculating the toxic emission inventories for these storage tanks.

While there are traditionally five sources of evaporative emissions for gasoline-powered motor vehicles, only two (diurnal and refueling) are important for GA aircraft. In 2017, there were approximately 172,000 active piston-engine GA aircraft based in the United States, which consumed about 192.43 million gallons of Grade 100LL and 3.87 million gallons of MOGAS (GAMA, 2018).[7] Using an estimated weighted aircraft tank fuel volume of 87 gallons (70 percent at 60 gallons and 30 percent at 150 gallons)[8] and a 10 percent ullage, gives a headspace of 52 gallons if tanks are half full. However, it is recommended practice that piston-engine aircraft refill after flight to reduce water vapor condensation into the stored fuel. If this full refill occurs one-half of the time, the average headspace would be 30 gallons. Using traditional EPA modeling techniques for diurnal and refueling emissions (EPA, 2014; Reddy, 1989), VOC, TEL, and EDB emissions in megagrams (Mg) can be estimated as shown in Table 3-3.

TABLE 3-3 Estimated 2017 Nationwide Evaporative Emissions from Piston-Engine General Aviation Aircraft (25°C) Mg

RVP (psi)	Diurnal VOC	Refueling VOC	Diurnal TEL	Refueling TEL	Diurnal EDB	Refueling EDB
5.5	2100	500	0.0681	0.00685	3.88	0.39
7.1	2485	645	0.0681	0.00685	3.88	0.39

The entries in the columns in Table 3-3 are not additive. For a best estimate for an annual inventory, the arithmetic average of the 5.5 and 7.1 psi RVP cases would seem representative. Taking one-half of the sum the diurnal and refueling VOC inventory values yield an annual value of 2,865 Mg. This is about 0.25 percent of the evaporative and refueling inventory for gasoline-powered highway motor vehicles.[9] There is no corresponding TEL or EDB inventory for gasoline-powered highway motor vehicles, because TEL is not used in unleaded gasoline and EDB is not necessary. The combined evaporative and refueling inventory for TEL is estimated to be 0.075 Mg; this is only about 0.012 percent of the estimated amount of TEL added to Grade 100LL. The combined evaporative and refueling inventory for EDB is 4.27 Mg, about 0.67 percent of the estimated amount of EDB added to Grade 100LL in 2017. More information about EDB is provided in Appendix D.

Industrial Hygiene and Occupational Health Requirements

Health effects studies of exposure to elemental lead and lead-bearing compounds provide a basis for the current occupational exposure standards and guidelines (ACGIH, 2001a-c, 2017; ATSDR, 2020). Furthermore, NIOSH has published some excellent general reference materials that provide information on occupational lead exposures).[10,11]

The OSHA occupational exposure standards and related requirements (29 CFR § 1910) apply to employees of fixed base operators (FBOs), repair and overhaul shops, and airports

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[7] See Tables 2.7 and 2.8 of GAMA (2018).

[8] Aircraft Bluebook, Spring 2020, Vol. 20-01. Available at: https://aircraftbluebook.com/Tools/ABB/ShowSpecifications.do.

[9] See pp. III-1 to III-19 of EPA (1999).

[10] See NIOSH workplace lead publications at: https://www.cdc.gov/niosh/topics/lead/publications.html.

[11] See the OSHA substance data sheet for occupational exposure to lead at https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1025AppA.

where exposures to lead bromide, TEL, or EDB may occur. The most common airport work areas with a potential for lead exposures are on and around the flight line and in repair and overhaul shops where GA aircraft that use avgas are maintained.[12] The OSHA requirements also extend to employees who may be incidentally exposed (i.e., employees not involved in work which would routinely involve lead exposure but may work nearby or have very short-term or transient exposure periods). Potential exposures to flight crews are covered by FAA requirements instead of OSHA requirements.[13] Responsible authorities in some states operate their own occupational safety and health programs under OSHA auspices (see Appendix E).

Lead Dibromide

Because lead dibromide is a combustion product found in engine exhaust, it could originate anywhere the aircraft engine is operating, including within maintenance and repair facilities and in operational areas on the airport grounds. With the large number of airports, aircraft operations, and the widespread use of leaded avgas, lead dibromide exposures are expected to occur commonly in workplaces involving ground support and maintenance operations or through incidental contact to those working nearby. As is discussed in detail in Appendix E, the expanded OSHA health standard for lead, 29 CFR § 1910.1025, contains a permissible exposure limit (PEL) for inorganic lead (e.g., lead dibromide) and has very detailed and specific requirements.

At a minimum, an employer is required to carry out an initial exposure determination for each employee or group of similarly exposed employees in the workplace to assess whether any employee may be exposed to airborne lead concentrations at or above an action level. The OSHA regulations cover personal exposure monitoring, education/training for any employee exposed to inorganic lead in the workplace and additional requirements for workplace controls, medical surveillance, and biological monitoring for exposures greater than the action level for employees within an exposure group. The regulations are also very prescriptive regarding communication with the exposed employees and recordkeeping. It is important to note that BLLs can remain elevated long after lead exposures have been reduced or eliminated, due to release of lead from adult bone into the blood.

TEL

Although the expanded OSHA standard for inorganic lead specifically excludes organic lead (e.g., TEL), it is covered by OSHA's air contaminant standards (29 CFR § 1910.1000 Table Z-1 and 29 CFR § 1926.55). Inhalation, ingestion, and dermal exposures to TEL can occur as a result of activities, such as handling engine parts that are wetted with leaded avgas by mechanics, the dispensing and inadvertent spillage of avgas that is being dispensed by aircraft ground service operators, or the improper use of avgas as a shop solvent for parts cleaning or perhaps other purposes.

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[12] For an example of a comprehensive airport lead workplace exposure and program assessment, see Chen and Eisenberg (2013).

[13] Personal communication, David Valiante, OSHA, June 17, 2020.

EDB

Inhalation, ingestion, and dermal exposures to EDB may occur as a result of activities, such as those identified above for TEL. Exposure assessments and related requirements for EDB are covered under OSHA's air contaminants standard (29 CFR § 1910.1000 Table Z-2 and 29 CFR § 1926.55).

There are separate PELs and action levels for TEL and EDB and an assessment is required for TEL and EDB exposures, as applicable. However, the OSHA standards are less prescriptive for these contaminants relative to inorganic lead and may allow for a negative initial determination to be made through either personal exposure monitoring, application of data from similar workplaces conducting similar tasks, engineering evaluation, or worst case exposure calculations. In this case, the exposure determination may be either qualitative or quantitative. If the initial assessment indicates that the exposure is above the action level, this must also be documented and either more personal exposure monitoring or workplace controls, or both may be required. Either way, the basis for this determination must be documented and the records retained.

The assessment and response to workplace lead is complicated because inorganic lead and TEL exposures have an additive health impact. This requires that in addition to the assessments and responses for exposures for each contaminant (inorganic lead and TEL) for those employees exposed to both, the assessment must also include evaluation of the exposure as a mixture (see Appendix E).

FINDINGS AND RECOMMENDATIONS

There are no known safe levels of human lead exposure, as measured by blood lead levels. Lead exposure can result in significant negative health effects, particularly among children, and unlike some other metals there is no known biological function of even trace amounts of lead in the human body. The importance of reducing lead pollution motivates the development and implementation of mitigation measures to reduce or eliminate lead emissions from GA aircraft (Finding 3.1).

Assessing the feasibility and effectiveness of the airport-specific application of potential mitigations would benefit from an improved understanding of individual airport characteristics. Airports differ in traffic activity, layouts, and proximity to the local population. They serve as bases for different types and numbers of aircraft that provide different functions within the community. Therefore, additional analyses are needed that take into account airport-specific conditions and attributes, including the geographic distribution of lead around the airport. Such analyses would inform the selection, design, and effectiveness assessment of lead mitigation efforts at individual airports (Finding 3.2).

> EPA should conduct more targeted monitoring and enhanced computational modeling of airborne lead concentrations at airports of potential concern, as indicated by its recent screening study, to evaluate aircraft operations that are main contributors to lead hot spots and design airport-specific mitigation measures. (Hot spots often refer to a spatial zone of emissions impact where the airborne lead concentration is significantly elevated above background.) In addition to airports found to have airborne lead concentrations exceeding the concentration of the lead National Ambient Air Quality Standards (NAAQS),

> additional monitoring and modeling should include airports found to have lead concentrations that are lower, but approaching, the NAAQS concentration (Recommendation 3.1).

Past emissions from piston-engine aircraft that deposited to soil and other surfaces can contribute to present-day lead exposures at locations within and near airports (Finding 3.3).

> EPA and NIEHS should sponsor research to enhance the understanding of lead exposure routes and their relative importance for people living near airports and working at them. The research should include studies, such as observations of blood lead levels among children, in communities representing a variety of geographic settings and socioeconomic conditions that are designed to examine the effectiveness of the lead mitigation strategies over time (Recommendation 3.2)

Lead in piston-engine aircraft exhaust has been observed to occur in the form of beads about 4 nanometers (nm) in diameter embedded in particles with diameters less than 20 nm. Those particles are smaller than the lead particles observed in automobile exhaust. Smaller particles may deposit and distribute in the body differently than larger-sized particles that have been the subject of more research in past. Thus, it is important to understand the particle size properties of lead emitted from aircraft and how those properties affect atmospheric transport and deposition as well as human exposure-response relationships (Finding 3.4).

> EPA and NIEHS should sponsor research to improve the understanding of the physical state of the lead-containing particulate matter emitted from various types of GA-aircraft piston engines, including turbocharged engines, using fuel formulations of different lead content, including an existing grade of avgas with a lower lead content (100VLL), to inform future studies of atmospheric transport and deposition, human exposure, and health risks of lead emissions form GA aircraft (Recommendation 3.3)

Based on the nature of the workplace activities with GA aircraft, lead exposures are expected to occur for flight line and maintenance shop workers, including those employed by the airport itself, FBOs, and repair/overhaul facilities. Workplace lead exposures include not only inhalation of airborne emissions, but also inhalation, ingestion, and dermal absorption of the fuels additives TEL and EDB as a result of aircraft refueling and maintenance activities. OSHA regulations, including permissible exposure limits and related requirements, apply for each of these contaminants (Finding 3.5).

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4

Changing Operations and Practices at Airports to Reduce Aviation Lead

Pilots and the employees of airports and airport tenants—particularly aircraft technicians and line service workers who refuel aircraft—may be exposed to lead contamination and be contributing to lead emissions to varying degrees from practices during the dispensing of leaded aviation gasoline (avgas), pre-flight fuel inspections and engine checks, and the maintenance and repair of piston-engine aircraft. This chapter examines these practices, what is known about their contribution to lead pollution and exposures, and options for changing them. Because piston-engine aircraft operate from a wide array of airports that can differ widely in characteristics such as traffic activity, the availability of on-site facilities and services, geographic and environmental settings, and airfield configurations, the importance of these sources of lead pollution and exposure will differ by airport. At the same time, because many options to influence these practices would not involve burdensome or costly interventions, even the promise of modest lead mitigation could favor their implementation.

This chapter begins by identifying practices at airports that create lead emissions and exposures. Consideration is then given to steps that can be taken to change practices. Airports have long been the loci of similar efforts to mitigate concerns such as noise and wildlife hazards, often in partnership with the Federal Aviation Administration (FAA); other government agencies at the federal, state, and local levels; and the general aviation (GA) community. Like these other efforts, the recommendations in this chapter call for a multi-pronged and multi-partner approach to lead mitigation, and one that places a great deal of emphasis on ensuring that pilots, airport personnel, and airport service providers are well informed and aware of lead pollution risks and mitigation opportunities.

CONTRIBUTORS TO LEAD EMISSIONS AND EXPOSURES AT AIRPORTS

The U.S. Environmental Protection Agency (EPA) has noted that among the potentially largest sources of lead exposure at airports are the following activities (not in any particular order):

- Aircraft fueling operations;
- Pre-flight fuel sampling by pilots;
- Aircraft maintenance and repair; and
- Engine run-ups during pre-takeoff checks.[1]

Background on each of these contributors to lead emissions and exposures is provided in the following sections before considering options for reducing their contributions.

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[1] 75 Federal Register 22440-22468. April 28, 2010. Advance Notice of Proposed Rulemaking on Lead Emissions from Piston-Engine Aircraft Using Leaded Aviation Gasoline; Proposed Rule. See https://www.govinfo.gov/content/pkg/FR-2010-04-28/pdf/2010-9603.pdf.

Fueling Operations

As discussed in Chapter 2, fueling services at airports are usually provided by the airport operator or a tenant contractor, such as a fixed base operator (FBO), through either full-service or self-service dispensing. Self-service dispensing at unattended stations has become a popular option because it can lower avgas prices and save the pilot time and inconvenience by not having to wait for a mobile fueling truck or to refuel only during regular FBO operating hours. Indeed, at many airports that service piston-engine aircraft self-service is the only refueling option available. In cases where fueling services are not available, or if the pilot would rather not use the onsite fueling service, the pilot may self-fuel using avgas purchased off-site.

The two basic methods of refueling are gravity-fed "over-the-wing" fueling and single entry point fueling using pressurized systems. Over-the-wing fueling—where the avgas is dispensed through ports on top of the wings—is the most common method for small piston-engine aircraft and for self-service operations generally. Avgas may also be delivered to the aircraft by mobile fueling trucks, especially when refueling through a single-entry point. Refueling trucks may obtain the avgas from an off-site fuel source, but more commonly from storage tanks located at the airport. A small airport may have a single tank for avgas storage with a capacity of 10,000 gallons or less, whereas an airport with more operations may have multiple tanks and a storage capacity of 100,000 gallons or more (NASEM, 2019).

Whether the avgas is provided by full-service operators, through self-service stations, or by the pilot self-dispensing from a can, there is risk of exposure to lead from accidental overfilling, splashing, and spills onto the aircraft, ground, and body and clothes of the person doing the refueling. Exposures of fuel service personnel can also occur when loading and unloading avgas into and from the storage tanks. In its 2002 PBT National Action Plan for Alkyl-lead, EPA identified fuel service personnel, as well as pilots and aircraft technicians, as potentially being exposed to lead by inhaling vapor emitted during refueling, from spills, and from unused gasoline remaining in the engine or fuel tanks (EPA, 2002). The report also noted the potential for dermal absorption of lead from spilled avgas. However, EPA was not able to quantify the incidence and severity of these lead exposure sources.

In implementing the Clean Air Act (CAA) and the Clean Water Act (CWA), EPA has established pollution control standards that apply to fuel evaporative emissions and spills but that include some exemptions for avgas. In the case of the CAA, the agency has established national emission limitations and management practices for hazardous air pollutants emitted during the loading of gasoline storage tanks and during its dispensing at fueling stations (40 CFR PART 63 SUBPART CCCCCC). Under these regulations, stations are required to install vapor recovery units to capture gasoline evaporative emissions. However, while the CAA standards apply to most facilities that dispense gasoline to end users (such as road users), they do not apply to storage and dispensing operations for avgas. The regulations state that "loading of aviation gasoline into storage tanks at airports, and the subsequent transfer of aviation gasoline within the airport" are not subject to requirements that establish national emission limitations and management practices for hazardous air pollutants (40 CFR PART 63 SUBPART CCCCCC). States may have their own regulations governing airport fuel dispensing and storage.

Lead is also regulated as a toxic pollutant under the CWA. When avgas spills onto the aircraft parking surface, the lead in it can move in the environment in a number of ways as discussed in Chapter 3. EPA's stormwater provisions under the CWA (National Pollutant Discharge Elimination System [NPDES] program) make it unlawful for industrial facilities to discharge any pollutant from a point source into nearby water bodies or indirectly via storm sewer systems without a permit.[2] Air transportation is a covered sector in the permitting program,[3] and certain airport activities are specifically identified by EPA as potential sources of pollutant discharges, including deicing and anti-icing operations, fueling, and the servicing, repairing, and maintaining of aircraft. Common requirements for an industrial stormwater permit (usually administered by states under EPA delegation) include the development of a written stormwater pollution prevention plan and implementation of the planned prevention and control measures. Many smaller airports are covered under general NPDES permits, while some larger airports are more likely to have an activity-specific, individual permit because of the need to monitor and control runoff from chemical deicing operations (NASEM, 2016a). However, unlike these controlled deicing chemicals, lead is not likely to be the subject of similar pollutant-specific runoff controls by smaller airports that possess general NPDES permits only.

In the case of FAA requirements pertaining to aircraft refueling, the agency's regulations and guidelines, issued in various Advisory Circulars (ACs) and other publications, are safety-driven, intended mainly to prevent fire hazards. For instance, AC 150/5230-4B (FAA, 2012) requires airport fueling service providers and personnel to follow the codes and standards contained in the most recent edition of National Fire Prevention Association 407, "Standard for Aircraft Fuel Servicing Training Programs." State and local regulations may also apply, and many individual airports will have their own requirements governing the training of fueling personnel; the siting, operation, maintenance, and inspection of fuel storage and dispensing systems; and the reporting of spills. It merits noting, however, that airports that receive federal aid from the Airport Improvement Program and that are part of the National Plan of Integrated Airport Systems (NPIAS) are required by grant assurances (obligations) to allow pilots to perform preventative maintenance on their aircraft, including self-fueling, without imposing unreasonable restrictions.

Besides the federal government, individual states, local jurisdictions, and airport operators may have their own requirements that pertain to aircraft fueling hazards. In addition, even as they implement some of the CAA and the CWA requirements cited above, states will generally have their own set of environmental laws and regulations. Regarding fuel spills and evaporative emissions, these state and local requirements may be aviation-specific or loosely fall under other regulated industry sectors such as aboveground storage tanks or general environmental protection. Unfortunately, a state-by-state review of all applicable regulations that could apply to lead pollution at airports was not possible within the resources and scope of this study.

The bottom line is that scant data are available on the frequency and magnitude of lead emissions and exposures from avgas evaporative emissions and spills from fueling operations at airports, in part because of the large number of airports, extensive self-fueling activity, and limited requirements by federal pollution control regulations for monitoring these emissions and discharges. However, even in the absence of information quantifying the extent to which fueling operations may contribute to lead pollution at airports, it is reasonable to assume such contributions are not always trivial and that any opportunities to mitigate them that are not

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[2] Per 40 CFR 302.4, the reportable quantity of spilled tetraethyl lead (TEL) is 10 pounds, which would require about 1,655 gallons of leaded avgas to be spilled assuming 2.74 grams of TEL per gallon. See https://www.govinfo.gov/content/pkg/CFR-2004-title40-vol26/pdf/CFR-2004-title40-vol26-sec302-4.pdf.

[3] Multi-Sector General Permit for Stormwater Discharges Associated with Industrial Activity Sector S—Air Transportation Facilities.

especially costly or burdensome deserve consideration. Some examples of such opportunities are identified in the second half of this chapter.

Pre-Flight Fuel Sampling

As part of a typical aircraft pre-flight inspection, a pilot will strain, or sump, a small amount of avgas from the fuel system into a sampling receptacle and visually inspect it for contamination and condensation. The pilot may return the sample to the fuel tank if it appears to be uncontaminated or pour it into a container for safe disposal. Some pilots may discard the sampled fuel to the ground, a practice that is undesirable for the same reasons that spills from refueling are of concern. In this case, the discarded fuel can become a potential point source pollutant that will be discharged into the stormwater collection system and eventually to receiving water during the next precipitation event.

A study on pilot fuel sampling and disposal practices was conducted by the FAA-sponsored Airport Cooperative Research Program (ACRP) in 2013 (TRB, 2014). Data on these practices were collected through an online survey of pilots asking them for details on their fuel sample disposal methods. Of the 146 pilots who responded to the survey, 36 percent indicated that they discard all samples to the ground regardless of visible contamination, while another 19 percent reported that they discard only contaminated samples to the ground and return uncontaminated samples to the tank. The remaining respondents reported that they either return the samples to the tank by using a fuel straining device (e.g., mesh screen) (26 percent), dispose of only the contaminated samples into a container (e.g., gas can or bucket) (4 percent), or dispose of all samples into such a container (16 percent). Based on these survey data, as well as FAA data on aircraft operations and assumptions about the share of inspected samples that are contaminated, the ACRP report authors estimated that between 75,000 gallons and 175,000 gallons of avgas are discarded to the ground annually following pre-flight fuel inspections. The applicability of this volume range today is unclear, because pilot behaviors may have changed since 2013, and because avgas consumption has continued to decline.

The ACRP report also contains findings about airport practices for ensuring the safe disposal of inspected fuel. The researchers observed fuel sampling and disposal practices at three airports and consulted with a number of airport managers, FBOs, flight schools, and airport managers to identify procedures followed by pilots at different airports. While the researchers found that many airports provide fuel disposal containers, they also found evidence that the containers are not being used regularly. While the researchers observed a wide range of practices being employed when handling fuel samples, none of them could be linked to guidance from an industrywide consensus practice for how fuel sampling and disposal should be conducted. For instance, numerous pilot operating handbooks were reviewed for the ACRP study, and while many made reference to pre-flight fuel sampling, none explained how the pilot should manage the fuel sample once inspected.

Based on these pilot surveys, observations of practice, and consultations with wide range of airport operators, the ACRP report was able to identify some potential best practices for reducing the frequency of pilots discarding fuel to the ground. These practices are discussed later in this report when considering opportunities for reducing the incidence of lead emissions and exposures from fuel spills, evaporate emissions, and inappropriate fuel disposal after pre-flight sampling.

Aircraft Maintenance

Because a percentage of the lead in avgas is retained in the aircraft engine and engine oil, aircraft owners and technicians can be exposed to lead deposits and residue when performing scheduled aircraft maintenance and repairs. A health hazard evaluation report issued by the National Institute for Occupational Health and Safety pointed to the removal and cleaning of spark plugs as a potentially significant source of lead exposure (Chen and Eisenberg, 2013). Lead bromide deposits are created in the combustion chamber by the reaction of tetraethyl lead and the scavenging agent ethylene dibromide. As a result, the electrodes of spark plugs will become fouled and need to be cleaned during scheduled maintenance or sooner by aircraft technicians. Other engine parts, including cylinders, will also be contaminated and they too may be handled, and indeed sometimes washed in leaded avgas, by technicians during aircraft servicing and repair.

Fouled spark plugs are typically cleaned by technicians in the shop using methods involving vibration and abrasive blasting. Some of the lead bromide that is agitated free from the electrode becomes fine lead dust and suspended in the air. By taking surface and air samples at observed shops, researchers have documented the presence of lead dust in the air, on shop surfaces, and on worker clothing (Beers, 2003). Some of the aircraft technicians who were observed during this research performed the cleaning unaware that the deposits being removed contained toxic lead, and they worked without the use of personal protective equipment, such as respirators or aprons. In the shops observed, no provisions were made for the technicians to shower and change clothing before they go home to potentially expose family members to lead dust. While Occupational Safety and Health Administration (OSHA) standards establish minimum requirements for compliance when a lead exposure hazard exists in a workplace (CFR 1910.1025), Beers (2003) noted that a review of federal regulations and government publications did not yield any prescribed process for the safe cleaning of aircraft spark plugs, nor any guidance on personal protective equipment or the avoidance of take-home exposures.

