Research Needs Associated with Particulate Emissions at Airports

DETAILS

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AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP REPORT 6

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AIRPORT COOPERATIVE RESEARCH PROGRAM

Airports are vital national resources. They serve a key role in transportation of people and goods and in regional, national, and international commerce. They are where the nation's aviation system connects with other modes of transportation and where federal responsibility for managing and regulating air traffic operations intersects with the role of state and local governments that own and operate most airports. Research is necessary to solve common operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the airport industry. The Airport Cooperative Research Program (ACRP) serves as one of the principal means by which the airport industry can develop innovative near-term solutions to meet demands placed on it.

The need for ACRP was identified in *TRB Special Report 272: Airport Research Needs: Cooperative Solutions* in 2003, based on a study sponsored by the Federal Aviation Administration (FAA). The ACRP carries out applied research on problems that are shared by airport operating agencies and are not being adequately addressed by existing federal research programs. It is modeled after the successful National Cooperative Highway Research Program and Transit Cooperative Research Program. The ACRP undertakes research and other technical activities in a variety of airport subject areas, including design, construction, maintenance, operations, safety, security, policy, planning, human resources, and administration. The ACRP provides a forum where airport operators can cooperatively address common operational problems.

The ACRP was authorized in December 2003 as part of the Vision 100-Century of Aviation Reauthorization Act. The primary participants in the ACRP are (1) an independent governing board, the ACRP Oversight Committee (AOC), appointed by the Secretary of the U.S. Department of Transportation with representation from airport operating agencies, other stakeholders, and relevant industry organizations such as the Airports Council International-North America (ACI-NA), the American Association of Airport Executives (AAAE), the National Association of State Aviation Officials (NASAO), and the Air Transport Association (ATA) as vital links to the airport community; (2) the TRB as program manager and secretariat for the governing board; and (3) the FAA as program sponsor. In October 2005, the FAA executed a contract with the National Academies formally initiating the program.

The ACRP benefits from the cooperation and participation of airport professionals, air carriers, shippers, state and local government officials, equipment and service suppliers, other airport users, and research organizations. Each of these participants has different interests and responsibilities, and each is an integral part of this cooperative research effort.

Research problem statements for the ACRP are solicited periodically but may be submitted to the TRB by anyone at any time. It is the responsibility of the AOC to formulate the research program by identifying the highest priority projects and defining funding levels and expected products.

Once selected, each ACRP project is assigned to an expert panel, appointed by the TRB. Panels include experienced practitioners and research specialists; heavy emphasis is placed on including airport professionals, the intended users of the research products. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, ACRP project panels serve voluntarily without compensation.

Primary emphasis is placed on disseminating ACRP results to the intended end-users of the research: airport operating agencies, service providers, and suppliers. The ACRP produces a series of research reports for use by airport operators, local agencies, the FAA, and other interested parties, and industry associations may arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by airport-industry practitioners.

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FOREWORD

By Christine L. Gerencher
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ACRP Report 6: Research Needs Associated with Particulate Emissions at Airports provides guidance on the most important research needed by the airport community in the area of particulate emissions. This report examines the state of industry research on aviation-related particulate matter (PM) emissions and identifies knowledge gaps that existing research has not yet bridged. These gaps and related research needs are then prioritized based on the ability of research in those areas to address airports' needs for more thorough and accurate aviation-related PM emissions inventories. While the main purpose of this report is to identify key research areas important to the airport community for ACRP consideration, research communities at large will also benefit from this report's comprehensive analysis of aviation PM emissions-related research needs.

Domestic airports and the aviation-industry partners that rely on these airports must assure compliance with current particulate matter (PM) controls, as called for in existing environmental requirements and state implementation plans (SIPs) and in the National Ambient Air Quality Standards (NAAQS) as enforced by the U.S. Environmental Protection Agency (EPA). In response to a U.S. General Accounting Office (GAO) report released in February 2003 titled "Aviation and the Environment: Strategic Framework Needed to Address Challenges Posed by Aircraft Emissions" (GAO-03-252), the Federal Aviation Administration (FAA), in consultation with the EPA and National Aeronautics and Space Administration (NASA), is developing a strategic framework for addressing emissions from aircraft-related PM sources, known as the Aircraft Emission Characterization (AEC) Roadmap.

A foundational part of the AEC Roadmap is identifying needed research on aircraft PM emissions. However, from an airport operator's perspective, PM emissions from aircraft is only one component of the overall airport PM emissions inventory. Specifically, the relative contributions of other sources of PM, including the ambient environment, diesel combustion processes, and non-combustion releases of PM (and its precursors) from other airport equipment and sources, are not explicitly known. This report subsequently builds on the knowledge gained from the AEC Roadmap process by evaluating all significant knowledge gaps that affect the airport community's understanding of aviation-related PM emissions in their environment, and prioritizes research needs to bridge those gaps based on their ability to assist airports in conducting more thorough airport PM emissions inventories.

ACRP Report 6 concludes by identifying three suggested research projects for ACRP consideration, including detailed problem statements for submittal through the ACRP solicitation process. These problem statements identify the highest priority research projects for airports relative to aviation-related PM emissions that are not included in other PM research programs.

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CHAPTER 1

Summary

Particulate matter (PM) emissions from aircraft engines and other emission sources at airports are a concern because of the lack of information on their quantity and their impacts on health and the environment. The level and nature of these emissions are growing in importance as demand for air travel grows. Data on PM emissions from aircraft have not been well defined or quantified. Yet as airports expand to meet future capacity needs, they must be able to evaluate their impact on the community and the local environment. The Clean Air Act specifically requires states to demonstrate compliance with ambient PM standards. Residents adjacent to airports are voicing concern over exposure to potentially hazardous and toxic pollutants, which might be chemicals or small particles. In addition, citizens are reporting that material is being deposited on their property from airport activity. Airports do not have an authoritative source to reference research findings concerning this material or to acknowledge that additional research is needed. Without better information about PM emissions, airports potentially will face increasing barriers to airport improvement and expansion projects.

Sources of airport-related PM emissions include aircraft engines, auxiliary power units (APU), ground support equipment (GSE), construction vehicles and related activity, ground access vehicles (e.g., passenger cars, delivery and freight trucks, and rental car vans), and stationary equipment. Particulate emissions from ground vehicles (including GSE and ground access vehicles), construction activity, and stationary sources are generally well characterized, at least for particle emission mass; emissions from aircraft main engines and APUs much less so. Also, data on the combined emissions from all airport sources have not been developed.

Several studies in the past few years have begun to collect detailed data on aircraft engine PM emissions, since it is an important PM source at airports. More work is needed, however, to relate aircraft and airport operations to PM emissions.

The present understanding of particle properties is insufficient to evaluate the health and environmental effects from exposure to various types and sizes of PM. Aircraft emissions are comprised primarily of ultrafine (< $PM_{0.1}$) particles, and general understanding of their health effects is limited. Volatile PM may include toxic and hazardous compounds, and these need to be identified and quantified along with information on the degree to which airport workers and residents living close to airports are exposed.

There are many sources of PM emissions associated with airport activity and from nearby sources in the community such as cars, trucks, and other commercial activity. As a result, monitored data include both the background (nonairport) emissions and the emission sources of interest (airport-related), and separating the contributing sources from the data ensemble is not currently feasible since particle size distribution and chemical composition are not adequately defined for all sources. Quantifying the individual sources is essential to developing reliable inventories and effective emission mitigation strategies.

Models and analytical tools used to evaluate airport emissions and their impacts do not yet have the required data to capture a complete and thorough PM picture, one that would include primary PM (both nonvolatile and volatile particles) directly emitted and secondary PM formed later in the atmosphere from NO_x, SO_x, and organics.

Without a better understanding of PM emissions from airport sources, airport operators will be unable to address the regulatory and community demands for assurance that airports are not damaging the local environment or the health of their workers or nearby residents. Without these assurances, airports may not be allowed to expand to meet the growing demands for their services, which are only expected to increase over the coming years.

Project Overview

This report presents an overview of the needs of the airport and scientific communities for further information on PM emissions from airport sources. The following are key accomplishments of the project:

- Eighty (80) airports were surveyed to determine their views of the significance of airport PM emissions and to solicit their thoughts on what information they need to manage their concerns.
- Detailed interviews were conducted with several airport operators and PM researchers to gain a more complete understanding of current need for information on airport PM emissions.
- Scientific literature was reviewed to gather the latest data and information on PM emissions from airports and emission characterization for airport sources.
- The information collected in the previous steps was compiled and summarized to present an overview of current knowledge of PM emissions from aircraft, APUs, GSE, ground access vehicles, construction equipment, and other emission sources at airports. This allowed us to identify current knowledge gaps, which were used to define a prioritized research agenda.
- The research agenda and information about active PM research currently underway or planned for the near future led to the assessment of the need for three proposed projects.

This report describes the project accomplishments, offers an assessment of research needs relative to PM emissions, and presents problem statements for future research to meet the most critical needs that would be of significant benefit to airport operators.

Prioritized Research Agenda

Based on research findings, the authors have identified five areas of investigation in which additional work can close the most significant knowledge gaps in understanding airport PM emissions.

1. Expand the current database of aircraft engine emissions to capture data on current advanced technology engines, which will become the most significant airport PM emissions sources within airport planning horizons.
2. Develop a deeper understanding of the evolution of PM, especially the volatile component, as it moves from the engine exit to the point of impact on airport workers, passengers, and local communities.
3. Improve the characterization of PM emissions from APUs, GSE, and aircraft brakes and tires to enable source apportionment of airport PM inventories.
4. Develop measurement methods to improve the characterization and understanding of PM from the various airport sources, especially the volatile components.
5. Expand current understanding of the health impacts of PM emissions, especially for the fine and ultrafine particles, which are believed to have the most significant impacts on human health.

The knowledge gained from pursuing these avenues of investigation will allow the aviation community to address its environmental impacts confidently and plan effectively for the future.

To prioritize research projects for ACRP to pursue, the authors considered other research initiatives currently underway or planned. Existing aviation PM research initiatives funded by FAA, NASA, DOD, and other research organizations are developing plans to expand the aircraft engine PM emissions database and include advanced technology engines in their research plans. EPA and public health researchers are investigating the effects of particles on human health and the focus of their efforts continues to move toward the smaller particles. With this in mind, the following priority projects are proposed for ACRP consideration to address the remaining priority knowledge gaps for understanding aviation PM emissions.

Priority 1—Characterize PM emissions of APUs, GSE, tires, and brakes for source apportionment.

Emissions from these sources remain either unknown or at best poorly characterized and represent a unique focal point for ACRP. Reliance on any existing estimates of such emissions to predict emissions inventories for future airport activities is likely to result in significant overestimations, which may impose unnecessary restrictions on needed expansion.

Priority 2—Develop an understanding of the atmospheric evolution of aviation PM.

One distinguishing feature of aviation emissions is the significant presence of volatile particle precursors that condense on preexisting particles or create new, very small particles as hot exhaust gases cool. Information regarding the evolution of these particles is required to assess airport impacts on employees, passengers, and the local community. To address this lack of understanding, a study of the atmospheric evolution of PM emissions–coupling operational factors with source emissions within the airport fence line–is needed.

Priority 3—Review airport emissions data for source chemical markers or fingerprints.

Particulate matter emissions from various airport sources combine as they move off the airport and it is difficult to isolate individual emission sources, for example, when evaluating the impact of airport operations on nearby communities. It would be a significant benefit to airports if characteristic markers or "fingerprints," based on for example, particle size, mass, composition, or a combination of these, could be defined that were unique to individual sources. Some airport emission sources have been studied individually and others are proposed in the top priority project. These data should be reviewed to identify the unique features or chemical compositions representative of individual sources.

CHAPTER 2

Background

The Clean Air Act requires airports to demonstrate compliance with PM emission standards for current operations as well as for expansion and construction projects. Currently airports must meet these requirements using very limited data on PM emissions from aircraft engines and no data on PM emissions from auxiliary power units (APUs). Data on other sources vary in quality and availability, and only limited data are available on ambient PM around airports.

Aviation engine PM data are rapidly evolving and with this evolution there is an urgent need to consolidate the work done in the past with the most recent state-of-the-art measurements. The scientific community's understanding of the nature of aircraft-related PM emissions is hindered since current data remain incomplete for large fractions of common engines operating in the domestic and global fleets. While there are no data available on APU PM emissions, APUs are essentially small jet engines that consume much less jet fuel and consequently emit much less than aircraft main engines, even in the airport vicinity. Their emissions are believed to be similar in composition to main engine emissions but this is yet to be determined.

The need to fill existing data gaps has been identified and initial steps taken in projects recently funded by FAA, NASA, and Transport Canada in their Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) Center of Excellence. Quite a bit of data have been acquired, especially in the last 3 years, on both military engines—much under DOD's Strategic Environmental Research and Development Program (SERDP) sponsorship—and on commercial-type wide-body transports and regional jets. Many gaps remain, however. The current state of available data is described in this report. From this, gaps in the current knowledge base are identified. Understanding the gaps guided the development of *project statements* for future research.

ACRP Report 6 presents the project results. A survey of 80 airports was conducted, ranging from large hubs to small general aviation airports, inquiring about the significance of PM emissions at that airport. Interviews were conducted with airport operators and researchers who have specific knowledge about PM emissions at airports. The team also conducted a literature review of available information and ongoing research about PM emissions at airports.

Based on the findings from the survey, the interviews, the literature review, and the professional knowledge of the team, the researchers prepared an assessment of the current state of knowledge of aviation PM emissions. This final report assesses research needs relative to PM emissions and presents problem statements for future research to meet the most critical needs that would be of significant benefit to airport operators.

Chapter 3 of this report presents a primer on PM emissions from aviation to provide a baseline of information for readers who may be unfamiliar with PM emissions generally and issues faced by the aviation community specifically. Chapter 4 summarizes the findings of the PM survey of airports and interviews with airport operators and PM researchers. Chapter 5 describes current knowledge and gaps regarding PM emissions from aircraft engines. Chapter 6 describes the current state of knowledge concerning other airport emission sources and Chapter 7 summarizes research needs. Chapter 8 includes a prioritized research agenda and problem statements for projects to address airports' highest priorities. Chapter 9 includes the literature review and the project bibliography. Appendix A includes a list of airports receiving the survey, a copy of the survey, and a summary of the survey responses. Appendix B includes notes recorded during the interviews. Appendix C presents a summary of hazardous air pollutants for reference. A glossary of key terms is also included.

CHAPTER 3

Primer on Particulate Matter Emissions From Aviation

This section presents basic information on particulate matter (PM) emissions in general and aviation emissions specifically. Research activities are described, as are regulatory requirements. Analytical tools that are used to analyze these emissions are also described. Much of the general information on particulate matter is adapted from U.S. EPA data and information compiled in support of the National Ambient Air Quality Standards (NAAQS) for particulate matter.[1,2,3]

What is PM?

Particle pollution from fuel combustion is a mixture of microscopic solids, liquid droplets, and particles with solid and liquid components suspended in air. Solid particles are referred to as nonvolatile particles and liquid droplets are referred to as volatile particles. This pollution, also known as particulate matter, is made up of a number of components, including soot or black carbon particles, inorganic acids (and their corresponding salts, such as nitrates and sulfates), organic chemicals from incomplete fuel combustion or from lubrication oil, abraded metals, as well as PM present in the ambient air due to natural sources, such as soil or dust particles, and allergens (such as fragments of pollen or mold spores).

The diameters of particles in the ambient atmosphere span five orders of magnitude, ranging from 0.001 μm (or 1 μm) to 100 μm. Larger particles, such as dust, soil, or soot, are often large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope. Particle size is critical to the health effects it poses since smaller particles can be inhaled more deeply into the lungs, with a more significant potential health impact compared to larger particles. Residence time in the air is also dependent on size. Particle size also is a key determinant of visibility impacts.

Larger particles, those smaller than 10 μm[4] but larger than about 2.5 μm, are referred to as coarse particles and typically represent most of the mass included in PM_{10}, the mass of particles smaller than 10 μm. Particles between 2.5 μm and 0.1 μm are referred to as fine particles. A particle 2.5 μm in diameter is approximately one-thirtieth the diameter of a human hair. Particles below 0.1 μm are considered ultrafine particles. Together, fine and ultrafine particles are represented as $PM_{2.5}$, meaning all particles less than 2.5 μm.

How is PM Formed?

Different particle types tend to have different sources and formation mechanisms. Coarse particles around airports are generally primary particles from sources such as wind-blown dust, sea spray, sand or salt storage piles, construction activity, or crushing or grinding operations (most commonly associated with construction activity). Ultrafine particles can arise from a number of sources as well, including primary PM produced during combustion or newly nucleated (e.g., condensed) particles formed in the atmosphere or in aircraft plumes from condensable gases. Ultrafine particle emission sources at airports include various fuel combustion sources such as aircraft, auxiliary power units (APU), ground support equipment (GSE), power turbines, diesel emergency generators, and vehicle traffic in and around the airport, as well as the atmospheric generation of new volatile particles from condensation. Ultrafine particles in aircraft exhaust include a variety of particle types ranging from those that form in the combustor (carbon particles), to those that nucleate from

[1] Fine Particle (PM 2.5) Designations, Basic Information http://www.epa.gov/pmdesignations/basicinfo.htm.
[2] Particulate Matter, Basic Information http://www.epa.gov/oar/particlepollution/basic.html.
[3] Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information, December 2005, http://www.eap.gov/ttn/naaqu/standards/pm/data/pmstaffpaper_20051221.pdf.

[4] In this paper, particle size descriptions refer to the aerodynamic diameter (see definition for "classical aerodynamic diameter" in glossary).

condensable gases (sulfuric acid, partially burned fuel, and vaporized lubrication oil) and grow larger as a result of coagulation and condensation onto the particle surfaces in the 0.1 to 0.5 μm range. Diesel particles from GSE and other ground vehicles tend to be larger than aircraft particles and aggregate into chain particles rather than the more spherical particles seen from aircraft engines. The particles described here, which are emitted directly from a source or form in the immediate vicinity of the source, are referred to as primary particles or primary PM. Figure 1 illustrates the range of PM commonly encountered.

Secondary particle formation, which results from complex chemical reactions in the atmosphere and/or particle nucleation processes, can produce either new particles or add to pre-existing particles. Examples of secondary particle formation include: (1) the conversion of sulfur oxides (SO_x), which are produced by oxidation of the sulfur in fossil fuels, to sulfuric acid (H_2SO_4) vapor, which then forms droplets as the sulfuric acid condenses due to its low vapor pressure. The resulting sulfuric acid aerosol can further react with gaseous ammonia (NH_3) in the atmosphere, for example, to form various particles of sulfate salts (e.g., ammonium sulfate $(NH_4)_2SO_4$); (2) the conversion of nitrogen dioxide (NO_2) to nitric acid (HNO_3) vapor that interacts with PM in the atmosphere, and reacts further with ammonia to form ammonium nitrate (NH_4NO_3) particles; and (3) reactions involving gaseous volatile organic compounds (VOC), yielding condensable organic compounds that can also contribute to atmospheric particles, forming secondary organic aerosol particles. The complex reactions that take place as a result of nucleation, condensation, accumulation, and reaction illustrate why measuring PM emissions can be so complex. Aircraft engine emission standards apply at the engine exit, yet PM of concern to regulators and the community is not fully formed at that point. Figure 2 illustrates the evolution of primary and secondary particles.

Ultrafine, fine, and coarse particles typically exhibit different behaviors in the atmosphere as the ambient residence time of particles varies with size. Ultrafine particles have a relatively short life, on the order of minutes to hours, and generally travel from less than a mile to less than 10 mi since they are likely to grow larger into fine particles. Fine particles remain suspended longer in the atmosphere since they do not grow larger and are too small to readily settle out or impact on stationary surfaces. They can be transported thousands of miles and remain in the atmosphere from days to weeks. Coarse particles can settle rapidly from the atmosphere with lifetimes ranging from minutes to hours (occasionally a few days) depending on their size, atmospheric conditions, and altitude. Large coarse particles are generally too large to follow air streams and tend to settle out gravitationally and by impacting onto stationary surfaces, rarely traveling more than 10 mi.

Fine and ultrafine particles suspended in the atmosphere absorb and reflect light, which is the major cause of reduced visibility (haze) in parts of the United States. Sulfates, nitrates, organic matter, and elemental carbon are primary components of these small particles.

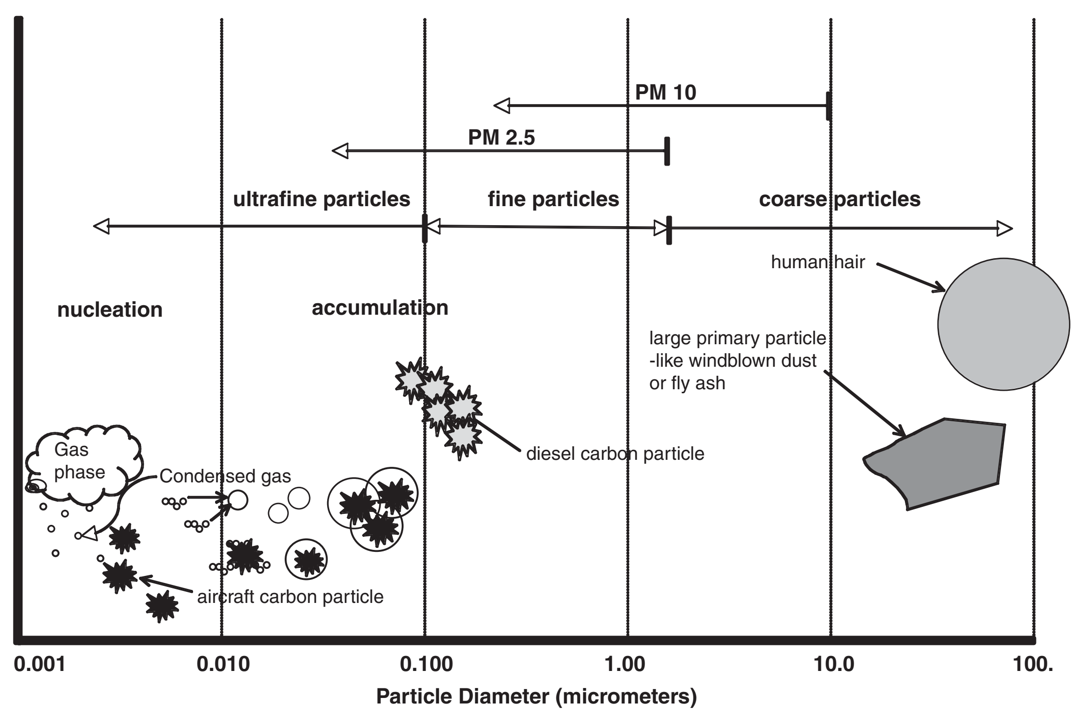
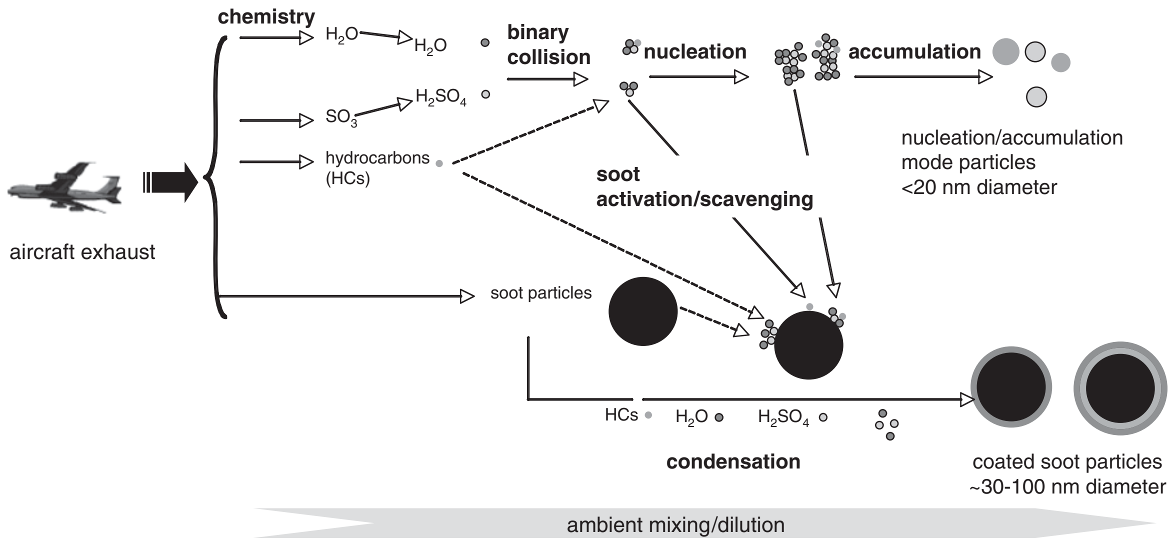


Figure 1. Particle size of airport PM emission.



Aircraft engines emit a mixture of soot and volatile gases. As pictured above, these gases cool to ambient temperature by mixing with ambient air and convert to the particle phase by condensation and nucleation/growth. The nucleation/growth mode particles and soot coatings are complex mixtures of sulfuric acid, water, partially burned hydrocarbons, and engine oil.

Figure 2. Evolution of particulate matter from aircraft engine exhaust.

How Does PM Affect Health?

Coarse particles can be inhaled but tend to remain in the nasal passage. Smaller particles are more likely to enter the respiratory system. Health studies have shown a significant association between exposure to fine and ultrafine particles and premature death from heart or lung disease. Fine and ultrafine particles can aggravate heart and lung diseases and have been linked to effects such as cardiovascular symptoms, cardiac arrhythmias, heart attacks, respiratory symptoms, asthma attacks, and bronchitis. These effects can result in increased hospital admissions, emergency room visits, absences from school or work, and restricted activity days. Individuals that may be particularly sensitive to fine particle exposure include people with heart or lung disease, older adults, and children.

How is PM Regulated in the United States?

A wide range of regulatory provisions intended for environmental purposes applies to airport activity and equipment. Aircraft engines have certification requirements for smoke emissions; ground access vehicles are subject to tailpipe emission standards; the composition of jet fuel, diesel fuel, and gasoline is regulated to limit harmful emissions; many operational activities and equipment require operating permits; and airport construction and expansion plans are subject to constraints where the regional air quality does not meet healthy standards. EPA sets most regulatory standards and many are administered by state agencies. FAA is responsible for ensuring these regulations do not pose conflicts with safety and other requirements especially for aircraft operations. This regulatory structure has developed over the past several decades.

As a result of health and visibility concerns from PM, EPA set the first NAAQS for PM in 1971. At the time, standards for "total suspended particles" (TSP) were based on the mass-based concentration of particles between 25 and 45 µm, which then was the state-of-the-art for particle samplers. The primary (health-based) standard was set at 260 µg per cubic meter of ambient air, 24-hour average, not to be exceeded more than once per year and 75 $\mu g/m^3$ annual average. A secondary (welfare-based) standard of 150 $\mu g/m^3$, 24-hour average, not to be exceeded more than once per year was also established. The standards were revised in 1987 (moving from TSP to PM_{10}), 1997 (adding $PM_{2.5}$), and again in 2006. The 2006 standards set levels for PM_{10} of 150 $\mu g/m^3$ for 24-hour average and for $PM_{2.5}$ of 35 $\mu g/m^3$ for 24-hour average and 15 $\mu g/m^3$ annual average. The welfare-based secondary standards were made the same as the primary standard in 2006. EPA no longer regulates particles larger than 10 µm (e.g., sand and large dust) since they are not deemed readily inhalable. Recent studies by EPA have shown that $PM_{2.5}$ cannot be used as a surrogate for ultrafine particles, so future regulatory reviews may emphasize smaller particles, possibly using $PM_{1.0}$ as the regulatory standard.

The regulatory approach of the EPA sets standards for ambient air quality in geographic regions that generally represent metropolitan areas. The local PM concentration is the sum of all regional sources of PM and the regional ambient background. The EPA estimates the annual average background for PM_{10} ranges from 4 to 8 $\mu g/m^3$ in the western

United States and 5 to 11 μg/m[3] in the eastern United States; for $PM_{2.5}$, estimates range from 1 to 4 μg/m[3] in the west to 2 to 5 μg/m[3] in the east. Particulate matter emissions from airport and other regional sources mix relatively quickly with the ambient background PM. The combination of emissions from airports and other regional sources and ambient concentrations of PM result in a combined atmospheric PM loading that depends on complex, nonlinear atmospheric processes, including chemical reactions and pollution transport. This makes it difficult to isolate the contribution of airport activity from all other emissions sources in an area.

In addition to the NAAQS, there are other regulations that directly or indirectly effect PM emissions from aviation. For example, the International Civil Aviation Organization (ICAO) has established aircraft engine certification standards[5] that limit smoke emissions, as measured by "smoke number." Since smoke is a component of total PM, these standards indirectly influence aircraft PM emissions.

The ICAO has also established international certification limits for oxides of nitrogen (NO_x) from jet engines. These limit the amount of NO_x emitted, which can produce nitrates that condense in the atmosphere hours to days after emissions forming secondary volatile particles. The EPA has adopted ICAO's certification standards as national regulations and FAA in turn monitors and enforces engine certification.

Sulfur in jet fuel combines with oxygen from the air during combustion, producing sulfur dioxide (SO_2). This SO_2 is further oxidized to sulfuric acid after leaving the engine, and eventually all of the fuel sulfur becomes sulfate. A small fraction (a few percent or less) of the sulfur converts to sulfate before the engine plume disperses, and is considered part of the primary particulate matter emissions. The remaining sulfur converts to sulfate hours to days after the emission, contributing to secondary particulate matter. Sulfur emissions are directly related to the sulfur content of the fuel. Internationally accepted standards[6] for Jet A, which is the commercial aviation fuel used in the United States, limit fuel sulfur content to 0.30% wt. maximum. In practice, however, Jet A sulfur content ranges between 0.04 and 0.06% wt.[7]

Nonroad diesel equipment, such as GSE, is not required to have emission controls like diesel vehicles licensed for on-road use. Under new national regulations, EPA is requiring diesel fuel suppliers for nonroad equipment to reduce fuel sulfur content, eventually to the same ultra-low sulfur limits required for on-road diesel. This will allow the nonroad equipment to use advanced emission control technologies, which may be a requirement for these vehicles in the future. These requirements for diesel fuel sulfur limits and engine emission standards are being phased in between now and 2014. Reducing the fuel sulfur content and adding emission controls will reduce PM emissions from nonroad equipment by 90%.[8] GSE using alternative fuels such as compressed natural gas, propane, or electricity[9] have very little or no PM emissions.

Stationary emission sources at airports include various facilities and equipment like boilers, emergency generators, incinerators, fire training facilities, and fuel storage tanks. Many of these equipment types require specific operating permits with PM emission limits. Stationary sources typically represent about 1% of PM emissions at airports.

The National Environmental Policy Act of 1969 (NEPA) established a policy to protect the quality of the human environment and requires careful scrutiny of the environmental impacts of federal actions, which could include grants, loans, leases, permits, and other decisions or actions requiring federal review or approval. For airports, NEPA applies to most major construction projects as a result of FAA funding or approval. One of the most common assessments used to confirm NEPA compliance for airport projects is "general conformity," which seeks to ensure that actions approved by the federal government do not cause increases in emissions that could exceed air quality standards. This serves to indirectly limit increases in ambient PM and other emissions.

What are the Sources of PM at an Airport?

There are many individual PM emission sources at airports. These include the following:

- Aircraft engines,
- Aircraft auxiliary power units (APU),
- Ground support equipment (GSE),
- Passenger vehicles,
- Tire and brake wear,
- Stationary power turbines,
- Training fires,
- Sand and salt piles, and
- Construction grading and earth moving.

Particulate matter emissions from each of these sources are different in terms of size, composition, and rate. Emissions from these sources can be quantified by direct measurement using monitoring equipment or estimated using emission

[5] International Civil Aviation Organization, International Standards and Recommended Practices, Environmental Protection, Annex 16 to the Convention on International Civil Aviation, Volume II, Aircraft Engine Emissions.

[6] ASTM International D 1655-04a, Standard Specification for Aviation Turbine Fuels.

[7] Intergovernmental Panel on Climate Change, Aviation and the Global Atmosphere (1999).

[8] Environmental Protection Agency, Office of Transportation and Air Quality, *Final Regulatory Analysis: Control of Emissions from Non-Road Diesel Engines*, EPA420-R-04-007, May 2004.

[9] PM is emitted during electricity generation at the power plant; however, utility power production is well controlled compared to internal combustion engines and the net result is fewer PM emissions.

inventory methods. Historically for airport sources, emissions inventory methods have been most prevalent. These methods generally require information about each source's population, size, activity rate, and a PM emission factor or emission index. An emissions factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., milligrams of particulate emitted per kilogram of fuel burned). Such factors make it easier to estimate emissions from various sources of air pollution.

In some cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category (i.e., a population average). EPA maintains a reference[10] of emission factors for many sources. In other cases, specific emission factors are compiled for each emission source. For example, gaseous emission factors specifically for aircraft are included in the ICAO Aircraft Engine Emissions Data Bank.[11] Unfortunately, PM emission factors for aircraft, the largest PM source at airports, are not included in the Emissions Data Bank. Aircraft engine particulate emissions have not been well studied or characterized in the past and are only now being tested. Smoke number data are in the ICAO databank, but are only surrogates for PM emissions via the First Order Approximation (FOA) (see below).