Given the large number of piston-engine aircraft in the GA fleet (~170,000) and the adherence of many of their owners to an annual preventive maintenance schedule that usually includes examining, cleaning, and gapping spark plugs implies that aircraft technicians and owners, in the aggregate, are performing thousands of spark plug cleanings per year in which lead exposures are potentially taking place. Although the exposures from these procedures have not been quantified, they would appear to be a candidate for more targeted actions to ensure that aircraft owners and maintenance workers are aware of and protected from the hazards. Some potential opportunities for doing so are identified later in the chapter.

Engine Run-Ups

The practice of “running up” the aircraft engine when stopped prior to takeoff is noted in Chapter 2. A pilot is expected to operate the aircraft in accordance with its FAA-approved Pilot Operating Handbook or Aircraft Flight Manual in which the run-up procedures are specified. Typically, pilots will perform an engine check by advancing the throttle(s) to high RPM, at about two-thirds the RPM required for takeoff, to verify that the engine appears capable of producing takeoff thrust. Most pilots perform an engine run-up each time they operate an aircraft to ensure operational readiness. In cases where an aircraft is flown several times a day, such as during pilot training, this practice may result in multiple engine run-ups by the same aircraft during the course of the day.

A key part of the engine run-up is a magneto (and alternator/charging) test, which is performed while stopped at a throttle setting that produces a moderately high fuel consumption rate; whereas other pre-takeoff checks will occur at engine idle with much lower fuel flow. While magneto tests are typically on the order of one minute in duration, ACRP researchers observing operations found a large variation in these test times when, including some magneto tests that were much longer than the average (NASEM, 2015). In addition, engine run-ups are performed following engine repair or maintenance in order confirm post-repair operability. The duration of these run-ups was found by the ACRP researchers to be highly variable because of their situational nature (NASEM, 2015).

Many airports have specific areas where pre-takeoff engine run-ups usually take place, either by designation or where they are commonly practiced by pilots. The area is frequently near the runway end or alongside the taxiway, usually in the close proximity to where takeoff will occur. The run-up area may be located where noise and air blast from engine or propeller wash do not create problems for other aircraft, structures, or ground traffic. In the case of maintenance run-ups, they may be performed near the repair facility or FBO. The only guidance that is provided relevant to the pre-takeoff or maintenance run-up location in FAA's Airplane Flying Handbook is that the engine check should be performed on a firm surface (e.g., smooth, paved, or turf surface if possible) to minimize the potential for damage to the propeller from debris and in a windward direction to reduce the potential for engine overheating (FAA, 2016).

Airport lead air quality studies conducted by EPA and ACRP have shown that pre-flight run-ups contribute a significant, if not predominant, share of ambient peak lead concentrations at airports (EPA, 2010; NASEM, 2015). ACRP evaluated lead emission sources and concentrations at three airports in detail, as noted earlier in Chapter 3. The researchers found run-up area activities (magneto test plus engine idle time) to be the source of 16 percent of total airport emissions on average for the three facilities studied, with 24 percent produced by the magneto test and 76 percent produced during engine idle time (NASEM, 2015). The researchers also found that the plume of emissions from run-up operations can combine with emissions plumes from other operations, especially takeoffs, when occurring near one another.

In the next section, consideration is given to options for reducing lead emissions from engine run-ups and for controlling lead concentrations in proximity to run-up areas. These options include potential relocation of run-up areas to increase the distance between these checks and takeoff operations (thereby reducing the probability of overlapping plumes), the use of multiple run-up locations to serve the busiest runway (to redistribute run-up emissions), and increasing the size of the run-up area to serve multiple airplanes (to increase the surface area over which the emissions occur, potentially minimizing unnecessary idling that may otherwise occur due to traffic congestion). By and large, the cited ACRP reports provide the basis for the discussion of these options.

OPPORTUNITIES TO REDUCE LEAD EMISSIONS AND EXPOSURES

Each of the practices and activities discussed above presents opportunities to reduce lead emissions and exposures at airports through means such as increased education, training, and awareness of pilots, airport managers, and aircraft maintenance personnel; changes in airport environmental planning and policy guidance; and research to obtain a better understanding of how airport activities are contributing to lead emissions and exposures and to identify best practices for reducing those contributions. Examples of opportunities are given next.

Pilot and Airport Personnel Awareness, Education, and Training

There is evidence, as discussed above, that many pilots and airport personnel may not fully appreciate the extent to which their own actions and behaviors are contributing to lead emissions and exposures, including their own exposure. Aircraft technicians and pilots performing repairs and maintenance may be exposed unknowingly to lead deposited on aircraft components, including spark plugs and other engine parts. Lead residue and dust can concentrate in shops where maintenance is performed, exposing the technicians to lead and potentially their families as a result of lead deposits brought home on clothing. Pilots and line personnel may be exposed to evaporative emissions that are not captured during refueling and when fuel is spilled or improperly discarded after sampling. Finally, when conducting their pre-takeoff checks, pilots may not fully appreciate how their decisions about where and how long to perform these operations can affect concentrations of lead at airports.

This study could not assess the full extent to which existing government authorities and regulations could be better targeted to reduce these airport-related sources of lead emission and exposures, such as EPA’s authority to regulate evaporative emissions during fuel dispensing and storage. Nevertheless, there may be opportunities for EPA to draw more attention to lead emissions and discharges at airports. For example, in its list of best management practices for “good housekeeping” by airports to control spills and leaks during aircraft refueling, the agency could identify specific management practices for reducing lead pollution specifically (EPA, 2006). Such practices might include airports reminding pilots that topping off can lead to fuel spills and providing fuel waste containers at strategic locations and ensuring that these containers are regularly emptied.

To be sure, any concerted effort to improve airport lead management practices would need to include efforts aimed at ensuring that pilots and airport personnel have greater awareness of how their activities and practices can contribute to lead pollution and how that pollution can be harmful to their own health and that of others. However, a review by this committee of the following FAA-issued documents pertaining to aircraft operations, flight training, airport management, and aircraft maintenance protocols, methods, and standards found no mention of lead emissions and exposures as an environmental risk or health hazard:

- Airplane Flying Handbook, 2004 (FAA, 2004);
- Airplane Flying Handbook, 2016 (FAA, 2020);
- Airport Compliance Manual, 2009 (FAA, 2009);
- Aviation Emissions and Air Quality Handbook, 2015 (FAA, 2015);
- Aviation Instructor’s Handbook, 2020 (FAA, 2020);
- Aviation Maintenance Technician Handbook, 2018 (FAA, 2020);
- Aviation Maintenance Technician Handbook—Powerplant, 2018 (FAA, 2020); and
- Pilot’s Handbook of Aeronautical Knowledge, 2016 (FAA, 2020).

These handbooks and manuals, which are intended to have broad reach to GA pilots, aircraft technicians, and airport managers and line personnel, would therefore seem to be prime candidates for the inclusion of awareness and educational information on lead sources and risks and on practical means for reducing them. One such opportunity is the ground operations chapter of the Airplane Flying Handbook, 2004 (FAA, 2004), which is developed to assist student pilots learning to fly as well as to improve the flying proficiency and aeronautical knowledge of experienced pilots. Chapter 2 of the handbook discusses pre-flight checks and assessment procedures. If an update of this handbook is planned, FAA could alert pilots to sources of lead emissions and exposures during ground activities such as self-service refueling, fuel inspection, and engine run-ups. The chapter could also contain guidance on best practices for ensuring fuel is not spilled and that inspected fuel is properly discarded. Likewise, the Pilot's Handbook of Aeronautical Knowledge, 2016 (FAA, 2020), which is intended to be a reference for pilots as they progress through pilot training, could include similar information that emphasizes lead mitigation as one element of the basic knowledge important for piloting GA aircraft. To ensure that the next generation of pilots is similarly informed and develops good habits, the Aviation Instructor's Handbook, 2020 (FAA, 2020) could emphasize such best practices, providing an early opportunity to instill airport environmental awareness in student pilots. Pilot training curricula could include instructions for ensuring that new pilots understand the environmental implications of aviation (including those of lead emissions) and are knowledgeable about best practices for activities such as fuel sampling, responsible engine run-up (i.e., how to choose safe locations and the amount of time needed to perform the check), and the desirability of using unleaded fuel where available and compatible with the aircraft.

Both the general Aviation Maintenance Technician Handbook, 2018 and Aviation Maintenance Technician Handbook—Powerplant, 2018 (FAA, 2020) are FAA guidance documents specifically for aircraft mechanics and technicians. Both volumes of the latter handbook (on engines and exhaust systems) discuss lead fouling of spark plugs, but do not alert technicians to the risks they may face from lead exposures, nor do they refer to any safety or protective measures. Updates or supplements to these volumes would likewise present FAA with an opportunity to ensure that aircraft mechanics and technicians are aware of these risks and possible mitigation techniques to reduce personal exposure. Advice contained in Chen and Eisenberg (2013) could be consider to inform such an update—for instance, by reference to the document's recommendations on the use of respirators during sandblasting of spark plugs, keeping children out of work areas, washing hands thoroughly before eating and drinking and before leaving the workplace, leaving work clothes at the workplace, and wearing disposable shoe covers when working.

FAA issues many other handbooks, manuals, and guidance documents that are even more specific to segments of the GA community, including operators of ultra-light, amateur-built, and rotary-wing aircraft (FAA, 2020). These documents also may provide opportunities to alert and educate aviators and technicians to the aviation lead problem and to identify possible mitigation measures.

Similar opportunities exist to provide airport operators and managers with more information on lead risks and practices for reducing them. For instance, the Airport Compliance Manual, 2009 (FAA, 2009) contains guidance on airport operator responsibilities for the operation and maintenance of airports that receive federal grants. FAA's latitude to amend this manual to include guidance on best practices for reducing lead emissions and exposures is unclear. Nevertheless, to the extent that latitude exists, the manual could be a place to prompt airport operators to follow best practices, such as for designating appropriate locations for engine run-ups and for advising pilots and airport personnel about relevant operational procedures for avoiding fuel spills and managing inspected fuel samples. The previously discussed ACRP report on Best Practices for General Aviation Aircraft Fuel-Tank Sampling identifies several such practices that could potentially be incorporated into this guidance (TRB, 2014).

FAA's Aviation Emissions and Air Quality Handbook, 2015 (FAA, 2015) is intended to assist airports with the planning and completion of air quality assessments conducted for aviation-related projects and operations. Lead is identified as one of the six criteria pollutants regulated under the CAA. The handbook points to EPA methods for calculating lead emissions from piston-engine aircraft operations. The information in this handbook could therefore be expanded to assist airport operators in modeling and calculating lead emissions from other airport sources, such as from engine run-up, refueling, and aircraft maintenance. Similar information might also be included in the Airport Compliance Manual, 2009 (FAA, 2009).

While a more explicit and detailed treatment of lead emissions and exposure sources and risks in such FAA handbooks, manuals, and other guidance documents would seem to be an essential first step in a general campaign to make airport personnel and aviators more attuned to the lead problem and aware of best practices for managing it, such a campaign would need to capitalize on the other collaborative opportunities to expand awareness across the GA community. In particular, FAA's longstanding partnerships with organizations representing airports, aircraft manufacturers, pilots, flight instructors, and aviation educational institutions could be leveraged, such as by coordinating with the General Aviation Manufacturers Association (GAMA), the Aircraft Owners and Pilots Association (AOPA), the Experimental Aircraft Association (EAA), the National Air Transportation Association (NATA), the American Association of Airport Executives (AAAE), the Small Aircraft Manufacturers Association (SAMA), the National Association of Flight Instructors (NAFI), the Society of Aviation and Flight Educators (SAFE), and the Professional Aviation Maintenance Association.

FAA has a long-standing history of collaborating with these GA organizations on initiatives such as noise abatement, flight safety, wildlife hazard mitigation, and the development of lead-free fuels. Ensuring that lead awareness information and educational materials are provided in the handbooks, guides, and curricula materials of these organizations could be a key element of a more comprehensive campaign, which could also include special exhibits at GA events. It is notable, for instance, that FAA is a regular exhibitor at the EAA AirVenture Oshkosh and Sun'n Fun Kissimmee fly-ins, where it has sponsored related exhibits on the Piston Aviation Fuel Initiative. Thousands of GA pilots participate in these and other fly-ins (such as AOPA regional fly-ins), which could provide broader awareness among aviators about lead problems and potential mitigation efforts.

These are just a few examples of the wide array of aviation industry and enthusiast trade shows, conferences, and other forums that could be tapped by such an awareness campaign if sponsored by FAA in partnership with the GA community. Working with FAA, aviation associations and their members could have direct roles in disseminating information on appropriate best practices though a variety of other means such as newsletters, webinars, website guidance, and modifications to important documents such as the pilot and operator handbooks issued by aircraft manufacturers. There are numerous models for such awareness campaigns, including the "Know Before You Fly" education campaign to promote awareness by aviators of drones (AUVSI, 2020).

Airport Planning and Environmental Policy Guidance

FAA has oversight and regulatory authority for those airports that receive federal aid and that are included in the NPIAS. In 2013, the Office of Airport Planning and Environmental Division issued the following interim guidance to airports on mitigating public risks associated with lead emissions from pre-takeoff run-ups (FAA, 2013).

- If existing run-up areas typically cause propeller wash to be directed off airport property or into areas where the general public can be exposed, the airport operator should consider shifting either the location or orientation of run-up activities to locations where the emissions can be better contained to non-public areas of the airport.
- In cases where it is not immediately feasible to reduce lead emissions, consider minimizing the public's outdoor air exposure to lead emissions by either shifting fences (to increase the distance between run-up areas and public observation areas) and/or posting signs to discourage loitering by the public in those areas where there may be potential and unnecessary exposure to lead from piston-engine aircraft emissions.

This FAA guidance, which was characterized as "interim," has not been updated since it was issued in 2013. The guidance points to the importance of shifting the location or orientation of run-up activities to locations where emissions can be contained to non-public areas; however, it is silent about whether airports should consider moving their run-up locations away from runway ends that have high volumes of aircraft taking off. As discussed in Chapter 3, ACRP examined the option of relocating run-up areas or redistributing the use of existing run-up areas in order increase the dispersion of emissions and reduce peak ambient lead concentrations (NASEM, 2016b). To see if changes in run-up areas would reduce the magnitude of these lead hot spots, the ACRP research team modeled emissions at three airports where run-up areas were relocated and dispersed away from the runways ends. Runway ends were determined to be hot spots for lead concentrations because the emissions from run-ups will mix with the emissions from aircraft taking off. The results of the ACRP study, issued 3 years after FAA's interim guidance, suggest that it may be time to update the guidance, in particular to address the desirability of moving run-up areas away from runway ends to other locations as long as they do not expose the general public to emissions or present other concerns such as degraded safety or excessive noise.

FINDINGS AND RECOMMENDATIONS

A review of FAA-related manuals and handbooks pertaining to flight training, aircraft maintenance, and airport management found scarce mention of lead emissions and exposures as an environmental risk or health hazard nor guidelines for refueling to avoid spills and emissions, ensuring the safe disposal of inspected fuel, and reducing exposures to lead deposits when performing aircraft maintenance and repairs (Finding 4.1).

> FAA should coordinate its efforts to reduce lead pollution and exposures at airports with those of other federal agencies that have key responsibilities for protecting public health,

> safety, and the environment at airports, including the Occupational Safety and Health Administration (OSHA) as well as EPA. FAA should collaborate with these agencies to explore the regulatory and programmatic means within their respective jurisdictions that can be brought to bear and combined in a complementary manner to reduce lead emissions and exposures at airports (Recommendation 4.1).
>
> FAA, in partnership with prominent organizations within the GA community, should initiate an ongoing campaign for education, training, and awareness of avgas lead exposure that is targeted to GA pilots, aircraft technicians, and others who work at airports. Informed by research on the most effective approaches for reaching these audiences, the campaign should be multi-pronged by ensuring that information on lead risks and mitigation practices is prominent in relevant manuals, guidelines, training materials, and handbooks for pilots, airport management, and aircraft technicians. Where appropriate, it should also be covered in relevant certification and licensure examinations. In addition, the information should be featured on FAA and GA organization websites and included in written materials distributed at GA industry conferences, tradeshows, and fly-ins (Recommendation 4.2).

Airport lead air quality studies have shown that engine run-ups, whereby a pilot confirms shortly before takeoff that the engine is operating safely by briefly bringing the engine up to full power for system checks while the aircraft is stopped, can contribute to significant airborne lead concentrations at designated run-up areas. Aircraft maintenance personnel may also perform extensive engine tests at run-up areas. Run-up area planning guidance provided by FAA has not been updated to reflect the results of air quality studies that suggest it may be desirable for airports to move their run-up locations away from being close to where human activities occur (including activities both on-airport and in neighboring communities) and away from high-traffic locations such as runway ends where lead is also emitted from aircraft taking off (Finding 4.2).

> FAA should update its guidance on the location of run-up areas to reflect the results of research since the latest interim guidance was issued in 2013, including the need to account for both the emissions of engine run-ups and of takeoffs when analyzing the geographic distribution of lead emissions at the airport. This analysis should support decisions of whether to move run-up areas to reduce people's exposure to lead emissions while also accounting for other concerns including safety and aircraft noise (Recommendation 4.3).

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5

Existing Fuel Options for Piston-Engine Aircraft to Reduce Lead

This chapter reviews existing fuel options for piston-engine aircraft and considers their potential to reduce lead use by the general aviation (GA) fleet. The chapter begins with an explanation of the reasons lead is added to aviation gasoline (avgas), including the almost universally used grade, 100LL. This discussion is followed by a review of other grades of avgas that have lower (100VLL) or no added lead (UL94) and that are available for purchase at some airports or approved in current fuel specifications. Consideration is then given to the applicability of unleaded automotive or "motor" gasoline supplies—sometimes referred to as MOGAS—to the piston-engine aircraft. The prospects for more widespread use of these fuels are assessed and each fuel's potential impact on GA emissions of lead is estimated. The chapter concludes with findings and recommendations applicable to each fuel type.

ROLE OF LEAD IN AVGAS

Aviation has always had a great need for engines with high power-to-weight ratios because of the importance of minimizing aircraft weight to achieve high levels of performance. In reciprocating engines, high power to weight can be achieved by increasing the brake mean effective pressure (BMEP). For a four-cycle engine, this relationship is

$$P = \frac{(RPM)\, V_d\, p_{me}}{120}$$

where V_d is the engine displacement (the cumulative cylinder volume) and p_{me} is the BMEP.

BMEP can be increased by either (a) increasing the compression ratio within the cylinders/pistons of the engine or (b) supercharging or turbocharging the inlet air. However, increasing BMEP in an engine design requires selecting fuels that are able to burn at higher pressures and temperatures without detonation. Detonation is rapid combustion, similar to an explosion involving a supersonic flame front and shock wave. Detonation in a reciprocating engine is often called "knock" because of its characteristic sound. Knocking can lead to failure of critical engine components in flight and must be avoided. A primary measure of a fuel's resistance to knock is the octane number. Fuels with higher octane can be operated in higher compression engines (i.e., engines with higher BMEP). Chemicals are typically added to avgas to achieve the higher octane. The most used additive is tetraethyl lead (TEL),[1] which was developed and marketed beginning in the 1920s. Until that time, avgas did not contain lead. In addition to its role in increasing octane, TEL (1.0 gram of which contains 0.64 grams of lead) helps reduce engine valve wear by lubricating valve seats and guides.

Adding lead to avgas also has many disadvantages. In addition to being toxic to humans (as discussed in Chapter 3), lead deposits foul spark plugs and other engine components. To prevent unacceptable lead buildup in engine combustion chambers and on components, the lead

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[1] $(CH_3CH_2)_4Pb$.

scavenger ethylene dibromide is added to avgas. Nevertheless, lead deposits still require periodic cleaning, and the scavenger itself causes the creation and emission of lead dibromide as well as the formation of hydrobromic acid. Because this acid can cause internal corrosion in engine components, more frequent oil changes may be required to minimize engine damage.

Because of the need for a fuel's octane number to be commensurate with an engine's BMEP, fuel selection and engines are inextricably linked. Aviation engine types are certified (type certificate [TC]) for airworthiness by the Federal Aviation Administration (FAA) to operate with a fuel meeting specifications identified by the TC applicant (the engine or aircraft manufacturer). While FAA does not approve specific fuels for use in aircraft engines, it certifies aircraft and engine types based on the fuels identified by the aircraft and engine manufacturer in the TC application. The fuel is then regulated as an operating limitation (FAA, 2018). Once a particular grade of avgas has been defined as an operating limitation for an aircraft, it may only be changed by a TC amended by the manufacturer for the aircraft type or a supplemental type certificate (STC) obtained from FAA by the owner of an individual aircraft. FAA, however, can issue a Special Airworthiness Information Bulletin (SAIB) indicating that a grade of avgas is acceptable for use by designated aircraft and engine types that were certified for operation with other specified fuels.

Fuel operating limitations are defined in the aircraft's TC data sheet and flight manual. The operator is required to use only the fuels listed in those documents. The fuel operating limitations, therefore, must be precise to help the operator ensure the engine and aircraft continue to conform to the operating limitations of their certification. In turn, fuel refiners and suppliers need this precision to produce and distribute fuels suited to the mix of aircraft in the fleet. While some engines—typically older, lower compression types—are certified to operate with a lower octane fuel, they can also operate safely with higher octane fuels. Other engines are certified only for higher octane fuels. Accordingly, a fuel with an octane value that can satisfy both segments of the fleet may be preferred by fuel refiners and suppliers to allow for the efficiencies of higher production, distribution, and dispensing volumes.

HISTORICAL AND CURRENT USE OF LEADED AND UNLEADED AVGAS

The specific properties of avgas are defined in American Society for Testing and Materials (ASTM) specifications for the supply and purchase of avgas. Until the 1960s, avgas grades were commonly expressed as two successive octane numbers, such as 80/87 and 100/130. The first number is the lean motor octane number (MON), which is typically used in referring to avgas grades, and the second number, which is seldom used, is the rich rating. The most prevalent avgas grade is 100LL, where the "100" refers to the MON rating and "LL" stands for "low lead." According to ASTM standard D910, which contains specifications for leaded avgas, 100LL cannot have a lead content that is less than 0.28 grams per liter or greater than 0.56 grams per liter. Prior to the introduction of 100LL, lead content could be as high as 1.12 grams per liter. While 100LL dominates the avgas market and can be used by all piston-engine aircraft, ASTM has specified other avgas grades for use in all or a large share of the piston-engine fleet, including the "very low lead" (VLL) 100 MON grade and an unleaded (UL) 94 MON grade. According to ASTM D910, 100VLL cannot have a lead content less than 0.28 grams per liter or greater than 0.45 grams per liter. Thus, the minimum allowable lead content is the same for 100LL and 100VLL, but the maximum allowable lead content is 19.6 percent lower for 100VLL. With SAIB NE-11-55 issued on September 14, 2011, FAA indicated that 100VLL is acceptable for use by all aircraft that require 100LL (or a lower MON) but as explained below this grade of avgas is not being produced. While 100VLL is not now available for purchase, the fact that it is specified by ASTM and has been approved for use by all piston-engine aircraft warrants its consideration as an existing fuel option.