The second largest PM source at airports is commonly GSE, sometimes comparable to aircraft as a PM source. Ground support equipment is mostly powered by diesel engines although a smaller percentage have gasoline engines and a smaller percentage still use electric power. The diesel and gasoline engines used by GSE are common engine types found in trucks and other industrial vehicles. Particulate matter emissions from these engines are well characterized for mass of emissions; however, in emission factor references, GSE is typically lumped into a diverse set of equipment referred to as nonroad vehicles. These also include lawn and garden equipment, agricultural equipment, commercial marine vessels, recreational equipment, and other vehicle types. This makes it difficult to compute PM inventories that reflect airport-specific emissions.

What are the Most Recent Aviation PM Research Efforts?

To remedy the lack of information about PM emissions from aircraft, several initiatives have been pursued in the last few years. The FAA developed the FOA, initially in 2002, as an approach to estimate emissions based on smoke number, a measure of soot obscuration in aircraft plumes. More recently, FAA, NASA, EPA and others funded a series of aircraft engine emission measurement programs known as APEX (Aircraft Particle Emissions eXperiment). The information from the first APEX1 tests, initially published in 2006, is basic, fundamental data on the quantity and characteristics of PM from a single engine type. The JETS-APEX2 study, from which a report has been released by the California Air Resources Board (CARB), and APEX3, from which a report is to be released soon, cover a range of commercial engines, but the data are still limited relative to the entire fleet.

Another initiative organized to help close the knowledge gap on aviation PM emissions is the National PM Roadmap for Aviation. It is a PM research collaboration among federal agencies (e.g., FAA, NASA, DOT, DOD, and EPA), universities, aircraft and engine manufacturers, airports, airlines, and other stakeholders. It was organized in 2004 to coordinate aviation PM research and leverage limited resources to focus on the most important research needs.

Recently, the ACRP funded this study of aviation PM emissions and a second study (ACRP 02-04A), which is an assessment of the data from the APEX tests. ACRP initiatives should help bring needed focus to airport-specific PM emission concerns.

Why are Aviation-Related PM Issues so Important to Airport Operators?

Airports today are faced with community, employee, and regulatory concerns about PM emissions, yet they have very limited data on PM emissions from aircraft engines and APUs, data on other sources varies in quality and availability, and only limited data are available on ambient PM around airports. Newly tightened ambient air quality standards and greater health and environmental concerns present hurdles for airports as they need to modernize and expand to meet the increasing demand for air transportation. Yet airports represent only one PM emission source category among many in a region.

In addition to complying with general conformity requirements and assisting states in complying with national ambient air quality standards, airports must address complaints from communities and employees who are concerned about health impacts resulting from exposure to airport emissions. Many airports also receive complaints about deposits of soot, grit, and the oily residue that airport neighbors find on their cars and outdoor furniture, which the complainants believe must come from airport activity.

Several airports have conducted particle deposition studies in nearby and adjacent communities to evaluate whether

[10] AP-42, http://www.epa.gov/ttn/chief/ap42/index.html.

[11] ICAO Aircraft Engine Emissions Data Bank http://www.caa.co.uk/default.aspx? catid=702&pagetype=90.

airport activity is responsible for the deposition of concern to the citizens. Deposition studies have been conducted near Los Angeles International Airport, T.F. Green Airport (Providence, R.I.), Boston Logan International Airport, Charlotte/Douglas International Airport, Detroit Metropolitan Wayne County International Airport, John Wayne-Orange County Airport, Seattle-Tacoma International Airport, Ft. Lauderdale-Hollywood International Airport, and Chicago O'Hare International Airport. None of these studies have shown a definitive link between the airports and the deposited material. These studies commonly find the deposits are typical of the material found throughout urban areas that come from diesel trucks, construction activity, wind-blown dust, pollen, and mold. This is perhaps not unexpected since the PM from aircraft and APUs is comprised of fine or ultrafine particles, which are too small to settle gravitationally or to be deposited by impacting stationary surfaces and remain suspended in the atmosphere. These studies are not conclusive, however, since they used different methodologies and many only sampled dry deposition and did not collect material deposited through rainfall, which is a primary mechanism for scrubbing suspended particles from the atmosphere. Future deposition studies will be able to build both on these findings and on new information coming from aircraft PM research to improve our understanding of the contribution of airport emissions to deposited PM.

As noted earlier, little was known about aircraft PM emissions until recently when several federally funded research programs were conducted. To date, a great deal is known about a few engines with no testing done on most of the engine models in the fleet. The research results are still being analyzed to better understand PM formation in aircraft engines and its evolution in the plume. Even for those engines studied, more testing will be required to gain the data needed to develop emission factors with the same level of confidence as for emission factors used for other emission sources, which can relate operating conditions to final state PM emissions.

With regard to GSE, EPA has taken steps to reduce PM emissions from nonroad vehicles. In response to national environmental regulations, refiners will begin producing low-sulfur diesel fuel for use in locomotives, ships, and nonroad equipment, which includes GSE. Low-sulfur diesel fuel must meet a 500 parts per million (ppm) sulfur maximum. This is the first step of EPA's nonroad diesel rule, with an eventual goal of reducing the sulfur level of fuel for these engines to meet an ultra-low standard (15 ppm) to enable new advanced emission-control technologies for engines used in locomotives, ships, and other nonroad equipment. These most recent nonroad engine and fuel regulations complement similarly stringent regulations for diesel highway trucks and buses and highway diesel fuel for 2007.

Beginning June 1, 2006, refiners began producing clean ultra-low sulfur diesel fuel, with a sulfur level at or below 15 parts per million (ppm), for use in highway diesel engines. Low-sulfur (500 ppm) diesel fuel for nonroad diesel engines will be required in 2007, followed by ultra-low sulfur diesel fuel for these vehicles in 2010.[12] Stringent emissions standards for new GSE will be phased in between 2008 and 2014 as part of this rule. Whether and when similar reductions in fuel sulfur content will occur in aviation jet fuel has yet to be determined.

What Tools are Available for Evaluating PM Emissions at Airports?

As noted earlier, airport emissions are analyzed by applying emission factors (drawn from emissions testing data of representative sources) to airport-specific operational data for various emission sources. All sources are then combined into an "emissions inventory." Inventories are usually represented in mass emissions per unit of time (e.g., lbs/day or tons/year). Inventories are typically compiled for criteria pollutants and their precursors (i.e., NO_x, SO_x, CO, VOC, and PM). Various analytical tools are available to support these complex computations and aid in analyzing the results.

Emissions and Dispersion Modeling System[13]

The Emissions and Dispersion Modeling System (EDMS) is used to assess air quality at civilian airports and military air bases. The model was developed by FAA in cooperation with the United States Air Force (USAF) and is used to produce an inventory of emissions generated by sources on and around the airport or air base, and to calculate pollutant concentrations in these environments.

Particulate matter emissions are computed for aircraft main engines in EDMS version 5.0.2 by applying the First Order Approximation version 3.0a, where smoke number data are available. Particulate matter emissions for on-road vehicles are computed using the MOBILE model, described below. Similarly, PM emissions for GSE are computed using the NONROAD model. EDMS also contains a database of PM emission factors for stationary sources that are commonly found at airports. No data currently exist for modeling PM from aircraft auxiliary power units (APU).

[12] Environmental Protection Agency Clean Air Nonroad Diesel – Tier 4 Final Rule, http://www.epa.gov/nonroad-diesel/2004fr.htm.

[13] Emissions and Dispersion Modeling System Homepage http://www.faa.gov/about/office_org/headquarters_offices/aep/models/edms_model/.

MOBILE[14]

As mentioned above, EDMS uses the EPA-developed MOBILE model (version 6.2 is included with EDMS 5.0.2) to compute emission factors for on-road vehicles. MOBILE allows the user to model emission factors for a fleet of vehicle types or an individual vehicle class based on the mix of vehicle types and age, and considers vehicle speed and ambient meteorological conditions as well.

NONROAD[15]

Similar to MOBILE, EPA's NONROAD model provides emission factors for ground support equipment at airports that consider the rated horsepower of the engine, fuel type, and the load factor. The traditional application of the model is to use the embedded database of county-level nonroad fleet information; however, the EPA extracted the underlying vehicle data for use in EDMS to allow the emissions for individual vehicles to be computed.

First Order Approximation 3.0a[16]

First Order Approximation 3.0 (FOA3) is being developed by the ICAO Committee for Aviation Environmental Protection (CAEP) Working Group 3 to estimate PM emissions from commercial aircraft engines in the absence of acceptable data or emission factors. Data from the APEX aircraft engine emission tests are being used in its development. FOA3 models three components of PM using the sum of three separate equations: a power and polynomial function of smoke number for nonvolatile PM, a constant for SO_4, and a function of HC emission indices for fuel organics. EDMS uses the FOA3a methodology for U.S airports, which includes additional reasonable margins to accommodate uncertainties. FOA3a adapts the FOA3 equations to be more conservative in the calculation of SO_4 and fuel organics while keeping the equations the same for nonvolatile PM.

Aviation Environmental Design Tool[17]

The Aviation Environmental Design Tool (AEDT), presently under development and testing, is designed to incorporate and harmonize the existing capabilities of the FAA to model and analyze noise and emissions. Building on current tools, including EDMS, common modules and databases will allow local and global analyses to be completed consistently and with a single tool. With this tool, users will be able to analyze both current and future scenarios to understand how aviation effects the environment through noise and emissions on a local and global scale.

Aviation Environmental Portfolio Management Tool[18]

The Aviation Environmental Portfolio Management Tool (APMT) is currently being developed by the FAA as a component of AEDT to allow tradeoffs between noise and emissions to be better understood. The tool has three primary capabilities: (1) cost-effectiveness analysis, (2) benefit cost analysis, and (3) distributional analysis. The "costs" and "benefits" are computed at a societal level by considering economic and health effects.

Community Multiscale Air Quality Model[19]

The Community Multiscale Air Quality Model (CMAQ) was developed through a NOAA-EPA partnership and allows the analyst to model a variety of air quality effects, including: tropospheric ozone, toxics, acid deposition, and visibility degradation. This is accomplished by including robust modeling of the atmospheric physics and chemical reactions. The scale of the model is variable with grid sizes ranging from less than 4 km to over 36 km depending on the needs of the analysis.

Microphysical Models

Microphysical models refer to a class of atmospheric models intended to predict cloud formations based on the formation and size of droplets and the nucleation of particles. The same techniques used to predict water-based clouds in the sky can be applied toward predicting the formation of plumes of aerosols and particulate matter. Microphysical modeling has been used to model aviation PM evolution both at altitude and at ground level.

[14] MOBILE 6 Homepage http://www.epa.gov/otaq/m6.htm.
[15] NONROAD Homepage http://www.epa.gov/otaq/nonrdmdl.htm.
[16] Kinsey, J., Wayson, R.L, EPAct PM Methodology Discussion Paper (2007).
[17] Federal Aviation Administration, Office of the Environment and Energy *AEDT News,* (1:1), September 2007.
[18] Aviation Environmental Portfolio Management Tool (APMT) Prototype http://www.faa.gov/about/office_org/headquarters_offices/aep/models/history/media/2006-02_CAEP7-WG2-TG2-6_IP02_APMT_Prototype.pdf .
[19] CMAQ Homepage http://www.epa.gov/asmdnerl/CMAQ/cmaq_model.html.

CHAPTER 4

Survey and Interview Findings

Survey

The airport PM survey was mailed to 80 airports—34 large hub, commercial airports; 15 medium hub, commercial airports; 10 small hub, commercial airports; and 21 predominantly general aviation airports. Respondents could reply by mail or by using an online survey form. To boost the response rate, we contacted each airport that did not respond by the survey deadline at least once by phone.

Of the 80 airports receiving the survey, 38 responded, a 47.5% response rate. The number of responding airports in each category and the response rate by category was: large hub 20 (58.8%), medium hub 5 (33.3%), small hub 5 (50%), and general aviation 8 (38.1%). Together the responses included a good mix of large, medium, and small commercial and general aviation airports. Sixteen airports (42.1%) are located in nonattainment areas while 6 airports (15.8%) did not know their attainment designation. (Note: According to EPA designations, two of these airports were nonattainment for $PM_{2.5}$ while the others were attainment.)

Of the 38 respondents, 18 (47.4%) reported that they have received complaints about PM emissions from the airport. All of these reported receiving complaints from the community. Half also reported complaints from employees, and six airports reported receiving complaints from regulators or elected officials, while one reported receiving a complaint from a customer. The nature of reported complaints includes soot deposits on outdoor surfaces (38.8%) and dust from construction and other activities (27.8%). Airports also reported complaints about odors (22.2%), noise (5.5%), and greenhouse emissions (5.5%).

Half of the respondents report having conducted an environmental study that included an analysis of PM emissions. Of those, 13 of 19 (68.4%) offered a copy of some related material. Sections of environmental impact statements (EIS) that were prepared in support of airport improvement projects were most commonly presented. One risk assessment was provided that primarily addressed hazardous air pollutants.

Sources of PM emissions reported in the survey from airport activity included landside vehicles and construction equipment plus a variety of other airside vehicles such as snow removal equipment. 65.8% of respondents reported oil fired boilers and the same number fire training facilities, 63.2% reported having sand and salt piles, and about 60% reported having diesel powered turbines (60.5%) and diesel emergency generators (57.9%). Other unspecified sources were reported by 44.7% of respondents.

When asked whether they had any alternatively fueled equipment that reduced PM emissions, 23 (60.5%) replied that they did while 14 (36.8%) replied that they did not. Most of the alternatively fueled equipment used compressed natural gas, with some low emission vehicles, hybrids, and clean diesel vehicles reported. Several mentioned use of biodiesel in some equipment.

Six airports (15.8%) reported that they have done PM-specific emissions analyses at their airports. These analyses included annual air emission inventories and permitting for construction and equipment modifications/installations (e.g., new diesel emergency generators). One airport reported plans to initiate a PM/HAPs monitoring study in 2007. These airports were candidates for follow up phone interviews.

Most airports (55.3%) report interacting with state or local agencies on air quality. These contacts typically were related to routine reports on criteria pollutants. Five airports reported they are focusing additional attention on PM to develop a better understanding of the issues and acquire a capability to develop PM inventories. Two airports mentioned PM or PM/HAP specific studies, one of which is complete.

When asked whether they were concerned about PM issues, 16 (47.1%) said they were. Their concerns included being able to quantify PM emissions from aircraft, the capabilities of EDMS and other air emission methodologies, the need to report PM emissions regularly, and general concerns about dust emissions.

A list of airports receiving the survey, a copy of the transmittal letter, the survey form, and a summary of survey responses are included in Appendix A.

Interviews

As noted above, many U.S. airports have prepared environmental studies in support of expansion programs or for other reasons. Some airports have hosted PM sampling programs for research projects. To capture the knowledge of scientists and other experts involved in these projects, the team conducted 11 interviews, either in person or by phone. These interviews included four PM research scientists (one interviewed twice to discuss two separate projects), four airport environmental managers, and two airport environmental consultants.

John Froines, Professor of Environmental Health and Head of EPA PM Center at UCLA. Froines conducted a PM research project at Los Angeles International Airport (LAX) focusing on ultrafine (<$PM_{1.0}$) particles. Air quality in the vicinity of the airport was clearly influenced by airport operations generally and aircraft specifically. The scale of the impact is difficult to define and work in this area is needed. Froines speculates that ultrafine particulates affect human health greater than their mass proportion, in part because they can penetrate cell membranes and accumulate in the mitochondria. Froines believes EPA should make ultrafine particles a research priority.

John Pehrson, Principal, Camp, Dresser and McKee, Irvine, California. Pehrson believes the significance of PM issues will increase in the future as the result of greater emphasis on PM emissions in airport EISs. Source apportionment is especially important for airports and markers or fingerprints for the various sources are needed. Emission factors for current advanced engines also are needed.

Tom Nissalke, Director of Environmental and Technical Services, Hartsfield-Jackson Atlanta International Airport. According to Nissalke, airport PM emissions are drawing greater scrutiny from the Georgia EPA as improvements to automobile emissions are achieved. At the same time, even defining the magnitude of the problem is difficult due to uncertainty in how to measure PM. At this time, PM emissions are not a big community issue.

Donald Hagen, Co-Principal Investigator, Delta-Atlanta Hartsfield Study (formerly UNA-UNA), University of Missouri Rolla Center of Excellence for Noise and Emissions (UMRCOE). The combination of dedicated engine tests and an airport-wide study was informative, thorough, atmospherically relevant, and novel. The data are shedding light on many issues associated with airport PM emissions but additional data analysis is needed to maximize the benefits of the study.

Carrol Bryant, KB Environmental Sciences, Inc., consultant for Hartsfield-Jackson Atlanta International Airport. Particulate matter is not considered a big problem for Atlanta except for the need to comply with air quality regulations and must be analyzed for EISs. There is a great deal of public uncertainty about the toxicity of and consequently the significance of airport PM emissions.