A different ASTM standard, D7547, governs unleaded avgas, but it applies only to fuel grades with a MON rating of 94 or lower. Simply removing TEL from 100LL would result in a fuel with approximately 94 MON although some reformulation would be required to comply with all of the specifications of ASTM D7547. Currently the single grade of avgas that meets this standard, a proprietary UL94, is only available for sale in a select number of airports, mainly in the Midwest. There is currently no ASTM specification for an unleaded fuel having a MON higher than 94, nor has FAA approved such a fuel as an operating limitation of any engine or aircraft TC or STC. Following a short primer on the history of leaded avgas and how 100LL became prevalent, the status of these two other lower-lead and unleaded grades (100VLL and UL94) is discussed.

Convergence to 100LL Avgas

As noted above, TEL was found to be beneficial as an anti-knock agent in avgas during the 1920s. Indeed, by 1930 the U.S. Army Specification 3 referenced TEL in 80 MON fuel. At the time, however, virtually all piston-engine aircraft were satisfied with 80 MON avgas, with or without TEL. The development of high-performance combat aircraft in the 1930s drove the development of much higher octane avgas through the addition of TEL. 100 MON and even 115 MON grades were developed to satisfy engines with higher compression ratios and forced induction through turbocharging and supercharging.

Although initially introduced for military aircraft, higher performance engines were quickly adopted for civilian passenger and cargo aircraft to provide the higher payloads, greater range, and higher ceilings enabled by the 100 and 115 MON fuels. In 1947, the first ASTM specification (ASTM D910) for leaded avgas was introduced covering 91, 100, and 115 MON grades. By 1954, most avgas contained lead. In 1960, ASTM D910 included 80, 91, 100, 108, and 115 MON grades, all which were leaded, with a footnote referencing unleaded 80 MON at least until 1995.

During the1960s, most of the military and commercial air transport fleet had changed over from large piston-engines to turboprops and turbojets burning jet fuel, eliminating most of the demand for avgas grades with MON ratings exceeding 100 and substantially reducing demand for 100 MON by limiting the avgas market to GA mainly. By the late 1960s, the reduced consumption of avgas could no longer support the commercial production of multiple grades, each associated with separate requirements and infrastructure for production, distribution, storage, and dispensing. By 1972, the four existing grades of leaded avgas covered by ASTM D910 converged on one grade, 100LL, which became the de facto standard. No regulatory action was required because 100LL satisfied requirements for legacy aircraft, which were typically certified for 80 or 91 MON, as a minimum. This convergence permitted the use of a common avgas distribution system and one type of avgas storage tank and dispensing system at an airport to serve all gasoline-engine aircraft. Thus, even though many aircraft in the piston-engine fleet are able to use avgas grades with a MON lower than 100 (and thus with lower levels of TEL or no TEL) based on their applicable TCs or STCs, the grade of avgas offered for sale is generally limited to the universally usable 100LL.

Even with this convergence, 100LL avgas can be described as a boutique fuel when considered in terms of the total market for gasoline. For example, according to the U.S. Energy Information Administration (EIA), national automobile gasoline consumption averaged about 400 million gallons per day in 2019, while avgas consumption was less than 200 million gallons for the entire year (about 525,000 gallons per day), or the yearly avgas consumption was less than half of the daily consumption of automobile gasoline.[2] According to EIA, from 1981 to 2019 the demand for avgas (as measured by the amount of product supplied by the refineries) had dropped by nearly 60 percent (468 million gallons in 1981 to 197 million gallons in 2019).[3] Because of this decreased demand, fewer than 10 percent of some 120 North American gasoline refineries currently produce 100LL (NASEM, 2019), and only one chemical manufacturer supplies TEL, as the demand for this additive declined dramatically following the removal of lead from automotive gasoline.

100VLL Avgas

Concerns over the toxicity of TEL led to the addition to ASTM D910 of a second grade of 100 MON avgas, 100VLL, in 2011. As noted above, 100VLL has the same minimum allowable lead content as 100LL, but 100VLL has a maximum allowable lead content that is reduced by 19.6 percent. Undoubtedly, some 100LL fuel batches will meet the 100VLL standard because they do not exceed the upper limit, but they are not marketed as such. Indeed, samples of 100LL tested by the Coordinating Research Council (CRC) had an average lead content of 0.47 grams per liter (CRC, 2010), which is slightly higher than the maximum allowable lead content (0.45 grams per liter) for 100VLL.

100VLL fuel would satisfy every aircraft that currently operates on 100LL, as the minimum allowable lead content (0.28 grams per liter) of the two grades is the same. Therefore, total replacement of 100LL by 100VLL appears to offer an opportunity to reduce overall lead consumption in piston-engine aircraft, provided that fuel producers are able to meet the D910 specifications together with 100VLL's upper lead limit. However, 100VLL has not taken hold in the marketplace for reasons that are not entirely clear, but perhaps because there are no strong incentives to use the more expensive hydrocarbon blending components and meet the tighter tolerances needed to achieve 100 MON with less added lead.[4]

Unleaded Gasoline Alternatives

The drawbacks to the use of TEL in avgas, particularly its toxicity, have led to interest in lead-free fuels for aviation use. The two specific types of unleaded gasolines that are currently or potentially available for purchase today and permitted as operating limitations for some aircraft are a proprietary UL94 avgas and an appropriately formulated automotive gasoline, or MOGAS. This section starts with a discussion of UL94 and follows with a discussion of MOGAS.

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[2] See https://www.eia.gov/petroleum/data.php.

[3] See https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=mgaupus1&f=a.

[4] According to an FAA presentation to the committee on February 25, 2020, a higher quality alkylate may be needed, for example.

UL94 Avgas

Whereas the specifications for leaded avgas are contained in ASTM D910, the specifications for unleaded avgas are contained in ASTM D7547. Simply removing TEL from 100LL would result in a fuel with approximately 94 MON, although some reformulation would be required to comply with all the specifications of ASTM D7547. In 2011, FAA examined nearly 2,700 TC datasheets for every aircraft and engine type in the 2010 U.S. Aircraft Registry of 189,415 aircraft with piston engines to determine the mix of fuel specifications in the operating limitations (FAA, 2011). These aircraft, some dating from the 1930s, were produced by more than 2,600 manufacturers. While a review of about 500 of the TC datasheets indicated that they covered nearly 85 percent of the fleet, the remaining 15 percent required a review of more than 2,000 data sheets. From this analysis, FAA determined that approximately 43 percent of the piston-engine fleet requires a 100 MON grade avgas while approximately 57 percent could be satisfied with a 94 MON grade. This determination is sometimes used to support the notion that even if an unleaded lower octane avgas were to become widely available and used by a significant portion of the fleet, a 100 MON avgas would still need to be available to satisfy a large share (43 percent) of the fleet.

Several factors warrant consideration when assessing the potential for an unleaded, lower octane avgas to have an appreciable effect on aviation lead emissions. First, it should be noted that FAA's 2011 estimate of 57 percent of piston-engine aircraft being able to safely use a 94 MON avgas is based on fleet data that are now 10 years old and include aircraft that are no longer active. This time lag may be a minor consideration, however, because GA aircraft have long service lives and fewer than 1,000 new piston-engine aircraft enter the fleet annually, which means the active fleet, estimated in Chapter 2 to contain about 170,000 piston-engine aircraft, is not likely to have changed significantly over a decade. Second, and perhaps more importantly, many aircraft certified since the early 1970s specify only 100LL as the operating fuel in their TC because no other avgas grade was available for purchase when the aircraft was produced. It seems likely, however, that many of those aircraft are equipped with older-design, lower-power engines that had been originally certified for an 80 or 91 MON grade. If so, those aircraft could presumably be safely operated using a 94 MON fuel, although their operating limitations would need to be amended to permit the fuel's use. Consequently, it seems reasonable to assume that a share that is higher than 57 percent of the existing piston-engine fleet could use a 94 MON avgas.

Swift Fuels of West Lafayette, Indiana, is the only fuel manufacturer currently offering a UL94 grade based on a proprietary formulation.[5] The company has estimated that some 26,500 aircraft identified in the 2011 FAA study as requiring 100LL could in fact operate on UL94, and consequently about 68 percent of the current fleet (rather than 57 percent) could use this grade if allowed by an amended TC, STC, or applicable SAIB.[6] Indeed Swift Fuels sells STCs to owners of aircraft that are operationally capable of using UL94 but have a TC that does not explicitly identify UL94 as a permissible fuel.[7]

In 2016, FAA issued SAIB-HQ-16-05R1 clarifying that aircraft that require 80 and 91 MON can safely operate on UL94 avgas, and the bulletin also confirmed that aircraft types approved for UL94 under an earlier ASTM standard (D7592) could use UL94 grades that

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[5] See the Swift Fuels website at https://www.swiftfuelsavgas.com.

[6] Data supplied to the committee by Chris D'Acosta, Swift Fuels, March 16, 2020.

[7] See https://www.aopa.org/news-and-media/all-news/2020/march/10/swift-fuels-cuts-price-of-unleaded-avgas-stc.

conform to current ASTM D7547. Lycoming Engines, which is among the three largest producers of piston aircraft engines, has published a service bulletin (SI 1070) that specifies fuel compatibility for all of its engines.[8] According to this bulletin, approximately one-third of Lycoming's roughly 200 engine model variants can use unleaded avgas that meets ASTM D7547. Unfortunately, without knowing how many aircraft in the current fleet have these engine variants it not possible to translate this information into aircraft fleet counts.

The other current manufacturers of piston engines for aviation who have significant sales market shares are Continental Aerospace Technologies and Rotax. All current Rotax engines are approved to operate using 91 AKI (anti-knock index) unleaded automotive gas, which is essentially 87 MON. So as not to confuse aircraft owners, Continental has not published engine-by-engine guidance on the use of unleaded fuels, deferring to the airframe manufacturers who hold greater authority for fuels used in the aircraft they produce.[9]

One potential technical challenge for users of UL94, or any other unleaded gasoline, is finding a way to replace the often beneficial effect of lead on maintaining engine valve health. Lycoming explicitly requires a specific lubricity oil additive when using unleaded avgas, while Rotax recommends occasional modest 100LL use to provide lubrication. Continental's position is that its engines do not depend on TEL for valve lubrication and wear resistance, although it anticipates that certain proposed unleaded fuel formulations may drive changes in aviation lubricants while remaining compatible with the prevailing SAE J1899/J1966 standards.[10]

The uncertainty about the precise share of the piston-engine fleet that can operate on an unleaded 94 MON avgas is accompanied by additional uncertainty about the extent to which total 100LL consumption could be reduced by the use of this unleaded alternative by the eligible portion of the piston-engine fleet. The reason for uncertainty about the impacts on total consumption of leaded avgas is that 100 MON avgas is generally required by the higher performance aircraft in the fleet that are frequently described as the fleet's most heavily used and high-fuel consuming "working" aircraft. The Aircraft Owners and Pilots Association (AOPA) has estimated that these high-performance aircraft consume up to 70 percent of the total amount of 100LL sold annually (AOPA, 2010). Hence, if this estimate is accurate and remains relevant to the current fleet, then even if UL94 were used by all eligible aircraft, the reduction in leaded fuel consumption would be substantially smaller (on the order of 30 percent) than simple counts of eligible aircraft (57 or 68 percent of the fleet) would suggest is possible.

Nevertheless, even if aircraft that can use UL94 account for only about 30 percent of the 100LL consumed each year, there would be a proportional 30 percent reduction in lead emissions from their transition to UL94 and the co-benefit of savings to operators in engine maintenance due to less lead fouling.[11] As noted earlier, however, the challenge facing a producer of UL94, or any other fuel alternative, is that the avgas market is already small, making it potentially uneconomic to produce and widely distribute a second low-volume fuel that would have accompanying requirements for investments in new fuel storage and dispensing systems at many small airports.

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[8] See https://www.lycoming.com/service-instruction-no-1070-AB.

[9] Personal communication, Christopher Pollitt, Continental, April 28, 2020.

[10] Personal communication, Christopher Pollitt, Continental, April 28, 2020.

[11] This presumes leaded fuel is periodically used to ensure valve health.

MOGAS

The Statement of Task for this study requires an examination of the applicability to piston-engine aircraft of unleaded motor gasoline, presumed to be in reference to the MOGAS listed as an operating limitation in some aircraft STCs. While FAA has not defined MOGAS, it generally refers to the automotive gasoline that could be purchased by the aircraft owner at the time an STC was issued permitting the use of this octane fuel. MOGAS is identified as an operating fuel for thousands of aircraft in the current piston-engine fleet because of STCs approved some 40 years ago. At that time, automotive gasoline based on ASTM standard D439 was the fuel that would have been evaluated for the STC applications (FAA, 1980). It is important to keep in mind, however, that this standard is no longer valid and many changes have been made to automotive gasoline since the 1980s, raising questions about whether the MOGAS tested and approved for STCs many years ago is consistent with the automotive gasoline being produced and dispensed today.

The STC application process, as noted earlier, is a method to demonstrate that aircraft and engines can meet performance and safety objectives when using fuels other than those identified in the primary TC. Motivated by a desire to use less expensive automotive gasoline, several innovators and entrepreneurs in the aviation community performed the testing needed to secure FAA approval of STCs with a MOGAS fuel operating limitation using FAA AC 91-33A (FAA, 1984). Most of the MOGAS STCs were developed by the Experimental Aircraft Association (EAA) and Petersen Aviation in the early 1980s. Since that time, some 62,000 MOGAS STCs have been issued; 24,000 by EAA and 38,000 by Petersen Aviation.[12] The STCs were largely for aircraft and engines whose TCs specified 80/87 MON avgas, which had been widely available decades earlier but whose production had been phased out a decade earlier in favor of the universal 100LL grade. The gasoline produced for automobile use at the time (early 1980s) satisfied the 80/87 MON requirements for the aircraft that obtained MOGAS STCs. Thus, when many of the STCs were issued, MOGAS would have been the finished conventional premium gasoline (either unleaded or leaded[13]) commonly dispensed at automobile filling stations.[14]

During the 1980s when the MOGAS STCs were approved, ethanol was sometimes blended into automotive gasoline due to tax incentives and as an oxygenate to increase the octane rating of unleaded grades. Because alcohol is a polar solvent that attracts water, its addition to fuel can greatly increase the chances of fuel system corrosion, shorten the storage life of fuel, and lead to phase separation in the aircraft fuel tank causing potential vapor lock problems at altitude. Accordingly, ethanol-blended automotive gasoline would not have been permitted, and indeed, the MOGAS STCs require the user to exercise caution in ensuring the use of a fuel that is alcohol-free. However, ethanol blending was not required, and finished leaded and unleaded gasoline that was free of alcohol would have been available at many filling stations throughout the decade. Moreover, because the ethanol was usually added to the gasoline at bulk terminals before distribution to retail outlets, these terminals could have been the source of ethanol-free, pre-finished gasoline supplies for use in aviation, as long as the fuel met the properties (such as Reid Vapor Pressure [RVP]) and quality control requirements of the MOGAS STC.

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[12] See https://www.eaa.org/eaa/pilots/EAA-STC-Program/auto-fuel-stc.

[13] Conventional leaded premium gasoline contained up to 1.12 grams of lead per liter.

[14] Conventional gasoline is defined as finished motor gasoline not including oxygenated or reformulated gasolines.

Given that more than 60,000 aircraft received MOGAS STCs during the 1980s, tens of thousands are likely to remain in the fleet today. However, much has changed in the automotive fuels market since these STCs were approved in the 1980s. A revised automotive gasoline standard, ASTM D4814, was introduced in 1988 and replaced ASTM D439. This new specification accounted for the blending of oxygenates.[15] FAA approved D4814 as a "non-applicable ASTM fuel specification," which permits it to be identified as an operating limitation for fuel in a TC or STC. However, according to FAA A/C 20-24D, TC and STC holders must apply for an amendment each time the revision number changes for an ASTM standard. Because D4814 did not exist at the time the MOGAS STCs were approved, fuels that conform to the standard do not necessarily meet the STC's operating limitations.

The applicability of MOGAS as an aviation fuel option has decreased even more over the past 30 years because of further developments in the automotive fuels market. Of particular significance were new EPA regulatory requirements implementing the Clean Air Act Amendments of 1990 that would have marked effects on the composition and physical properties of automotive gasoline starting in the mid-1990s (Martel, 1995). Not only did the requirements cause changes in the composition of finished automotive gasoline, but they also led to changes in intermediate refinery stocks. The new intermediate products, known as CBOB (conventional gasoline for oxygenate blending) and RBOB (reformulated gasoline for oxygenate blending),[16] were formulated specifically to address the effects of ethanol in increasing RVP and octane. For example, a 10 percent ethanol blend will increase RVP by about 1 psi (from a 9 psi base gasoline) and increase octane by about 3 octane numbers of the anti-knock index (AKI) used for automotive gasoline (slightly less for MON) (Bailey and Russell, 1981). Accordingly, CBOB and RBOB refinery stocks were formulated to have a lower MON and RVP to account for the effects that ethanol would have on these properties when blended to produce the finished gasoline dispensed at filling stations. Accordingly, even refinery products could no longer be generally relied on as a source of MOGAS by the end of the 1990s.

The composition of automotive gasoline was further impacted by the Renewable Fuel Standard (RFS) created under the Energy Policy Act of 2005 and amended by the Energy Independence and Security Act of 2007. The RFS program is a national policy that requires a certain volume of renewable fuel be used per year to replace or reduce the quantity of petroleum-based transportation fuel, heating oil, and jet fuel. To meet the program's requirements, which do not apply to avgas or gasoline used for non-highway applications, ethanol is blended at 10 percent in essentially all dispensed automotive gasoline.[17] As a result, the supplies of unleaded automotive gasoline grades that are widely available at filling stations today are substantially different from the supplies that were widely available when thousands of MOGAS STCs were approved 40 years ago to take advantage of the lower-priced automotive gasoline.

According to the website AiRNav, 87 fixed base operators (FBOs) dispensed a fuel said to be "MOGAS (auto)" (and thus presumably unleaded) during August and September 2020,[18] or about 2.5 percent of the more than 3,572 FBOs reported to be dispensing 100LL. AiRNav also reported that the price of this unleaded fuel averaged about $1 per gallon less than the price of 100LL. However, neither the validity of this count nor the properties of this fuel, including its

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[15] ASTM Standard D4814-20a, Standard Specification for Automotive Spark Ignition Engine Fuel.

[16] See 40 CFR 80.2.

[17] In 2006 U.S. EPA removed the regulatory requirement that reformulated gasoline have 2.0 percent oxygenate by weight. See 71 FR 26691, May 8, 2006.

[18] See http://airnav.com/fuel/report.html as of September 16, 2020.

full and consistent compliance with the operating limitations of aircraft that may be using it, could be assessed for this study.

ANALYSIS OF EXISTING FUELS TO REDUCE LEAD

Current lead emissions from avgas are estimated by EPA to be about 468 tons per year.[19] Considering the three fuels that are discussed above as possible pathways to reducing these emissions, namely UL94, MOGAS, and 100VLL, there remain technical, regulatory, and market challenges that differ in each case. A significant challenge for the first two unleaded options (UL94 and MOGAS) is that they would still require significant use of 100LL or 100VLL to accommodate high-performance aircraft, and thus would require the production, distribution, storage, and dispensing of at least two aviation fuels, each in smaller quantities than 100LL today. As has been noted, by the early 1970s the avgas market had shrunk to the point that it was economically feasible to support only one avgas grade (100LL), even though GA fuel demand was about twice as large as it is today. Moreover, FAA now forecasts that demand for avgas will decline about 0.6 percent per year through 2040.[20] This downward trend in avgas consumption, if it happens as forecast, would produce its own reductions in lead emissions of about 10 percent in 20 years. However, the same downward trend in fuel demand would also make a dual-fuel option even less viable economically because it would need to be accompanied by investments by fuel suppliers and airports in additional fuel production, distribution, storage, and dispensing capacity.

MOGAS as a Mitigation Option

From a retail perspective, the most widely available lead-free gasoline is automotive gasoline. When considering the potential for this fuel alternative to reduce lead emissions from aviation, however, this outcome seems questionable for several reasons. As discussed above, the formulations and grades of finished automotive gasoline as they existed 40 years ago (87 and 91 AKI or 83 and 87 MON) when STCs were approved to permit the use of MOGAS have essentially disappeared. The automotive gasoline that is dispensed today almost invariably contains at least 10 percent ethanol, detergent additives, and significant variations in RVP.

Some refiners and blenders may have access to or be able to create the alkylate-blend stocks needed to reformulate a portion of the CBOB and RBOB stocks used for premium automotive gasoline to make these supplies suitable for piston-engine aircraft (i.e., a product with AKI of 87 or 91 or 83 or 87 MON developed under ASTM D7547). However, that unleaded product specifically amended for aviation use would no longer be the same mass produced, widely available, and relatively inexpensive fuel that prompted interest in using automotive gasoline when the MOGAS STCs were approved decades ago. In this regard, the pursuit of such a niche, aviation-tailored fuel would seem to offer no economic advantage over the unleaded avgas grade (e.g., UL94) now available. The investments that would be needed for the significant

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[19] 2017 National Emissions Inventory. Note that this estimate of lead emissions may be high, as EPA assumes that all 100LL avgas contains the maximum amount of TEL permitted by ASTM, or 0.56 grams per liter. CRC (2010) reported that the average lead content of 100LL is 0.47 grams per liter, which would reduce the EPA estimated annual total to 393 tons. However, the higher EPA estimate is used as a baseline here.

[20] See Table 31 of "FAA Aerospace Forecast FY 2020-2040" at https://www.faa.gov/data_research/aviation/aerospace_forecasts.

changes required at the refinery or blending facilities to make such a suitable MOGAS, and the added downstream requirements for distribution and storage, suggest that interest in supplying another lower octane gasoline for aviation that is derived from automotive gasoline stocks is likely to be negligible.

It merits noting that in 2015, EIA estimated that about 5.3 billion gallons per year of ethanol-free (E0) gasoline were provided to final consumers.[21] Setting aside questions about the logistics and distribution of these stocks for aviation access, this volume greatly exceeds what would be needed to meet any MOGAS demand by GA. It is possible that this reported volume was an unused blending component for regular, mid-grade, or premium gasoline or some other refinery stream. However, the MON and RVP of this ethanol-free fuel are not known. Thus, even if similar volumes exist today and a diligent purchaser is able to find an ethanol-free gasoline that is commercially available locally, the product's qualities such as RVP, octane, and additive packages may not be readily known, and therefore its compliance with MOGAS STC requirements would not be assured. It is important recognize the high level of quality control associated with all aviation products, including aviation fuel, which is sampled and checked for conformance to specifications at multiple points in the supply chain. Supplies of MOGAS do not have these quality controls.