Brenda Pope, Vice President Environmental Management Service, Rhode Island Airport Corporation, T.F. Green Airport. Elevated cancer rates found in the vicinity of the airport, both upwind and downwind, prompted the Rhode Island Department of Environmental Management (DEM) to initiate emissions monitoring around the airport. The community has expressed concern over butadiene and formaldehyde in addition to PM.

Barbara Morin, Department of Environmental Management, Rhode Island (RI-DEM), Project Manager for T.F. Green Airport Air Quality Study. The Rhode Island DEM is leading the study monitoring $PM_{2.5}$ and black carbon at T.F. Green. Total particulate mass was dominated by large particles, which seem to be influenced by prevailing ambient conditions; however, black carbon correlated with ultrafine particulate matter and was airport influenced. The role of PAHs (polycyclic aromatics) is poorly understood and the link between black carbon and ultrafine particles and human health affects needs to be understood. Better understanding of aviation PM is needed to determine what regulations may be required.

Donald Hagen, Co-Principal Investigator, JETS APEX2, UMRCOE. This was a two-phase study involving dedicated engine and advected plume measurements. The dedicated engine study involved both old and new technology CFM56 engines representing the most common classes of aircraft turbine engines operating in the United States. The study measured emissions of CO, CO_2, NO_x, and PM number size and mass as well as speciated PM and speciated hydrocarbons at multiple thrust settings. Measurements were taken 1m behind the engines as well as 50 m downstream. The advected plume measurements were made on approximately 300 aircraft during normal operation. There are several major PM-related conclusions from these studies. Size distributions for exit plane were generally lognormal. Strong and sometimes nonlinear dependencies were observed with engine power settings. The particle composition includes both sulfate and organic volatile fractions at downstream distances. The sulfate contribution has little dependence on engine power, while the organic contribution is greatest at low engine powers. Plume processing in the exhaust plume results in the production of a large number of small particles not present at the engine exit plane. On average for the 737-700 series, a newer technology engine, EIm is less than half that for the older technology -300 series.

Britt Johnson, Airport Environmental Planner, Oakland International Airport (OAK). Currently at OAK, HAPs, notably acrolein (C_3H_4O, a hazardous air pollutant that is a product of incomplete combustion), are a more significant concern than PM although PM is likely to receive additional scrutiny as a result of the ultrafine particles identified in airport studies. Johnson is anticipating that release of the JETS APEX2 data will shed light on the significance of both HAPs and PM.

Paul Manasjan, Environmental Affairs Director, San Diego International Airport (SAN). According to Manasjan, PM emissions are an immediate problem at SAN with respect to an emissions inventory being prepared as a component of an expansion-related EIS. This is driving their interest in more and better data on PM emissions. Also, particle deposition on surfaces in the vicinity of the airport is a persistent source of complaints. For SAN, PM is a more prominent concern than HAPs. Nonaviation sources of dust, such as unpaved areas, are also a problem. Markers or fingerprints to apportion PM emissions among various sources (e.g., aircraft, GSE, landside vehicles) are needed.

Roger Gardner, Chief Executive, OMEGA, Manchester Metropolitan University Center for Air Transport and the Environment, United Kingdom. Mass estimates for PM from brakes and tires are similar to that for engine-generated PM. Priority PM emission data needs from his perspective are: (1) airside vehicle emission factors, (2) relationship between operations and emissions loadings, (3) environmental impacts of alternative (synthetic) fuels, and (4) gaining a full understanding of emissions in and around airports. As automobiles get cleaner, environmental impacts from aviation in and around airports takes on greater significance.

The overriding message from these interviews is that airports would like assistance in being able to address regulatory requirements with good, reliable estimates of the airport contribution. The concerns are that there is much uncertainty with current data, yet they will need to live with the current data unless and until better estimates and methods can be developed.

Highlights from the interviews are discussed here. Complete notes from each of the interviews are included in Appendix B.

CHAPTER 5

Composition and Physical Properties of Particulate Matter From Aircraft Engines—Knowledge and Gaps

Soot (Nonvolatile PM)—Knowledge

Historically, soot from aircraft engines has been monitored indirectly through measurement of smoke number. Smoke numbers are a required measurement during engine certification testing and have been recorded in the ICAO database since the mid 1970s. Smoke numbers, required to be reported only at the engine power for which it is maximum, are available for all large turbine engines currently employed in the commercial fleet. A smoke number measurement involves drawing a known volume of engine exhaust through a filter. Post exposure, the filter is examined optically and its reflectance relative to a calibrated light source is used to calculate a "smoke number." Clearly a smoke number provides a relative measure of the sootiness of a particular engine as a function of its operation but it imparts no information on the physical and chemical properties of the PM such as size, number, shape, mass, composition, and reactivity.

The inadequacy of smoke number and the need for detailed aircraft engine particulate matter (PM) characterization became apparent in the early 1990s as the atmospheric and environmental scientific communities started to assess the impact of aviation emissions on the atmosphere at cruise altitudes (e.g., NASA's Atmospheric Effect of Aircraft Program (AEAP)). Since that time groups in the United States and Europe have developed and continue to develop methods for detailed aircraft engine PM characterization using fundamental physical and chemical parameters. Around 2000, in response to a request for information from ICAO, the SAE E31 committee established a special PM subcommittee charged with developing a recommended practice for aircraft engine PM characterization based on fundamental physical and chemical parameters.[20]

[20] Society of Automotive Engineers Aerospace Information Report 5892 copyright © 2007 SAE.

Armed with these new methods for fundamental parameterization, research programs have been funded to characterize the PM emissions with respect to size, number, mass, and composition as a function of engine operating condition for a significant subset of engines currently in service in the commercial fleet. These engines include CFM56-2C1, JT8D-219, CF6-80A2, CF6-80C2B8F, PW 2037, CFM56-3B1, CFM56-7B22, AE3007A, PW 4158, RB211-535E-4B, and CJ610. The engine class most extensively studied is the CFM56 with a total of 11 engines being examined. For the CFM56 class, measurements have been made at or close to the exhaust nozzle (within 2m), in the near-field plume (~ 10 m, 30 m, and 50 m) and in advected plumes (100 m to 300 m downwind). Smaller datasets exist for the other engines studied to date.

Assessment of the results of these studies leads to the following conclusions on PM characteristics and measurement methods.

PM Characteristics

- At the exit plane the exhaust contains nonvolatile or refractory PM, combustion gases, and the precursors for volatile PM evolution (i.e., sulfate and organics). As the plume evolves new particles form through nucleation of volatile organics and sulfates and some of the nucleated particles agglomerate on the nonvolatile PM surfaces.
- With respect to the nonvolatile PM from aircraft engines the following characteristics have been established:
  - Number-based emission index (EI_n) falls in the range of 10^{14}–10^{16} particles/kg fuel burned.
  - Mass-based emission indices (EI_m) fall in the range of 0.01–0.5 g/kg fuel burned.
  - Particles tend to have approximately spherical geometry and are made up of aggregates of smaller spherical particles, which tend to be smaller and less highly coagulated than the chain aggregates typical of diesel PM.

- Size distributions are typically lognormal with number-based geometric mean diameters in the range 20 nm to 80 nm.
- Nonvolatile PM is largely made up of (elemental) carbon.
- Nonvolatile PM dominates the PM mass distributions at high engine powers.
- From near field plume and advected plume measurements, the physical properties of the nonvolatile PM do not change but provide surfaces upon which volatile material condense and volatile PM in the plume can agglomerate.

Measurement Methods

- Reliable and accurate diagnostic tools for PM size and number have been developed.
- A methodology for nonvolatile PM characterization is in the advanced stages of development.

These conclusions fairly represent the current state of knowledge for the nonvolatile PM component of aircraft engine PM and the state of the art for measurement methods.

Knowledge Gaps

Using the foregoing summary of the state of knowledge for nonvolatile PM generated by aircraft engines, the following gaps in our knowledge and understanding become apparent.

PM Characteristics

- The engine PM emissions database is incomplete. In particular it lacks data for current advanced technology engines such as the GE 90, PW GP7000, and RR Trent 900.
- There is little knowledge on the impact of engine-to-engine variability on nonvolatile PM emissions for engines of the same type.
- There is little or no knowledge of impact of engine age and maintenance on nonvolatile PM emissions for engines of the same type.
- The nature of nonvolatile PM density and structure as a function of engine operating condition and particle size is not known.
- There is only limited knowledge of the dependence of nonvolatile PM emissions on fuel composition, especially alternate fuels.
- There is a lack of knowledge of the health impacts of nonvolatile PM, particularly as a function PM size, number, and composition although some recent European studies may provide some information.

Measurement Methods

- There are open questions with line loss and sampling methods although these will be answered in part in the reports of the NASA and SERDP-sponsored methodology development studies in 2006–2007.
- Real-time calibrations for line loss and instrument performance are essential but currently surrogate PM calibration sources have to be used since no reliable combustion aerosol calibration source exists.
- Currently there are no reliable or practical direct mass measurement tools. Long run times are required when using current filtration techniques, which are impractical and cost prohibitive for aircraft emission sampling.
- Existing direct mass measurements are time-consuming and are subject to sampling artifacts and interferences. There is limited connection between fast time response instruments for size and number and a direct mass measurement appropriate for measuring aircraft emissions.

Applications

- There are no data available to develop correlations between emissions data acquired under standard testing conditions and emissions predictions for aircraft under actual operations.
- Standard testing conditions provide no information on the nature of transients, especially the impact of changes in ambient temperature, pressure, relative humidity, and the engine operating conditions during actual operations. The Delta ATL and OAK advected plume studies may provide insights into the influence of ambient conditions on the production of nonvolatile PM emissions.
- While the FOA (First Order Approximation) provides a means of estimating PM emissions based on the best data available, it remains an approximation. Developing a comprehensive database of PM emission indices would provide a reliable and accurate source for modeling PM emissions.

Volatile PM—Knowledge

Volatile particles are defined to be those that are formed from condensable gases after the exhaust has been cooled to temperatures below engine exit conditions (e.g., sulfuric acid particles).[21] Thus they do not exist at the engine exit plane as particles and the associated mass is only present as gas-phase particle precursors. Their formation and evolution can

[21] Society of Automotive Engineers Aerospace Information Report 5892 copyright © 2006 SAE.

happen either in the plume as the exhaust mixes and cools with the ambient air or in a probe and sampling system. While the volatile contribution to the particles does not occur in concert with the combustion process, the volatile particles that are emitted into the atmosphere may affect local air quality. EPA rules require airports to evaluate both nonvolatile and volatile PM emissions. For this reason it is essential that the aviation community develop a better understanding of and capability for quantifying the volatile PM emissions from aircraft engines. Good tools have been developed for quantifying the number, size, and composition of these volatile particles, using the same tools as for nonvolatile particles for number and size. Techniques for quantifying the mass of volatile particles are not well developed and further work is needed on them.

Volatile PM Characteristics

- Sulfate and organic precursor gases both contribute to volatile PM mass.
- Sources of the organic component may include contributions from both partially combusted fuel (products of incomplete combustion) and engine lubricants.
- Three modes of particles are typically measured that have a volatile component:
  - newly formed PM (totally volatile particle formed in the exhaust plume),
  - coated nonvolatile PM, and
  - coated ambient particles (ambient particles entrained in the plume that take on a coating from condensable exhaust gases).
- The volatile PM characteristics are dependent on fuel composition, most dramatically evident in the sulfate contribution being dependent on fuel sulfur levels.
- Volatile PM dominate the total number of particles at downstream locations where the exhaust has cooled to ambient temperatures.
- The volatile component evolves as plume expands and the resulting particle properties depend on ambient conditions such as temperature, relative humidity, and background pollutant levels. This dependence of volatile PM properties on ambient conditions presents complications for measurement using conventional nonvolatile PM measurement methods.

Measurement Methods

- Good tools have been developed for quantifying the number, size, and composition of these volatile particles, using the same tools as for nonvolatile particles for number and size.
- Due to the dependence on ambient conditions, volatile PM measurement methodology development is still in its initial stages.
- The compositional characterization of volatile particles is still not complete. In particular, the speciation of the organic contributions has not been definitive since the organic make up is apparently quite complex.

Knowledge Gaps

Using the foregoing summary of the state of knowledge for volatile PM generated by aircraft engines, the following gaps in our knowledge and understanding become apparent.

- Current understanding is incomplete concerning volatile PM evolution in the plume (or sampling system) and its dependence on atmospheric conditions such as temperature, relative humidity, and background pollution levels.
- No model currently exists that adequately describes the full evolution of volatile PM as it forms and grows in the exhaust plume.
- Laboratory-based tools for simulating the complex evolution of volatile PM have not yet been developed, although EPA has been working on understanding this process for some time.
- To provide proper inputs to local- and regional-scale air quality models, there is a need to adequately represent the thermodynamic and photochemical state of the volatile PM that is emitted into the atmosphere.
- There is currently only a minimal understanding of organic speciation of the volatile PM component relative to carcinogens and other toxic compounds.
- In particular, the contribution of lubrication oil to volatile PM is poorly understood, especially as it relates to variations in engine technology and operational procedures.
- There is at present limited knowledge of the dependences of volatile PM emission properties on fuel composition, including how the use of alternate fuels may impact volatile contributions.
- Although health impacts are a significant driver for the measurement of volatile particles, we lack knowledge of health impacts of volatile PM as a function of size, number, and composition. There is extensive literature on the health effects of PM; however, there is little specificity on the small particles common to aircraft engine emissions. EPA has found that smaller particles are of greater concern than larger particles and has adjusted its regulatory structure over time to focus more intensively on smaller particles. Also, health effects based on particle composition are not well understood.

Measurement Methods

- The methodology development for volatile PM is still in the initial stages.
- The specific gaps identified for nonvolatile particles also apply to volatile particles.

Applications

- As for nonvolatile particles, correlations must be developed that make a connection between emissions data acquired under standard testing conditions and emissions predictions for aircraft under actual operations.
- Research is currently underway to connect the local air quality model, the Emissions and Dispersion Modeling System (EDMS), with the regional Community Multiscale Air Quality (CMAQ) tool. Further research into methods for modeling the volatile elements of PM in both local and regional-scale air quality models is needed, however.

CHAPTER 6

Particulate Matter From Other Airport Sources

In addition to the airplane engines, aircraft can also emit PM from other on-board sources. These other aircraft sources include auxiliary power units (APUs) and aircraft brake and tire emissions during touchdown. Beyond the airplanes themselves, other sources also abound at any given airport, including ground support equipment (GSE) and a wide range of airport facility equipment for power generation, cooking, international waste incineration, construction, and so forth. Vehicles bringing passengers, freight, and equipment and supplies can also contribute to emissions associated with airport operations, and thus the sources associated with all of the roadside transport activity must also be accounted for when quantifying PM emissions.

Knowledge

- Particles in GSE exhaust are well characterized, especially with respect to mass, since the engines used in GSE are the same as those found in vehicles in construction, industrial, and commercial applications as well as in on-road vehicles. The GSE equipment market is too small for purpose-built engines so production engines from manufacturers are used. Particulate matter testing, measurement, and characterization conducted by EPA and others effectively describe the particles found in GSE exhaust.
- The EPA's emission standards for nonroad equipment apply to GSE. Emission factors for these vehicles are estimated by using EPA's NONROAD model.
- Federal regulations requiring the use of ultra-low sulfur diesel in nonroad equipment are being phased in and will apply to GSE. These regulations will significantly reduce PM emissions from GSE.
- Diesel particulate filters are available for use on equipment fueled with ultra-low sulfur diesel which, when combined with the fuel sulfur reduction, can result in a 90% reduction in PM emissions.
- The EPA's standards for on-road vehicles apply to ground access vehicles. Emission factors from on-road vehicles are estimated by using EPA's MOBILE 6 model. Fleet characteristics such as vehicle mix and age, as well as operating cycles, are well defined and embedded in the MOBILE model.
- Most ground access vehicles are fueled with gasoline, which produces very little PM.
- For ground access vehicles fueled with diesel, ultra-low sulfur diesel fuel is being phased in and diesel particulate filters will be required for on-road use. This will substantially reduce PM emissions from diesel-fueled ground access vehicles.
- Airport facility equipment emissions are often defined by EPA standards. Emission factors for stationary sources can be found in a variety of sources, most commonly from AP-42[22] and Air Quality Procedures for Civilian Airports and Air Force Bases (The Air Quality Handbook).[23] Emission factors for most common stationary equipment at airports are contained in EDMS.

Gaps

- GSE operational practices are not well characterized. GSE spend much of their operational time idling and only limited periods under load. For example, a baggage tug may be idling while awaiting the arrival of an aircraft at a gate. It is then positioned adjacent to the aircraft where it sits at idle. Once bags are loaded on or unloaded from the aircraft, the tug moves back to the terminal area and may sit at idle. Operating practices vary considerably from airport to airport.