UL94 as a Mitigation Option

The expanded availability of an unleaded 94 MON fuel holds more promise than MOGAS as an approach for reducing lead use because this fuel is already approved for use by many aircraft and has the potential to be approved for use by more. Its use by the lower-performance aircraft in the piston-engine fleet would not eliminate lead entirely but could reduce the amount of lead consumed substantially, on the order of 30 percent (as calculated using the assumptions above) if made widely available and purchased by operators of all eligible aircraft. A proprietary UL94 developed by at least one manufacturer (Swift Fuels) that is compliant with ASTM 7547 already exists in the marketplace, albeit in only a fraction of potential refueling locations (fewer than 100 airports). Because any transition to this fuel would require a change in operating limitations, many aircraft owners interested in using it would need to obtain an STC. The requirements to demonstrate that such a proposed fuel change would not adversely affect safety of flight are understandably onerous, and thus potentially expensive for those owners of aircraft not already certified for UL94. As a result, Swift has developed STCs that can be purchased at nominal cost by owners of many aircraft types. It is notable that Section 565 of the FAA Reauthorization Act of 2018 authorizes FAA to permit the use of unleaded fuel in aircraft certified on leaded fuel in cases where the aircraft can operate safely on the unleaded alternative. Presumably, this authority could be used to streamline the regulatory process to allow widespread use of unleaded fuels such as UL94 without requiring individual STCs.[22]

If every aircraft that could use UL94 did use this unleaded grade, perhaps 57 to 68 percent of annual fleet lead emissions would be removed, or 267 to 318 tons from the annual baseline of 468 tons cited above. However, if previously cited AOPA estimates are correct (i.e., the residual 32 to 43 percent "working" fleet burns as much as 70 percent of the 100LL),

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[21] See https://www.eia.gov/todayinenergy/detail.php?id=26092.

[22] In addition to an appropriate STC, suitable placarding and directions to maintain valve seat health may be necessary. For example, valve seat health could probably be maintained with the occasional use of 100LL as long as it remains available, or the use of oil lubricity additives, such as those specified by Lycoming.

reductions in lead emissions would be about 140 tons. In either case, of course, the availability of UL94 would need to be almost universal if it were to be used by all eligible aircraft, and therefore nearly all airports that serve a wide variety of GA aircraft would need supplies of the fuel on site for dispensing. As a result, one would expect the lead reductions to be lower than calculated, under the assumption that many small airports would not have capacity to dispense UL94, which might only be available at larger airports that have the financial capability and economic incentive to add the needed fueling capacity.

It merits noting that these estimates of lead reductions from using UL94 do not consider the period over which the transition to this fuel would occur. Keeping in mind that overall consumption of avgas is expected to decline over the next two decades as a result of reduced GA activity generally, the annual lead tonnage reductions attributable to the transition to UL94 would be smaller in absolute terms the further out in time this transition begins.

100VLL as a Mitigation Option

For the past decade, 100VLL has been approved for use by all aircraft that require 100LL or an avgas with a lower MON. Its availability for purchase could therefore bring about a meaningful reduction in lead emissions because the entire fleet could use it without any STCs, subject to the ability of the refiners to produce 100VLL within its more tightly specified lead additive range. In being universally usable, 100VLL would not require any new investments in fuel storage and dispensing capacity if it were to replace 100LL at all airports or even some airports. Misfueling or comingling of 100LL and 100VLL would not be a concern for operators of high-performance aircraft as they would for a leaded fuel being accompanied by a lower octane unleaded grade.

As noted earlier, the average lead content of 100LL has been found to be 0.47 grams per liter. The average lead content of 100VLL cannot be determined because it is not being produced. However, if it is simply assumed that the average lead content of 100VLL would be 19.6 percent lower than 0.47 grams per liter (consistent with the 19.6 percent lower maximum allowable lead content in 100VLL), then the average lead content for 100VLL would be about 0.36 grams per liter [0.47 – (0.196 × 0.47)]. If 100VLL were to replace 100LL entirely, then one would expect a corresponding 19.6 percent reduction in the amount of lead emissions from avgas consumed across the piston-engine fleet. A 19.6 percent reduction in lead emissions, using the baseline of 468 tons per year referenced above, would yield a reduction of 92 tons per year. As noted earlier, these annual tonnage reductions would depend on the timing of the transition of 100VLL, because total lead emissions will decline also as a result of long-term reductions in GA activity.

An advantage of transitioning to 100VLL is that it could yield appreciable reductions in lead use without dividing the already small avgas market or requiring new investments in fuel supply infrastructure. However, if a switch to 100VLL were accompanied by a switch to UL94 by all aircraft that can use it, much larger lead reductions could be achieved. Even if one assumes that 70 percent of all avgas is consumed by high-performance aircraft that require 100 MON, their use of 100VLL with 19.7 percent lower lead content than 100LL would still result in a 13.7 percent reduction in total lead use (0.7 × 19.6). When added to the 30 percent reduction in lead use that might be achieved by the remaining share of fleet that fully transitions to UL94, the total reduction could exceed 40 percent, or about 205 tons of lead per year.

FINDINGS AND RECOMMENDATIONS

While the downward trend in GA activity should yield gradual reductions in lead emissions from avgas consumption, larger reductions will require lower-lead or unleaded fuel alternatives to 100LL. Because the activity of the piston-engine fleet has been declining by an average of 1.6 percent per year during the past four decades and is expected by FAA to continue to decline by 0.6 percent per year during the next two decades,[23] total lead use by the GA sector has been on a modest downward trajectory and is projected to be 10 percent lower within 20 years (Finding 5.1).

100VLL is the only currently ASTM-specified fuel other than 100LL that could be used by all piston-engine aircraft in the existing fleet. The upper lead limit of 100VLL is 19.6 percent lower than the upper limit in 100LL. Fleetwide use of 100VLL, therefore, offers a potential means of reducing total lead emissions from avgas by an amount approaching 20 percent. However, 100VLL is not currently being produced, presumably because there are no regulatory requirements or apparent economic incentives for fuel producers to supply fuel that can meet the tighter lead ranges in its ASTM standard (Finding 5.2).

At least 57 percent, and perhaps as much as 68 percent, of the current piston-engine fleet could use UL94, which is the only existing grade of unleaded avgas. However, this outcome would require special FAA certifications for some aircraft. The eligible fleet consists mostly of smaller, lower-performance aircraft that are not used as frequently as the higher-performance fleet that requires leaded avgas. Therefore, the reduction in leaded avgas use from making UL94 widely available is not likely to be proportional to the large share of lower performance aircraft in the fleet. Nevertheless, if all these aircraft were to use UL94, lead emissions would be reduced by an estimated 30 percent. In addition, if higher-performance aircraft were to use 100VLL, reductions in lead emissions would exceed 40 percent (Finding 5.3).

An unleaded fuel, such as UL94, approved for only part of the piston-engine fleet would require creating a second supply chain and fuel distribution system across the nation. Such a fragmentation of avgas supplies into two grades that are each produced in lower volumes could also lead to higher avgas prices due to the loss of scale economies. Furthermore, the cost for airports to add storage and distribution facilities for a second fuel could be significant and potentially prohibitive, especially for small airports. Consequently, widespread availability of UL94 might be overly optimistic, and more likely to be restricted to a portion of airports that have or can afford to add the required fueling facilities (Finding 5.4).

Automotive gasoline formulations are no longer a viable option for reducing lead emissions from the piston-engine fleet. Thousands of piston-engine aircraft were approved during the 1980s to use automotive gasoline formulations—loosely called MOGAS—that were then deemed to be safe substitutes for low octane avgas grades (80/87 MON) permitted by the aircraft's original TCs. However, the composition of automotive gasoline has changed considerably during the past 30 years, particularly to include ethanol blends that are not compatible with almost all aircraft engines (Finding 5.5).

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[23] See Table 31 of "FAA Aerospace Forecast FY 2020-2040" at https://www.faa.gov/data_research/aviation/aerospace_forecasts.

> FAA should research public policy options, which could be implemented as quickly as possible at the federal and state levels as well as by Congress, for motivating refiners to produce and airports to supply 100VLL. The objective would be to reduce lead emissions from the entire piston-engine fleet while unleaded alternatives are being pursued for fleetwide use (Recommendation 5.1).
>
> FAA should research public policy options that will enable and encourage greater use of available unleaded avgas by the portion of the piston-engine fleet that can safely use it. Possible options include (a) issuing a Special Airworthiness Information Bulletin that will permit such use and (b) providing airports with incentives and means to supply unleaded fuel, particularly airports that are eligible for FAA-administered federal aid as part of the National Plan for Integrated Airport Systems (Recommendation 5.2).
>
> A mechanism should be established for facilitating the increased availability of existing grades of unleaded avgas across the fleet of piston-engine aircraft. Fulfilling that need would likely require congressional involvement, such as by providing incentives for pilots to use existing unleaded avgas and for more small airports to add requisite fuel storage and dispensing capacity (Recommendation 5.3).

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Potential Future Lead-Free Fuels and Propulsion Systems

The previous chapter considered the potential for replacing the almost universally used 100LL grade of aviation gasoline (avgas) with other avgas grades that are lead-free or have lower lead content and that are currently available for purchase at some airports (i.e., a proprietary UL94), or at least specified in an American Society for Testing and Materials (ASTM) standard (i.e., 100VLL). A conclusion from the analyses in Chapter 5 is that a reduction in lead emissions by nearly 20 percent, but possibly more than 40 percent, is plausible from these existing unleaded and lower-lead alternatives when used in varying combinations by the current piston-engine fleet. Consideration was also given to the potential for substituting widely available grades of unleaded automotive gasoline based on approvals during the 1980s for thousands of piston-engine aircraft to use motor gasoline (MOGAS). However, gasoline formulations that would meet the specifications of those engines and aircraft certified for MOGAS can no longer be obtained in the automotive fuel market and are unlikely to become available in the future.

The higher end of the lead reduction range (e.g., a roughly 40 percent lead reduction) from replacing 100LL would require the substitution of this grade by100VLL and potentially large and widespread airport investments in new fuel storage and dispensing capacity to make UL94 available to those aircraft that can use it. As a practical matter, such investments may not be forthcoming in a general aviation (GA) industry characterized by many small airports with limited capital and a total avgas demand that is already very small, projected by the Federal Aviation Administration (FAA) to decline further, and difficult to subdivide economically into specialty grades. Whether pilots would be motivated to use UL94 is another matter, and a potential obstacle to its increased use if aircraft owners need to expend considerable time, money, and effort to obtain the needed FAA certifications.

A solution, at least conceptually, to the vexing problem of having to supply and motivate the use of two avgas grades—one leaded and one unleaded—is to develop and introduce a lead-free, high-octane avgas that can meet the needs of the entire piston-engine fleet and can fully and quickly replace 100LL (or 100VLL). Currently there is no ASTM specification for an unleaded fuel with a motor octane number (MON) above 94, much less a 100 MON or higher, nor has one been approved in an engine aircraft type certificate. Moreover, even an unleaded fuel that has a 100 MON rating may not satisfy the requirements of some high-performance legacy aircraft that are only able to operate on a leaded fuel having a 100 MON rating because the tetraethyl lead (TEL) additive, as discussed below, provides an anti-knock “bonus” that may be equivalent to several additional octane numbers. Accordingly, the actual MON of an unleaded replacement fuel may need to exceed 100 (i.e., 100+ MON).

A full replacement for 100LL/VLL is sometimes referred to as a “drop-in” fuel because it would not require any changes to the existing piston-engine fleet, new FAA certification approvals, modifications to future engines and aircraft, or new investments in fuel storage and dispensing capacity.[1] This ideal means of lead mitigation, however, presents formidable technical challenges. To convey these challenges, the chapter considers findings from past research on octane-enhancing TEL alternatives and the history and accomplishments of the

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[1] The transition to a drop-in fuel could nevertheless require steps to prevent inadvertent mixing of the fuel with residual leaded grades in aircraft fuel tanks and airport fueling systems.

FAA's Piston Aviation Fuels Initiative (PAFI) collaborative with fuel suppliers and the GA industry. PAFI was created in 2013 for the specific purpose of hastening the development and availability of an unleaded 100+ MON avgas that can satisfy the entire piston-engine fleet without introducing new adverse safety, environmental, or health impacts. To date, however, the collaborative has not yielded the desired drop-in fuel.

Following the discussion of PAFI, and what has been learned more generally about the challenges associated with developing and deploying a satisfactory unleaded, high-octane fuel, consideration is given to retrofitting existing GA aircraft and changing the future fleet so that more aircraft can use existing grades of unleaded avgas or other lead-free sources of energy. While technology refinements are making some traditional lead-free propulsion systems, such as diesel and gas turbine engines, better suited to small aircraft, continued advances in battery- and hybrid-electric motor technologies also hold promise for farther-out applications. An uncertain development and implementation pathway that is likely to take decades to transition the legacy fleet suggests that waiting for fundamentally different small aircraft technologies to solve the aviation lead problem would be a mistake. Nevertheless, successive generations of new GA aircraft that do not require leaded avgas could make transitioning away from leaded avgas more manageable.

SEARCHING FOR AN UNLEADED 100+ MON AVGAS

Following passage of the Clean Air Act Amendments in 1990, the U.S. Environmental Protection Agency (EPA) issued regulations to eliminate lead from the gasoline used in on-road engines and vehicles. Although avgas was excluded from the new requirements, concerns about the potential for future actions prompted FAA to undertake more concerted investigations of unleaded fuel formulations at its William J. Hughes Technical Center starting in the mid-1990s (UAT ARC, 2012). In more recent years, as EPA has continued to assess the public health risks associated with lead and the possibility of restricting the use of leaded avgas, FAA has intensified efforts to understand and overcome technical challenges that have hindered the development of a universally usable unleaded avgas.

Technical Challenges with Unleaded, High-Octane Fuel Formulations

Decades of research have revealed many technical challenges to the development and introduction of an unleaded avgas offering 100+ MON, particularly in finding a suitable chemical additive in a gasoline formulation that provides the required octane level and knock resistance. Major categories of octane-enhancing additives to gasoline are aromatics, oxygenates, aromatic amines, and metals, each of which brings its own set of technical issues and formulation requirements. After screening more than 250 combinations of additives and gasoline formulations during the 1990s and early 2000s, researchers using FAA's fuel and engine testing facility conducted full-scale engine testing on nearly 50 of the most promising blends. However, when the octane-enhancing additives were used in quantities needed for anti-knock performance, the blends could not meet all other essential performance requirements for properties such as vapor pressure, hot and cold starting capability, material compatibility, water separation, storage stability, freeze point, and toxicity (CRC, 2010).

Table 6-1 lists the main categories of octane-enhancing additives in fuel alternatives examined, gives some specific examples of additives, and notes advantages and disadvantages associated with each example as cited by FAA.[2] A major disadvantage cited, particularly for the non-metals, is assuring material compatibility. Aircraft fuel systems, from the tank to the carburetor or fuel injector, have many rubber components, synthetic elastomers, sealants, carbon fiber, composite components, and surface treatments that are potentially susceptible to damage by fuel additives. Ensuring material compatibility, however, is further complicated by the demographics of the legacy fleet. Because the average age of aircraft in the piston-engine fleet is about 50 years, many of the manufacturers of the aircraft and their engines and components no longer exist, and their material specifications have been lost to history. Other disadvantages, as listed in the table, involve concerns about toxicity, groundwater contamination, and fouling of engines and other aircraft components, particularly for metals that otherwise offer good anti-knock performance.

TABLE 6-1 Examples of Octane Enhancers in Fuel Alternatives Under Development to Replace TEL in Avgas

Category	**Examples**	**Advantages**	**Disadvantages**
Aromatics	Toluene, Mesitylene	Low toxicity	Known combustion issues, exhaust sooting, some material incompatibility concerns.
Oxygenates	Ethyl tert-butyl ether (ETBE), Methyl tert-butyl ether (MTBE), Ethanol	Good octane enhancer	Aircraft range impacts, potential groundwater contamination, water solubility, odor, restrictions on transportation across some state lines.
Aromatic Amines	Aniline, m-Toluidine	Good octane enhancer	Aggressive toward elastomers, polysulfide sealant, fuel bladder, and some paints. Engine deposits may be an issue, possible cold-flow issues.
Metals	Methylcyclopentadienyl manganese tricarbonyl (MMT)	Good to excellent octane enhancer. Compatible with most materials. Most similar to TEL additive in existing 100LL.	Toxicity concerns, issues with engine deposits, plug fouling, and UV sensitivity. Approved for use in small quantity in auto fuel.

SOURCE: Adapted from FAA presentation to committee, November 2019.

As noted above, candidate additives may also fall short in their ability to fully replace TEL's anti-knock enhancement in excess of 100 MON. While 100 MON is widely used as a shorthand for satisfactory detonation avoidance, there is evidence that the presence of lead in 100LL grants some additional detonation margin over a lead-free 100 MON grade. For instance, a 2010 study by the Coordinating Research Council (a petroleum and automotive equipment

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[2] FAA presentation to the committee, November 19, 2019.

industry collaborative), which was informed by work at FAA's Technical Center, concluded that high-performance engines (depending on power output and configuration) can require unleaded fuels in excess of 100 MON to achieve knock-free operation and that the added resistance of TEL may be as high as 3 MON (CRC, 2010).

If these and other technical challenges can be met to identify a qualifying unleaded 100+ MON fuel, development of an ASTM specification would be a required next step, followed by aircraft and engine types needing to be certified to use the fuel. Testing performed to identify the fuel would aid in the development of the ASTM specification and inform FAA certification. The latter could be hastened appreciably by the recent authority granted by Congress (under Section 565 of the 2018 Reauthorization Act) for FAA to permit broad-based authorizations of a satisfactory unleaded fuel. Once these authorizations are granted, aircraft and engine manufacturers could update their service recommendations to include the new fuel alternative.

Even with expedited approvals for the use an unleaded 100+ MON avgas, the deployment of the unleaded fuel could require major changes to fuel refining processes that will take time and investments to implement. If those requirements are accompanied by a need to use more expensive fuel ingredients this could have implications on the fuel's price, availability, and competitiveness of production, especially if there are proprietary aspects. Additionally, transitional steps would need to be taken while the limited amount of refining and refueling infrastructure is converted from a leaded to an unleaded fuel distribution, storage, and dispensing system. In the case of the automotive sector, for instance, the downstream conversion from leaded to unleaded gasoline was made easier by most filling stations having multiple dispensers and underground storage tanks, allowing both fuels to be offered simultaneously. As discussed in the previous chapter, similar redundancy does not exist throughout much of the aviation sector.

PAFI Collaborative

After nearly two decades of searching for an unleaded drop-in avgas without success, in 2012 FAA established the Unleaded Avgas Transition Aviation Rulemaking Committee (UAT ARC) comprised of GA trade and membership associations, aircraft and engine manufacturers, fuel producers, and EPA.[3] In doing so, FAA acknowledged that the development and deployment of a satisfactory and safe drop-in avgas would require a coordinated public- and private-sector effort. In response, UAT ARC recommended the use of FAA's Technical Center for centralized testing of candidate fuels offered by developers accompanied by a deliberate process for soliciting and selecting the fuels to be tested. A purpose of centralized testing was to generate standardized qualification and certification data that could be used to support development of ASTM specifications and FAA fleetwide certifications, thereby eliminating potentially redundant testing and shortening the time for fuel development and mass introduction. UAT ARC further recommended that FAA establish a technical review board to evaluate the feasibility of the candidate fuels and a special fuels program office dedicated to implementing the recommendations through the creation of an FAA-industry collaborative, which became PAFI.

In response to these recommendations, in June 2013 FAA issued a solicitation for proposers of unleaded fuels to participate in the testing program and formed a government-industry PAFI Steering Group to establish fuel evaluation and testing protocols and to coordinate and oversee the evaluation program. Fuel developers were given 1 year to submit data packages for fuel formulations for prescreening based on considerations such as chemical makeup,

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[3] See https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/UATARC-1312011.pdf.

performance properties, emissions, toxicology properties, and projected production and distribution potential. The plan called for a year-long Phase 1 evaluation in which fuels that passed the prescreening criteria (focused on identifying unacceptable flaws) would be subject to laboratory and rig testing at the Technical Center and two or three of the most promising candidates would be selected for Phase 2 evaluations that would involve testing on specific and representatively configured engine and aircraft models to assess their suitability across as much of the existing piston-engine fleet as possible. The ambitious aim of Phase 2, expected to take about 2 years to complete, was to generate data for development of an ASTM specification and to certify most of the existing fleet to operate on the fuel. FAA formed a technical committee to serve as the primary evaluator of the fuels, with guidance and technical input from an advisory committee of aircraft and engine manufacturers.

According to periodic FAA updates posted on its website[4] and provided in study committee briefings, PAFI received 17 fuel proposals from six fuel developers by August 2014. By January 2016, prescreening and Phase 1 testing was completed, and two fuel formulations, one from Shell[5] and another from Swift Fuels,[6] were selected to participate in Phase 2's extensive tests on about 15 engine and 10 aircraft models. In June 2018, FAA reported that Phase 2 testing of the two formulations, which began in mid-2016, was being suspended with the aircraft test program approximately one-third complete and the engine test program about halfway complete. Because of proprietary agreements in the PAFI process, FAA was not able to report the specific reasons for the suspended testing but noted unacceptable aspects of the two fuels that required the fuel suppliers to conduct further research and development to find solutions.

In early September 2018, FAA announced that Swift Fuels had decided to pursue the development and testing of its candidate fuel outside the PAFI structure. FAA further announced that Shell's efforts to mitigate the issues identified in Phase 2 testing appeared promising and that Phase 2 testing would resume, including testing on material compatibility, durability, detonation, and performance issues, before additional aircraft testing would be conducted. However, in June 2019 FAA reported that engine test results with the optimized Shell fuel were not successful and that additional refinements to the fuel would be required before testing could resume.

In reporting the status of the testing of Shell's fuel, FAA pointed out that the PAFI experience had further revealed the magnitude of the technical challenge in finding an acceptable unleaded drop-in fuel.[7] The agency announced that the scope of PAFI would be expanded to support the needed fuels research and development while also attracting developers of other candidate fuels for evaluation, including fuel formulations not proposed during the original 2013 solicitation. In its August 2020 PAFI update, FAA reported that developers of new fuels would be asked to complete the following prescreening tests prior to a proposed fuel being accepted for more extensive testing through PAFI:

- Successful completion of a 150-hour engine endurance test on a turbocharged engine using PAFI test protocols or other procedures coordinated with FAA;

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[4] FAA updates on PAFI progress are available at https://www.faa.gov/about/initiatives/avgas.
[5] See https://www.shell.com/business-customers/aviation/aviation-fuel/avgas.html.
[6] See https://www.swiftfuels.com/swift-100r.
[7] See https://www.faa.gov/about/initiatives/avgas.

- Successful completion of an engine detonation screening test using the PAFI test protocols or other procedures coordinated with FAA; and
- Successful completion of a subset of the material compatibility tests using the PAFI test protocol or other procedures coordinated with FAA.