[22] Environmental Protection Agency, AP 42, *Compilation of Air Pollutant Emission Factors*, http://www.epa.gov/otaq/ap42.htm.
[23] Federal Aviation Administration, United States Air Force, *Air Quality Procedures for Civilian Airports & Air Force Bases*, April 1997.

- Populations and age, which are needed to reliably quantify GSE emissions, are often difficult to determine. Many airport environmental studies use estimates of number of vehicles and engine run time needed to service an aircraft; however, these estimates are not well documented and again vary considerably from airport to airport. This lack of consistent, reliable GSE emission estimation procedures is reflected in the variation seen in airport emission inventories, where GSE PM emissions can vary from less than 15% to more than 50% of the inventory total.
- Minimal PM data are available for APU emissions. APUs are essentially small jet engines and it is expected their emissions would be similar to those of the aircraft main engines; however, APU have different operating cycles. They typically operate at three power settings: no load, environmental control condition,[24] and engine start condition.[25]
- Fuel consumption for APUs is unknown, however, they use much less fuel than the main aircraft engines, and their emissions are expected to be proportionately less.
- For the purpose of developing PM inventories, lack of knowledge on APU usage (duration and rate), even once PM emissions data might become available, remains a gap.
- All gaps for aircraft engine PM, both nonvolatile and volatile, also apply to APUs since very little PM measurement work has been performed on APUs.
- The magnitude of the contribution to airport PM inventories from APU's use is currently highly uncertain although expected to be relatively small.
- There is currently no data on PM number, size, and mass for brake and tire emissions from landing aircraft. LIDAR data collected in the UK suggest that this could be a significant PM source at airports. While it is evident that aircraft leave a great deal of rubber on the runway in the vicinity of touchdown, it is also evident that a puff of smoke or particulate matter is created during touchdown.
- The relationships between aircraft brake and tire emissions and brake and tire emissions from roadside vehicles (and GSE) are not well defined; however, their use would not be expected to cause similar brake and tire wear compared to landing aircraft. The materials and usage patterns are also quite different for aircraft and road vehicles.
- The contribution to airport PM inventories from aircraft brakes and tires is highly uncertain at present.
- The level of detail on PM emissions in non–aircraft-engine emission sources is not commensurate with that being acquired for aircraft. While number, size, mass, and composition as a function of engine operating condition is being acquired for aircraft engines, often average numbers are used for other emissions sources. Understanding number, size, and composition may be less important for compiling emission inventories than for understanding the health effects of these PM sources.
- Due to various data limitations, we currently lack a means to estimate the relative contributions from aircraft and other PM sources to airport PM inventories that reflect actual, source-specific PM data and source operational procedures. Where airport PM inventories have been reported, it is not clear that consistent, reliable methodologies, equipment counts, and appropriate operating cycles were used for each emissions source.

[24] This is an intermediate power level needed to maintain the aircraft cabin's environmental control system including the air conditioning and ventilation system.
[25] This is essentially maximum power needed to start the main aircraft engines.

CHAPTER 7

Needed Research

The following five topics identify the most pressing research needs and all are of comparable priority. Some sequencing of projects will be required to address the knowledge gaps most efficiently; however, the information gained from these proposed research areas is needed to complete airport PM inventories with commonly acceptable confidence levels. Chapter 8 proposes two separate research projects and a synthesis report, describing rationale and estimated cost, to address several of these needs. The other research needs described in Chapter 8 are being addressed in research sponsored by other organizations.

- **Broader Engine Emissions Database**
  - Studies to correlate aircraft engine emissions to engine age and maintenance history (critical role for airlines)
  - Studies to correlate fuel composition to PM production
  - APU emissions database for PM
  - Role of lubrication oils in aircraft PM emissions
- **PM Evolution Studies**
  - Measurements
  - Modeling
    - Link emissions datasets to local and regional air quality models
  - Laboratory simulations
- **Develop Means of Estimating Relative Contributions of Aircraft and Other PM Sources to Airport PM Inventory**
  - Inputs to models for PM inventory predictions focused on coupling operations to emissions data and on a systematic study of the PM emissions of the most advanced turbofan technology, GSE, APUs, and piston-engine aircraft
  - Evaluation of aircraft PM emissions data to possibly develop chemical or other markers or fingerprints for aircraft
  - Size number, mass, and compositional studies for aircraft brake and tire PM emissions, including possibly markers or fingerprints
  - Size number, mass, and compositional studies for other airport sources, particularly GSE and APUs, including possibly chemical or other markers/fingerprints
- **Methodology Development**
  - Measurement methods for volatile PM properties to be developed (density, evolution, and sampling system, etc.)
  - Measurement methods for nonvolatile PM properties to be refined
- **Health Impacts**
  - Health impacts of nonvolatile PM as a function of size, number, and composition
  - Health impacts of volatile PM as a function of size, number, and composition
  - Organic speciation relative to carcinogens and other toxic compounds for volatile and coated nonvolatile PM

CHAPTER 8

Proposed Research Agenda and Problem Statements

Concern about particulate matter (PM) emissions from aircraft engines and other emission sources at airports is increasing as demand for air travel grows. Without better information about PM emissions, airports will face increasing barriers to expansion. This paper has provided a detailed assessment of current knowledge on PM emissions and has identified the gaps that exist in our knowledge of airport-related PM. With this in mind and an understanding of other research initiatives that address this interest area, two problem statements and a synthesis report are proposed for future ACRP funding that address the following three high-priority research needs.

1. Characterizing PM emissions of GSE, APUs, tires, and brakes for source apportionment is our first priority proposal. These emissions remain either unknown, or at best, poorly characterized and represent a unique focal point for ACRP. Reliance on any existing estimates of such emissions to predict emissions inventories for future airport activities is likely to result in significant overestimations, which may impose unnecessary restrictions on needed expansion.
2. Developing an understanding of the atmospheric evolution of aviation PM is our second priority project proposal. One distinguishing feature of aviation emissions is the significant presence of volatile particle precursors that condense on preexisting particles or nucleate new PM, forming nanometer-sized particles as hot exhaust gases cool. Information regarding the evolution of these particles, especially in the near field, is required to assess airport impacts on airport workers, passengers, and the local community. The mechanisms and time-scales of these processes are poorly understood, however, as are the contributions from the various sources. To address this lack of understanding, a study of the atmospheric evolution of PM emissions—coupling operational factors with source emissions in the near and far field—is needed.
3. Reviewing airport emissions data for source chemical markers or fingerprints is proposed as a synthesis project. PM emissions from various airport sources combine as they move off the airport and it is difficult to isolate individual emission sources, for example, when evaluating the impact of airport operations on nearby communities. It would be a significant benefit to airports if there were characteristic markers or "fingerprints" that were unique to individual sources. Some airport emission sources have been studied individually and others are proposed in our top priority project. These studies will produce data such as particle size number, mass, and composition that can serve as a resource for this proposed synthesis project.

Combined, these projects will eliminate critical knowledge gaps identified in this report. The data these projects yield will permit the airport community to prepare credible and accurate future impact assessments. Detailed problem statements are presented at the end of this chapter.

As noted in previous chapters, PM emissions from aircraft main engines represent possibly the most significant gap in our understanding of all airport emissions. Existing emissions data have been acquired on older technology engines. Although these engines represent a significant fraction of the current commercial fleet they are not representative of the engines in the next generation air transportation system. FAA's PARTNER research program, NASA, and DOD, however, have already identified the development of a broader aircraft emissions database as the most pressing need for the entire air transportation system and the constituencies they serve, especially for newer technology engines. Combined they have recently proposed multiyear, multimillion-dollar research programs to address these needs. For this reason, we are not proposing that ACRP initiate main engine testing programs, however, it should continue to monitor progress in this area. This may also be a fruitful area for information about HAPs emissions from aircraft. Also, health-related impacts are generally not considered the province of ACRP.

Each problem statement, including its estimated budget and time to complete, is self-contained. ACRP could achieve certain synergies and cost savings, however, by combining certain tasks within these projects with those funded by other stakeholders such as the FAA and NASA. There are economies of scale that would reduce costs by using monitoring equipment and staff for multiple projects once they have been positioned at a cooperating airport. For example, after collecting data from the main aircraft engines, it may be less expensive to then collect data on APU emissions and GSE rather than beginning a separate project at a later date necessitating a redeployment of equipment. The primary analytical capabilities and instrumentation requirements are similar or identical for all of the projects.

Following the completion of these projects there would be a benefit to the airport community from conducting a synthesis project evaluating the combined data from all projects. That analysis may produce insights that an evaluation of the data from any single project alone would not. Preparing a problem statement for this evaluation has been left for ACRP consideration in the future. The proposed synthesis report is described at the end of this chapter.

Problem Statement 1

I. PROBLEM TITLE

PM Emission Characterization for Source Apportionment for GSE, APUs, and Aircraft Tires/Brakes

II. RESEARCH PROBLEM STATEMENT

Particulate matter (PM) emissions from aircraft engines and other emission sources at airports are growing in importance as demand for air travel grows. Without better information about PM emissions, airports will face increasing barriers to expansion. Little or no data are available on APUs, GSE, and tire and brake emissions during landing operations, and their source apportionment. One distinguishing feature of all aviation emissions is the presence of volatile particle precursors (sulfate and organic material), which will, with proportions that depend on the environment, condense on preexisting particles or nucleate new particles, forming nanometer-sized particles as the hot exhaust gases cool. Information regarding both the volatile and nonvolatile components of these particles is required to assess airport impacts on local and regional air quality. To address this lack of data on emissions from APUs, GSE, and tires and brakes, a measurement campaign for quantifying these PM emissions at the source tailpipe and in the near field of these sources is needed.

III. OBJECTIVE

Perform a high quality multidimensional study of PM emissions from GSE, APUs, and brakes and tires coupling source emissions at the tailpipe/exhaust plane and in the near field to define specific source profiles that along with emissions inventories can produce reliable source apportionment estimation tools for airports. This study should include an investigation of the impact of alternative fuels such as ultra-low sulfur diesel (and possibly biodiesel) on the nature of the PM emissions. These high quality multidimensional studies should include a thorough physical (size, number, mass) and chemical composition analysis at the emissions source and in the near field (<20m downstream). (Note: it may not be feasible to capture tire and brake emissions at the source on an active airport in which case it may be necessary to determine this in brake and tire friction laboratories.)

IV. RESEARCH PROPOSED

The research proposed would be envisaged to be similar to the approach defined in the APEX and Delta Atlanta Hartsfield series of experiments for aircraft engine emissions using point source extractive sampling.

- Task 1—Select and coordinate airport measurement sites with appropriate mix of GSE, APUs, tires, and brakes.
- Task 2—Develop airport specific measurement plan for available GSE, APUs, tires, and brakes, to include exit plane and near field measurements where appropriate (e.g., APU).
- Task 3—Execute measurement plan; anticipated 7 days at airport venue to complete all measurements.
- Task 4—Develop a detailed equipment/incident inventory for GSE, APUs, and aircraft touchdowns (for tire and brake emissions) at the airport, including operating cycles, time of use, equipment vintage, and similar data to accurately capture all data needed to develop an emissions inventory. Document methodology as appropriate for future use at other airports.
- Task 5—Reduce and analyze data with a goal of producing emissions indices.
- Task 6—Develop source apportionment computational tools (or modules for existing tools such as EDMS) for GSE, APUs, tires, and brakes.
- Task 7—Develop a model and associated manual for airports on PM emissions and source apportionment strategies using the tools developed in this study.
- Task 8—Prepare and submit draft and final report.

The anticipated product is a data set with interpretation consistent with a thorough physical (size number, mass) and chemical composition analysis for each emission source studied. The results should include emission factors suitable for EDMS.

V. ESTIMATE OF THE PROBLEM FUNDING AND RESEARCH PERIOD

Recommended Funding: A total of $500,000 is estimated for completing the program.

Research Period: A one-year program is proposed.

VI. URGENCY AND PAYOFF POTENTIAL

Airports are currently being required to estimate PM emissions from airport-related sources without sufficient data to confidently compute the inventories. On this basis, the need to be able to quantify PM emissions from the sources of this study is critical. The payoff of the proposed research would be emissions estimates that could be used directly in developing airport inventories needed to support airport expansion plans and to make decisions on how to most cost-effectively mitigate PM emissions when and if needed.

VII. RELATED RESEARCH

The proposed work would be a new project for APUs, GSE, and tire and brake emissions. Measurement of APU emissions has been suggested as a component of future aircraft engine measurement campaigns but is not currently planned. Research on aircraft engine PM emissions similar to that proposed for these sources has been done under APEX (1-3), Delta/Atlanta-Hartsfield, and similar field campaigns. Recent work under PARTNER Project 11 also has looked at time-integrated emissions from an airport in total.

VIII. PERSON(S) DEVELOPING THE PROBLEM

Sandy Webb, Environmental Consulting Group, LLC in association with: Phil Whitefield (Whitefield Scientific Consulting), Richard C. Miake-Lye (Aerodyne, Inc.), and Ted Thrasher (CSSI, Inc.).

IX. PROCESS USED TO DEVELOP PROBLEM STATEMENT

This problem statement is the product of ACRP Project 02-04, carried out by the authors of this Problem Statement.

X. DATE AND SUBMITTED BY

This problem statement is submitted by Sandy Webb, Environmental Consulting Group, LLC in association with: Phil Whitefield (Whitefield Scientific Consulting), Richard C. Miake-Lye (Aerodyne, Inc.), and Ted Thrasher (CSSI, Inc.) as part of the project report for ACRP 02-04 on December 21, 2007.

Problem Statement 2

I. PROBLEM TITLE

Atmospheric Evolution of Aviation PM to Identify Properties at Point of Exposure

II. RESEARCH PROBLEM STATEMENT

Particulate matter (PM) emissions from aircraft engines and other emission sources at airports are growing in importance as demand for air travel grows. Without better information about PM emissions, airports will face increasing barriers to expansion. One distinguishing feature of all aviation emissions is the presence of volatile particle precursors (sulfate and organic material) which will, with proportions depending on the environment, condense on preexisting particles or nucleate new PM, forming nanometer-sized particles as the hot exhaust gases cool. The makeup of PM in the exhaust plume, including particle composition, size, and count, changes rapidly as the plume ages and moves across and eventually off the airfield. Information regarding the evolution of these particles is required to assess airport impacts on local and regional air quality but the mechanisms and time-scales of these processes are poorly understood, as are the contributions from the various sources. To address this lack of understanding a study of the atmospheric evolution of PM emissions—coupling source emissions in the near field and far field with operational factors and ambient atmospheric conditions—is needed.

III. OBJECTIVE

Perform a measurement campaign of PM emissions from aircraft engines, GSE, and APUs that evaluates both the source emissions and the near filed and far field emissions, allowing correspondences to be made, and how they depend on operational factors and ambient atmospheric conditions. These measurements should be made in conjunction with coincident ambient PM monitoring in order to explore fractional source apportionment estimates.

IV. RESEARCH PROPOSED

The research proposed would be envisaged to follow the approach defined in the APEX 2 and Delta Atlanta Hartsfield studies.

Task 1—Select and coordinate measurements at two airports. Important selection criteria for the chosen airports includes: willingness of the airports and tenant airlines to participate, ambient temperature expected during measurement campaign with a hot, dry airport and a cool, humid airport preferred to evaluate PM temperature dependence, and a mix of aircraft and GSE types representative of many commercial airports.

Task 2—Develop airport specific measurement plan focused on near field and far field measurements downwind of various airport functions including runways, taxiways, and the terminal.
Task 3—Execute measurement plan; anticipated 5 days at each airport venue to complete all measurement.
Task 4—Reduce and analyze data.
Task 5—Prepare and submit draft and final report.

The anticipated product is a data set with interpretation consistent with that produced in the JETS APEX2 and Delta Atlanta Hartsfield series of studies containing emission factors suitable for EDMS and estimates of source apportionment.

V. ESTIMATE OF THE PROBLEM FUNDING AND RESEARCH PERIOD

Recommended Funding: A total of $600,000 is estimated for completing the program.
Research Period: A one-year program is proposed.

VI. URGENCY AND PAYOFF POTENTIAL

Airports are currently being required to provide estimates of PM emissions from airport-related sources without sufficient data to confidently compute the characteristics or concentration at the airport fence-line, so the need to be able to quantify PM emissions from the sources of this study is critical. The payoff of the proposed research would be an improved understanding of how these PM emissions evolve as they are transported to exposed populations, including airport workers, passengers, and nearby residents. The resulting PM emissions data could be used directly in developing airport inventories and supporting risk assessments of nearby community groups.

VII. RELATED RESEARCH

The proposed work would be a new project related to the evolution of the PM from sources named. A separate project, ACRP 02-08 has been defined to relate airport operation to impacts in ambient air off the airport. ACRP 02-08 *will not* evaluate the end state of PM evolution from airport sources (primarily aircraft and GSE), which is necessary to understand exposure impacts to airport workers, passengers, and citizens living adjacent to the airport. Some related work has been done on aircraft engine emissions under JETS/APEX2 and the Delta/Atlanta-Hartsfield projects and similar field campaigns. Recent work under PARTNER Project 11 also has looked at time-integrated emissions from an airport in total. Neither project has fully evaluated particle evolution, especially for all airport sources.