FAA has offered the Technical Center's engine testing services to developers to perform these prescreening evaluations, with testing tentatively scheduled to resume in 2021 depending on developments with the coronavirus pandemic. FAA has also continued to emphasize that it stands ready to support other fuel applicants who have decided to pursue engine and airframe approvals that would allow the use of their fuel formulations through traditional certification processes separate from PAFI.[8]

During this study, the committee became aware of at least two initiatives in addition to those of Shell and Swift Fuels to develop an unleaded 100 MON fuel. Phillips 66 and Afton Chemical are developing a fuel that contains manganese to replace TEL, a proprietary scavenger formulation, and an antioxidant.[9] LyondellBassel is also developing an unleaded high-octane fuel. In addition, General Aviation Modifications, Inc. (GAMI) claims to be developing a fuel formulation intended to replace 100LL.[10] However, the committee could not find publicly reported technical information on GAMI's fuel or its development status. During the summer of 2020, Swift Fuels announced that FAA certification testing and ASTM fuel specifications were in progress for an unleaded 100 MON fuel, named 100R.[11] However, details on the fuel and its testing status are not publicly available for review.

ENGINE MODIFICATIONS AND CONVERSIONS FOR UNLEADED AVGAS

As discussed in Chapter 5, FAA has estimated that 43 percent of the existing piston-engine fleet cannot be operated safely using an avgas grade that has an octane rating lower than 100 MON. For at least a subset of these high-performance aircraft, it seems likely that it would be technically possible to engineer changes to their engines to enable operations with unleaded, lower octane avgas, such as through modifications to lower the compression ratio coupled with ignition calibration changes. Several modern high specific-output turbocharged engines are certified for operation using UL94, such as the Continental TSIO-550K[12] and Rotax 914 and 915 series (which can use an 85 MON fuel),[13] which suggests it would be technically feasible to retrofit at least some aircraft in the legacy fleet. In such cases, a challenge would be to limit any penalty to payload, range, ceiling, and runway performance that would discourage conversion investments by the aircraft owner. Ensuring safety, of course, is paramount, and any planned retrofit would require the aircraft owner to undertake the necessary testing to obtain an FAA supplemental type certificate (STC). Where conversions to a lower performance engine raise safety issues, such as by reducing performance during critical phases of flight (e.g., takeoff), the technical challenge of obtaining approval for a retrofit could be formidable.

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[8] See https://www.faa.gov/about/initiatives/avgas.

[9] See https://www.phillips66aviation.com/about-us/news/industry-news/focused-on-the-future-of-avgas-ul100-qa.

[10] See https://gami.com/g100ul/g100ul.php.

[11] See https://www.swiftfuels.com/swift-100r.

[12] See http://www.continental.aero/uploadedFiles/Content/Engines/Gasoline_engines/550AvGas-SpecSheet.pdf.

[13] See https://www.flyrotax.com/produkte/detail/rotax-915-is-isc-2.html.

Considering that any re-engine program would be both costly to the owner and technically challenging to implement, lower-cost retrofit options may deserve exploration. One such option is an anti-detonation injection (ADI) device that injects a water-methanol mixture into the induction system to cool the combustion event during very high load operating conditions, such as takeoff and initial climb. The ADI concept is decades old, once employed by several piston-engine military aircraft.[14] During the 1980s, FAA granted a number of ADI STCs for families of aircraft and engines (e.g., IO-470 and IO-520 families, Cessna 188 and 210, Beech Baron)—and examples of these aircraft with STCs remain in the fleet today. Originally marketed as a way to use less expensive automotive gasoline, ADI systems are still available and thus could enable the safe use of unleaded 94 MON fuel in at least some aircraft that otherwise require 100 MON. ADI conversion kits can be purchased and installed at a fraction of the cost of a full engine retrofit, but would nevertheless require outlays for the testing required to obtain the needed STC.

By and large, the major investments required for development, testing, and installation suggest that an engine retrofit program targeted to an aging legacy fleet would not appear to be a promising way to reduce aviation lead. Considering that if fuel developers are successful in introducing an unleaded 100+ MON avgas, then some of these large investments in engine retrofits will have been made for naught. An additional factor that may warrant consideration in assessing this option is the incentive structure created by the General Aviation Revitalization Act of 1994 (P.L. 103-298).This legislation addressed the substantial impact of product liability litigation on GA aircraft and engine manufacturers, and the resulting increases in the price of aircraft. The act set a limit of 18 years on product liability claims post-purchase, but one provision is that this 18-year liability period is reset for manufacturers of the installed modifications.[15] Hence if a major retrofit were performed on any aircraft built more than 18 years ago, which is the vast majority of the legacy fleet, owners of these older, modified aircraft could pursue liability claims, and owners of newer aircraft that are modified could have an extended product liability period. Such new and extended liabilities could limit manufacturer interest in retrofit programs.

As an aside, the conversion of the motor vehicle fleet in the United States to unleaded gasoline during the 1980s and 1990s might be viewed as a model for converting the piston-engine GA fleet from leaded avgas to unleaded alternatives. For reasons explained in Box 6-1, however, the factors that prompted and enabled this conversion for automotive vehicles do not have strong parallels in the GA sector, particularly because of the need for backward avgas compatibility, the higher rate of automotive fleet turnover, and the large size of the automotive fuel market. Retrofitting existing motor vehicles was not necessary because of rapid turnover and the ability of older vehicles to run on unleaded gas without safety issues.

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[14] Todd Petersen. Unpublished document. Anti-Detonation Injection & Low Octane Fuel. See https://www.flyinpulse.com/user/file/73220.pdf.

[15] The statute has a rolling date for any new component, system, subassembly, or other part which replaces or is added to the aircraft and which causes the accident. In these circumstances, the statute runs from the date the new component is added or replaced.

BOX 6-1 Conversion to Unleaded Gasoline by Automobiles and Challenges for Aviation

The complete conversion of the automotive fleet in the United States from leaded to unleaded gasoline, which was completed less than 30 years ago, might be viewed as a model for such a conversion by the piston-engine fleet. The circumstances in the two sectors, however, were very different. As explained below, a key difference is that the automotive transition to vehicles that can use only unleaded fuel was not hampered by the need for leaded gasoline by legacy vehicles. As fleet turnover caused the number of legacy vehicles that could use leaded fuel to decline dramatically within two decades, so too did the demand for leaded fuel and any interest in supplying it. By comparison, in order to completely eliminate lead from avgas, aviation is constrained by the absence of an unleaded fuel that can satisfy a significant portion of its legacy fleet, which can be expected to remain significant for decades because of very slow turnover.

Automotive Experience

At the start of the 1970s, the national light-duty automotive fleet consisted of about 130 million vehicles, all satisfied with a range of leaded fuels with different octane levels. However, in anticipation of more stringent requirements in 1975 for allowable tailpipe emissions of hydrocarbons (HCs) and carbon monoxide (CO), automotive original equipment manufacturers (OEMs) determined that oxidation of HCs and CO through the use of catalytic converters would be essential for regulatory compliance and the catalytic converters, in turn, would require the use of unleaded fuel so as not to poison the catalyst. (Attempts to develop lead-tolerant catalysts proved fruitless.) Unleaded fuel with comparable octane levels became available quickly to accommodate catalyst-equipped vehicles entering the fleet from model year 1975. Because about 15 million new vehicles were added to the fleet each year, there was a rapidly developing market for unleaded gasoline. The unleaded grades could be used by older vehicles, but to prevent potential inadvertent misfueling of the new vehicles with catalysts, they were equipped with a narrower filler neck and unleaded gasoline was dispensed through a smaller diameter gas pump nozzle. The leaded gasoline pump nozzle would not fit through this filler neck.

Subject to a phaseout schedule from the U.S. Environmental Protection Agency (EPA), some leaded gasoline was supplied until January 1996 to satisfy older vehicles, a small number of new cars that could comply with the 1975 standards while using leaded fuel, and gasoline-powered trucks without catalytic converters. Meanwhile, because of the millions of new vehicles added to fleet every year and the average service life of automobiles at the time was less than 12 years, the number of vehicles that could use leaded fuel had dropped precipitously by the late 1980s, such that the demand for leaded gas had all but dried up. Thus, the automotive conversion to unleaded gasoline can be characterized as having a forward focus. That is, an unleaded grade was introduced to facilitate the use of a new generation of emission control systems and leaded fuel was phased out during two decades to allow for fleet turnover to largely alleviate backward compatibility issues.

Conversion Challenge for General Aviation

The piston-engine GA fleet of about 170,000 active aircraft is satisfied with one standard leaded fuel, as was the case for automobiles in 1970. However, the GA fleet turns over at much slower rate, with low attrition (as average aircraft lives span many decades) and the addition of only about 1,000 new piston aircraft per year. Going forward, those 1,000 new aircraft that are not already able to use an unleaded fuel could potentially be equipped to run on UL94, and if a UL100 were developed, they could use that fuel too. Therefore, the more vexing problem is how to accommodate the aircraft in the legacy fleet that now require a 100 MON gasoline, which is available only in leaded form. Retrofitting these aircraft to reduce octane requirement, such as through engine rebuilds to lower compression ratio and the adoption of electronic ignition, is not a promising route because the low average value of a legacy aircraft.[a]

[a] FAA estimated that aircraft in the piston-engine fleet in 2014 had an average value of about $60,000, while the average value of an aircraft in the pre-1984 portion of that fleet was $44,000. See https://www.faa.gov/regulations_policies/policy_guidance/benefit_cost/media/econ-value-section-5-resto.pdf.

NON-GASOLINE PROPULSION SYSTEM DEVELOPMENTS

The committee cannot estimate when and if an unleaded 100+ MON avgas will be developed and introduced to safely accommodate the current and future piston-engine fleet, and as the preceding discussion makes clear the prospects of retrofitting substantial portions of the legacy fleet appear to be limited for technical and economic reasons. Aviation technology, however, is not static and even with low annual fleet turnover there may be opportunities to reduce lead emissions at least gradually from the GA sector through the development and introduction of new propulsion systems that do not depend on gasoline. Many of these technologies would raise the cost of aircraft but offer certain other advantages that may be compensating, particularly when applied to the commercial and working sector of the GA fleet, which accounts for a disproportionate share of avgas consumption and resulting lead emissions.

In the sections that follow, a number of non-gasoline propulsion options are discussed, starting with the most technically ready systems such as diesel and turbine engines and then considering electric propulsion, which may be the most promising of all due to rapid advances in energy storage and onboard power generation and the potential for such systems to meet the low weight, size, and cost requirements of small aircraft. Although the discussion and examples given are not comprehensive, the systems described are indicative of a GA sector whose future direction is almost certain to be shaped in some way by propulsion technologies other than the traditional gasoline-powered, spark-ignition engine. It is important to note that the discussion of lead-free propulsion technologies does not include consideration of other potential emissions or environmental effects (e.g., changes in non-lead emissions such as greenhouse gases and fine particulate matter) that might be associated with their broad implementation in GA aircraft.

Diesel Propulsion

Diesel cycle, compression-ignition aircraft engines date back to the earliest days of powered aviation because of their attractive qualities of reduced flammability, increased thermodynamic efficiency, and higher energy density than gasoline. For instance, the Packard Motor Car Company was awarded the National Aeronautic Association’s Collier Trophy in 1931 for the introduction of a nine-cylinder, air-cooled, diesel aviation engine.[16] Nevertheless, even though it

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[16] See https://naa.aero/awards/awards-and-trophies/collier-trophy/collier-1930-1939-winners.

was used in a number of aircraft and airships, the diesel engine never gained traction in the GA sector, perhaps eclipsed by the rapid pace of development in the automotive sector of gasoline-powered engines. As automotive gasoline engine technology developed, the growing GA market benefited from engine advances and the widespread availability of inexpensive automotive gasoline. Weight was also a factor, as gasoline engines generally have better power-to-weight ratios than the heavier diesel engine and aircraft flight performance is highly dependent on weight. While diesel engines can generally run on jet fuel (Jet-A) with adequate cetane number, the unavailability of this fuel at most small airports is likely to have been an additional reason the diesel engine never caught on, and this factor may be a deterrent to its future popularity for GA uses.[17]

Modern diesel aviation engines that offer up to 300 horsepower are nevertheless available and have been in production for use in retrofits and new GA-type aircraft for several decades, buttressed by continual advances in weight-competitiveness, reliability, and performance capabilities. Diesel propulsion is more common in Europe than in the United States, perhaps because the availability of 100LL can be limited in European airports, while jet fuel is more widely available.

Performance and Cost Considerations

A direct comparison between gasoline and diesel propulsion can be difficult to make because of differences in airframe/engine installations, engine weight, and fuel weight, which must also account for the higher energy content of jet fuel relative to avgas (~11 percent more BTUs per gallon) and the diesel engine's high compression that contributes to about 30 percent less fuel consumption per horsepower output. From a performance standpoint, diesel engines are competitive with gasoline engines having similar horsepower, but also offer some distinct advantages. As noted, the diesel cycle is more energy efficient. Moreover, the engines are normally liquid cooled, so temperature control is easier, and without magnetos, ignition and engine control can be managed with a full authority digital engine control (FADEC) system.

The modern diesel engine is sufficiently advanced that it has the potential to be used in new aircraft or retrofitted in some existing aircraft in the GA fleet. However, the conversion of a small, 4-cylinder, gasoline-powered aircraft to a comparable diesel-powered system (including the addition of water cooling, necessary propeller and engine display modifications, and flight testing) would be costly, estimated by FAA to be about $100,000, which is more than the market value of an average small aircraft in the legacy fleet, which FAA estimated in 2017 was about $60,000.[18] Accordingly, such conversions are not likely to be a practical option except among the most heavily utilized GA aircraft that operate in airports where diesel or jet fuel are available. The cost to retrofit an existing airframe would include the engine acquisition cost, the airframe and installation modifications, and the flight test program before final acceptance for an STC, which in many cases would exceed the value of the existing aircraft. While conversions would

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[17] An August 2018 article in *Flying* magazine outlines many of the benefits of diesel technology with an emphasis on the absence lead emissions, but suggests that one reason GA pilots have shown limited interest in newer diesel options is the ready availability of relatively inexpensive 100LL. Mark, R. 2018. Inside the Diesel Revolution. *Flying*. August 1. See https://www.flyingmag.com/inside-aviation-diesel-revolution.

[18] The $100,000 retrofit cost is based on an estimate provided by FAA in a November 19, 2019, briefing to the committee. The average value of piston-engine aircraft was estimated by FAA, as noted in Chapter 2. See https://www.faa.gov/regulations_policies/policy_guidance/benefit_cost/media/econ-value-section-5-resto.pdf.

seem to have many economic and practical drawbacks, the same challenges do not exist for new aircraft that would be optimized for diesel propulsion.

Current Production and Future Prospects

While the economic viability of a diesel propulsion system would seem greater for new aircraft, the airframe and engine makers considering such a system must weigh the sales potential in light of the upfront investments required to develop and produce the aircraft, including absorbing the cost of an extensive certification process. There are nevertheless several diesel aircraft engines in production worldwide that are designed for GA aircraft categories. For instance, the engine manufacturer Continental offers a range of diesel engines providing up to 300 horsepower, which the company states have logged more than 7 million flight hours by the more than 6,000 units delivered.[19] Continental offers an STC for a diesel modification of the Cessna 172 and several other aircraft that are heavily used for pilot training. The other major GA engine maker in the United States, Lycoming, also offers a diesel engine derived from a European model.[20] The 200 horsepower engine is presently in operation in an unmanned aircraft, but the company states that it intends to certify it for piloted aircraft. Other aviation engine makers developing diesel engines include EPS, which offers engines in the 320 to 420 horsepower range,[21] and DeltaHawk, which makes a diesel engine that provides 180 horsepower.[22]

Currently, many of these diesel engine variants are intended for conversions, because there are few diesel aircraft in production in the United States. Although Cessna developed and certified the diesel-powered Turbo Skyhawk JT-A, it ended production in 2018. Outside the United States, the Austrian aircraft maker Diamond Aircraft Industries sells a twin-engine aircraft, the DA-42 NG, which is powered by the Austro AE-300 turbo diesel engine, and this aircraft is certified in the United States.

Diesel propulsion is thus a proven technology that is available now for existing and new GA aircraft. Its promise as an alternative to gasoline engines will nevertheless continue to depend on advances that reduce weight and cost, as well as its appeal to GA aviators interested in purchasing high-utilization aircraft. The potential for large-scale conversions of legacy aircraft to diesel systems appears low given the unlikely prospects that owners of most aircraft could recoup the high conversion cost.

Turbine Propulsion

The three general classes of turbine-powered aircraft, which burn jet fuel, are turboprop, turbofan, and turbojet designs. A turboprop aircraft uses a gas turbine to drive a shaft and propeller that provide thrust forces to propel the airplane, with a small amount of thrust from the turbine exhaust. In the turbofan aircraft, the turbine powers a forward-mounted fan system. Depending on the bypass ratio, most thrust is created by the fan, although some thrust is still derived from the jet exhaust. Conversely, a turbojet engine develops all of its thrust from the

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[19] See https://www.continentalmotors.aero/diesel/diesel-engines.aspx.

[20] See https://www.lycoming.com/engines/del-120.

[21] AOPA ePublishing staff. 2019. EPA Gives Certification Update on Diesel Engine. January 23. See https://www.aopa.org/news-and-media/all-news/2019/january/23/eps-gives-certification-update-on-diesel-engine.

[22] Conrad, J.W. 2019. DeltaHawk Diesel Makes First Flight to AirVenture. July 26. See https://www.eaa.org/airventure/eaa-airventure-news-and-multimedia/eaa-airventure-news/eaa-airventure-oshkosh/07-26-2019-deltahawk-diesel-makes-first-flight-to-airventure.

exhaust gas. A powerful turbine engine coupled to a propeller provides for the efficient generation of static thrust for a given horsepower, particularly at lower airspeeds. As a result, turboprops can be used on shorter runways than turbofan aircraft and can be used for applications that require the use of unpaved fields and amphibious service. A number of GA aircraft are turboprop designs, but they are used almost exclusively for short-haul passenger and cargo service and total fewer than 10,000 units (about 5 percent of the GA fleet).[23] The Beechcraft Super King Air, Piper PA-46 family, and Cessna 208 Caravan are examples of turboprop GA aircraft.

Performance and Cost Considerations

Turboprop engines have a number of advantages over gasoline engines. They are considerably lighter in weight for the same power output and can operate at higher altitude. Whereas the performance of normally aspirated piston-engine aircraft drops rapidly above 15,000 feet mean sea level (MSL), the turboprop can be flat rated at sea level power at 25,000 feet MSL or higher. This enables the aircraft to fly at higher speed at altitude and cover distances more rapidly, offering cruising speeds of 200 to 350 mph and ranges in excess of 1,200 miles.

There are significant deterrents to the use of turboprops for typical GA applications, including higher non-recurring and recurring engine maintenance costs, the need for additional pilot ratings, and performance characteristics that are not aligned with the needs of local and recreational flying. Even the smallest turboprops can cost $2 million to $4 million, which are multiples of the price of comparably sized piston-engine models. Nevertheless, turboprops have proven utility for a small segment of the high-utilization GA sector and that market could potentially expand if future technology improvements reduce the cost of ownership. While jet fuel is available at many larger airports that serve turbine aircraft, its lack of availability at most smaller airports could be problematic for more widespread use.

Current Production and Future Prospects

One can find examples of turbine engine makers working on turboprop systems that could have greater attraction for GA uses. Rolls Royce has discussed the development of a RR-500 family of turboprop engines capable of 300+ horsepower, and it has participated with the Mooney Aircraft Company in a market investigation intended to explore this and other alternative power options for private aircraft. Running at full power, the engine would burn approximately 21 to 24 gallons of jet fuel per hour, but at the higher expected airspeeds it has the potential to exhibit similar fuel efficiency (in nautical miles per gallon) as a gasoline-powered aircraft possessing similar horsepower.[24] Focusing on even smaller turboprop aircraft, PBS Aerospace, a company based the Czech Republic, advertises that its TP100 engine is capable of 188 horsepower at cruise speed. The company maintains that the engine is especially well suited to small aircraft and unmanned aerial vehicles, for uses such as search and rescue services, reconnaissance, and agriculture applications.

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[23] See https://www.bts.gov/content/active-us-air-carrier-and-general-aviation-fleet-type-aircraft.

[24] See https://www.avweb.com/air-shows-events/mooney-rolls-royce-look-at-turbine-single and https://www.youtube.com/watch?v=j2nD7Nqh7B4.

Electric and Electric Hybrid Propulsion

Electric propulsion has accelerated during the past 10 years, with new application concepts for GA, commercial air transport, and even urban air mobility. Several new technologies have enabled electrical propulsion to expand into the aviation domain, including improved battery storage technology and high efficiency/high power density electric motors. Advances are being made along various technology fronts including improved battery storage for pure electric propulsion and for hybrid systems that use battery storage in combination with electric power produced onboard the aircraft through means such as fuel cells and turbo-generators.

Performance and Cost Considerations

Because space, weight, and power are critical aircraft design parameters, the potential for a battery-powered aircraft propulsion system is largely driven by the energy capacity per weight and volume of the battery system. The lithium ion battery dates back several decades, but its practical applications have grown as energy storage capacity and operating times between recharges have increased. The specific energy of lithium cells is now on the order of 250 watt-hours per kilogram, which still limits aeronautical applications. However, ongoing research into solid state lithium-metal battery technology suggests this figure could double within the next few years and enable the development of longer endurance and longer range aircraft if issues related to safety, operational lifetime, and manufacturability can be overcome.

While higher specific energy in batteries is being pursued to enable pure electric aircraft, hybrid propulsion systems that use electricity that is both stored and generated onboard the aircraft are also an option. Several candidate types of power generators are being investigated, including diesel and spark ignition piston engines, hydrogen proton exchange membrane (PEM) fuel cell systems, and regenerative turbo-generators using jet fuel. In a PEM fuel cell, lightweight hydrogen is converted through an electrochemical reaction to produce electricity to drive motors and/or to store in batteries. A regenerative turbo-generator consists of a turboshaft engine in which air entering the compressor is pre-heated through a heat exchanger by the high temperature exhaust exiting the turbine, resulting in high efficiency. This turboshaft engine is then coupled to an electric generator to produce electricity for use in powering electric motors or storing in batteries.

Current Production and Future Prospects

The GA sector is already benefiting from advances in battery technology and lightweight motors. For example, Bye Aerospace is seeking FAA certification for a two-seat battery electric light aircraft, called the eFlyer, for flight training missions.[25] The eFlyer carries lithium-ion batteries and is powered by a Siemens 70 kilowatt continuous power motor. Siemens has also developed a 260 kilowatt, 350 horsepower motor weighing about 104 pounds. A potential indicator of the future prospects for electric propulsion is the recent purchase of the Siemens aircraft electric motor business by Rolls Royce, a major aircraft engine maker intent on furthering the electric and hybrid-electric aircraft market.