VIII. PERSON(S) DEVELOPING THE PROBLEM

Sandy Webb, Environmental Consulting Group, LLC in association with: Phil Whitefield (Whitefield Scientific Consulting), Richard C. Miake-Lye (Aerodyne, Inc.), and Ted Thrasher (CSSI, Inc.)

IX. PROCESS USED TO DEVELOP PROBLEM STATEMENT

This problem statement is the product of an ACRP project (ACRP02-04), carried out by the authors of this Problem Statement.

X. DATE AND SUBMITTED BY

This problem statement is submitted by Sandy Webb, Environmental Consulting Group, LLC in association with: Phil Whitefield (Whitefield Scientific Consulting), Richard C. Miake-Lye (Aerodyne, Inc.), and Ted Thrasher (CSSI, Inc.) as part of the project report for ACRP 02-04 on December 21, 2007.

Synthesis Report

Airport Emission Source Markers or Fingerprints

A wide variety of PM emission sources operate at commercial airports. Their emissions combine in the ambient air and are then transported off of the airport through normal atmospheric processes. Once off the airport it is difficult to isolate individual emission sources, for example, when evaluating the impact of airport operations on workers, passengers, and nearby communities. It would be a significant benefit to airports if there were characteristic markers or "fingerprints" of individual sources that were unique to those sources. Such markers would also enhance particle deposition studies around airports, more reliably identifying the presence of airport-related emissions

Many airport emission sources have been studied individually (e.g., APEX 1, 2, and 3) and others are proposed in this report (e.g., Problem Statements 1 and 2). These studies will produce data such as particle size number, mass, and composition from a range of aircraft engines, APUs, GSE, and other emission sources. Individual or combined particle characteristics (i.e., size number, mass, composition) may uniquely represent emissions from specific sources. Once the experimental data from all completed projects referenced above are available, a synthesis review should be conducted to identify unique markers or fingerprints for as many source categories as possible. This will aid airports in addressing community complaints and analyzing community impacts. As with other ACRP synthesis reports, the budget for this report would be $25,000; however this is a minimal budget for conducting such a study and it may not be feasible to identify markers for all airport sources in a single synthesis study.

CHAPTER 9

Literature Review and Bibliography

Literature Review

The *Web of Science* (Thomson Reuters) database was used to search the archival literature for publications relevant to the impact of airports on local air quality. Figure 3 is a record of the search terms used to interrogate the database. *Web of Science* can be interrogated using author, subject, source, address, and date terms. Most of the current search terms were of the subject variety, but several author search terms were used. Shown here are searches for the author "Herndon" in "Billerica, MA." Though not shown here, the author search terms "B.E. Anderson," "P. Whitefield," and "J. Froines" were also used to query the database. ARI is concurrently reviewing the available literature relevant to the airport-related contribution of hazardous air pollutants (HAPs) to the regional air shed. In addition to the articles identified in the PM-based search, the team's review of the HAPs-related literature uncovered several articles of relevance to this activity. Of those deemed relevant, well over half of them have been retrieved in electronic form. The remainder was not readily available in electronic form at the time that this report was written. Most of the articles that have been identified as relevant but not yet retrieved are reports of air-quality studies published in the 1970s. Obtaining hard-copy versions of these publications will be a future activity.

Figure 4 summarizes the articles that have been retrieved to date and the total number that were identified. In this exhibit, the literature is divided into subject categories. Articles that are directly relevant to the issue of airborne PM concentrations in the vicinity of airports include reports on the measurement of PM emissions of on-wing gas turbine engines and ground service equipment (GSE), studies on the use of emissions data and dispersion models to predict the effect of airports on regional air quality, and measurements of air quality at airports. Although GSE exhaust was not initially included in the search, one article on this topic was identified and retrieved. Subsequently, a directed search identified a second article describing GSE exhaust, but it has yet to be retrieved.

In addition to the publications that are of direct relevance, there are several categories of publications that are of peripheral relevance, including: reports on cabin air quality in in-flight aircraft, toxicological studies of jet fuel and turbine lubrication oil, particulate emissions of jet engines at altitude, physicochemical properties of gas turbine exhaust, and particulate emissions of laboratory burners that simulate gas turbine engines.

Characterization of the particulate and trace gas emissions of in-flight jet aircraft has been the topic of many reports. The team obtained electronic copies of a representative sample of these articles. Due to the influence that ambient conditions (temperature, pressure, and relative humidity) and power condition (idle, taxi, approach, take-off, and cruise) are expected to exert on PM emissions, the relevance of articles devoted to describing measurements and analysis of particulate emissions of jet engines at altitude to the current activity may be small.

Bibliography

This section includes the report bibliography organized by primary topic. The last item is an annotated bibliography that includes miscellaneous PM references and deposition reports generally not found in searches of technical literature that were reviewed but not necessarily used for the findings of this report. They are included here for completeness.

- General Aviation: Airport Operation and Expansion, Social Costs, and Future Demands
- Air Quality in Cabins of In-Flight Aircraft
- Toxicology: Jet Fuel
- Toxicology: Lubrication Oils
- Toxicology: General
- PM Measurements: On-Wing Gas Turbine Engines
- PM Measurements: Ground Service Equipment
- Soot Properties: Gas Turbine Engines

Search History (For complex set combinations, use Advanced Search)

Combine Sets AND OR COMBINE	Results	SAVE HISTORY OPEN SAVED HISTORY	Delete Sets SELECT ALL DELETE
#15	35	AU=(herndon) AND AD=(billerica) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#14	11	AU=(herndon, s) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#13	12	TS=(particulate* and aviation) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#12	32	TS=(aerosol and aviation) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#11	74	TS=(air quality and airport) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#10	12	TS=(particulate* and aviation) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#9	26	TS=(particulate and airport) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#8	61	TS=(particle* and airport) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#7	61	TS=(particle* and airport) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#6	61	TS=(particle* and airport) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#5	75	TS=(particle* and aviation) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#4	58	TS=(particle* and turbine and jet) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#3	10	TS=(airport and regional and air and quality) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#2	7	TS=(airport and lung) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
#1	16	TS=(airport and epidemiological) *DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1973-2007*	
AND OR COMBINE			SELECT ALL DELETE

Search Tag Key: TS=Topic, **TI**=Title, **AU**=Author, **GP**=Group Author, **SO**=Source, **PY**=Publication Year,

Figure 3. **Web of Science *search term history.***

- Soot Properties: Jet Fuel Combustion in ICE's and Other Burners
- Modeling Air Quality at Airports and in Their Vicinity
- Measurements of PM in the Vicinity of Airports
- Annotated Bibliography

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Subject Category	# Articles Retrieved	# Articles Identified
PM in aircraft engine exhaust and ground service equipment exhaust	8	9
Ambient air quality at airports: measurements and exposure assessment	2	3
Impact of aviation on local or regional air quality: models	6	14
Gas turbine lubrication oil, composition, toxicology, break-down products	9	9
Gas turbine engine soot, general characteristics	4	4
Jet fuel: exposure and toxicology	4	4
Exposure studies of airport workers	3	3
Physicochemical characteristics of soot particles generated by gas turbines	6	7
Measurements and impacts of emissions from in-flight aircraft	14	Many
Cabin air quality	2	4

Figure 4. Articles identified and retrieved.

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AQMD conducted a study to address concerns about the pollutant levels to which LAX staff may be exposed. Although PM_{10} 24-hour measurement levels at LAX exceeded the South Coast Air Basin averages on most sampling days, these levels were still below federal ambient PM_{10} standards for 24 hours.

Barbosa, et al., *Air Monitoring Study of Felton and Lloyd Schools*, South Coast Air Quality Management District, September 2001.

Studied VOC, carbonyls, carbon (organic and elemental), and metals; school is in the prevailing wind trajectory of Los Angeles International Airport (LAX); no impact of airport was discernible.

Eden, et al., *Air Monitoring Study in the Area of Los Angeles International Airport*, South Coast Air Quality Management District, April 2000.

Key compounds detected in the study are associated with mobile sources; all key compounds are lower at residential sites than at aviation and Felton School sites, which are influenced by emissions from major highways. Fallout samples depict greater abundance of larger-than-PM_{10}-sized combusted oil soot particles than is observed at most other locations in the South Coast Basin.

Goldman, Alan, *Soot and Odor*, KM Chng Environmental Inc.

Summary of soot studies at several airports concluded that studies to date have shown that deposits have been made up of fungus, minerals, and soil, particles from wood burning, particles from automobile and diesel truck exhausts, or general urban contamination. While there may be a very small contribution from aircraft exhaust in the deposits in the neighborhoods, the deposits are almost entirely made up of non–aircraft-related components.

Hoffnagle, *Community Impact of Aircraft Particle Emissions*, TRC Environmental Corporation, Fall 1996.

Chemical mass balance analysis of particles collected with deposition plates on Logan Airport (BOS) and in communities surrounding the airport; airport sources examined included engine swipes and tire wear/brake wear; materials from examined sources represented up to 8.5% of fallout collected on airport site; materials from community sites represented less than 0.3% of fallout.

Inglewood Particulate Fallout Study Under and Near the Flight Path to Los Angeles International Airport, South Coast Air Quality Management District, September 2000.

Combusted oil soot particles were not present in abundance in the majority of samples collected during the study, but no conclusions can be drawn from this finding due to the limited sampling period; the composition of the fallout is consistent with that typically found in other areas of the Basin; there is no discernible pattern of either carbon mass or total fallout mass under LAX's flight path that would indicate a predominant influence from aircraft fallout; the concentration and growth of gasoline and diesel powered vehicle traffic in and around the airport is a concern from an emissions impact perspective.

LAX Master Plan—Technical Report Deposition Monitoring, Camp Dresser & McKee, Inc., March 1998.

Data collected at the six monitoring stations tend to eliminate the airport as the major deposition source for the areas directly adjacent to the airport; the deposition rate data implicate freeway traffic for high daytime concentrations; copper composition data indicate that a small fraction of the total deposition seen in the daytime is potentially from aircraft breaking.

Stolzenbach, et al., *Measuring and Modeling of Atmospheric Deposition on Santa Monica Bay and the Santa Monica Bay Watershed*, Institute of the Environment, University of California, Los Angeles, and Schiff, et al, Southern California Coastal Water Research Project, September 2001.

Annual rate of atmospheric transport and deposition of trace metals to Santa Monica Bay is significant; most of the mass of metals deposited by dry deposition on Santa Monica Bay and its watershed originates as relatively large (>10 microns) aerosols from area sources (off-road vehicles and small businesses); for metals the most important sources of emissions to the atmosphere are nonpermitted area sources.

Suarez, et al., *Fine Particulate Matter ($PM_{2.5}$) Monitoring During the Ft. Lauderdale–Hollywood International Airport Air Runway Overlay Project,* Broward County Environmental Protection Department, Air Quality Division, Ambient Monitoring Section, August 31–October 21, 2004.

Concentrations of $PM_{2.5}$ experienced at sampling site under the temporary flight path were higher than at sampling site under the normal flight path (unused during overlay project); however, the differences were consistent during normal operations, which suggests that the differences are not dependent on the increased

air traffic caused by the resurfacing of the primary runway at FLL; changes in concentrations at the two sites mimicked each other, which may be indicative of the material contained in the air mass over the broader area.

Summary of Two Logan Soot Studies, KM Chng Environmental Inc., Fall 1996.

There were no ongoing chronic soot impacts from airport-related activity either for departing or arriving aircraft or from other Logan activity; there were no indications of raw jet fuel in the soot samples analyzed; the contribution of inorganic particles from brake wear and tire wear drop off rapidly and are not observed in the nearby communities.

Venkatesan, *Analysis of Hydrocarbons and Trace Metals in Environmental Samples in support of Los Angeles International Airport 2015 Master Plan Expansion Project EIS/EIR,* Institute of Geophysics and Planetary Physics, University of California at Los Angeles; and Boyle, Department of Organismic Biology, Ecology, and Evolution, University of California at Los Angeles, July 1998.

Study commissioned to characterize aircraft emissions in the vicinity of Los Angeles International Airport; jet aircraft exhaust apparently does not contribute significantly to the saturated hydrocarbons found in the atmospheric particles, soils, plant surface, and water samples evaluated from the area of potential effect; saturated hydrocarbons present in samples appear to be comparably influenced by regional atmospheric deposition; with the exception of vanadium, aerial deposition of trace metals and boron is occurring in the El Segundo Dunes at levels that are consistent with studies of other urban areas; concentrations of trace elements in ambient PM_{10} were within expected valued for urban locations.

Glossary

Advected plume—wind-transported exhaust plume, subject to local meteorological conditions

Aircraft gas turbine engine[1]—any gas turbine engine used for aircraft propulsion or for power generation on an aircraft, including those commonly called turbojet, turbofan, turboprop, or turboshaft type engines

Black carbon—nonvolatile diesel particulate matter, often used interchangeably with soot or elemental carbon (see below), although it is most often used when discussing optical properties

Classical aerodynamic diameter[1]—diameter of an equivalent unit density sphere with the same settling velocity in still air as the particle in question

Coarse particle[2]—particle with a classical aerodynamic diameter between 2.5 and 10 μm

Deposition—an airborne pollutant that reaches the ground by force of gravity, rain, or by attaching to other particles

EIm[1]—Emission Index (mass), the mass of emissions of a given constituent per thousand mass units of fuel burned (e.g., g/kg fuel); also total mass of particulate emissions in the same units

Elemental carbon[1]—often referred to as EC and frequently used interchangeably with black carbon and soot, although it is most often used when referring to chemical properties; the refractory carbon found in combustion-generated particulate matter; the portion of a sample of combustion-generated particulate matter that remains after volatile components have been removed; also known as graphitic carbon

Engine exit plane—any point within the area of the engine exhaust nozzle at an axial distance within 0.5 diameters (or equivalent, if not circular) downstream from the outer edge of the nozzle

Fine particle[2]—particle with a classical aerodynamic diameter less than 2.5 μm

Geometric mean[2]—the nth root of the product of *n* numbers

HAPs—hazardous air pollutants, 188 pollutants that the Clean Air Act Amendments of 1990 required EPA to regulate; also referred to as "air toxics"; the complete list of pollutants can be found in Appendix C: The Clean Air Act Amendments of 1990 List of Hazardous Air Pollutants and on the EPA website: http://www.epa.gov/ttn/atw/orig189.html; for the purpose of this report, particulate matter, while hazardous and potentially toxic, are not included in the definition of HAPs (See also related report ACRP 02-03, *Aircraft and Airport-Related Hazardous Air Pollutants: Research Needs and Analysis*)

Line loss—percent of particles lost during transit through a given sample line; particle loss mechanisms include impaction, diffusion, settling (gravitational), and thermophoresis (thermodiffusion)

Lognormal[3]—a normal distribution that is the distribution of the logarithm of a random variable

Normal distribution[2]—a probability density function that approximates the distribution of many random variables (as the proportion of outcomes of a particular sort in a large number of independent repetitions of an experiment in which the probabilities remain constant from trial to trial) and that has the form f(x) = (1/(σ<sqroot>2π)) $e^{(-1/2[(x - \mu)/\sigma]2}$ where μ is the mean and σ is the standard deviation

Nonroad—mobile emission sources not commonly operated on public roadways such as airport ground support equipment, lawn mowers, etc.

Nonvolatile particles[1]—particles that exist at engine exit plane temperature and pressure conditions

Nucleation[4]—the process of initial formation of a particle from vapor; this process is usually facilitated by the presence of small particles called condensation nuclei, which serve as sites for condensation

Organic carbon[2]—often referred to as OC, is a major component of particulate carbon and is composed of many compounds, most of which partition between the gas and aerosol phases at ambient conditions and are referred to as semi-volatile organic compounds (SVOC) (EPA)

Parameterization—to express in terms of statistically representative characteristics

Parts per million (ppmv) —the unit volume concentration of a gas per million unit volumes of the gas mixture of which it is part; also applicable to mass measurements as referred to as ppmm[1]

Photochemical—the interaction of atoms, molecules, and light

PM_{10}, $PM_{2.5}$, $PM_{1.0}$—regulatory designations of particulate matter less than or equal to 10 micrometers, 2.5 micrometers, and 1.0 micrometers, respectively, in diameter; these measures are similar to the terms coarse, fine, and ultrafine, respectively

Primary particle—a particle that is emitted directly from the source

Refractory—resistant to heat: nonvolatile

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[1] Definition from Society of Automotive Engineers, *Aerospace Information Report 5892*, copyright © 2007, Society of Automotive Engineers.

[2] Definition from http://www.epa.gov/pmdesignations/faq.htm.