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[25] Lincoln, A. 2019. eFlyer Developmental Prototyoe Flight Tests Confirm Benefits of Electric PropulsionBye Aerospace. October 21. See https://byeaerospace.com/eflyer-developmental-prototype-flight-tests-confirm-benefits-of-electric-propulsion.

At least two companies, Scaled Power and Turbotech, are developing small regenerative turbo-generators suitable for small GA aircraft. Scaled Power advertises a turbo-generator that it claims offers better performance than piston or fuel cell systems.[26] Turbotech, which is based in France, advertises a regenerative gas turbine in either a generator or turboprop configuration.[27] Boeing conducted a successful proof of concept flight of a light aircraft using a battery/fuel cell system as early as 2008[28] and PEM fuel cells are now being used in production automobiles including the Toyota Mirai.

The ability of airports to install the needed charging infrastructure, and possibly even hydrogen storage and dispensing systems, could be an important factor driving interest in the future use of battery electric and hybrid electric aviation propulsion.

FINDINGS AND RECOMMENDATIONS

While a lead-free, high-octane (100+ MON) avgas to fully replace leaded avgas for the entire fleet without requiring changes to aircraft or their engines would be ideal, it faces many challenges that more than 25 years of research into hundreds of fuel formulations has not been able to yet address. While several fuel suppliers are actively trying to develop such a fuel, their prospects for success could not be assessed directly in this study because the fuel formulations and testing results are proprietary. It is uncertain when such a fuel can be developed, tested, and accepted, and the costs associated with its adoption and use are not known, nor are the challenges of deploying it at airports across the country (Finding 6.1).

The FAA-industry PAFI collaborative represents a systematic and holistic approach for screening, evaluating, and selecting an acceptable unleaded replacement for leaded avgas for fleetwide use, as well as for overcoming certification and other obstacles to the commercialization and widespread introduction of a lead-free alternative fuel. Although it has not yet yielded a viable replacement, PAFI has led to the development of a fuel testing and evaluation process, prompted supplier interest in developing replacement fuels, and sought solutions to the many regulatory, economic, and other practical challenges associated with developing, introducing, and broadly supplying an unleaded replacement fuel (Finding 6.2).

> FAA should continue to collaborate with the GA industry, aircraft users, airports, and fuel suppliers in the search for and deployment of an acceptable and universally usable unleaded replacement fuel. The collaboration should be carried out through PAFI or an alternate holistic process for evaluating all the properties and conditions necessary for production, distribution, and safe use of the fuel, including the use of common test protocols and procedures and by making available the needed testing facilities for the development of the data required to support FAA approvals for the fuel to be used by existing piston-engine aircraft (Recommendation 6.1).

Retrofitting current aircraft to enable fleetwide use of currently available unleaded fuels and other lead-free means of propulsion would require incentives to develop new technologies for those aircraft where retrofits do not currently exist. Incentives also would need to motivate

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[26] See http://www.scaled-power.com.

[27] See http://www.turbotech-aero.com.

[28] Koehler, T. 2008. A green machine. Boeing Frontiers. May. See https://www.boeing.com/news/frontiers/archive/2008/may/ts_sf04.pdf.

large and potentially prohibitive investments by aircraft owners in systems such as anti-detonation injection, replacing engines along with other critical components, and undergoing costly recertification processes (Finding 6.3).

Tangible success is being demonstrated by aircraft engine makers in creating high-performance gasoline engines that can run on existing unleaded avgas, and innovations in alternative, lead-free propulsion systems (such as diesel, electric, and gas turbine) are showing increasing potential for GA aircraft. Implementation of these new technologies can result in the phasing in of aircraft that do not use leaded fuel and would not be subject to the uncertainty of waiting for an unleaded 100 MON fuel to be developed and deployed widely. Such a technology transition, however, would be limited by the slow turnover rate of GA fleet, barring new incentives to hasten it (Finding 6.4).

> A clear goal should be established that all newly certified gasoline-powered aircraft after a certain point in time (e.g., within 10 years) are approved to operate with at least one ASTM-approved unleaded fuel. Also, an additional amount of time should be identified by which all newly produced gasoline-powered aircraft, including those currently produced with older type certificates, would attain that same goal. Congressional action to establish the goal and timeframes would ensure achievement of those important results. For example, that congressional action would promote the development of new engine variants compatible with existing unleaded fuels, which could possibly yield prescriptions to support the eventual retrofit of some legacy aircraft and engines as they reach required overhaul milestones (Recommendation 6.2).
>
> FAA initiatives—including collaborations with industry and other government agencies such as the National Aeronautics and Space Administration—should be used to promote the development, testing, and certification of safe and environmentally desirable lead-free emerging propulsion systems (such as diesel, electric, and jet fuel turbine engine) for use in GA aircraft, including the requisite airport refueling and recharging infrastructure. Congressional encouragement and provision of resources as required would ensure the success of those initiatives (Recommendation 6.3).

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UAT ARC (Unleaded Avgas Transition Aviation Rulemaking Committee). 2012. FAA UAT ARC Final Report. Part I Body. Unleaded AVGAS Findings and Recommendations. February 17. Available at: https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/Avgas.ARC.RR.2.17.12.pdf.

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Conclusion

Since lead was phased out of automotive gasoline more than 30 years ago, the leaded aviation gasoline (avgas) used by piston-engine aircraft has become the predominant source of lead pollution in the United States. Lead exposure can result in an array of negative health effects in humans and there are no known safe levels of lead exposure, as measured by blood lead concentrations. For example, exposure to low concentrations of lead, including prenatal exposure, has been linked to decreased cognitive performance in children, because of the susceptibility of the developing nervous system. The importance of reducing lead pollution motivates the development and implementation of mitigation measures to reduce or eliminate lead emissions from general aviation (GA) aircraft.

Today, nearly all avgas is formulated to contain between 0.28 and 0.56 grams of lead per liter. Lead is added to avgas in the form of tetraethyl lead (TEL). The reason for adding TEL to avgas is to boost its octane to levels that will enable the reliable operation of high-compression piston engines at the wide range of altitudes and climates in which they operate. Without leaded avgas, tens of thousands of piston-engine aircraft, used for a wide range of beneficial GA purposes, could not be safely flown. Decades of research on octane-enhancing additives have failed to find an alternative to lead that performs in an operationally safe manner for all GA aircraft in use today. Hence, eliminating lead from avgas is a highly desirable public health goal, but one that has been difficult to achieve.

As understanding of the adverse effects of lead pollution has grown, the U.S. Environmental Protection Agency (EPA), the Federal Aviation Administration (FAA), the National Institute of Health Sciences (NIEHS), the GA community, and other organizations have been working to identify where important environmental exposures occur and find ways for reducing lead emissions from piston-engine aircraft.

Other researchers have examined how operations and practices at airports, including pre-flight checks, refueling practices, and aircraft maintenance activities, contribute to lead emissions and human exposures. FAA has been collaborating with fuel suppliers and the GA industry, through the Piston Aviation Fuels Initiative (PAFI), to find an unleaded avgas that can satisfy the entire piston-engine fleet. Some fuel suppliers have been working independently to develop avgas alternatives, resulting in at least one grade of unleaded avgas that can satisfy a portion of the piston-engine fleet that does not require fuel with high octane and a grade of avgas that has a lower lead content, which can be used by all piston-engine aircraft. Meanwhile, advancements continue in the development of lead-free propulsion technologies for small aircraft, including diesel, turbine, and electric-powered systems.

As a result of those efforts, it has become increasingly clear that significantly reducing, and ultimately eliminating, the lead added to avgas and the sources of lead exposures at and near airports is a multi-faceted problem requiring multiple mitigation strategies. Forecasted long-term reductions in GA activity are likely to result in declining avgas use and lower lead emissions over time, but only marginally—on the order of 10 percent over the next 20 years. Consequently, additional actions would be needed to reduce lead emissions faster and further. Because the piston-engine fleet, consisting of about 170,000 aircraft, serves many important purposes, any actions that risk major disruptions in the use of these aircraft would be impractical and undesirable. Only a small number of new aircraft are added to the fleet each year and very few aircraft are retired, meaning that transitioning to a fleet that consists exclusively, or even predominantly, of aircraft not requiring high-octane avgas would take decades.

Major technical challenges have slowed the development of a high-octane unleaded avgas that can serve all of the aircraft in this existing piston-engine fleet. Moreover, the fleet operates from more than 13,000 airports, including many smaller facilities that have limited fuel storage and dispensing capacity and few incentives and resources to offer both leaded and unleaded grades of avgas to satisfy specific segments of the fleet. All piston-engine aircraft, including those that do not require high-octane fuel, can operate safely using the leaded avgas available for purchase today. Many small airports, therefore, are inclined to supply only this grade of avgas, and fuel suppliers are likewise incentivized to offer only this grade because the total demand for avgas is already relatively small and expected to decline.

Under the requirements of the Clean Air Act (CAA), if EPA were to determine that lead emissions from the use of leaded avgas cause or contribute to air pollution, which may reasonably be anticipated to endanger public health or welfare, the agency would need to develop regulations for controlling lead emissions from piston-engine aircraft. No such regulations are currently in place. In 2006, the Friends of the Earth (FOE) filed a petition requesting that EPA issue a finding that lead emissions from piston-engine aircraft endanger public health and welfare, or conduct a study of lead emissions from the aircraft if there was insufficient information to make a determination.[1,2] During the 14 years since that petition, EPA sought public comment twice on various issues related to lead emissions from aircraft and has completed several field monitoring and air quality modeling studies to help address open questions.[3,4,5] EPA had planned to issue a proposed endangerment finding (either positive or negative) by 2017, but the agency did not meet its target date.[6]

The uncertainty surrounding a proposed endangerment finding from EPA complicates assessments of the array of policy options that are, or may become, available to mitigate aviation lead pollution. Given that uncertainty, the committee did not consider regulatory tools that might be issued by EPA under the CAA. However, if those tools were to become available, they would almost certainly have a prominent role in a lead mitigation strategy and be high among the candidate policy options for lead mitigation. An update published by EPA on the status of its endangerment assessment, along with identifying any open issues and any additional information needs, would be helpful for parties who are interested in the outcome of EPA's endangerment assessment. While a formal EPA determination is not a prerequisite for introducing measures to mitigate lead emissions, it would add more clarity about the array of regulatory and non-regulatory means available for this purpose.

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[1] Endangerment finding is often used as a short-hand reference to a judgment as to whether lead emissions from aircraft engines resulting from the use of avgas cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare.

[2] Friends of the Earth. 2006. Petition for Rulemaking Seeking the Regulation of Lead Emissions from General Aviation Aircraft Under § 231 of the Clean Air Act. October 3. See https://www.epa.gov/sites/production/files/2016-09/documents/foe-20060929.pdf.

[3] See 72 FR 64570 (November 16, 2007) and 75 FR 22440 (April 28, 2010).

[4] These comments are also available in EPA docket EPA–HQ–OAR–2007–0294.

[5] See https://www.epa.gov/regulations-emissions-vehicles-and-engines/epas-data-and-analysis-piston-engine-aircraft-emissions.

[6] Letter, Gina McCarthy EPA to Deborah Behles, Golden Gate University, and Marianne Lado, Earthjustice, January 23, 2015. See https://www.epa.gov/sites/production/files/2016-09/documents/ltr-response-av-ld-foe-psr-oaw-2015-1-23.pdf.

RECOMMENDED RESEARCH TO INFORM MITIGATION EFFORTS

As discussed above, the challenges associated with reducing lead emissions and human exposures resulting from the use of leaded avgas are formidable. However, the evidence of lead pollution's hazard demands that those challenges not become an excuse for inaction, but instead become the subject of concerted, sustained, and multi-pronged efforts to find and implement mitigation measures. While development of a "drop-in" unleaded fuel that can satisfy the entire piston-engine fleet is a highly desirable goal, attainment of that goal is not assured, and a singular focus on achieving it risks the neglect of other opportunities to reduce lead emissions from GA aircraft and subsequent human exposures.

Assessing the feasibility and effectiveness of the airport-specific application of potential mitigation measures in mitigating hot spots for ambient lead concentrations would benefit from an improved understanding of individual airport characteristics. The airports that serve piston-engine aircraft differ in traffic activity, layouts, and proximity to the local population. They serve as bases for different types and numbers of aircraft that provide different functions within the community. Therefore, additional analyses are needed that account for airport-specific conditions and attributes, including the geographic distribution of lead around the airport. Such analyses would inform the selection, design, and effectiveness assessment of lead mitigation efforts at individual airports.

> EPA should conduct more targeted monitoring and enhanced computational modeling of airborne lead concentrations at airports of potential concern, as indicated by its recent screening study, to evaluate aircraft operations that are main contributors to lead hot spots and design airport-specific mitigation measures. (Hot spots often refer to a spatial zone of emissions impact where the airborne lead concentration is significantly elevated above background.) In addition to airports found to have airborne lead concentrations exceeding the concentration of the lead National Ambient Air Quality Standards (NAAQS), additional monitoring and modeling should include airports found to have lead concentrations that are lower, but approaching, the NAAQS concentration (Recommendation 3.1).

Lead in piston-engine aircraft exhaust has been observed to occur in the form of beads about 4 nanometers (nm) in diameter embedded in particles with diameters less than 20 nm. Those particles are smaller than the lead particles observed in automobile exhaust. Smaller particles may deposit and distribute in the body differently than larger-sized particles that have been the subject of more research in the past. Thus, it is important to understand the particle size properties of lead emitted from aircraft and how those properties affect atmospheric transport and deposition as well as human exposure–response relationships.

> EPA and NIEHS should sponsor research to improve the understanding of the physical state of the lead-containing particulate matter emitted from various types of GA-aircraft piston engines, including turbocharged engines, using fuel formulations of different lead content, including an existing grade of avgas with a lower lead content (100VLL), to inform future studies of atmospheric transport and deposition, human exposure, and health risks of lead emissions form GA aircraft (Recommendation 3.3).

Based on the nature of the workplace activities involving piston-engine aircraft, lead exposures are expected to occur for flight line and maintenance shop workers, including those employed by the airport itself, fixed base operators (FBOs), and repair and overhaul facilities. Workplace lead exposures include not only inhalation of airborne emissions, but also inhalation, ingestion, and dermal absorption of the fuels additives TEL and the fuel additive ethylene dibromide, as a result of aircraft refueling and maintenance activities. Occupational Safety and Health Administration (OSHA) regulations, including permissible exposure limits and related requirements, apply for each of those contaminants.

> EPA and NIEHS should sponsor research to enhance the understanding of lead exposure routes and their relative importance for people living near airports and working at them. The research should include studies, such as observations of blood lead levels among children, in communities representing a variety of geographic settings and socioeconomic conditions that are designed to examine the effectiveness of the lead mitigation strategies over time (Recommendation 3.2).

Airborne lead, which is usually in the form of particulate matter, can be inhaled by people in communities surrounding airports. In addition, particles containing lead can deposit onto soil and other surfaces and be ingested through activities, such as hand-to-mouth contact with surfaces where the particles have deposited. Deposited lead also can be resuspended into the air as dust and inhaled. Therefore, past emissions from piston-engine aircraft that deposited to soil and other surfaces can contribute to present-day lead exposures at some locations within and near airports.

Lead exposures to workers at airports present another area of concern warranting possible mitigation. For example, the practices and protections of some airport personnel and aircraft technicians may need to be modified to reduce occupational and take-home exposures, for instance, from lead deposits and residue in aircraft engines, oil, and spark plugs.

POTENTIAL MITIGATION PATHWAYS

Previous chapters of this report identify candidate mitigation pathways that could result in a more holistic approach to addressing lead emissions from piston-engine aircraft and possibly eliminate the problem in the future. Table 7-1 presents the pathways in three categories: airport operations and practices, existing specified fuels and fleet, and new lead-free technologies (fuels and propulsion systems). The table also provides various considerations associated with each pathway.

As indicated in Table 7-1, the advent of an unleaded drop-in fuel could greatly reduce or even eliminate aviation lead. However, the formidable technical challenges and associated uncertainties about whether and when such a fuel could be developed and deployed suggest that it should not be relied upon as the sole mitigation measure. This suggests that a multi-pathway approach that pursues lead emission and exposure reductions is needed in which the development of a drop-in fuel proceeds as a part of broader mitigation pathway focused on the development and deployment of lead-free fuels and new propulsion technologies, in combination with mitigation pathways focused on airport operations and practices and on existing fuels and aircraft. Pursued simultaneously, these pathways would differ in their potential to yield near-term reductions in lead emissions and exposures and present different implementation requirements and levels of certainty about effectiveness. However, such a multi-pathway approach that pursues lead reductions in combination is more likely to produce tangible and sustained results.

Each of the mitigation pathways considered in Table 7-1 would require the adoption of a range of policies to prompt the participation of pilots; airport owners, managers and personnel; fuel suppliers; and aircraft engine, propulsion, and airframe manufacturers. For some pathways, candidate policy options are easy to identify while, for others, the most suitable policies are difficult to define because they could involve combinations of financial assistance and incentives, regulatory requirements, support for technology research and development, and other potential interventions to motivate and enable the desired response.

The steps recommended in this report that are intended to further each mitigation pathway are given next, while recognizing that important differences in the timing of when each will reduce aviation lead and the magnitude and certainty of those reductions are reasons for pursuing them simultaneously.

TABLE 7-1 Candidate Pathways for Aviation Lead Mitigation Measures

	Airport Operations and Practices		**Existing Specified Fuels and Fleet**		**New Lead-Free Technologies (Fuels–Propulsion Systems)**		
Considerations	Aircraft Operations at Airports	Pilot and Airport Personnel Practices	100VLL Used by All Aircraft or with Some Using UL94	UL94 Used by Low-Performance Aircraft	UL94 in New Aircraft Including High-Performance Aircraft	100+UL in All Aircraft	New Propulsion Systems (new aircraft and retrofit some legacy aircraft)
Potential Reduction in Lead Exposures[a]	Small and Variable, depends on individual airport conditions, activity, and hot spots	Small and Variable, but could be particularly important for aircraft technicians	Up to 20% reduction (could exceed 40% if combined with UL94 use by low-performance aircraft)	Up to 30% reduction (could exceed 40% if combined with 100VLL use by all other aircraft)	~0.5% reduction per year	100% reduction	~0.5% reduction per year
Time Frame for Lead Reduction Benefits If Started Soon	Near-term	Near-term	Near- to mid-term	Mid-term	Far-term for appreciable reductions and will require technical advances	Unknown, may require technical breakthrough	Far-term, pace of reduction depends on cost, rate of innovation, and extent of applicability to GA fleet
Focus of Implementation	Airport Management	FAA Flight Standards, pilot instruction and training	Fuel supply chain, especially refiners	Fuel supply chain and airports, especially fuel storage and	Engine and aircraft makers	Fuel supply chain, especially fuel developers;	Technology developers, aircraft manufacturers, aircraft owners

		programs, GA community		dispensing capacity		engine and aircraft makers	
Possible Policy Actions for Facilitating Implementation	Provide data and tools for analysis and identifying operations changes	Provide training and education materials, engage in awareness campaigns	Directives and/or incentives, perhaps focused on refiners	Incentives and financial assistance for airports to add fueling capacity, eased FAA certification	Directives and/or incentives applicable to GA industry	Public–private collaborative (PAFI-like) for R&D, testing, and certification	R&D support, FAA certification, incentives for aircraft owners to incur expense
Main Sources of Uncertainty in Achieving Effective Implementation	Variability in airport-specific factors	Potential to affect practices	Refiner capacity to meet tighter lead specifications	Feasibility of adding fuel supply chain (refiners and airports), certification	Ability to design suitable engines for all high-performance aircraft	Potential to meet fuel performance requirements	Rate of innovation, certification challenge, cost and owner interest
Ancillary Benefits and Concerns	Greater lead awareness and interest in lead-free fuels and propulsion	Greater lead awareness and interest in lead-free fuels and propulsion				Environmental and health impacts related to other fuel components	Changes in pollutants, including greenhouse gases over life cycle

[a] Where percentages are given, they refer to estimates of reductions in lead from the total fuel consumed by the piston-engine fleet.

RECOMMENDATIONS

Airport Operations and Practices

The committee's review of FAA-related manuals and handbooks pertaining to flight training, aircraft maintenance, and airport management found scarce mention of lead emissions and exposures as an environmental risk or health hazard nor guidelines for refueling to avoid spills and emissions, ensuring the safe disposal of inspected fuel, and reducing exposures to lead residue when performing aircraft maintenance and repairs.

> FAA should coordinate its efforts to reduce lead pollution and exposures at airports with those of other federal agencies that have key responsibilities for protecting public health, safety, and the environment at airports, including OSHA as well as EPA. FAA should collaborate with these agencies to explore the regulatory and programmatic means within their respective jurisdictions that can be brought to bear and combined in a complementary manner to reduce lead emissions and exposures at airports (Recommendation 4.1).
>
> FAA, in partnership with prominent organizations within the GA community, should initiate an ongoing campaign for education, training, and awareness of avgas lead exposure that is targeted to GA pilots, aircraft technicians, and others who work at airports. Informed by research on the most effective approaches for reaching these audiences, the campaign should be multipronged by ensuring that information on lead risks and mitigation practices is prominent in relevant manuals, guidelines, training materials, and handbooks for pilots, airport managers, and aircraft technicians manuals, guidelines, training materials, and handbooks. Where appropriate, it should also be covered in relevant certification and licensure examinations. In addition, the information should be featured on FAA and GA organization websites and included in written materials distributed at GA industry conferences, tradeshows, and fly-ins (Recommendation 4.2).

Airport lead air quality studies have shown that engine run-ups, whereby a pilot confirms shortly before takeoff that the engine is operating safely by briefly bringing the engine up to high power for system checks while the aircraft is stopped, can contribute to significant airborne lead concentrations at designated run-up areas. Maintenance personnel may also perform extensive engine tests at run-up areas. Run-up area planning guidance provided by FAA has not been updated to reflect the results of air quality studies that suggest it may be desirable for airports to move their run-up locations away from being close to where human activities occur (including activities both on-airport and in neighboring communities) and away from high-traffic locations such as runway ends where lead is also emitted from aircraft taking off.

> FAA should update its guidance on the location of run-up areas to reflect the results of research since the latest interim guidance was issued in 2013, including the need to account for both the emissions of engine run-ups and of takeoffs when analyzing the geographic distribution of lead emissions at the airport. This analysis should support decisions of whether to move run-up areas to reduce people's exposure to lead emissions

while also accounting for other concerns including safety and aircraft noise (Recommendation 4.3).

Existing Fuels and Fleet

While the downward trend in GA activity should yield gradual reductions in lead emissions from avgas consumption, larger reductions will require lower-lead or unleaded fuel alternatives to 100LL. Because the activity of the piston-engine GA fleet has been declining by an average of 1.6 percent per year during the past four decades and is expected by FAA to continue to decline by 0.6 percent per year during the next two decades,[1] total lead use by the GA sector is on a modest downward trajectory and projected to be 10 percent lower within 20 years.

100VLL is the only other currently ASTM-specified fuel other than 100LL that could be used by all GA piston-engine aircraft. Fleetwide use of 100VLL, therefore, offers a potential means of reducing total lead emissions from avgas by nearly 20 percent. However, 100VLL is not currently being produced, presumably because there are no regulatory requirements or apparent economic incentives for fuel producers to formulate fuel that can meet the tighter lead ranges in the ASTM standard.

At least 57 percent, and perhaps as much as 68 percent, of the current piston-engine fleet could use UL94, which is the only existing grade of unleaded avgas. However, this outcome would require special FAA certifications for some of the aircraft. The eligible fleet consists mostly of smaller, lower-performance aircraft that are not used as frequently as the higher-performance fleet that requires leaded avgas. Therefore, the reduction in leaded fuel use from making UL94 widely available is not likely to be proportional to the large share of lower performance aircraft in the fleet. Nevertheless, if all these aircraft were to use UL94, lead emissions would be reduced by an estimated 30 percent. In addition, if higher-performance aircraft were to use 100VLL, reductions in lead emissions could exceed 40 percent.

An unleaded fuel, such as UL94, approved for only part of the piston-engine fleet would require creating a second supply chain and fuel distribution system across the nation. Such a fragmentation of avgas supplies into two grades that are each produced in lower volumes could also lead to higher avgas prices due to the loss of scale economies. Furthermore, the cost for airports to add storage and distribution facilities for a second fuel could be significant and potentially prohibitive, especially for small airports. Consequently, widespread availability of UL94 might be overly optimistic, and more likely to be restricted to a portion of airports that have or can afford to add the required fueling facilities.

Automotive gasoline formulations are no longer a viable option for reducing lead emissions from the piston-engine fleet. Thousands of piston-engine aircraft were approved during the 1980s to use automotive gasoline formulations—loosely called MOGAS—that were then deemed to be safe substitutes for low octane avgas grades (80/87 MON) permitted by the aircraft's original TCs. However, the composition of automotive gasoline has changed considerably during the past 30 years, particularly including ethanol blends that are not compatible with almost all aircraft engines.

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[1] See Table 31 of "FAA Aerospace Forecast FY 2020-2040" at https://www.faa.gov/data_research/aviation/aerospace_forecasts.

> FAA should research public policy options, which could be implemented as quickly as possible at the federal and state levels as well as by Congress, for motivating refiners to produce and airports to supply 100VLL. The objective would be to reduce lead emissions from the entire piston-engine fleet while unleaded alternatives are being pursued for fleetwide use (Recommendation 5.1).
>
> FAA should research public policy options that will enable and encourage greater use of available unleaded avgas by the portion of the piston-engine fleet that can safely use it. Possible options include (a) issuing a Special Airworthiness Information Bulletin that will permit such use and (b) providing airports with incentives and means to supply unleaded fuel, particularly airports that are eligible for FAA-administered federal aid as part of the National Plan for Integrated Airport Systems (Recommendation 5.2).
>
> A mechanism should be established for facilitating the increased availability of existing grades of unleaded avgas across the fleet of piston-engine aircraft,. Fulfilling that need would likely require congressional involvement, such as by providing incentives for pilots to use existing unleaded avgas and for more small airports to add requisite fuel storage and dispensing capacity (Recommendation 5.3).

Future Lead-Free Fuels and Propulsion Systems

While a lead-free, high-octane (100+ MON) avgas to fully replace leaded avgas for the entire fleet without requiring changes to aircraft engines would be ideal, it faces many challenges that more than 25 years of research into hundreds of fuel formulations has not been able to address. While several fuel suppliers are actively trying to develop such a fuel, their prospects for success could not be assessed directly in this study because the fuel formulations and testing results are proprietary. It is uncertain when such a fuel can be developed, tested, and accepted, and the costs associated with its adoption and use are not known.

The FAA-industry PAFI collaborative represents a systematic and holistic approach for screening, evaluating, and selecting an acceptable unleaded replacement for leaded avgas for fleetwide use, as well as for overcoming certification and other obstacles to the commercialization and widespread introduction of a lead-free alternative. Although it has not yet yielded a viable replacement, PAFI has led to the development of a fuel testing and evaluation process, prompted supplier interest in developing replacement fuels, and sought solutions to the many regulatory, economic, and other practical challenges associated with developing, introducing, and broadly supplying an unleaded replacement fuel.

> FAA should continue to collaborate with the GA industry, aircraft users, airports, and fuel suppliers in the search for and deployment of an acceptable and universally usable unleaded replacement fuel. The collaboration should be carried out through the Piston Aviation Fuels Initiative PAFI or an alternate holistic process for evaluating all the properties and conditions necessary for production, distribution, and safe use of the fuel, including the use of common test protocols and procedures and by making available the needed testing facilities for the development of the data required to support FAA approvals for the fuel to be used by existing piston-engine aircraft (Recommendation 6.1).

Retrofitting current aircraft to enable fleetwide use of currently available unleaded fuels and other lead-free means of propulsion would require incentives to develop new technologies for those aircraft where retrofits do not currently exist. Incentives also would need to motivate large and potentially prohibitive investments by aircraft owners in systems, such as anti-detonation injection, replacing engines along with other critical components, and undergoing costly recertification processes.

Tangible success is being demonstrated by aircraft engine makers in creating high-performance gasoline engines that can run on existing unleaded avgas, and innovations (such as diesel, electric, and gas turbine) are showing increasing potential for GA aircraft. Implementing these new technologies can result in the phasing in of aircraft that do not use leaded gas and are not subject to the uncertainty of when fuel alternatives alone can eliminate GA lead emissions, albeit limited by the slow turnover rate in the fleet barring new incentives to change.

> A clear goal should be established that all newly certified gasoline-powered aircraft after a certain point in time (e.g., within 10 years) are approved to operate with at least one ASTM-specified unleaded fuel. Also, an additional amount of time should be identified by which all newly produced gasoline-powered aircraft, including those currently produced with older type certificates, would attain that same goal. Congressional action to establish the goal and timeframes would ensure achievement of those important results. For example, that congressional action would promote the development of new engine variants compatible with existing unleaded fuels, which could possibly yield prescriptions to support the eventual retrofit of some legacy aircraft and engines as they reach required overhaul milestones (Recommendation 6.2).
>
> FAA initiatives—including collaborations with industry and other government agencies such as the National Aeronautics and Space Administration—should be used to promote the development, testing, and certification of safe and environmentally desirable lead-free emerging propulsion systems (such as, diesel, electric, and jet fuel turbine engine) for use in GA aircraft, including the requisite airport refueling and recharging infrastructure. Congressional encouragement and the provision of resources as required would ensure the success of those initiatives (Recommendation 6.3).

Over the coming decades, efforts to reduce GHG emissions from the production and use of transportation fuels may influence the availability and composition of petroleum-based aviation fuels and hasten the introduction of aviation propulsion systems that do not require petroleum. It will be important that the transition to using avgas with lower or no lead content also coordinate with efforts seeking to reduce or eliminate GHG emissions, given the shared concerns with developing and certifying new aircraft technology, the supply and distribution systems for GA aircraft fuels, and broad awareness within the GA community.

CONCLUDING COMMENTS

There are no known safe lead exposures as measured by blood lead levels; lead's adverse effects on human health, and particularly on the development of children, are well established. While the elimination of lead pollution has been a U.S. public policy goal for decades, the GA sector continues to be a major source of lead emissions, largely because of the complex challenge of eliminating those emissions that is documented in this report. However, the evidence of lead pollution's hazard demands that those challenges not become an excuse for inaction, but instead become the subject of concerted, sustained, and multipronged efforts to find and implement mitigations.

It is important to note that EPA has been studying airborne lead concentrations at airports for the past decade to determine whether lead emissions endanger public health or welfare. However, the agency has not yet proposed such a formal determination, positive or negative. Given the uncertainty of this development, CAA-specific regulatory tools were not considered in this study, but if they were to become available, they would almost certainly have a prominent role in a lead mitigation strategy.

A key message of this report is that a lead mitigation strategy focused almost entirely on developing an unleaded drop-in fuel that would eliminate aviation lead emissions has a high degree of uncertainty of success given the formidable technical challenges. Additional mitigation measures are available that could be applied in the near and mid-terms to make progress in reducing lead emissions and exposures while other approaches having the potential for much larger impacts are being pursued.

Appendix A
Committee Member Biographies

Amy R. Pritchett, *Chair*, is a professor and the head of the Department of Aerospace Engineering at The Pennsylvania State University. Previously, Dr. Pritchett was on the faculty of the Schools of Aerospace Engineering and Industrial and Systems Engineering at the Georgia Institute of Technology, and she served via the Intergovernmental Personnel Act as the director of NASA's Aviation Safety Program for 2 years. Her research focuses on the intersection of technology, expert human performance, and aerospace operations, with a particular focus on designing to support safety. Dr. Pritchett's research topics have included autonomous flight and unmanned aerial vehicles, vehicle dynamics and controls, and vehicle systems engineering. Sheis a fellow of the American Institute of Aeronautics and Astronautics, and the Human Factors and Ergonomics Society . Dr. Pritchett has received the AIAA Lawrence Sperry Award, the RTCA William Jackson Award, and, as a member of the Executive Committee of the Commercial Aviation Safety Team, the 2008 Collier Trophy. She has served on many National Academies' committees, including chair of the Committee for a Study of FAA Air Traffic Controller Staffing and as a member of the Committee on Assessing the Risks of Unmanned Aircraft Systems (UAS) Integration, and Committee of the Federal Aviation Administration Research Plan on Certification of New Technologies into the National Airspace System. In addition, Dr. Pritchett served as a member of the National Academies' Aeronautics and Space Engineering Board. She earned a ScD, SM, and SB in aeronautics and astronautics from MIT.

Brian J. German is the National Institute of Aerospace Langley Associate Professor in the Daniel Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. He is also the founding director of the Georgia Tech Center for Urban and Regional Air Mobility. Dr. German's research involves aircraft design and optimization, including development of multidisciplinary optimization techniques. He also develops aerodynamic, propulsion, and performance models suitable for aircraft conceptual and preliminary design studies. A recent focus of his work has been aircraft design and operations for new forms of urban and regional air mobility, with emphasis on aircraft sizing, aerodynamics of distributed propulsion, battery and hybrid electric propulsion modeling, and operations research problems for innovative scheduled and on-demand air services. Dr. German is a recipient of the NSF CAREER award and an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He received a PhD, MS, and BS in aerospace engineering from the Georgia Institute of Technology.

Jack D. Griffith is the Kenan Distinguished Professor of Microbiology and Immunology in the Lineberger Comprehensive Cancer Center at the University of North Carolina (UNC) at Chapel Hill. Previously, at Caltech he developed electron microscopic (EM) methods for visualizing bare DNA bound by proteins and used this to visualize replicating DNA complexes. At Stanford, he obtained the first images of the basic chromatin particle termed a nucleosome and determined the amount of DNA in the nucleosome. At UNC his group combined EM and biochemistry to examine recombining DNAs, the nature of triplet repeat disease DNA, and the architecture of moving replication forks. In 1999 he demonstrated that the ends of eukaryotic chromosomes are arranged into a loop and that looping hides the DNA ends from being recognized as simple double strand DNA breaks. This discovery provided the answer to a question first raised 80 years ago when telomeres were identified and shown to protect chromosome ends. However, the way in which protection was accomplished at a molecular level remained unknown until Dr. Griffith's discovery of telomere looping. His contributions have been acknowledged by the Herbert A. Sober award from the Associated Societies for Biochemistry and Molecular Biology and the Grand Gold Medal of Comenius University. Dr. Griffith was elected to the American Academy of Arts and Sciences in 2006 and the National Academy of Sciences in 2018. Relevant to this study panel, Dr. Griffith holds Single Engine Land, Single Engine Sea , and Instrument ratings. He owns and flies a Piper Super Cub in North Carolina and in his home state of Alaska on floats. He received a PhD in biophysics from Caltech and was a postdoctoral fellow at Stanford with Nobel Prize winner Arthur Kornberg.

Kimberly A. Kenville is a professor of aviation at the University of North Dakota, focusing on airport management. The university owns and operates more than 120 piston and turbine-powered aircraft and helicopters with training sites in North Dakota and Arizona. Previously, she worked for Detroit (DTW), Milwaukee (MKE), and Minneapolis airports in the airport operations department. Dr. Kenville has completed several Transportation Research Board Airport Cooperative Research Program (ACRP) projects that pertain specifically to airports and their response and recovery to emergencies, social media, funding industrial aviation development, aviation education, strategic planning, and organizational effectiveness. She chaired the ACRP Project Panel on Updating the Guidebook for Managing Small Airports and is a member of the ACRP Oversight Committee. Dr. Kenville recently served as chair of the North Dakota Aeronautics Commission and is a current voting member of the commission. She is a private aircraft pilot. She received a PhD in organization and management from Capella University.

Marie Lynn Miranda is the provost and a professor of computational mathematics and statistics at the University of Notre Dame. Previously, she served as a professor of statistics and the Howard R. Hughes Provost at Rice University. In addition, she was Samuel A. Graham Dean in the School of Natural Resources and Environment at the University of Michigan and Director of Undergraduate Programs for the Nicholas School of the Environment at Duke University. Dr. Miranda specializes in research on environmental health, especially how the environment shapes health and well-being among children. Her research topics include a geospatial analysis of the effects of aviation gasoline on childhood blood lead levels. She is the founding director of the Children's Environmental Health Initiative, a research, education, and outreach program committed to fostering environments where all people can prosper. The initiative's peer-reviewed research has been cited extensively, including in the U.S. Environmental Protection Agency's (EPA's) integrated science assessment on revisions to the national ambient air quality standards for lead. Dr. Miranda received a PhD in economics from Harvard University.

Robert A.K. (Bob) Mitchell is an independent aerospace researcher and consultant. Previously, he served as vice president for Northrop Grumman Aerospace Systems and the chief executive officer of Teledyne Ryan Aeronautical, prior to its acquisition by Northrop Grumman. He led the capture and development of the Global Hawk high-altitude, long-endurance unmanned aircraft system (UAS), the Fire Scout vertical UAS, the Navy Triton UAS (derived from Global Hawk), and several restricted programs. Prior to taking over Teledyne Ryan Aeronautical, Mr Mitchell spent 12 years working on the Space Shuttle. Mr. Mitchell is a member of the National Academy of Engineering and he has received numerous other awards for his contributions in the field of aerospace, including the Reed Award from AIAA. He attended the Royal Air Force College, Cranwell, was commissioned, became a pilot, and served 16 years. Mr. Mitchell received an MS in astronautical engineering from the USAF Institute of Technology at Wright-Patterson Air Force Base.

Glenn W. Passavant recently retired from Ingevity Corporation as a senior engineer in Technology and Regulatory Affairs, focusing on the advancement of vehicle evaporative and refueling emission control technology. Previously, he was Center Director and senior program manager with the EPA Office of Transportation and Air Quality, where he led development of regulatory programs related to a wide variety of mobile sources, including passenger cars, light trucks, motorcycles, heavy-duty engines, marine vessels, nonroad equipment, locomotives, and aircraft. In this capacity, he represented EPA in interactions with government and industry and led the development and assessment of provisions for vehicles/equipment, their fuels, related test procedures, and other necessary regulatory requirements. He worked on EPA’s evaluation of lead emissions impacts from general aviation aircraft that use leaded aviation gasoline to determine whether those emissions cause or contribute to air pollution which may endanger public health or welfare. He had a long career in the USAF in the positions of meteorologist, bioenvironmental engineer, and squadron commander. Mr. Passavant received an ME in environmental engineering from the University of Illinois at Urbana-Champaign.

Bernard I. Robertson is retired senior vice president, Engineering Technologies and Regulatory Affairs, and general manager-Truck Operations at the Daimler Chrysler Corporation. His primary research interests are ground vehicles, their fuels and supporting infrastructure. A particular specialty has been emissions and environmental impact, including development of powertrain and fuel technology. While involved in all aspects of vehicle design and development, he has focused on alternate powerplant and fuel research and development worldwide. He has relevant technical experience in gasoline-fueled engines and all aspects of aviation. Mr. Robertson is a member of the National Academy of Engineering. His previous service on National Academies committees includes the Committee on Review of the FreedomCAR and Fuel Research Program and the Committee for Stakeholder Input in Developing the Airport System Management Services Component of the National Airspace System. In addition, he served as a member of the Board on Energy and Environmental Systems. He has been a general aviation pilot and aircraft owner for 40 years. Mr. Robertson received an MEng in mechanical sciences from the University of Cambridge, an MS in automotive engineering from the Chrysler Institute of Engineering, and an MBA from Michigan State University.

Jay R. Turner is a professor of energy, environmental and chemical engineering, and vice dean for education in the James McKelvey School of Engineering at Washington University in St. Louis. His research primarily focuses on air quality characterization with emphasis on field measurements and data analysis to support a variety of applications in the atmospheric science, regulation and policy, emissions estimation, exposure assessment, and health studies arenas. He was co-investigator and Washington University lead on two ACRP projects awarded to Sierra

Research: Quantifying Aircraft Lead Emissions at Airports (02-34); and Reducing the Impact of Lead Emissions at Airports (02-57). He is currently the principal investigator (PI) for a UNICEF-funded project in Mongolia to develop air quality monitoring systems for children's health and is co-PI for three National Institutes of Health–funded projects to: examine relationships between air pollution and neurodegenerative disease; conduct passive and mobile platform measurements to assess the air quality impacts of a neighborhood-scale greening intervention; and develop and deploy a high-time resolution monitor for mobile mapping of volatile organic compounds. In the last 2 years, he was also PI for a Federal Highway Administration/Department of Transportation–funded project to quantify the efficacy of an engineered vegetative buffer to attenuate near-road air pollution. Dr. Turner currently serves on EPA's chartered Science Advisory Board (SAB) and recently chaired the SAB panel for Screening Methodologies to Support Risk and Technology Reviews: A Case Study Analysis. Dr. Turner is a past president of American Association for Aerosol Research. He received a DSc in chemical engineering from Washington University.

Asciatu J. Whiteside is an environmental program manager with Dallas/Fort Worth (DFW) International Airport's Department of Environmental Affairs**.** She has worked at DFW for more than 18 years assisting the airport to become a leader in environmental performance and sustainability through the management of core programs, including Resource Conservation and Recovery Act Waste Management Program, Pretreatment, Storm Water, and Environmental Management Systems. She also provides environmental oversight and technical support for Capital Improvement Projects related to rehabilitating airport infrastructure, including deicing collection systems. In addition, she coordinates and communicates airport programs, public outreach, compliance-related initiatives, sustainability and Leadership in Energy & Environmental Design–related goals and objectives to internal stakeholders, airport tenants, and regulators. Ms. Whiteside has served on several TRB ACRP projects involving water quality toxicity testing and winter weather operations at airports. She holds an MS in environmental science and management from Duquesne University and a BS in chemistry from Emory University.

Appendix B
Open-Session Meeting Agendas

Committee on Lead Emissions from Piston-Powered General Aviation Aircraft

First Meeting: November 19-20, 2019
National Academy of Sciences Building
2101 Constitution Avenue, NW, Washington, DC 20418

Tuesday, November 19, NAS Board Room

8:00-9:45 AM EXECUTIVE SESSION: Only for Committee Members and National Academies Staff

OPEN SESSION

10:00	**Opening Remarks and Introduction of Committee Members** Amy Pritchett, Committee Chair
10:10	**Topic I. Charge from Congress and Regulatory Context of Task** Monica Merritt (FAA) and Marion Hoyer (EPA)
11:05	**Topic II. Ambient Lead Concentrations** Marion Hoyer (EPA)
11:45	Lunch break
12:45	**Panel Discussion on Topic II** *Moderator:* Amy Pritchett *Discussants:* Philip Fine (South Coast Air Quality Management District, CA, Amanda Giang (University of British Columbia), Marion Hoyer (EPA)
1:45	**Topic III. Fuel Alternatives** Mark Rumizen (FAA) and Boyd Rodeman (FAA)
2:25	Break
2:40	**Panel Discussion on Topic III** *Moderator:* Amy Pritchett *Discussants:* Chris D'Acosta (Swift Fuels), Doug Macnair (Experimental Aircraft Association), Ryan Manor (Phillips 66), Mark Rumizen (FAA), Boyd Rodeman (FAA), Tim Shea (Shell)
3:40	**Opportunity for Public Comment**

Each commenter will have a maximum time limit of 3 to 5 minutes. Accompanying written materials are encouraged.

4:10 End of open session

4:25 EXECUTIVE SESSION: Only for Committee Members and National Academies Staff

Wednesday, November 20, NAS Lecture Room

OPEN SESSION

8:30 **Opening Remarks and Introduction of Committee Members**
Amy Pritchett, Committee Chair

8:35 **Topic IV. Potential Mitigation Measures**
Warren Gillette (FAA)

9:15 **Panel Discussion on Topic IV**
Moderator: Amy Pritchett
Discussants: Warren Gillette (FAA), Marion Hoyer (EPA), Ryan Manor (Phillips 66), Boyd Rodeman (FAA)

10:15 End of Open Session

10:30 EXECUTIVE SESSION: Only for Committee Members and National Academies Staff

Second Meeting: February 18-19, 2020
National Academy of Sciences Building
2101 Constitution Avenue, NW, Washington, DC 20418

Tuesday, February 18, NAS Room 125

8:00 AM-12:30 PM EXECUTIVE SESSION: Only for Committee Members and National Academies Staff

OPEN SESSION

12:45 **Opening Remarks and Introduction of Committee Members**
Amy Pritchett, Committee Chair

12:50 **Aircraft Owners and Pilots Association Perspectives on the Committee's Task**
Christopher Cooper, AOPA

1:20 **General Aviation Manufacturers Association Perspectives on the Committee's Task**
Lowell Foster (GAMA) and Mike Kraft (Lycoming Engines)

1:50 **Panel Discussion of GAMA-Related Issues**
Moderator: Amy Pritchett
Discussants: Raymond Best (Textron Aviation), Walter Desrosier (GAMA), Lowell Foster (GAMA), Jeffrey Knutson (Cirrus Aircraft), Mike Kraft (Lycoming Engines), Jennifer Miller (Lycoming Engines)

2:35 Break

2:50 **Recent EPA Reports on Ambient Lead Concentrations and Populations Near U.S. Airports**
Marion Hoyer, EPA

3:50 **National Air Transport Association Perspectives on the Committee's Task**
Megan Eisenstein, NATA

4:30 **Pilot Education and Training**
Jeremy Roesler, University of North Dakota (via Internet)

5:10 **End of Open Session**

Wednesday, February 19, NAS 125

OPEN SESSION

8:30 **Opening Remarks and Introduction of Committee Members**
Amy Pritchett, Committee Chair

8:35 **Airport Planning and Policy Issues Relevant to the Committee's Task**
Elliott Black, FAA

9:50 **Basics of Aircraft Certification**
Boyd Rodeman, FAA

11:05 **End of Session**

Appendix C
Statutory Provisions
(42 U.S.C. §§ 7571-7573 and 49 U.S.C. § 44714)

The Administrators of the U.S. Environmental Protection Agency (EPA) and the Federal Aviation Administration (FAA) share authority and responsibility regarding emissions from aircraft and the properties of aviation fuels.