[3] Definition from *Merriam-Webster Online Dictionary*, copyright © 2005, Merriam-Webster, Inc.

[4] Definition from Baron P.A. and Willeke K. (eds) *Aerosol Measurement Principles, Techniques and Applications*, 2nd ed., John Wiley and Sons, New York, 2001.

Secondary particle—a particle that forms as the result of a chemical reaction or other means by combining with other elements after leaving the source

Smoke—Small gas-borne solid particles, including but not limited to black carbonaceous material from the burning of fuel, which in sufficient concentration create visible opacity

Smoke number (SN)—the dimensionless term quantifying smoke emission; SN increases with smoke density and is rated on a scale from 0 to 100; SN is evaluated for a sample size of 16.2 kg of exhaust gas/m^2 (0.0239 lb/in^2) of filter area

Soot—nonvolatile diesel particulate matter, also referred to as black carbon or elemental carbon (see above)

Total carbon[1]—the sum of elemental carbon and organic carbon

Transients—a momentary or temporary variation in a variable of interest, e.g., engine power, ambient pressure, temperature

Ultrafine particles—particles with a classical aerodynamic diameter of less than 0.1 μm

Volatile particles[1]—particles formed from condensable gases after the exhaust has been cooled to below engine exit conditions

APPENDIX A

Airport Survey

The following airports were sent the Airport PM Survey instrument on 2/8/07 with a requested response date of 2/23/07. The airports shown in bold face responded to the survey.

Commercial Airports—Large Hubs

Anchorage (ANC)
Atlanta (ATL)
Baltimore (BWI)
Boston Logan (BOS)
Charlotte (CLT)
Chicago Midway (MDW)
Chicago O'Hare (ORD)
Cincinnati (CVG)
Dallas/Ft. Worth (DFW)
Denver (DEN)
Detroit (DTW)
Ft. Lauderdale (FLL)
Honolulu (HNL)
Houston (IAH)
Las Vegas (LAS)
Los Angeles (LAX)
Miami (MIA)
Minneapolis (MSP)
Newark (EWR)
New York Le Guardia (LGA)
New York Kennedy (JFK)
Orlando (MCO)
Philadelphia (PHL)
Phoenix Sky Harbor (PHX)
Pittsburgh (PIT)
Portland (PDX)
Salt Lake City (SLC)
San Diego (SAN)
San Francisco (SFO)
Seattle (SEA)
St. Louis (STL)
Tampa (TPA)
Washington Dulles (IAD)
Washington National (DCA)

Commercial Airports—Medium Hubs

Albuquerque (ABQ)
Cleveland (CLE)
Columbus (CMH)
Indianapolis (IND)
Kansas City (MCI)
Louisville (SDF)
Memphis (MEM)
Nashville (BNA)
Oakland (OAK)
Ontario (ONT)
Raleigh/Durham (RDU)
Reno (RNO)
Sacramento (SMF)
San Antonio (SAT)
San Jose (SJC)

Commercial Airports—Small Hubs

Albany (ALB)
Birmingham (BHM)
Boise (BOI)
Dayton (DAY)
Des Moines (DSM)
Little Rock (LIT)
Richmond (RIC)
Spokane (GEG)
TF Green (PVD)
Toledo (TOL)

General Aviation Airports

Aspen (ASE)
Boeing Field (BFI)
Brookhaven (HWV)
Centennial (APA)
Chandler Muni (CHD)
Essex County (CDW)
Frederick Muni, MD (FDK)
Frederick Muni, OK (FRK)
Flying Cloud (FCM)
Hooks Memorial (DWH)
Lake Tahoe (TVL)
Leesburg Executive (JYO)
North Las Vegas (VGT)
Pompano Beach (PMP)
Prove Muni (PVU)
Richard Jones (RVS)
Ryan Field (RYN)
Santa Monica (SMO)
St. Louis Downtown (CPS)
Teterboro (TEB)
Van Nuys (VNY)

The Environmental Consulting Group LLC

The Environmental Consulting Group LLC
191 Main Street, 2nd Floor Phone 410 626 1002
Annapolis, MD 21401 Fax 410 269 1530
Sandy@EnvironmentalAssistant.com

February 8, 2007

«MrMs» «First_Name» «Last_Name»
«Address__1»
«Address_2»
«Address_3»
«City», «State» «Zip»

Dear «MrMs» «Last_Name»:

The Environmental Consulting Group, LLC is conducting Project 02-04: "Research Needs Associated with Particulate Emissions at Airports," under the Airport Cooperative Research Program (ACRP). The ACRP is an applied, contract research program carried out under the auspices of the National Academy of Sciences, Transportation Research Board. The objective of this project is to develop a prioritized research plan addressing airport sources of particulate matter (PM) emissions. Additional information on the project can be found on the ACRP web site at http://www.trb.org/trbnet/projectdisplay.asp?projectid=132.

Task 1 of the project is to identify PM emissions issues confronting airports. An essential part of the task is to survey a variety of airports on the significance of PM emissions. The enclosed survey form is intended to help us understand your concerns. It was designed to take a minimum of time to answer and a stamped return envelope is enclosed for your convenience. The survey can also be completed online at http://int.cssiinc.com/airportsurvey_pm/. Only a few airports are included in the survey so your response is very important to us.

I am sure you have many requests for information about activities at the airport, including from other ACRP projects, and I know they take up a lot of your time. However, the success of the project depends on your input. If you have specific questions about the project or the survey, please call me at 410.626.1002 or contact me by email at sandy@environmentalassistant.com.

Thank you in advance for your participation in this survey.

Sincerely,

Sandy Webb
Managing Director
Environmental Consulting Group LLC

Environmental Consulting Group, LLC

AIRPORT PM SURVEY

Name: ______________________________ Title: ______________________

Airport: ____

Street: ____

City, State, ZIP ______________________________________

County: ____

Telephone: (W) ____________________

(M) ____________________

Email: ____

Date: ____________________

This survey is being conducted as part of a study by the National Academy of Sciences, Transportation Research Board, Airport Cooperative Research Program to identify research needed to understand particulate emissions at airports. Your participation is very important. If you need additional space to reply to the survey, please feel free to attach an additional page. The survey has been designed to minimize the time needed to complete and a stamped return envelope is enclosed. The survey can also be completed online at http://int.cssiinc.com/airportsurvey_pm. **Deadline for replying to the survey is February 23, 2007.** Please contact Mr. Sandy Webb, Environmental Consulting Group, LLC, 410.626.1002, sandy@environmentalassistant.com if you have questions about the survey.

1. Have you received complaints about Particulate Matter (PM) emissions from the airport? (Please include complaints received by both the airport Environmental Manager and the airport Noise Officer where applicable.)

   Yes ☐ No ☐ Don't know ☐

   1a. If yes, what were the sources of the complaints?

   Community☐ Employees ☐ State Regulators ☐ Federal Regulators ☐

   Other ____________________

   1b. What are the nature of the complaints? ______________________________

   ____

   ____

   ____

   ____

2. Has your airport conducted an environmental or other study (e.g., environmental impact statement, environmental assessment, or conformity analysis) in the past 5 years that included an analysis of PM emissions? Yes ☐ No ☐ Don't know ☐

   2a. If yes, please include a copy of the PM analysis portion of the study.

   ☐ Check if a PM analysis is included with response (or is available on request)

3. Aside from airline and ground support equipment (GSE) sources, what are the other sources of PM emissions at your airport?

   Mobile Sources

   ☐ Landside Vehicles (e.g., automobiles, trucks, buses, and vans)
   ☐ Construction Equipment (e.g., tractors, dozers, trucks, and compressors)
   ☐ Other ____________________
   ☐ Other ____________________

Stationary Sources

- ☐ Power Turbines (diesel)
- ☐ Emergency Generators (diesel)
- ☐ Incinerators
- ☐ Boilers (oil fired)
- ☐ Fire Training Facilities
- ☐ Sand and Salt Piles
- ☐ Other ______________________
- ☐ Other ______________________

4. Have you incorporated any alternatively fueled equipment that reduces PM emissions from airport sources, including construction equipment (e.g., compressed natural gas (CNG), electric, solar, fuel cells, etc.)? Yes ☐ No ☐

   4a. If yes, please describe: ______________________

5. Have you needed to do any PM-specific emissions analysis (e.g., inventories, permitting, or deposition) at your airport other than general environmental analyses addressed in question 2? Yes ☐ No ☐

   5a. If yes, please explain the circumstances: ______________________

6. Is your airport having any interactions with your state or local agencies on air quality?

   6a. If yes, please elaborate (What issues have come up? Is PM one of the issues?): ______________________

7. What is the attainment designation of your area for PM?

   Attainment ☐ Nonattainment ☐ Do not know ☐

8. Are there PM issues or concerns you have as an airport operator? ______________________

Surveys can be completed online at http://int.cssiinc.com/airportsurvey_pm. Alternatively, please return a hard copy of your survey to:

Mr. Sandy Webb
Environmental Consulting Group, LLC
191 Main Street, 2nd Floor
Annapolis, MD 21401
410.626.1002

Survey responses are due no later than February 23, 2007.

Summary of Responses

38 of 80 airports responded to the survey

1. Have you received complaints about Particulate Matter (PM) emissions from the airport?

   18 of 38 airports responded yes

   1a. If yes, what were the sources of the complaints?

   Community **18/18** Employees **9/18** State Regulators **2/18** Federal Regulators **2/18**

   Other **1/18 –** City Officials; **2/18** County Officials; **2/18** Elected Officials

   1b. What are the nature of the complaints?

   Soot deposits on outdoor surfaces (cars, furniture) 7/18

   Dust from construction or other activities 5/18

   Odors 4/18

   Noise 1/18

   Greenhouse emissions 1/18

2. Has your airport conducted an environmental or other study (e.g., environmental impact statement, environmental assessment, or conformity analysis) in the past 5 years that included an analysis of PM emissions? Yes **19/38** No **16/38** Don't know **1/18**

   Blank **2/18**

   2a. If yes, please include a copy of the PM analysis portion of the study.

   13/38 offered copy of some material (typically a section of an older EIS); one risk assessment completed for OAK was submitted

3. Aside from airline and ground support equipment (GSE) sources, what are the other sources of PM emissions at your airport?

   Mobile Sources

   37/38 Landside Vehicles (e.g., automobiles, trucks, buses, and vans)
   36/38 Construction Equipment (e.g., tractors, dozers, trucks, and compressors)
   4/38 Other **- miscellaneous air side equipment like snow removal vehicles**
   18/38 Other **– other unspecified**

   Stationary Sources

   23/38 Power Turbines (diesel)
   22/38 Emergency Generators (diesel)
   18/38 Incinerators
   25/38 Boilers (oil fired)
   25/38 Fire Training Facilities
   24/38 Sand and Salt Piles
   17/38 Other **Unspecified**

4. Have you incorporated any alternatively fueled equipment that reduces PM emissions from airport sources, including construction equipment (e.g., compressed natural gas (CNG), electric, solar, fuel cells, etc.)? Yes **23/38** No **14/28**

   4a. If yes, please describe:

   Mostly CNG, with some low emission vehicles, hybrids, and clean diesel. Some electric GSE. Some unspecified alternative fueled vehicles. Several mentioned use of biodiesel in various equipment.

5. Have you needed to do any PM-specific emissions analysis (e.g., inventories, permitting, or deposition) at your airport other than general environmental analyses addressed in question 2? Yes **6/38** No **32/38**

   5a. If yes, please explain the circumstances:

   Studies reported included: annual air emission inventories, permitting for construction and equipment modification/installation (e.g., new diesel emergency generators). One airport reported plans to initiate a PM/HAPs monitoring study in 2007.

6. Is your airport having any interactions with your state or local agencies on air quality? Yes **21/38** No **15/38**

   6a. If yes, please elaborate (What issues have come up? Is PM one of the issues?):

   Most comments related to routine interaction on criteria pollutants with no special attention to PM. Five airports note that they are focusing additional attention on PM to catch up with understanding and ability to develop inventories as with other pollutants. Two airports mentioned PM or PM/HAP specific studies, one of which is complete.

7. What is the attainment designation of your area for PM?

   Attainment**14/38** Nonattainment**16/38** Do not know **6/38**

8. Are there PM issues or concerns you have as an airport operator?

   Yes **16/38** No **15/38** No Answer **7/38**

   Five of 16 report concerns about dust, 5 of 16 report concerns about the need for reporting PM regularly as a criteria pollutant, and 6 of 16 report specific concerns about airports being able to quantify PM emissions from aircraft and the capabilities of EDMS and air emission methodologies.

APPENDIX B

Researcher and Airport Interviews

The following interviews were conducted during April 2007.

John Froines
Professor of Environmental Health and Head of EPA PM Center at UCLA

- The mentality of the PM centers is to link toxicology studies to emissions studies. This is the biggest gap.
- Froines has developed 6-8 assays that determine chemical/biological toxicity.
- Conducted a study at Los Angeles International Airport (LAX). Measurements were made on the airport grounds near a runway and also in a neighborhood to the west of the airport. The focus of the studies was measurement of ultrafine [defined here as $PM_{1.0}$] particles. Found evidence of a community-wide impact, both based on measurements and modeling. Although other parts of the LA basin have higher levels of air pollution, the air quality in this neighborhood was clearly influenced by the airport. There is relatively little vehicular traffic that might affect local air quality, which allows discrimination of the impact of the airport. Furthermore, measured peaks in ultrafine particle concentrations in the ambient air parallel aircraft activities. This implicates the role of the aircraft themselves.
- The scale of the problem is difficult to define. So far, measurements of ambient air quality have been made, but the toxicological effects are unknown. The impact to human health will define the importance of airport related emissions, but that impact has not yet been determined. There are some interesting physicochemical clues that indicate that an airport affects local air quality differently than other sources. For instance, the PAH's found to the west of the airport are much different than those on the east side of the basin which is not influenced by the airport. An outstanding research issue that should be addressed is the level of oxygenation of the hydrocarbons in the vicinity of LAX, especially as compared to other locations in the LA basin.
- Based on this study, measurements of particulate mass are unlikely to capture the scale of the PM problem. Ultrafine particles, which contribute very little mass, are able to penetrate cell membranes and accumulate in the mitochondria. Therefore, they are likely to have an impact on human health which is not proportional to their mass.
- Two collaborators conducted the field study and analyzed the data: R-C Yu (rcyu2000@yahoo.com) and Eleanor Fanning (efanning@ucla.edu). Froines recommends interviewing these two people at the same time.
- Froines also led a study at Santa Monica, though this was a much smaller effort.
- Froines believes that EPA should make ultrafine particles a research priority.
- In the LA area, the Coalition for Clean Air is interested in this work and may fund a study.
- Reports describing the activity at LAX should be available in late Spring 2007.

John Pehrson
Principal
Camp, Dresser and McKee

- PM is a current problem anticipated to increase in significance in the future
- The driver is the need to address PM in EIS's
- LAX study in final stages of negotiation
- UCLA report (Froines) most recent study

- Need to understand the relative contributions from ground transportation, GSE etc
- PM and acrolein are important and not well characterized
- Acrolein is measurable and health effects appear to be acute
- Identification of aircraft component important
- Need an aircraft related marker or fingerprint
- Need ground transportation, GSE marker or fingerprint
- Need reliable PM data on current advanced engines e.g. GE90 also need data for GA engines.

Tom Nissalke
Director of Environmental and Technical Services
Atlanta Hartsfield-Jackson International Airport (ATL)

- Due to improvements with automobile emissions, airport emissions (construction, aircraft, etc.) are coming under greater scrutiny from Georgia EPA. Airports would benefit from better EPA guidelines for measuring and reporting particulate emissions – as well as CO, NOx, and hydrocarbons – so that regulations might be satisfied. The PM issue is always lurking, but tackling it – even defining the magnitude of the problem – has been hampered by imprecise definitions of PM and how to measure it.
- At this time, however, airport contributions to airborne particles is not a big community issue.
- The most likely impacts of PM emissions will be to human health, and the problem is quite open ended as compliance may require continuous monitoring.
- Atlanta Airport currently monitors PM via its standard air quality analyses. An inventory was conducted in 2005 and a second is planned for 2009.

Donald Hagen
Co-PI Delta Atlanta Hartsfield Study
UMRCOE

- Delta-Atlanta/Hartsfield (previously known as UNA-UNA (Un-named Airline - Un-named Airport)) Study.
- There were two components to this study – dedicated engine tests and an airport study. Report due to FAA 30 April 2007 shows the tremendous promise for a fresh perspective on the magnitude and nature of aviation emissions under 'real-world' conditions.
- The analysis and interpretation of the data was greatly facilitated by the dedicated engine tests.
- These two approaches together form the basis of a combined aviation emissions characterization program which is informative, thorough, atmospherically relevant and novel.
- The findings from this study together with those from the other campaigns will reshape the understanding of aviation emissions associated with airport local and regional air quality and may settle several outstanding questions with respect to particulate emission from aviation sources.
- Finally, this report underscores a need for further analysis of these data.