ENDANGERMENT FINDING

Section 231 of the Clean Air Act (CAA) sets forth EPA's authority to regulate aircraft emissions of air pollution. Section 231(a)(2)(A) requires EPA to, "from time to time, issue proposed emission standards applicable to the emission of any air pollutant from any class or classes of aircraft engines which, in [the Administrator's] judgment, causes or contributes to air pollution which may reasonably be anticipated to endanger public health or welfare" (emphasis added). By instructing the Administrator to consider whether emissions of an air pollutant cause or contribute to air pollution, the law does not require the Administrator to find that emissions from any one sector or group of sources are the sole or even the major part of an air pollution problem. Section 231(a) does not contain a modifier such as "significant" or "major" on the term "contribute" and thus does not appear to set the magnitude of the contribution as a criterion for an affirmative endangerment finding.[1]

In 1976, EPA listed lead under CAA section 108, making it what is called a "criteria pollutant." As part of the listing decision, EPA determined that lead was an air pollutant, which, in the Administrator's judgment, has an adverse effect on public health or welfare. Once lead was listed, under section 109(b) EPA issued primary and secondary National Ambient Air Quality Standards (NAAQS) that the Administrator determined were requisite to protect public health with an adequate margin of safety and to protect public welfare from any known or anticipated adverse effects. EPA issued the first NAAQS for lead in 1978; the lead NAAQS level is now 0.15 $\mu g/m^3$, measured over a 3-month averaging period.[2]

According to a 2010 advance notice of proposed rulemaking from EPA (75 Federal Register 22440-22468), EPA has broad authority in exercising its judgment regarding whether emissions from certain sources cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare EPA has not yet made an "endangerment finding" with regard to lead emissions from piston-engine general aviation aircraft operations.

REGULATORY AUTHORITY FOR EMISSION STANDARDS

Section 231 of the CAA sets forth EPA's authority to regulate aircraft emissions of air pollution. As mentioned above, section 231(a)(2)(A) requires EPA to, from time to time, issue proposed emission standards applicable to the emission of any air pollutant from any class or classes of

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[1] 75 Federal Register 22440-22468. April 28, 2010. Advance Notice of Proposed Rulemaking on Lead Emissions From Piston-Engine Aircraft Using Leaded Aviation Gasoline; Proposed Rule. See https://www.govinfo.gov/content/pkg/FR-2010-04-28/pdf/2010-9603.pdf.

[2] National Ambient Air Quality Standards for Lead 73 FR 66965, November 12, 2008.

aircraft engines which, in [the Administrator's] judgment, cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare. In setting or revising standards, section 231(b) provides that EPA shall have them take effect after such period as EPA finds necessary (after consultation with the Secretary of Transportation) to permit the development and application of the requisite technology, considering the cost of compliance within such period. Section 231(c) then states that EPA's regulations regarding aircraft shall not apply if disapproved by the President, after notice and opportunity for public hearing, on the basis of a finding by Secretary of Transportation that such regulations would create a hazard to aircraft safety.

Section 232 of the CAA directs the Secretary of Transportation to issue and implement regulations to insure compliance with EPA's standards, while Section 233 pre-empts States and local governments from adopting or enforcing any aircraft emission standards that are not identical to EPA's standards.

In a relatively recent opinion which included a review of this statutory scheme, the U.S. Court of Appeals for the District of Columbia Circuit ruled that "this delegation of authority is both explicit and extraordinarily broad." The opinion also noted that "Congress has delegated expansive authority to EPA to enact appropriate regulations applicable to the emissions of air pollutants from aircraft engines."[3]

Regulatory Authority for Fuel Standards

Part A of Title II of the CAA contains sections 216 and 211. Section 216 defines "motor vehicle," "nonroad engine," and "nonroad vehicle." Section 211 (c) allows EPA to regulate any fuel or fuel additive used in motor vehicles and nonroad vehicles or engines if, in the judgment of the Administrator, any fuel or fuel additive or any emission product of the fuel or fuel product either: (A) causes or contributes to air pollution or water pollution that reasonably may be anticipated to endanger public health or welfare, or (B) will impair to a significant degree the performance of any emission control device or system which is in general use, or which the Administrator finds has been developed to a point where in a reasonable time it will be in general use were such a regulation to be promulgated. This section of the CAA was used to eliminate lead from fuel used in motor vehicles.

EPA's authority to regulate aircraft emissions resides in Part B of Title II of the CAA; the provisions of section 211 and the definitions of section 216 do not apply. Aircraft are not "nonroad vehicles," and aircraft engines are not "nonroad engines." EPA's authority to regulate fuels under section 211 does not extend to fuels used exclusively in aircraft, such as leaded aviation gasoline.

Instead, fuels used in aircraft engines are to be regulated by FAA under section 232 of the CAA and 49 U.S.C. § 44714. Under section 232, the Secretary of Transportation is to consult with the Administrator of EPA regarding implementation of EPA standards and is to modify Type Certificates as appropriate and necessary. Linking back to these CAA provisions, 49 U.S.C. § 44714 requires that: "the Administrator of the Federal Aviation Administration shall prescribe (1) standards for the composition or chemical or physical properties of an aircraft fuel or fuel additive to control or eliminate aircraft emissions the Administrator of the Environmental Protection Agency decides under section 231 of the Clean Air Act (42 U.S.C. 7571) endanger the

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[3] *NACAA v. EPA*, 489 F.3d 1221, 1229-30 (DC Cir. 2007).

public health or welfare; and (2) regulations providing for carrying out and enforcing those standards."

Beyond this, a 2018 addition to 49 U.S.C. § 44714 gives the Administrator of FAA authority to allow the use of a unleaded aviation gasoline in aircraft as a replacement for leaded aviation gasoline if FAA: (1) qualifies the unleaded gasoline as a replacement for approved leaded gasoline, (2) identifies the aircraft and aircraft engines eligible to use the unleaded gasoline, and (3) adopts a process other than the traditional Type Certification process to allow eligible aircraft and aircraft engines to operate using the qualified replacement unleaded gasoline in a manner that ensures safety. However, as stated in the statutory language, these new provisions are not intended to replace existing regulatory mechanisms by which an unleaded aviation gasoline can approved for use in an engine or aircraft.

The important overlapping authority and responsibility regarding lead emissions rests in two requirements. The first is the requirement for consultation between EPA and the U.S. Department of Transportation (DOT)/FAA regarding aircraft emission standards in CAA section 231(b). If EPA makes an endangerment finding and eventually proposes some form of measure(s) to reduce lead emissions. Before any final rule action, these potential measure(s) would need to be coordinated with FAA regarding the time the regulation takes effect after a period needed to permit the development and application of the requisite technology, considering the cost of compliance within such period." Furthermore, technical consultation would be needed under section 231(a)(2)(B)(i)-(ii), specifically that the regulation would not significantly increase noise and adversely affect safety.

Second, 49 U.S.C. § 44714 stipulates that FAA prescribe standards for the composition or chemical or physical properties of an aircraft fuel or fuel additive in response to a final EPA endangerment finding under section 231 of the CAA and that FAA prescribe regulations for carrying out and enforcing those standards.

Appendix D
Ethylene Dibromide

Ethylene dibromide (EDB [($C_2H_4Br_2$]) is added to leaded aviation gasoline as a scavenger to help remove lead, which is volatilized from tetraethyl lead (TEL [($Pb(C_2H_5)_4$)]) during aircraft engine operation. EDB, is transformed to lead bromide (PbBr2) when the vaporized lead from TEL reacts with the bromine during combustion. The ethylene is burned as fuel. The removal of this lead is critical to the performance, reliability, and durability of the engine.

The Toxic Substances Control Act (TSCA) requires the U.S. Environmental Protection Agency (EPA) to prioritize chemical substances for risk evaluation. In accordance with TSCA section 6(b) and 40 CFR § 702.7, on March 21, 2019, EPA initiated the prioritization process for 20 chemical substances identified as candidates for High-Priority Substance designation.[1] EDB was among the 20 chemical substances identified for risk evaluation. Subsequently, on August 23, 2019, EPA proposed to designate the same 20 chemical substances as High-Priority Substances for risk evaluation.[2]

Under TSCA section 6(b)(1)(B) and implementing regulations (40 CFR § 702.3), a High-Priority Substance is defined as “a chemical substance that [EPA] concludes, without consideration of costs or other non-risk factors, may present an unreasonable risk of injury to health or the environment because of a potential hazard and a potential route of exposure under the conditions of use, including an unreasonable risk to a potentially exposed or susceptible subpopulation identified as relevant by [EPA].”

A designation as a High-Priority Substance is not a finding of unreasonable risk. Rather, when prioritization is complete, for those chemicals designated as High-Priority Substances, EPA will have evidence on hazards and exposures that may support a finding that the substance may present an unreasonable risk of injury to health or the environment under the conditions of use. Final designation of a High-Priority Substance initiates the risk evaluation process (40 CFR § 702.17), which culminates in a finding of whether or not the chemical substance presents an unreasonable risk of injury to health or the environment under the conditions of use.

On April 9, 2020, EPA published a notice of the availability of two reports related to the draft risk assessment for EDB and sought comment on these reports.[3] The reports, “Draft Scope of the Risk Evaluation for Ethylene Dibromide CASRN 106-93-4” and “Draft Scope of the Risk Evaluation for Ethylene Dibromide Supplemental File: Data Extraction and Data Evaluation Tables for Physical-Chemical Property Studies CASRN: 106-93-4” and the related public comments can be found in EPA public docket EPA-HQ-OPPT-2018-0488. The timeline for EPA completing its assessment of whether EDB should be designated as a High-Priority Substance is not clear and any discussion of follow-on regulatory action is premature. However, this is of great significance to the future composition of additive packages for leaded aviation gasoline.

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[1] EPA Initiation of Prioritization Under the Toxic Substances Control Act (TSCA), 84 Federal Register 10491 (March 21, 2019).

[2] EPA. Proposed High-Priority Substance Designations Under the Toxic Substances Control Act (TSCA), 84 Federal Register 44300 (August 23, 2019).

[3] 85 Federal Register 19941, April 9, 2020.

Appendix E
Occupational Health

The U.S. Department of Labor's Occupational Safety and Health Administration (OSHA) has occupational exposure standards and related regulatory requirements designed to reduce health risks of workplace exposures to chemical contaminants to acceptable levels. The requirements are adopted, administered, and enforced by OSHA. There are 28 states and territories which operate their own occupational safety and health programs under a State Plan approved and monitored by OSHA. Twenty-two State Plans cover private-sector and state and local government workers; six State Plans cover state and local government workers only. State Plans adopt and enforce standards and investigate safety and health concerns in workplaces throughout the state. State Plans are required to have standards and enforcement programs that are at least as effective as those of OSHA but may have different or additional requirements.[1]

The OSHA standards apply to general aviation (GA) broadly and to occupational exposures to GA fuels and their combustion products. This discussion addresses three specific chemical compounds. These include inorganic lead (lead dibromide [PbBr2] [CAS# 10031-22-8]) as an exhaust emission product of the combustion of leaded aviation gasoline) and the fuel additives tetraethyl lead (TEL) $Pb(C_2H_5)_4$ (CAS# 78-00-02) and ethylene dibromide (EDB) ($C_2H_4Br_2$) (CAS# 106-93-4).[2]

INDUSTRIAL HYGIENE AND OCCUPATIONAL HEALTH

Table E-1 summarizes the current occupational exposure standards for lead exposure (inorganic lead and TEL) for the general industry as drawn from 29 CFR § 1910.1025 and Table Z-1 of 29 CFR § 1910.1000. Details on the industrial hygiene and occupational health control program requirements should be taken from the OSHA standards and requirements.[3] The acronyms used are defined in the footnote below.[4] Regarding the action level, under OSHA, the action level for any given air contaminant is generally set at one-half of the PEL, but the actual level may vary from exposure standard to exposure standard. The intent of the action level is to identify an 8-hour TWA exposure level, which, if achieved without respiratory protection, would indicate that the vast majority of randomly sampled exposures for the same employee group conducting the same workplace tasks will be below the PEL.

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[1] Personal communication, David Valiante, OSHA, June 17, 2020.

[2] OSHA standards would apply to exposures to other organic compounds in GA fuels (e.g., benzene and toluene) but this is outside of the scope of this assessment.

[3] Information on the requirements of the lead standard can be found at OSHA's Lead Safety and Health Topic Page. OSHA regulations for organic lead such as TEL are in the form of PELs and can be found under OSHA's air contaminants standard (29 CFR 1910.1000 and 29 CFR 1926.55). OSHA expanded health standard for lead, 1910.1025, specifically excludes organic lead (e.g., TEL). Overexposures under the lead standard apply only to inorganic lead (e.g., lead dibromide) and are assessed using both the action level and the PEL. See 29 CFR 1910.1025 for full detail.

[4] OSHA PEL: permissible exposure level; TWA: time-weighted average.

TABLE E-1 Occupational Exposure Standards for Lead Exposure

	TEL	**$PbBr_2$ as Lead (inorganic lead)**
OSHA & Cal OSHA PEL (8-hour TWA)	0.075 mg/m^3	0.050 mg/m^3 [a]
OSHA action level (8-hour TWA)	0.5 of PEL	0.030 mg/m^3

[a] The lead standard for general industry (29 CFR § 1910.1025) requires PEL adjustments with respect to extended work shifts (work shift longer than 8 hours). There are adjustments required for TEL in the OSHA regulations.

Measured and confirmed workplace exposures below the action level generally require a report documenting the monitoring results (a negative initial determination) but no further action by the employer. For inorganic lead, the action level is 60 percent of the PEL, but, as is discussed below, the employer's obligations to confirmed exposures above the action level are significant.

The OSHA general industry standard for exposure to TEL (29 CFR § 1910.1000 and 29 CFR § 1926.55) and inorganic lead (29 CFR § 1910.1025) applies to GA aircraft operations and aircraft engine maintenance activities where exposure to lead and/or TEL are possible. To be more specific the provisions of 29 CFR § 1910.1025 do not apply to TEL because it is an organic lead compound.

For inorganic lead ($PbBr_2$), under 29 CFR § 1910.1025 (d)(2), through personal exposure monitoring, the employer is required to make an initial determination as to whether employee exposures exceed the action level value. This exposure monitoring can be conducted on all employees or on a representative sample of employees who would be expected to encounter the highest airborne concentrations of lead over an 8-hour work period. For workplaces with a larger number of exposed employees, another approach would be to monitor exposures for a smaller group of randomly selected employees with similar exposures. For many locations, it is expected that the number of exposed employees would be small, and this could lead to a decision to either monitor all employees or a smaller number of employees based on those with the largest expected lead exposures.

It should be noted that the evaluation of the results of the personal exposure monitoring must also meet the accuracy requirements of 29 CFR § 1910.1025 (d)(9) and include a consideration of sampling and analysis error (SAE). This is necessary to account for occupational environment variations over the course of a work shift plus sampling and analytical errors. The analytical error is based on a standardized coefficient of variation for the analytical method used as provided by the National Institute for Occupational Safety and Health (NIOSH) while the occupational environment variations and sampling error are derived from the central tendency and spread of the sample distribution using data gathered from sampling exposures for randomly selected work days and randomly selected employees in the similar exposure group or an individual employee.[5,6,7] Thus, when evaluating the exposure results, against the PEL or action level, the determination is based on the value of the average exposure estimate relative to the 95 percent confidence levels for the data and the other SAE inputs.

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[5] OSHA Technical Manual (OTM), OSHA Instruction TED 01-00-015 [TED 1-0.15A], Section II, chapter 1. Available at: https://www.osha.gov/dts/osta/otm/otm_ii/otm_ii_1.html#receive_sample_results.

[6] For lead sampling and analytical information, see Lead by Flame AAS. In: NIOSH Manual of Analytical Methods (NMAM), Fifth Edition. Available at: https://www.cdc.gov/niosh/docs/2014-151/pdfs/methods/7082.pdf.

[7] NIOSH (1977).

Furthermore, regarding inorganic lead assessments, if the action level is exceeded, then the regulation prescribes that the employer conduct exposure monitoring for all exposed employees. The results of this monitoring are reported to all affected employees. If the PEL is exceeded, the employer is then required to implement engineering, work practice, administrative controls, and perhaps to supply various forms of personal protective equipment (PPE) to reduce levels air concentrations below the PEL and reduce skin and eye absorption. Beyond this, there are several work area housekeeping and hygiene facilities and practices requirements designed to eliminate the accumulation of inorganic lead dust or the re-entrainment of this lead dust, the inadvertent ingestion or absorption of this lead dust, or its transport outside of the work area.

In addition, there are explicit and detailed medical surveillance and biological monitoring requirements for employees exposed above the action level for more than 30 days per year, including specific requirements related to measurement of blood lead level (BLL) expressed in ug/deciliter. Also, there are explicit training requirements for any employee exposed to lead, as well as hazard communication requirements under the OSHA Hazard Communication Standard (29 CFR § 1910.1200) for lead.

The situation is less complex for exposures to TEL. There are no explicit requirements beyond establishing statistically (as described above for inorganic lead) that the average exposure estimate does not exceed the PEL or action level. In this case, the exposure determination may be either qualitative or quantitative. If exposures are above the action level, then it must be established statistically through additional sampling that they do not exceed the PEL. If exposures do exceed the PEL, then controls (engineering, work practice, PPE, administrative) are needed to reduce exposures. The OSHA standard does not explicitly call for personal exposure monitoring for TEL, so an analysis based on exposure measurements for similar workplaces and similar tasks, engineering evaluation, or worst-case exposure calculations may be a path for the required initial determination. A review of the chemical and physical characteristics of the material, quantity of use, frequency of use, conditions under which it is used and experience with similar operations may be sufficient to characterize exposures to a workplace hazard. Either way, the basis for this determination must be documented and the records retained.

The compliance determinations for inorganic lead and TEL may be complicated for airport workers exposed to both lead dibromide and TEL. In this case, OSHA standard 29 CFR § 19.1000 (d)(2)(i) treats this as a mixture and evaluates this as “combined” exposure because the effects could be additive:

$$[(\text{8-hr TWA TEL exposure}/0.075\ \text{mg/m}^3) + (\text{8-hr TWA Pb exposure}/0.05\ \text{mg/m}^3)].$$

Under the OSHA technical manual, the SAE (95 percent confidence) of the substances comprising the mixture can be pooled to give the SAE of the mixture and the determination rules described in the manual can then be applied to the mixture relative to unity as opposed to the PEL.[8] The concept of action level does not apply to the mixture, only the individual contaminants.

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[8] OSHA Technical Manual, OSHA Instruction TED 01-00-015 [TED 1-0.15A], Section IV D. 4. SAEs for Exposures to Chemical Mixtures. Available at: https://www.osha.gov/dts/osta/otm/otm_ii/otm_ii_1.html#receive_sample_results.

One final point regarding exposure to Grade 100 and 100LL vapor involves EDB. As was mentioned above, EDB is a fuel additive which performs the role of a lead scavenger in the exhaust gas. However, it also exists as a vapor in fuel tanks and is released to the atmosphere during refueling and while aircraft are parked. Its potential exposure routes include inhalation, absorption, ingestion, and contact. The PEL, ceiling and peak exposure standards and the action level from Table Z-2 of 29 CFR § 1910.1000 are presented in Table E-2; reference to OSHA standards and requirements of 29 CFR § 1910.1000 and § 1926.55 is recommended.

TABLE E-2 Ethylene Dibromide OSHA Exposure Standards

	EDB
OSHA PEL (8-hour TWA)/C/P	20 ppm/30 ppm any time/50 ppm-5 minute maximum peak
OSHA action level (8-hour TWA)	0.5 of PEL

Several times in this discussion mention has been made that TEL and EDB are an absorption hazard through dermal, mucous membranes, and eyes. Both compounds carry a skin hazard designation in the OSHA standard and evaluations of these three routes of exposure should be included in any industrial hygiene assessments for these workplaces.

FBOS, REPAIR AND OVERHAUL SHOPS, AND AIRPORTS

The purpose of the discussion above was to provide background for understanding occupational health requirements for exposures to leaded aviation gasoline and its combustion products. Specifically, there is the need for assessment of TEL, lead bromide, and EDB exposures in airport workplaces such as flight line operations and in those repair and overhaul shops where GA aircraft and engines using aviation gasoline are maintained.[9] It seems evident that exposures to lead are common for flight line and maintenance shop workers at airports with GA aircraft including those employed by the airport itself, fixed base operators (FBOs), and repair/overhaul facilities. This would include exposure to inorganic lead (lead bromide) because of the combustion of leaded aviation gasoline in aircraft engines and TEL and EDB as a result of refueling aircraft and maintenance activities. Even incidental exposures to employees not directly engaged in these work functions are also possible and these employees must be included in industrial hygiene assessments.

For TEL and EDB, there may be direct exposures as a result of activities such as the handling of engine parts wetted with leaded aviation gasoline by mechanics, the dispensing and inadvertent spillage of aviation gasoline by aircraft ground service operators, or the improper use of aviation gasoline as a shop solvent for parts cleaning, or perhaps other purposes. These TEL and EDB exposures may involve inhalation, ingestion, and absorption. Due to its vapor pressure at 25°C (0.23 psi) and its concentration in the liquid (based on a 1:1 molar ratio dosing rate for TEL and EDB), inhalation exposures to EDB are possible, especially during refueling. To some

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[9] For an example of a comprehensive airport lead workplace exposure and program assessment see Chen and Eisenberg (2013).

degree TEL and EDB contained in aviation gasoline vapor may be transported downstream of the location of the refueling event.

Lead bromide presents a different exposure picture. Lead bromide is a product of engine exhaust and could originate anywhere the aircraft engine is operating including maintenance and repair facilities and operational areas on the airport grounds. Aircraft lead dibromide emissions are transported downwind from the aircraft location. The concentrations vary with downwind distance and the local concentrations can vary with meteorology, terrain, and local factors. With the large number of airports and the widespread use of leaded aviation gasoline, lead dibromide is expected to be commonly found in many airport workplaces or as an incidental exposure to those working nearby.

As discussed above, there are different PELs for exposures to inorganic lead, TEL, and EDB and separate exposure assessments and compliance actions are required under OSHA regulations. At a minimum, an initial exposure determination is needed for each employee or group of similarly exposed employees in the workplace for each air contaminant found in the workplace. If the determination is that the exposure is below the action level, then a negative initial determination must be documented. If the initial assessment indicates that the exposure is above the action level, this must also be documented and either more personal exposure monitoring may be required to determine compliance and perhaps workplace controls. As discussed in (29 CFR 1910.1025), there are very specific additional requirements for inorganic lead exposures above the action level.

REFERENCES

Chen, L., and J. Eisenberg. 2013. Health hazard evaluation program: Exposures to lead and other metals at an aircraft repair and flight school facility. NIOSH Report No. 2012-0115-3186. Cincinnati, OH, U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. Available at: http://www.cdc.gov/niosh/hhe/reports/pdfs/2012-0115-3186.pdf.

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