Carrol Bryant
KB Environmental Science, Inc.
Consultant for Atlanta Hartsfield International Airport (ATL)

- Developed State Implementation Plan (SIP) for Atlanta Hartsfield International Airport.
- From the standpoint of the airport, PM is not considered to be a big problem at this point. Their primary concern is to comply with regulations and will be concerned with PM when it is specifically cited in the Environmental Impact Statement (EIS).
- From a regulation standpoint, a particular standard for airport air quality must be defined (e.g., PM10, PM2.5) and the airports may need to consider abatement policies to reach this goal.
- From the standpoint of the public, there is a great deal of uncertainty regarding the amount and toxicity of airport related emissions. There is not a clear public understanding of how harmful airport emissions may be.

Brenda Pope
Vice President Environmental Management Service
Rhode Island Airport Corp.
T.F. Green Airport (PVD)

- DEM (state environmental agency) is concerned as are neighbors. A DEM study found elevated cancer incidence in the vicinity of the airport and now there is pressure to identify the sources. Currently, there is no clear understanding if this is an issue due to vehicular traffic or airport activities. In fact, no difference was found in cancer incidence in the population downwind of the airport and that living upwind. Therefore, the findings of the DEM study may be related to the large amount of vehicular traffic in the vicinity of TF Green, traffic that is largely not related to airport activities.
- In terms of current activities, DEM has begun monitoring air quality but the data do not confirm the suspicions of people living in the community surrounding the airport. Their belief is that the DEM study is flawed. In addition to PM, there is concern regarding butadiene and formaldehyde.
- In the future, TF Green will continue to work with DEM and the Dept of Health to understand the problem.

Barbara Morin
Department of Environmental Management, Rhode Island
Project manager for TF Green Air Quality Study

- As part of an air quality study at TF Green, measured PM 2.5 and black carbon soot. The total particulate mass was dominated by large particles and measurements seemed to be influenced by prevailing ambient conditions. Black carbon matter correlated with ultrafine particulate matter and was airport influenced even when PM 2.5 was not. Black carbon was difficult to measure.
- Black carbon soot and link with ultrafine particles is an important issue to understand with respect to impact on human health. The role of PAH's is poorly understood.
- Airport PM is not tightly regulated, and current studies are required to define what regulations may be needed.
- Airport PM is driven primarily by potential health impacts. In terms of environmental impacts, an EIS was conducted to look at soot issues.
- The final report for the TF Green study should be available by late Spring 2007.

Donald Hagen
Co-PI JETS APEX2
UMRCOE

- A two phase emissions study was performed at OAK in August 2005
- The first phase was a dedicated engine study performed in the OAK GRE. The results are soon to be released in a CARB sponsored report entitled "The Development of Exhaust Speciation Profiles for Commercial Jet Engines.
- This study has resulted in the first quantitative values obtained using state of the art techniques of engine emission factors for PM and some TOG for the most common classes of gas turbine engines currently operating in the US domestic fleet.
- This study reports the emissions of CO, CO_2, NO_x, PM mass, speciated PM and speciated hydrocarbons at six thrust settings: 4%, 7%, 30%, 40%, 65% and 85%, measured from both engines on four parked 737 aircraft at the Oakland International Airport.
- Measurements were made on 4 of the engines at 1m and 50m downstream of the exhaust nozzle and on all 8 engines at 1m downstream.
- The engine types were selected to represent both old and new technologies.
- Tests were performed to determine whether or not all engines studied were operating in a representative manner.
- Of the 8 engines studied, only one was found to have performance deterioration and it was excluded from the engine average results. Size distributions from 5nm to 1µm were measured for all test points and associated aerosol shape parameters, and mass and number-based emission indices were evaluated along with real-time chemical speciation for some hydrocarbons. This work was conducted by the University of Missouri-Rolla and Aerodyne Research Inc.

The emission factors reported lead to the following conclusions:

- Measurement of NOx indicated that the general emissions performance of the engines was in keeping with certification measurements for the engines studied.

- Measurements of individual hydrocarbon species suggest that the Emission Indices for most of the major species decrease with increasing engine power, in proportion to each other, and specifically with formaldehyde, which is one of the most plentiful emitted hydrocarbons and can be measured accurately.
- The particle composition includes both sulfate and organic volatile fractions at downstream distances, adding to the carbonaceous aerosol that is present already at the engine exit plane. The sulfate contribution has little dependence on engine power, while the organic contribution is smallest at intermediate engine powers.
- The relative distributions of the substituted naphthalenes to non-substituted naphthalenes for the idle modes are in general agreement with the work from Spicer et al.1992, 1994.
- Chromium (VI) results, for all but one of the engines studied, were as expected.
- Size distributions for exit plane were generally lognormal. Strong and sometimes non-linear dependencies were observed with engine power settings.
- The aerosol Soluble Mass Fraction was found to increase with distance from the engine exit plane. Its value was negligible at the engine exit plane and was ~10% at 50m.

The bulk of the TOG speciation was pursued using off-line filter sampling approaches conducted by the University of California-Riverside.

After the field campaign was completed it became apparent that a leak had occurred in the sampling system for the sub-set of filters designated for light hydrocarbon and carbonyl analysis and the emission indices for these species are not quantifiable.

- The second phase was an advected plume study conducted during normal operations at OAK from 7:00am thru 7:00pm on Friday 26 August 2005.
- The prevailing wind was from the W/NW and the sampling location was situated downwind of the eastern end of the runway at OAK. The location selected for sampling the advected plumes was unique in the sense that it provided an opportunity to measure emissions as aircraft taxied to departure, departed, and landed on the single runway.
- Real-time PM and emission gas measurements, provided emission factors, size distributions and chemistry for over 300 aircraft under normal operating conditions. Aircraft tail numbers were also recorded for identification of the airframe and engine.
- Plume processing in the exhaust plume results in the production of a large number of small particles not present at the engine exit plane.
- The production of these small particles serves to shift Dgeom to smaller values and results in at least an order of magnitude increase in EIn when the plume data are compared to those acquired at the engine exit plane.
- These new particles do not significantly contribute to the mass dependent parameter values and no significant changes are observed in DgeomM and EIm.
- In some cases, because of the unique aircraft traffic patterns, sampling location, and prevailing wind direction at OAK, take-off and taxi plumes for different aircraft are found to mix prior to sample extraction, greatly complicating data interpretation. The PM data from these mixed plumes can be deconvolved to yield single aircraft specific information and such analysis is currently underway.
- On average for the -700 series, a newer technology engine, EIm is less than half that for the older technology -300 series.

Britt Johnson
Airport Environmental Planner
Oakland International Airport (OAK)
(submitted health risk assessment as a result of survey)

- From Britt's perspective the number one environmental issue for OAK is acrolein.
- At this time PM is a secondary issue for OAK however the observations of ultra-fines described in the UCLA study lead him to believe that PM will become a first priority issue also.
- OAK is developing a plan for a third runway and his primary concern in the required EIS is reliable data on acrolein. It is his opinion that the current estimates available are too high. He is aware that acrolein was measured during JETS APEX2 and feels that the anticipated report once released by CARB will shed much needed light on the acrolein issue.
- Although he was not the OAK POC for JETS APEX2 (that was Renee Dowlin who has since moved to Portland OR) he feels this research study will provide much needed input on PM and air toxics.

Paul Manasjan
Environmental Affairs Director
San Diego International Airport (SAN)
(submitted section of recent EIS)

- SAN is conducting an air quality emission inventory as a first step towards master plan for expansion.
- SAN is implementing an EMS
- For SAN, PM is an immediate problem
- Issue – deposition of PM? on surfaces in the vicinity of SAN; persistent periodic complaints
- Acrolein is not on the "local radar" in San Diego
- PM from non-aviation sources a problem e.g. dust from unpaved areas
- The driver is the need to address PM in EISs
- Need to understand the relative contributions from ground transportation, GSE etc.
- PM is important and not well characterized
- Identification of aircraft component important
- Need a aircraft related marker or fingerprint
- Need ground transportation, GSE marker or fingerprint

Roger Gardner
Chief Executive, OMEGA
Manchester Metropolitan University Center for Air Transport and the Environment, UK

- Mass estimates for PM from brakes and tires are estimated to be similar to that for engine generated PM
- Need air-side vehicle emission factors
- Need operations details to estimate loading from source emissions data
- As automobiles get cleaner then environmental impact from aviation in and around airports takes on greater significance
- Need to study potential environmental impacts of alternative (synthetic) fuels
- Need a full understanding of what is produced in and around airports.

APPENDIX C

The Clean Air Act Amendments of 1990 List of Hazardous Air Pollutants

CAS Number	Chemical Name
75070	Acetaldehyde
60355	Acetamide
75058	Acetonitrile
98862	Acetophenone
53963	2-Acetylaminofluorene
107028	Acrolein
79061	Acrylamide
79107	Acrylic acid
107131	Acrylonitrile
107051	Allyl chloride
92671	4-Aminobiphenyl
62533	Aniline
90040	o-Anisidine
1332214	Asbestos
71432	Benzene (including benzene from gasoline)
92875	Benzidine
98077	Benzotrichloride
100447	Benzyl chloride
92524	Biphenyl
117817	Bis(2-ethylhexyl)phthalate (DEHP)
542881	Bis(chloromethyl)ether
75252	Bromoform
106990	1,3-Butadiene
156627	Calcium cyanamide
105602	Caprolactam
133062	Captan
63252	Carbaryl
75150	Carbon disulfide
56235	Carbon tetrachloride
463581	Carbonyl sulfide
120809	Catechol
133904	Chloramben
57749	Chlordane
7782505	Chlorine
79118	Chloroacetic acid
532274	2-Chloroacetophenone
108907	Chlorobenzene
510156	Chlorobenzilate
67663	Chloroform
107302	Chloromethyl methyl ether
126998	Chloroprene
1319773	Cresols/Cresylic acid (isomers and mixture)
95487	o-Cresol
108394	m-Cresol
106445	p-Cresol
98828	Cumene
94757	2,4-D, salts and esters
3547044	DDE
334883	Diazomethane
132649	Dibenzofurans
96128	1,2-Dibromo-3-chloropropane
84742	Dibutylphthalate
106467	1,4-Dichlorobenzene(p)
91941	3,3-Dichlorobenzidene
111444	Dichloroethyl ether (Bis(2-chloroethyl)ether)
542756	1,3-Dichloropropene
62737	Dichlorvos
111422	Diethanolamine
121697	N,N-Diethyl aniline (N,N-Dimethylaniline)
64675	Diethyl sulfate
119904	3,3-Dimethoxybenzidine
60117	Dimethyl aminoazobenzene
119937	3,3'-Dimethyl benzidine
79447	Dimethyl carbamoyl chloride
68122	Dimethyl formamide
57147	1,1-Dimethyl hydrazine
131113	Dimethyl phthalate
77781	Dimethyl sulfate
534521	4,6-Dinitro-o-cresol, and salts
51285	2,4-Dinitrophenol
121142	2,4-Dinitrotoluene
123911	1,4-Dioxane (1,4-Diethyleneoxide)

CAS Number	Chemical Name
122667	1,2-Diphenylhydrazine
106898	Epichlorohydrin (l-Chloro-2,3-epoxypropane)
106887	1,2-Epoxybutane
140885	Ethyl acrylate
100414	Ethyl benzene
51796	Ethyl carbamate (Urethane)
75003	Ethyl chloride (Chloroethane)
106934	Ethylene dibromide (Dibromoethane)
107062	Ethylene dichloride (1,2-Dichloroethane)
107211	Ethylene glycol
151564	Ethylene imine (Aziridine)
75218	Ethylene oxide
96457	Ethylene thiourea
75343	Ethylidene dichloride (1,1-Dichloroethane)
50000	Formaldehyde
76448	Heptachlor
118741	Hexachlorobenzene
87683	Hexachlorobutadiene
77474	Hexachlorocyclopentadiene
67721	Hexachloroethane
822060	Hexamethylene-1,6-diisocyanate
680319	Hexamethylphosphoramide
110543	Hexane
302012	Hydrazine
7647010	Hydrochloric acid
7664393	Hydrogen fluoride (Hydrofluoric acid)
7783064	Hydrogen sulfide
123319	Hydroquinone
78591	Isophorone
58899	Lindane (all isomers)
108316	Maleic anhydride
67561	Methanol
72435	Methoxychlor
74839	Methyl bromide (Bromomethane)
74873	Methyl chloride (Chloromethane)
71556	Methyl chloroform (1,1,1-Trichloroethane)
78933	Methyl ethyl ketone (2-Butanone)
60344	Methyl hydrazine
74884	Methyl iodide (Iodomethane)
108101	Methyl isobutyl ketone (Hexone)
624839	Methyl isocyanate
80626	Methyl methacrylate
1634044	Methyl tert butyl ether
101144	4,4-Methylene bis(2-chloroaniline)
75092	Methylene chloride (Dichloromethane)
101688	Methylene diphenyl diisocyanate (MDI)
101779	4,4-Methylenedianiline
91203	Naphthalene
98953	Nitrobenzene
92933	4-Nitrobiphenyl

CAS Number	Chemical Name
100027	4-Nitrophenol
79469	2-Nitropropane
684935	N-Nitroso-N-methylurea
62759	N-Nitrosodimethylamine
59892	N-Nitrosomorpholine
56382	Parathion
82688	Pentachloronitrobenzene (Quintobenzene)
87865	Pentachlorophenol
108952	Phenol
106503	p-Phenylenediamine
75445	Phosgene
7803512	Phosphine
7723140	Phosphorus
85449	Phthalic anhydride
1336363	Polychlorinated biphenyls (Aroclors)
1120714	1,3-Propane sultone
57578	beta-Propiolactone
123386	Propionaldehyde
114261	Propoxur (Baygon)
78875	Propylene dichloride (1,2-Dichloropropane)
75569	Propylene oxide
75558	1,2-Propylenimine (2-Methyl aziridine)
91225	Quinoline
106514	Quinone
100425	Styrene
96093	Styrene oxide
1746016	2,3,7,8-Tetrachlorodibenzo-p-dioxin
79345	1,1,2,2-Tetrachloroethane
127184	Tetrachloroethylene (Perchloroethylene)
7550450	Titanium tetrachloride
108883	Toluene
95807	2,4-Toluene diamine
584849	2,4-Toluene diisocyanate
95534	o-Toluidine
8001352	Toxaphene (chlorinated camphene)
120821	1,2,4-Trichlorobenzene
79005	1,1,2-Trichloroethane
79016	Trichloroethylene
95954	2,4,5-Trichlorophenol
88062	2,4,6-Trichlorophenol
121448	Triethylamine
1582098	Trifluralin
540841	2,2,4-Trimethylpentane
108054	Vinyl acetate
593602	Vinyl bromide
75014	Vinyl chloride
75354	Vinylidene chloride (1,1-Dichloroethylene)
1330207	Xylenes (isomers and mixture)
95476	o-Xylenes
108383	m-Xylenes
106423	p-Xylenes

CAS Number	Chemical Name
0	Antimony Compounds
0	Arsenic Compounds (inorganic including arsine)
0	Beryllium Compounds
0	Cadmium Compounds
0	Chromium Compounds
0	Cobalt Compounds
0	Coke Oven Emissions
0	Cyanide Compounds*
0	Glycol ethers**
0	Lead Compounds
0	Manganese Compounds
0	Mercury Compounds
0	Fine mineral fibers***
0	Nickel Compounds
0	Polycylic Organic Matter****
0	Radionuclides (including radon)*****
0	Selenium Compounds

Source: www.epa.gov/ttn/atw/orig189.html.

NOTE: For all listings above that contain the word "compounds" and for glycol ethers, the following applies: Unless otherwise specified, these listings are defined as including any unique chemical substance that contains the named chemical (i.e., antimony, arsenic etc.) as part of that chemical's infrastructure. Includes mineral fiber emissions from facilities manufacturing or processing glass, rock, or slag fibers (or other mineral derived fibers) of average diameter 1 micrometer or less.

* X'CN where X = H' or any other group where a formal dissociation may occur. For example KCN or Ca(CN)2.

** Includes mono- and di- ethers of ethylene glycol, diethylene glycol, and triethylene glycol R-(OCH2CH2)n -OR' where n = 1, 2, or 3 R = alkyl or aryl groups R' = R, H, or groups which, when removed, yield glycol ethers with the structure: R-(OCH2CH)n-OH. Polymers are excluded from the glycol category. (See Modification.)

*** Includes mineral fiber emissions from facilities manufacturing or processing glass, rock, or slag fibers (or other mineral derived fibers) of average diameter 1 micrometer or less.

**** Includes organic compounds with more than one benzene ring, and which have a boiling point greater than or equal to 100° C.

***** A type of atom which spontaneously undergoes radioactive decay.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation