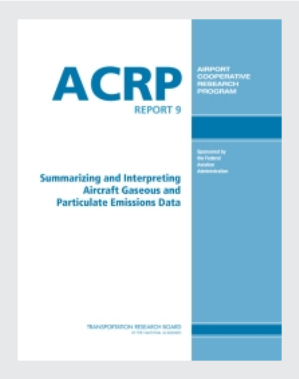

Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data

DETAILS

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AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP REPORT 9

Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data

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Aviation

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AIRPORT COOPERATIVE RESEARCH PROGRAM

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FOREWORD

By Christine L. Gerencher
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ACRP Report 9: Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data provides a summary of a series of government-sponsored aircraft emissions tests that were undertaken to gain a better understanding of gaseous and particulate emissions from aircraft engines. Copious amounts of data were collected as part of this scientific effort, known as the Aircraft Particle Emissions eXperiment (APEX) tests and Delta Atlanta Hartsfield test. This report summarizes the data gathered in these studies to help the airport community and general public understand how the data can be used to develop better air quality assessments in the airport environment.

The APEX and Delta Atlanta Hartsfield series of tests were a collaborative scientific research effort of the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), the Environmental Protection Agency (EPA), and the Department of Defense (DoD). Their main objective was to advance the understanding of particulate emissions by characterizing gaseous and particulate emissions from various in-service commercial aircraft engines. The participants in these tests performed an extensive set of measurements aimed at examining the effect of engine operating and ambient atmospheric conditions on emissions; simulating emissions at airports; and studying fuel effects on particulate emissions by varying fuel composition.

The first APEX test was conducted in April 2004 to collect a set of gaseous and particulate emissions data from a DC-8 aircraft with CFM-56-2C1 engines owned by NASA. This test was followed by the Delta Atlanta Hartsfield Study in September 2004 where two MD-88 aircraft with JT8D engines, two B757 aircraft with PW2037 engines, and two B767 aircraft with CF6-80 engines were examined. A third test in August 2005 examined emissions from two B737-700 aircraft with CFM56-7B22 engines and two 737-300 aircraft with CFM56-3B1 engines and a fourth test, conducted in October-November 2005, evaluated emissions from a Learjet25 aircraft with CJ610 engines, an A300-600 aircraft with PW4158 engines, two B757 aircraft with RB211-535E4B Phase 5 engines, an ERJ aircraft with AE3007-A1E engines, an ERJ aircraft with AE3007-A1P engines, and a B737-300 aircraft with CFM56-3B engines.

In addition to the gaseous and particulate emissions measurements from static aircraft tests, there were two occasions when aircraft taxi and take off emissions were measured downstream of an active runway during normal airport operations. One of these was at Oakland International Airport during the second APEX test, known as JETS-APEX2, and the other was at Hartsfield Jackson Atlanta International Airport during the Delta Atlanta Hartsfield Study. These sets of data afforded surveys of the particulate and gaseous emissions of a wide range of aircraft.

Substantial gaseous and particulate emissions data have been obtained from this series of tests, at a cumulative cost of almost $4 million. This report summarizes the extensive data and analyses of the test results to provide clarification for the airport community and general public on how the data can and cannot be used in the development of local air quality analysis.

CONTENTS

SUMMARY

Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data

The commercial aviation community is faced with the need to assess the impacts of aviation emissions on air quality. Until recent government-sponsored tests were undertaken, emissions of particulate matter (PM) from commercial jet engines were not well understood. Prior to the mid-1990s, jet engine PM emissions were identified as *smoke* and were exclusively quantified using the Society of Automotive Engineers (SAE) Recommended Practice 1179—Smoke Number (SAE 1991). The smoke number does not identify the key characteristics of the PM (morphology, chemical composition, distributional accounts of size and volume, or number and mass concentration) and is, therefore, of limited value to those parties analyzing environmental and health impacts of aviation emissions. As a result, alternative methods for characterizing PM emissions based on these key characteristics were developed. These methods were first applied to quantify PM emissions for military engines (Spicer et al. 1992, 1994; Howard et al. 1996; Whitefield et al. 2002). Although these methods and data served to improve the scientific community's understanding of aircraft engine PM emissions, these studies focused on engine technologies that are different from those currently used in the commercial fleet.

A series of tests was devised and conducted by NASA and the FAA's Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) Center of Excellence and other parties to address the need for data representative of engines in the commercial fleet. The data from these tests have recently been made public, however, until this report, they have not been distilled into a form directly useable and, in some cases, *understandable* by the airport community. Such a synthesis is the primary goal of this report. To facilitate understanding of test results, this report begins with four primer sections on

- PM characteristics, sources, air quality effects, and health consequences;
- Hazardous air pollutants;
- Field test methodologies; and
- Models for the estimation of emissions, air quality effects, and health consequences.

These primer sections are followed by a summary of test results and a review of relevant published material. The report is supported by four appendices that provide additional test details. Test data is available from the FAA and plans are being discussed on how to provide this information on a publicly accessible website.

The cumulative dataset from these tests is extensive. It includes studies that assist with understanding how emissions evolve with distance from the engine. For several stationary commercial aircraft, emissions were measured in the *near-field plume*, referring to the exhaust stream within 1 to 50 m (3 to 164 ft) from the engine exit. Measurements were also taken of emissions downwind (>100 m [>330 ft]) from moving aircraft during routine operation at

two large commercial airports. Each set of tests measured a range of particle characteristics, including number, size distributions, mass, and composition, as well as gaseous emissions concentrations, including nitrogen oxides (NO_x including nitric oxide, NO, and nitrogen dioxide, NO_2), carbon monoxide (CO), hydrocarbons (HC), and sulfur dioxide (SO_2). Gas-phase measurements complement particle measurements providing a more specific description of aircraft engine emissions than has been available to date. This more complete dataset will improve estimates of airport contributions computed by air quality models.

The primary observations and conclusions from these studies that are of interest to the airport community are

- Emissions data at the exhaust nozzle from a subset of engines operating in the commercial fleet have been collected. These include
  - CFM56-2C1 on a NASA DC8,
  - CFM56-3B1, -7B22 on B737s,
  - JT8D on MD-88s,
  - CF6-80 on B767s,
  - PW2037 on B757s,
  - PW4158 on A300s,
  - RB211 on B757s, and
  - AE3007 on ERJ 135/145s.

  Combined, these engine types are present on more than 70% of current aircraft operations in the U.S. domestic fleet.
- Particulate matter number and mass concentrations have been normalized by the amount of fuel burned to produce emission indices that allow the quantification of emissions per kilogram of fuel burned. The mass-based emission indices can be used to develop emissions inventories for the aircraft and engines studied. The PM First Order Approximation (FOA), which is implemented in the FAA's Emissions and Dispersion Modeling System (EDMS), is an application of this technique. Prior to the Aircraft Particle Emissions eXperiment (APEX) studies, it was not possible to compute an emissions inventory of aircraft PM that was representative of current and future aircraft fleets.
- In all cases, gaseous emissions and engine operating parameters revealed that the engines were operating in a representative manner (i.e., their combustion gas emissions were within the uncertainties of the emissions measurements conducted for certification). This being the case, it is reasonable to assume that the measured PM emissions are also representative and that the results reported should be used with confidence to develop emission inventories.
- Unburned hydrocarbons are emitted as a variety of compounds including ethylene, formaldehyde, acetaldehyde, and benzene. Most of these compounds are emitted at thrust levels <30%. Emissions of the various hydrocarbon (HC) species rise and fall with one another, regardless of engine type or thrust setting. Even when the absolute magnitudes increase by a factor of 10 or more (as is the case for older engine technology or for operation at low thrust condition or low ambient temperature), the ratio of one HC species to the next remains constant within the uncertainty of the measurement.
- Measurements were made both at the exhaust nozzle and at locations in the near-field plume (downstream). The non-volatile PM (i.e., particles that exist at engine exit plane temperature and pressure conditions) mass and size did not change appreciably between the exhaust nozzle and the downstream sampling points. Volatile PM (i.e., particles formed as the exhaust cools, from condensable gases such as sulfur oxides, HC, and engine oil) was observed at the exhaust nozzle in small quantities and increased by about a factor of 10 at the downstream sampling locations. Volatile materials entered the particle phase as new particles (<20 nm) and as coatings to preexisting particles.

- The following conclusions were drawn when emissions were sampled at the *exhaust nozzle*:
  - The measured PM parameters for each engine type (i.e., JT8D, CFM56, CF6, RB211, etc.) are unique. For example, in the case of the RB211, JT8D, and PW4158, the mass-based emission indices measured as a function of fuel flow ranged from 0.04 to 0.70, <0.01 to 0.32, and <0.01 to 0.18 g/kg-fuel respectively.
  - The measured PM parameters for engine subtypes are also unique. For example, for the CFM56-3B versus -7B engines, the ratio of their mass-based emission indices at takeoff was found to be 4:1 (-3B:-7B).
  - Credible inventories based on nozzle emission rates will require engine-specific data like that measured in these studies.
  - Black carbon PM (i.e., non-volatile particles) constitutes more than 80% of the mass of PM emissions at all thrust conditions. At takeoff thrusts, more than 95% of the total PM mass is black carbon PM.
- The following trends were observed when emissions were sampled *downstream in the plume* (greater than 10 m [33 ft] from the exhaust nozzle):
  - As the plume cools, condensable exhaust gases convert to the particle phase by nucleating new particles and by condensing onto black carbon PM. Collectively, the new particles and black carbon PM coatings are referred to as "volatile PM."
  - Newly formed volatile particles outnumber black carbon PM by a factor of 10-100 in the cooling exhaust gases. (The number of particles formed in the cooling plume is determined by sulfur from the fuel, the amount of black carbon PM surface area available for condensation, and ambient conditions.)
  - Besides sulfate and organic substances, no other volatile materials are present at concentrations greater than in the ambient background.
  - For most engines, HC sourced to incomplete combustion and lubrication oil constitute >95% of the volatile organic material that can be accurately characterized. The ratio of partially burned HC to lubrication oil depends on engine technology and thrust setting. For certain engines, lubrication oil constitutes up to 90% of the organic PM emitted at high thrust where combustor efficiency is maximized and unburned fuel is at a minimum.
  - The mass of particles in the plume does not change within experimental uncertainty as the plume travels downwind, but the number of particles increases by at least an order of magnitude. The large increase in PM number coupled with constant PM mass indicates that these newly formed particles do not contribute significantly to the total PM mass in the plume. This result indicates that a mass-based inventory alone will not capture this significant volatile PM production.
- Atmospheric conditions impact the measured parameters and need to be taken into account when measuring emission rates for inventory development. For example, a decrease in ambient temperature from 35°C to 26°C (95°F to about 79°F) at one test site (NASA Dryden, APEX1) resulted in the formation of new additional volatile particles at 30 m (nearly 100 ft) downstream of the exhaust nozzle, not observed at the higher temperature. These new particles had a mean diameter of <15 nm and increased the total number-based emission index by an order of magnitude at this distance.
- The length of time that the engine has been running also impacts the measured PM parameters. For example at JETS APEX2, the number-based emission index measured at idle for a CFM56-7B engine was 50% lower after the engine was fully warmed up, compared to the initially measured value.
- It was not possible to statistically determine if there was any variation among subsets of various engine types due to the limited numbers of engine variations tested.
- The engine-specific nature of PM emissions as described above indicates that additional studies will be needed to understand variability in PM emissions among engine types. Specifically,

tests that address the 50,000- to 100,000-lb thrust class employed by such aircraft as the B747, B757, B767, B777, B787, A300, A310, A330, A340, A350, and A380 have not been investigated.

These studies have improved our understanding of aircraft emissions. They have yielded data from more relevant engine technologies than had been available previously. The measurement methods developed in these studies provide an excellent foundation for future studies. The data can be confidently applied to assess and improve current predictive tools such as the FAA Aviation Environmental Design Tool/Emissions and Dispersion Modeling System (AEDT/EDMS) and their predictive subcomponents such as the PM FOA methodology.

CHAPTER 1

Primer on Particulate Matter Emissions from Aviation

This section presents general information on PM emissions with particular attention to the aircraft source. Analytical tools, research activities, and regulatory requirements are described. Much of the general information on PM is paraphrased from U.S. EPA data, information compiled in support of the National Ambient Air Quality Standards (NAAQS) for PM, and *ACRP Report 6: Research Needs Associated with Particulate Emissions at Airports* (U.S. EPA Oct 30, 2007; U.S. EPA Mar 6, 2007; U.S. EPA 2005; Webb et al. 2008).

1.1 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. Particles are frequently designated as volatile or non-volatile. Volatile particles are those that may evaporate if their surrounding conditions change—for example, if the temperature is increased. Water droplets are a common example of a volatile particle. Non-volatile particles are those that remain in a condensed phase even when their ambient conditions vary widely. Soot is a common example of a non-volatile particle. Particulate matter emissions are 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 nm) to 100 μm. Dust, soil, or soot particles 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 important 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.

Particles smaller than 10 μm (note: in this report, particle size descriptions refer to the aerodynamic diameter; see definition for "classical aerodynamic diameter" in Appendix B, Glossary of Terms) 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.

1.2 How and Where Is PM Formed at an Airport?

Different particle types tend to have different sources and formation mechanisms. 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;
- Construction grading and earth moving; and
- Some food preparation ovens (e.g., charbroilers).

Particulate matter emissions from each of these sources are different in terms of size, composition, and rate. Coarse

particles 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 arise from primary PM produced during combustion (carbon particles), or newly nucleated or condensed particles formed in the atmosphere and in aircraft plumes from gaseous emissions (sulfuric acid, partially burned fuel, and vaporized lubrication oil). Ultrafine particle sources at airports include the exhaust from various fuel combustion sources such as aircraft, APU, 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 nucleation. Ultrafine particles 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. Particles emitted directly from a source or formed in the immediate vicinity, are referred to as primary PM. Figure 1 illustrates the range of PM commonly encountered.

Figure 2 illustrates the evolution of primary particles. Particle illustrations are not accurate to comparative size; the horizontal axis showing diameter is logarithmic.

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 preexisting particles. Examples of secondary particle formation include the following:

- 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 nucleates due to its low vapor pressure—the resulting sulfuric acid aerosol can further react with gaseous ammonia (NH_3), for example, in the atmosphere to form various particles of sulfate salts, such as ammonium sulfate $(NH_4)_2SO_4$;
- 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
- Reactions involving gaseous volatile organic compounds (VOC), yielding condensable organic compounds that also can 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.

Ultrafine, fine, and coarse particles typically exhibit different behaviors in the atmosphere since the ambient residence time of particles varies with size. Ultrafine particles are likely

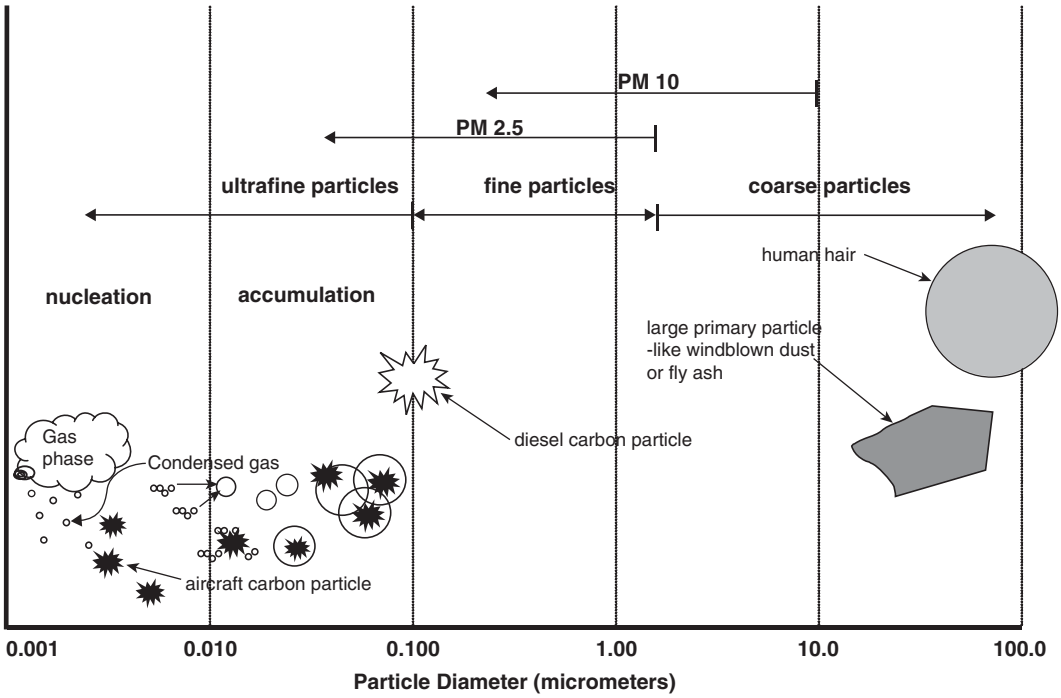
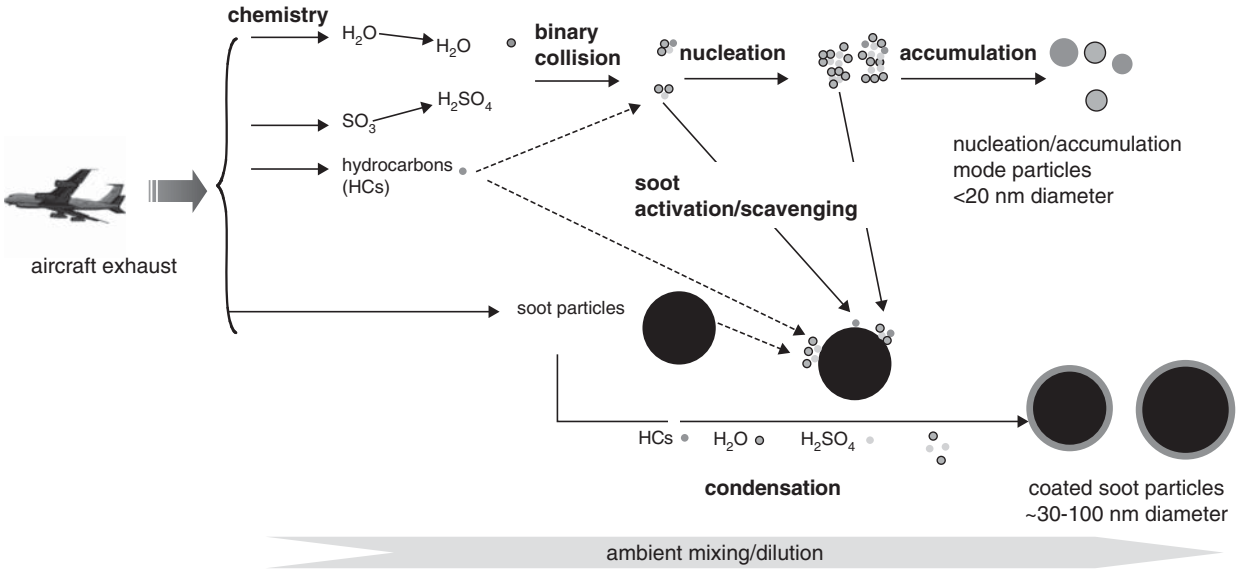


Figure 1. Particle size of airport PM emissions.



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 PM from aircraft engine exhaust.

to grow into fine particles on the order of minutes to hours, typically traveling less than 10 mi. Fine particles remain suspended 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, and have 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 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 the primary components of these small particles. Particles emitted at cruise altitude may contribute to global climate change effects; however, since these particles are emitted beyond the airport environment and were therefore outside of the scope of the tests being summarized in this report, these cruise-level particle emissions are not addressed in this report.

1.3 How Are PM Emissions Quantified?

Emissions from airport sources can be quantified by direct measurement using monitoring equipment or estimated using emission inventory methods. Historically, emissions inventory methods have been applied to assess the role of the airport source in determining air quality. Inventory methods generally require information about each source's population, size, activity rate, and a PM emission factor or emission index. An emission 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 the 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).

In some cases, emission 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). The EPA maintains a reference (U.S. EPA 2008) of emission factors for many sources. In other cases, specific emission factors are compiled for each emission source. For example, regulated gaseous emission factors for aircraft engines are included in the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions DataBank (ICAO 2008) but PM are not similarly regulated. Aircraft engine particulate emissions are characterized in the ICAO database using the smoke number, but this is a measurement of visibility and is only weakly correlated with the mass characteristics relevant to air quality assessments.

GSE are commonly the second largest PM source at airports, sometimes comparable to aircraft as a PM source. GSE are mostly powered by diesel engines although smaller percentages have gasoline engines, and a still smaller percentage use electric power. The diesel and gasoline engines used by GSE

are common engine types found in trucks and other industrial vehicles. Particulate matter mass emissions from these engines are well characterized, however, in emission factor references GSE are 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. Although research reports include information about diesel engine emissions, without having an emission factor reference that relates specifically to GSE, it is difficult to compute PM inventories that reflect airport-specific emissions.

1.4 How Is PM Regulated in the United States?

The EPA establishes the National Ambient Air Quality Standards (NAAQS), which limit the concentration of select pollutants in the outside air. The Clean Air Act requires the EPA to set the NAAQS at levels that protect (1) the public health with an adequate margin of safety (the primary NAAQS); and (2) the public welfare from any known or anticipated adverse effects (the secondary NAAQS). Particulate matter is one of the criteria pollutants regulated through the NAAQS.

Particulate matter emissions affect health and visibility and these issues underlie regulation in the United States. 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. Comprehensive summaries of PM health effects can be found in EPA documentation of their periodic NAAQS review. As of April 1, 2008, these documents were available at http://www.epa.gov/ttn/naaqs/standards/pm/s_pm_2006.html.

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 concentration of particles between 25 and 45 μm, which was the then state of the art for particle samplers. The primary (health-based) standard was set at 260 $\mu g/m^3$ of ambient air, 24-hr 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-hr 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-hr average and $PM_{2.5}$ of 35 $\mu g/m^3$ for 24-hr average and 15 $\mu g/m^3$ annual average. The welfare-based secondary standards were made the same as the primary standard in 2006. The 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 $PM_{1.0}$ or $PM_{0.1}$ 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 $\mu g/m^3$ in the eastern United States; for $PM_{2.5}$, estimates range from 1 to 4 $\mu g/m^3$ in the west to 2 to 5 $\mu g/m^3$ in the east. Particulate matter emissions from airports and other regional sources mix relatively quickly, on the timescale of minutes to hours, 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.

A wide range of regulatory provisions intended for environmental purposes apply to mobile sources, including those that operate at an airport. 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 are regulated; many operational activities and equipment require operating permits; and federal airport actions (such as construction) are subject to the general conformity regulations in locations where the regional air quality does not meet health standards. The EPA sets many such regulatory standards under the Clean Air Act, and many regulatory programs are administered by state agencies to which EPA delegates authority. The 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.

In addition to the NAAQS, other regulations directly or indirectly effect PM emissions from aviation. For example, the ICAO has established aircraft engine certification standards (ICAO 1993) that have been adopted in the United States as federal regulations. The FAA, in turn, monitors and enforces engine certification.

Certification standards that limit smoke emissions, as measured by smoke number, indirectly influence aircraft PM emissions since smoke is a component of total PM. Limits for oxides of nitrogen (NO_x) from jet engines have also been established. These limit the amount of NO_x emitted, which can produce nitrates that condense in the atmosphere hours to days after emissions contributing to secondary volatile particles.

Sulfur emissions are directly related to the sulfur content of the fuel. Internationally accepted standards for Jet A (ASTM D 1655-04a May 2005), which is the commercial aviation fuel used in the United States, limit fuel sulfur content to 0.30% weight maximum. In practice, however, Jet A sulfur content ranges between 0.04 and 0.06% weight (Penner et al. 1999), although lower sulfur jet fuels are now sometimes being seen as diesel fuel sulfur levels drop.

Nonroad diesel equipment, such as GSE, are not required to have emission controls like diesel vehicles licensed for on-road use. Under new national regulations, EPA requires 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 influence the introduction of advanced emission control technologies for nonroad equipment, which may be a requirement for these vehicles in the future. 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 is expected to reduce PM emissions from nonroad equipment by 90% (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). GSE using alternative fuels, such as compressed natural gas, propane, or electricity (U.S. EPA Jul 2004), 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, fuel storage tanks, and food preparation. 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. Required by NEPA is the consideration of emissions associated with a project and identification of the project-related effects as being significant if the project would result in an exceedance of the ambient air quality standards. When undertaking a federal action, before the federal agency can approve the action, it must first be shown to conform with the state implementation plan, the state's plan for assuring compliance with the health-based air quality standards. Conformity requires the federal agency to show that the project will not create a new exceedance of the standard or exacerbate any existing exceedances. The FAA must demonstrate conformity at airports located in a maintenance or nonattainment area for PM_{10} or $PM_{2.5}$.

1.5 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 First Order Approximation (FOA), initially in 2002, as an approach to estimate emissions based on smoke number, a measure of soot obscuration in aircraft plumes. Recently, NASA, EPA, FAA, California Air Resources Board (CARB), 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 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. This report describes the findings of these emission measurement programs in detail.

Another initiative organized to help close the knowledge gap on aviation PM emissions is the National PM Roadmap for Aviation, a research collaboration among federal agencies (e.g., FAA, NASA, U.S.DOT, the Department of Defense [DOD], and EPA), universities, aircraft and engine manufacturers, airports, airlines, and other stakeholders, that organized in 2004 to coordinate aviation PM research and leverage limited resources. Recently, the scope of this initiative has been expanded to include other emissions and has been renamed Aircraft Emissions Characterization (AEC) Roadmap.

Recently, ACRP published a study entitled *ACRP Report 6: Research Needs Associated with Particulate Emissions at Airports* and, now, this report. Such ACRP initiatives help bring needed focus to airport-specific PM emission concerns.

1.6 Why Are Aviation-Related PM Issues Important to Airport Operators?

In addition to complying with general conformity requirements and assisting states in complying with NAAQS, 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. However, airports have very limited data on PM emissions from aircraft engines and APUs. Data for other airport sources varies in quality and availability, and only limited data are available on ambient PM around airports.

Several airports have conducted particle deposition studies in nearby and adjacent communities near Los Angeles International Airport (Barbosa et al. 1999; Barbosa et al. 2001; Eden et al. 2000; Venkatesan 1998), Rhode Island's T.F. Green Airport (VHB, Inc. 2006), Boston Logan International Airport (Hoffnagle 1996; KM Chng 1996), Charlotte/Douglas International Airport (Goldman 2005; KM Chng 1998), John Wayne-Orange County Airport (Stolzenbach 2001), Seattle-Tacoma International Airport (Port of Seattle 1995), Fort Lauderdale Hollywood International Airport (Suarez et al. 2004; Webb 2006), and Chicago O'Hare International Airport (Goldman 2005; KM Chng 1999). 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 it was the results of the APEX studies that first clearly indicated that PM from aircraft is comprised of fine or ultrafine particles, which are too small to settle gravitationally or to be deposited on stationary surfaces and, thus, remain suspended in the atmosphere. The studies prior to APEX 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. Subsequent sections of this report discuss the movement of PM off the airport and gaseous emissions from aircraft engines.

As a result of federally funded research programs, PM emissions from a few engine types have been partially characterized, but most engine models in the fleet remain untested. Research results are still being analyzed to better understand PM formation in aircraft engines and its evolution in the plume. More testing will be required to acquire data needed to develop emission factors related to engine operating conditions with the same level of confidence as those available for gaseous 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, including 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 encourage the introduction of 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 ppm, for use in highway diesel engines. Low-sulfur (500 ppm) diesel fuel for nonroad diesel engines was required in 2007, followed by ultra-low sulfur diesel fuel for these vehicles in 2010 (U.S. EPA May 2004b). 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 not been determined.

CHAPTER 2

Primer on Hazardous Air Pollutants

In addition to PM, measurements during APEX and from older military engines indicate the presence of hazardous air pollutants (HAPs), alternatively referred to as air toxics. HAPs are regulated by the EPA based on the cancer and noncancer risk they pose with acute or chronic exposure. Volatile organic compounds (e.g., toluene), chlorinated volatile organic compounds (e.g., tetrachloroethylene), and metals (e.g., nickel) are three classes of HAPs. As dictated by the Clean Air Act, the EPA maintains a list of HAPs. Additionally, for mobile source emissions, the EPA maintains a "Master List of Compounds Emitted by Mobile Sources." Measurements of ambient HAP concentrations are not as widespread as those of the criteria pollutants. Descriptions of individual HAPs and their sources and emissions at airports have been provided in recent documents (URS 2003; FAA 2005). For more information on the human health effects of HAPs, see EPA's Integrated Risk Information System (http://www.epa.gov/iris).

In addition to aviation, many sources emit HAPs, including ground transportation, construction, power generation, and dry cleaning. At airports, several sources contribute to HAPs emissions. A partial list of "airside" sources includes baggage tugs, solvent use, and the aircraft themselves. Benzene and formaldehyde are two commonly known aircraft engine HAPs. Airport "roadside" sources include on-road vehicles (cars, buses, shuttles, etc.). A separate ACRP study has examined the issue of airport HAPs emissions and provides the results in *ACRP Report 7: Aircraft and Airport-Related Hazardous Air Pollutants: Research Needs and Analysis*.

CHAPTER 3

Primer on Field Studies

This chapter describes the field studies, and how they were conducted, in chronological order. A tabulation of missions, dates, locations, operators, airframes, and engines is provided in Appendix A. A list of particle and gas-phase species measured is provided in Appendix D.

3.1 APEX1

The Aircraft Particle Emissions eXperiment (APEX1) was the first ground-based experiment to simultaneously examine gas and particle emissions from a modern commercial aircraft over the complete range of engine thrust settings.

APEX1 was conducted at NASA Dryden Flight Research Center (DFRC), Edwards Air Force Base, California, between April 20-29, 2004. Particle and gas emissions from one of the NASA DC-8 aircraft's CFM56-2C1 engines were measured as functions of engine thrust, fuel composition, plume age, and local ambient conditions. The specific objectives were to examine the impact of fuel sulfur and aromatic content on non-volatile (soot) and volatile particle formation; follow the evolution of particle characteristics and chemical composition within the engine exhaust plume as it cooled and mixed with background air; examine the spatial variation of particle properties across the exhaust plume; evaluate new measurement and sampling techniques for characterizing aircraft particle and gas emissions; and provide a dataset for use in studies to model the impact of aircraft emissions on local air quality.

APEX1 was a collaborative research effort sponsored by NASA, EPA and DOD. It brought together scientists from three NASA centers, the EPA, the U.S. Army and Air Force (USAF), three universities, engine and airframe manufacturers, and two private research corporations.

During APEX1, particle and gas emissions were measured at 11 engine thrust settings for each of 3 different fuels (base, high-sulfur, and high-aromatic fuels) in samples drawn from probes located 1, 10, and 30 m (3, 33, 98 ft, respectively) downstream from the engine exhaust plane, see Figure 3. At the 1-m and 10-m (3-ft and 33-ft) sampling locations, multiple probe tips were used to examine the spatial variations of emissions properties across the exhaust plume. This testing matrix provided engine gas and particle emission information for more than 400 test conditions. Ambient conditions (during the testing period, the prevailing wind was from the southwest, but varied from all directions during the experiment period; wind speeds ranged from 0.4 to 14.3 m/sec (1.3 to 46.92 ft/sec); ambient temperature and dew point ranged from 16 to 36°C (61° to 97°F) and from −10 to −2°C (14° to 28°F), respectively; the wide ranges of ambient conditions impacted the engine operation and therefore the emissions data; some of the apparent variations in the measured data have been traced to changes in ambient conditions; ambient submicron particle concentrations measured at the testing site were typically <5 $\mu g/m^3$), as well as engine temperatures, fuel flow rates, and fan speeds, were carefully documented for each of the test points examined during the experiment. APEX results represent the first and most extensive set of gas and particle emissions data from an in-service commercial engine wherein multiple instruments were used to quantify important species of interest.

Two different engine testing matrices were used for each fuel used. The NASA test matrix was designed to investigate the effects of engine operating parameters on particle emissions. It included 11 steady-state engine thrust settings: 4, 5.5, 7, 15, 30, 40, 60, 65, 70, 85, and 100% rated thrust output. (Full take-off thrust at the high desert altitude corresponds to 93% of the rated engine thrust; henceforth, 100% will be used to denote 93%). Except for the 100% thrust level where run-time was limited to 1.5 min, approximately 10 min were spent at each thrust setting to allow adequate time for analyzing samples from each of the three downstream probes. The EPA test matrix followed the ICAO-defined LTO (landing-take off) cycle to simulate aircraft emissions at the airport, and consisted of approximately 26 min at idle (7%), 0.7 min at take off (100%),

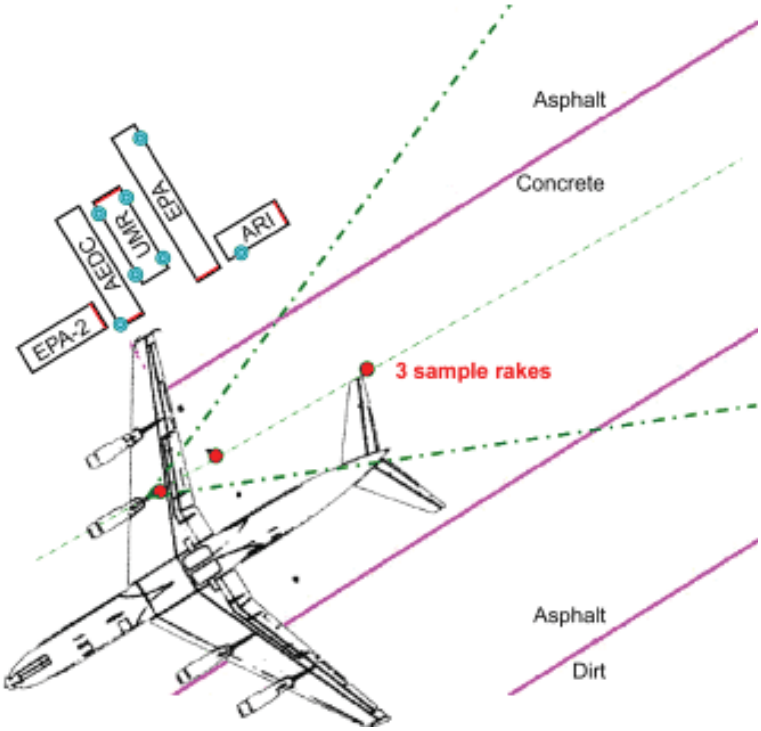


Figure 3. Schematic of NASA DC-8 with sampling rakes and mobile laboratories.

2.2 min at climb (85%), and 4 min at approach (30%) engine thrust settings. For the entire test matrix, each engine condition was repeated several times to get a measure of statistical repeatability and to allow adequate run time for the collection of time-integrated samples for chemical characterization.

A portable weather station was erected a short distance from the test site and used to continuously monitor and record ambient wind, temperature, and pressure throughout the engine runs.

Multi-port particle and gas sample rakes were designed, built, and deployed to map the spatial variations of emissions properties across the exhaust plume at the 1- and 10-m (3-ft and 33-ft) probe locations. As shown in Figure 4, these rakes held six traditional gas inlet ("G") probes and six particle inlet ("P") probes that allowed introduction of dilution air just downstream of the probe tip. To provide adequate flow for filter and whole-air samplers, six additional, large-diameter gas inlet ("GG") probes were attached to either side of the 1-m (3-ft) rake, aligned horizontally with the six, centerline-mounted gas probes. The particle and gas probes were mounted in an alternating pattern at 32-mm (1.26-in.) spacings and numbered from the top to bottom in the rake. The 1-m (3-ft) sample rake was minimally cooled with low-pressure water. At the 30-m (98-ft) location, a single probe sampled the mixed exhaust plume without further dilution.

The center of the 1-m (3-ft) rake was aligned approximately 77 mm (0.25 ft) to the side of the engine vent tube. Temperature probes (type-K thermocouples) and total and static pressure probes mounted on the rake were used to map the core-flow position.

Particle samples collected at 1 and 10 m (3 ft and 33 ft) used the same type of probes and sample transport tubing. At the 1-m (3-ft) location, particle samples were diluted at each particle probe tip with a concentric flow of dry nitrogen (N_2) to suppress particle-particle interactions and the generation of new aerosol due to gas-to-particle conversion involving water and sulfuric acid. The 10-m (33-ft) samples were typically not diluted. The 30-m (98-ft) location probe was a single probe

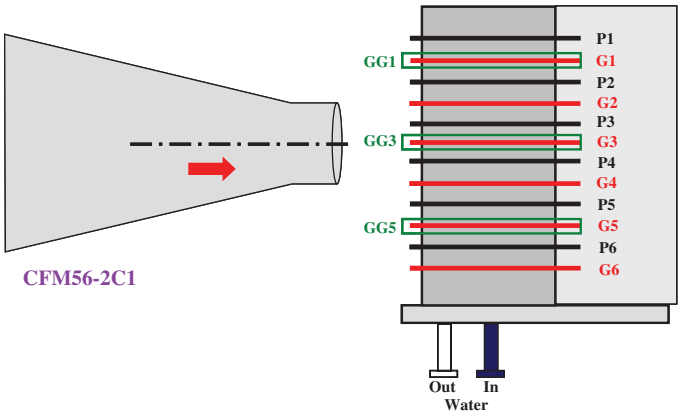


Figure 4. Orientation of sampling probes (P-particulate, G-gaseous, GG-external gaseous) with respect to the engine exit plane.

that sampled the exhaust plume gases without introducing any dilution because exhaust plume was already diluted significantly with ambient air. Samples to all particle instruments were distributed through the sample distribution manifold. Modification of the aerosol size and composition due to various mechanisms such as inertia, thermophoresis, and diffusional effects, can occur in the sample train and are accounted for with calibration experiments (Lobo, Hagen et al. 2007). Gas samples (undiluted) were transferred through about 30 m (98 ft) of heated (177°C [350°F]) sampling line and distributed to individual instruments.

3.2 Delta Atlanta-Hartsfield Study

The second of the APEX series of studies was carried out with the support of Delta Airlines at Hartsfield-Jackson Atlanta International Airport in September 2004. Mobile laboratories operated by Missouri University of Science and Technology (Missouri S&T), Aerodyne Research, Inc. (ARI), and the National Oceanic and Atmospheric Administration (NOAA) were deployed to conduct two series of measurements of aircraft engine-generated PM emissions. The first series was conducted at the maintenance facilities of Delta Airlines and focused on PM emissions in the vicinity of the exhaust nozzle of several different aircraft whose engines were cycled through a matrix of reproducible engine operating conditions as in APEX1. The second series introduced a novel approach focusing on emissions generated under actual operational conditions. This series was conducted by placing the mobile laboratories adjacent to, and downstream of, active runways. In these latter measurements advected exhaust plumes generated by a broad mix of commercial transport aircraft taxiing and departing the airport during normal operations were detected and analyzed.

The Atlanta study was originally subject to nondisclosure agreements between the research team and Delta Airlines and, until December 2006, was referred to as the Un-Named Airline—Un-Named Airport (UNA-UNA) Study. In November 2006, the nondisclosure statement was rescinded, permitting the public release of the data, and the study was henceforth known as the Delta-Atlanta Hartsfield Study. The Delta-Atlanta Hartsfield Study was the first opportunity to measure PM and gaseous emissions from in-service commercial transports.

Figure 5. Probe rake assembly used during Phase 1 of the Delta Atlanta-Hartsfield Study.

Dedicated engine tests on stationary aircraft took place between 10:00 P.M. and 5:00 A.M. on September 21-25, 2004. The aircraft tested were selected from those scheduled to be overnight at the airport. The exhaust plumes of each aircraft were investigated using both probe sampling at the engine exhaust nozzle exit (Missouri S&T-ARI), see Figure 5, and remote sensing using LIDAR (light detection and ranging) (NOAA) at a point in the plume close to the exhaust nozzle exit, thus permitting comparisons of measurement techniques. Another objective was a study of engine-to-engine variation within the same class and, where possible, two aircraft with the same engine class were studied. The airframes and engines studied are listed in Table 1.

The range of engine operating conditions examined focused on the LTO cycle with additional intermediate settings. For the JT8Ds, the complete range of thrust settings was explored, but for the higher thrust engines, transient instabilities induced vibration in the probe stands at mid- to high thrust, and this limited the range of thrusts sampled.

The probe sampling measurements by Missouri S&T focused on physical characterization measurements including particle size distribution, number- and mass-based emission indices

Table 1. Airframes and engines measured during the Delta-Atlanta Hartsfield Study.

Date	Aircraft Number	Airframe	Engine	Thrust (kN)
September 22, 2004	908	MD-88	JT8D-219	93
September 23, 2004	918	MD-88	JT8D-219	93
September 23, 2004	134	B767-300	CF6-80A2	217
September 24, 2004	1816	B767-400ER	CF6-80C2B8F	258
September 24, 2004	635	B757-200	PW 2037	166
September 25, 2004	640	B757-200	PW 2037	166

and soluble mass fraction. ARI focused on using an aerosol mass spectrometer and related supporting instruments to quantify the composition of the particles as a function of size and thrust. Concurrent with the probe sampling, remote sensing was performed by NOAA using a mobile LIDAR system. Also, NOAA supplied and operated the LIDAR, which used eye-safe ultraviolet light from a laser pulsing at 10 Hz and scanned the beam up and down in a vertical plane perpendicular to the direction of engine exhaust. The LIDAR system was contained in a trailer positioned about 300 m (984 ft) from the aircraft. The principal wavelength for this project was 355 nm. The back scatter (or reflection) of energy from the laser by the total aerosols emitted by the aircraft engine was measured just behind the rear stabilizer of the aircraft by the LIDAR.

Upon completion of the dedicated engine testing, the research groups turned their attention to measurements of aircraft emissions on the airfield at various locations near the ends of runways where takeoff operations were occurring. With the exception of the data acquired on September 26, it was not possible to collocate the LIDAR and the Missouri S&T-ARI measurement systems. Despite this limitation, for the overall project, both groups were successful in data collection with 344 takeoffs measured by LIDAR and more than 500 taxi and takeoff events by the Missouri S&T-ARI measurement system.

The Missouri S&T and ARI mobile laboratories were positioned (with assistance from airport operations staff) just downwind of an active runway, as shown in Figure 6. Two locations were selected to perform these measurements based on the prevailing wind direction on a given day. On September 27, 2004, the prevailing wind was from the N/NE, and Missouri S&T and ARI were collocated on the western end of the airport's southern runways. On September 28 and 29, 2004, the prevailing wind shifted to the W/NW direction, and Missouri S&T and ARI moved to the eastern end of the southern runways. In this work, exhaust plumes advected in the direction of the sampling systems were continuously analyzed. Exhaust pollutant emission ratios relative to exhaust CO_2 were determined for various gas-phase and particulate metrics by looking at the concomitant rise in the measurement of a target pollutant above background with increased CO_2. These emissions ratios were converted to fuel-based emissions indices using above-ambient CO_2 as an internal exhaust plume tracer. The characteristics of advected plumes—plume rise and plume spread (horizontal and vertical)—were measured using the LIDAR technique. These measured parameters are key variables in dispersion modeling.

3.3 JETS-APEX2

The impetus for the JETS-APEX2 study came from CARB. In late 2004, CARB had initiated discussions with the Missouri S&T Center of Excellence for Aerospace Particulate Emissions Research (Missouri S&T COE), the Port of Oakland for Oakland International Airport (OAK), and Southwest Airlines (SWA) to provide access to in-service commercial B737 aircraft for such measurements since SWA operates exclusively with B737s and is the major airline operating out of OAK. In the spring of 2005, Project JETS-APEX2 emerged as a study funded by multiple agencies (CARB, NASA, FAA, EPA, Missouri S&T, UCR, UCF, AEDC, GE, Boeing, SWA, OAK, and ARI) to produce the first measurements with state-of-the-art analytical equipment of speciated total organic gases (TOG) and PM from engines on typical in-use Boeing 737-type commercial aircraft.

JETS-APEX2 consisted of two series of experiments similar to the Delta Atlanta-Hartsfield study. The first series focused

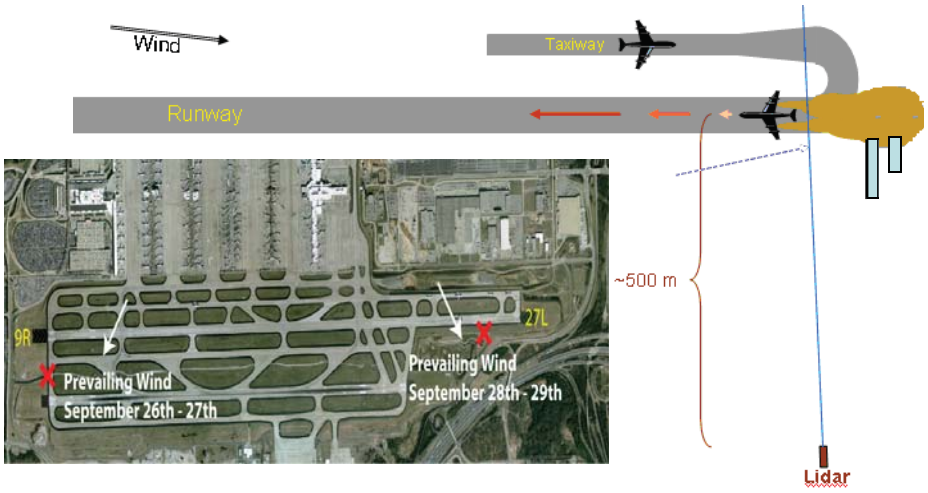


Figure 6. Schematic of layout of mobile laboratories during the downwind study at Delta Atlanta-Hartsfield.

on PM emissions in the vicinity of the exhaust nozzle of several different aircraft whose engines were cycled through a matrix of reproducible engine operating conditions as in APEX1. The second series focused on emissions generated under actual operational conditions, conducted by placing the mobile laboratories adjacent to, and downstream of, active runways. In these latter measurements, advected exhaust plumes generated by the mix of commercial transport aircraft taxiing and departing the airport during normal operations were detected and analyzed.

The first series of experiments relied heavily on experience gained in the previous APEX study where custom-designed probes and extensive support equipment were used to sample jet exhaust in the on-wing position at six thrust settings: 4%, 7%, 30%, 40%, 65% and 85%. In all, both engines of four parked 737 aircraft were tested.

Particle-laden exhaust was extracted directly from the combustor/engine exhaust flow through the probe, transported through a sample train, distributed, and analyzed in each group's suite of instrumentation. Sampling probes were located at different positions downstream of the engine exit plane: 1 m, 30 m, and 50 m (3 ft, 98 ft, and 164 ft) on the starboard side, and at 1 m (3 ft) on the port side of the aircraft. These aircraft engine emissions measurements were performed at the Ground Runup Enclosure (GRE) at OAK during August 2005 (see Figure 7). The engine types were selected to represent both old (-300 series) and new (-700 series) technologies. Real-time PM physical characterization was conducted by Missouri S&T. Size distributions from 5 nm to 1 µm were measured for all test points and associated aerosol parameters (i.e., geometric mean diameter, geometric standard deviation, total concentration, and mass and number-based emission indices were evaluated).

ARI made real-time measurements of gaseous emissions using: (1) tunable infrared laser differential absorption spectroscopy (TILDAS) based on both lead-salt diode and quantum cascade laser sources for several important trace species emissions; (2) proton-transfer reaction mass spectroscopy (PTR-MS) for HC; and (3) chemiluminescence measurement for NO. These measurements were converted to emission indices using CO_2 measured with a nondispersive infrared absorption technique. Chemical composition of the particle emissions was quantified using an aerosol mass spectrometer (AMS) in concert with a multi-angle absorption photometer (MAAP, for black carbon mass) and particle size and number measurements.

The TOG, PM, metals, and ions were collected on filter membranes by the University of California–Riverside Center for Environmental Research and Technology. Teflo filters were used to acquire PM mass, and metals and ions concentrations. For TOG, various sampling media—including SUMMA™ canisters, 2,4-dinitrophenyl hydrazine (DNPH)

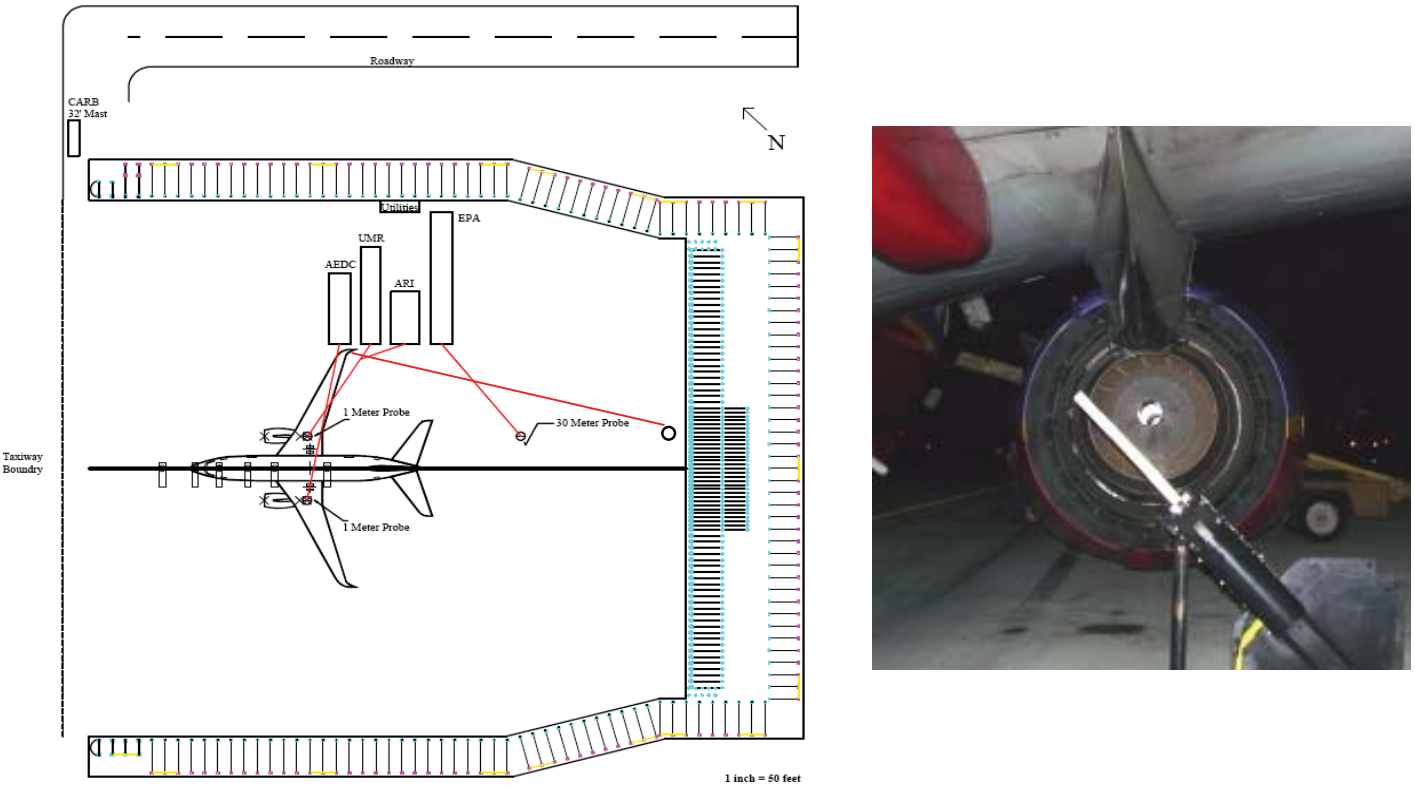


Figure 7. Layout of the mobile laboratories in the GRE and probe rake assembly used in JETS-APEX2.

cartridges, and thermal desorption tubes—were used. After the field campaign was completed, analysis of the DNPH cartridges and SUMMA canisters revealed anomalous CO_2 concentrations, which were attributed to a leak in a subsystem of the sampler. Also, C_4-C_{12} HC values based on the concentrations measured from the thermal desorption tubes (TDS) were much lower than expected from APEX1 and other research. Since this leak introduced an unquantifiable dilution in these subsystems, the emission factors for the light HC and carbonyls could not be calculated.

The second set of measurements sampled jet engine exhaust downwind of an active taxiway and runway at OAK while the aircraft performed standard LTO. The runway tests demonstrated the potential of downwind emissions monitoring adjacent to active taxiways and runways as a means to rapidly acquire evolving aircraft PM characteristics from in-service commercial aircraft. Emissions were monitored during a 12-hr period of daylight aircraft operations along a single runway where the downwind exhaust plumes for over 300 aircraft were sampled. An aerial view of the test venue is shown in Figure 8. Mobile laboratories from Missouri S&T and ARI were collocated downwind on the eastern end of the runway with the prevailing wind direction coming from the W/NW. The Missouri S&T laboratory focused on the physical characterization of the downwind PM and measurement of CO_2 (Whitefield et al. 2007). The ARI laboratory focused on characterization of PM composition and measurement of CO_2, and trace combustion gases (Herndon et al. 2007).

Over 300 aircraft landings and departures were detected and monitored during the period from 7 A.M. to 7 P.M. on August 26, 2005. Aircraft tail numbers and operational status (i.e. taxi, takeoff, and landing) were acquired through visual observation, including video recordings. Aircraft-specific airframe and engine data were obtained by correlating these tail numbers with an FAA database. Figure 9 illustrates the distribution of aircraft types operating at OAK during the day of the tests. In all, exhaust from 15 different airframe types was captured, and approximately 63% of the aircraft were B737s.

Figure 8. Aerial view of the OAK test venue for downwind plume monitoring.

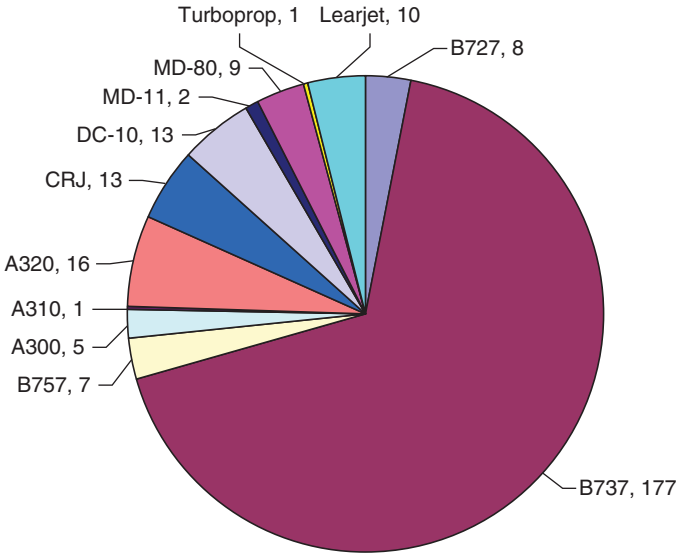


Figure 9. Distribution of aircraft activity as a function of airframe.

3.4 APEX3

APEX3 was the fourth campaign in the APEX series. The main objective of APEX3 was to advance the knowledge of aircraft engine particle emissions. APEX3 was conducted at Cleveland Hopkins International Airport (CLE) from October 26 to November 8, 2005. In APEX3, as in the three previous studies, engine exhaust emissions and plume development were examined by acquiring data from the exhaust nozzle and in the near-field plume from a range of stationary commercial aircraft. A complementary study of downwind plumes during normal operations was abandoned because the prevailing winds during the scheduled sampling times did not transport the plumes to the available sampling locations.

As with previous studies, APEX3 was a collaborative research effort and was supported by the following organizations:

(1) Researchers from NASA, EPA, U.S.DOT Volpe Center, the Air Force Arnold Engineering Development Center (AEDC), Missouri University of Science and Technology (Missouri S&T), Montana State University (MSU), and Aerodyne Research, Inc. (ARI);

(2) Engineers from the aviation industry including Continental, Express Jet, FedEx Express, General Electric, Pratt and Whitney, Rolls-Royce, and Rolls-Royce North America; and
(3) Sponsors from FAA, EPA, NASA, and Cleveland Hopkins International Airport.

Particulate matter and gas-phase emissions were acquired from a range of current in-service commercial aircraft engines including regional aircraft (ERJ 135/145 equipped with AE3007 engines) provided by Express Jet, passenger aircraft (B737-300 with CFM56-3B1 engines, B757 with RB211-535E-4B engines) provided by Continental Airlines, a freight aircraft (A300-600 with PW4158 engine) provided by FedEx, and the NASA general aviation aircraft (Learjet 25 with CJ610 turbojet engines). Engine exhaust was sampled at three different locations in the plume, nominally 1 m (3 ft) (i.e., exhaust nozzle), 15 m (49 ft), and 30 m (98 ft) for the small aircraft (regional jet and general aviation jet), and 1 m, 30 m, and 45 m (3 ft, 98 ft, and 148 ft) for the large aircraft.

CHAPTER 4

Primer on Models

A primary potential application of the APEX data is to aid compilation of airport emissions inventories. Inventories are typically compiled for criteria pollutants and their precursors (i.e., NO_X, SO_X, CO, VOC, and PM). Various analytical tools, described in this chapter, are available to support the complex computations and aid in analyzing the results.

4.1 Emissions and Dispersion Modeling System

The EDMS is a combined emissions and dispersion model for assessing air quality at civilian airports and military air bases. The model was developed by the FAA in cooperation with the 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 (FAA Jul 2, 2007).

Altough EDMS has always computed CO, HC, NO_x, and SO_x emissions for all airport sources and PM emissions for on-road vehicles, GSE, and stationary sources, Version 4.3 of the model introduced the ability to compute PM emissions for aircraft main engines using the FOA. EDMS Version 5.0.2 applies the FOA 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 APU so EDMS only computes the other criteria pollutants for APU.

4.2 MOBILE

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 (U.S. EPA 2007a).

4.3 NONROAD

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 load factor. The traditional application of the model is to use the embedded database of county-level nonroad fleet information, however, the underlying vehicle data were extracted by the EPA for use in EDMS to allow the emissions for individual vehicles to be computed (U.S. EPA 2007b).

4.4 First Order Approximation 3.0

The FOA3 was developed by the ICAO Committee on 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 APEX1 aircraft engine emission tests was used in its development. Three components of PM are modeled by FOA3, which uses the sum of three separate equations: a power and polynomial function of smoke number for non-volatile 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 H_2SO_4 and fuel organics while keeping the equations the same for non-volatile PM and adding a term for lubrication oil (Kinsey and Wayson 2007).

4.5 Aviation Environmental Design Tool

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 analysis 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 affects the environment through noise and emissions on a local and global scale (FAA Sep 2007).

4.6 Aviation Environmental Portfolio Management Tool

The Aviation Environmental Portfolio Management Tool (APMT) is currently being developed by the FAA as a complement to AEDT to allow tradeoffs between noise and emissions to be better understood. The tool has three primary capabilities, cost effectiveness analysis, benefit-cost analysis, and distributional analysis, computed at a societal level by considering economic and health effects. The AEDT noise and emissions computation modules can be directly exercised by APMT over a range of scenarios to allow a statistically significant result to be produced (FAA 2006).

4.7 Community Multi-Scale Air Quality Model

The Community Multi-Scale Air Quality Model (CMAQ) was developed through a NOAA-EPA partnership and permits modeling of chemistry and transport of emissions on a regional scale to follow 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 (2.5 miles to over 22.3 mi), depending on the needs of the analysis (U.S. EPA Sep 19, 2008).

4.8 Microphysical Models

Microphysical models refer to a class of kinetic models that follow the formation (nucleation) and evolution of particles interacting with condensable gases. Microphysical models are often used to simulate atmospheric processes and are designed to predict cloud properties based on the formation and size of the resulting aerosol particles. The same techniques used to predict water-based clouds in the sky can be applied to predict the formation of plumes of aerosols and PM in engine exhaust. Microphysical models have been used to simulate aviation PM evolution both at altitude and ground level.

CHAPTER 5

Individual Reviews of Data from the Aircraft Field Measurement Campaigns

5.1 APEX1

The emissions of a CFM56-2C1 engine burning a range of fuels (base, high aromatic, high sulfur) were measured during the APEX1 campaign. The PM parameters measured at APEX1 were particle size distributions and emission indices for particle number and mass (i.e., the number or mass, respectively, of particles produced per kilogram of fuel burned), including their volatile and non-volatile fractions. Emission indices were also measured for major combustion gases (carbon dioxide [CO_2], carbon monoxide [CO], nitrogen oxides [NO_x], total unburned hydrocarbons [UHC]) and trace combustion gases (specifically, sulfur dioxide [SO_2], nitrous oxide [N_2O], nitrous acid [HONO], and a number of volatile HC). All of the data recorded in the APEX1 database were acquired when the engine was declared to be stable for a given operating condition.

The PM in an engine exhaust plume was found to vary in composition and physical and chemical properties as the plume ages, and the total PM detected had volatile and non-volatile (black carbon) components depending on the sampling location in the plume. In terms of *non-volatile particle emissions*, the following conclusions were drawn from APEX1:

- Non-volatile particles ranged in diameter from smaller than 10 to 300 nm (i.e. 0.01 to 0.3 μm); see Figure 1 for size comparisons.
- The number mean diameter of the particles increased with thrust ranging from ~15 nm at idle to ~40 nm at take off
- For the three fuels tested, the non-volatile PM parameters did not vary.
- Non-volatile PM parameters did not depend on plume age (sampling distance downstream of the exhaust nozzle), indicating that the black carbon component of the exhaust does not change as the plume ages.
- The number-based emission index was highest at takeoff thrust, with a smaller peak at idle thrust, and revealed a minimum at thrust levels corresponding to approach.
- The number-based emission index at low thrust levels was found to decrease during the first couple of hours of engine *on* time. Number-based emission index similarly decreased as the ambient air temperature increased.
- The mass-based emission index increased with thrust, ranging from <20 mg/kg of fuel burned at idle through cruise thrust levels and rising to >200 mg/kg of fuel burned at takeoff.

Samples collected downstream of the exhaust nozzle often contained large numbers of volatile particles that contain materials that are gases at temperatures above 300°C (572°F). These volatile particles were not observed at the exhaust nozzle but were readily apparent downstream (~30 m [98 ft]). They evolve as the plume expands and mixes with the ambient air. In terms of *volatile particles,* the following conclusions were drawn from APEX1:

- Their number mean diameter ranged from smaller than 3 nm to 10 nm.
- At downstream sampling locations, the number-based volatile particle emission index was typically much higher than that of the black carbon and depended on fuel composition, thrust level, plume age, and ambient temperature.
- Compositional analysis of these volatile particles revealed that sulfur and HC species accounted for a significant fraction of the volatile mass, consistent with condensation and nucleation of sulfuric acid/sulfate and HC in the cooling plume.

In the case of the total PM, where no distinction is made between the volatile and non-volatile components, the following characteristics were observed:

- At high thrust levels, particle mass emissions were dominated by black carbon at all sampling locations in the plume.

- At low thrust levels, the number-based emission index was substantially greater downstream (~30 m [98 ft]) than at the exhaust nozzle, indicating that significant gas-to-particle conversion occurred as the plume cooled and aged.
- The number mean diameter of the total particles increased linearly with thrust.

From the gas-phase species measurements performed during APEX, the following conclusions were drawn:

- The emission indices for NO_X, CO, and HC agreed with values archived in the ICAO Aircraft Engine Emissions DataBank.
- The NO_2 fraction of NO_X varied from ~0.7 at idle to ~0.09 at take off.
- Although substantial at idle, the HC emission index decreased with increasing thrust and was below the minimum detection limit (roughly 0.01 to 0.05 g/kg-fuel depending on the species) above 15% rated thrust.
- The HC emission index depended strongly on ambient conditions such as temperature. A 20°C decrease in ambient temperature increased the emission index of HC species by a factor of 10.
- The emission index of SO_2 was greater for the high sulfur fuel (1600 ppm sulfur) than for either the high aromatic or base fuels (400 ppm sulfur).
- Unburned hydrocarbons are emitted as a variety of compounds, including ethylene, formaldehyde, acetaldehyde, and benzene. Emissions of the various HC species rise and fall with one another, regardless of engine type or thrust setting. Even when the absolute magnitudes increase by a factor of 10 or more (as is the case for older engine technology or for operation at low thrust condition or low ambient temperature), the ratio of one HC species to the next remains constant.
- Slight differences in formaldehyde emission index were observed between the various fuel types.

5.2 Delta Atlanta-Hartsfield Study

The second of the APEX series of studies was carried out with the support of Delta Airlines at Hartsfield-Jackson Atlanta International Airport in September 2004. Mobile laboratories operated by Missouri University of Science and Technology (Missouri S&T), Aerodyne Research, Inc. (ARI), and NOAA were deployed to conduct both dedicated engine tests and runway studies (see Chapter 3 for details). The full LTO cycle for MD-88 and JT8D engines was studied during the Delta Atlanta-Hartsfield Study. Only thrust settings less than 60% full rated thrust were examined for larger engines such as CF6 and PW2037.

The Delta Atlanta-Hartsfield Study yielded the following conclusions from the extractive sampling measurements:

- For the JT8D engines, number mean particle diameters increased with engine thrust.
- The number-based emission index was highest at takeoff, exhibited a smaller peak at idle, and revealed a minimum at thrust levels corresponding to approach.
- The mass-based emission index behaves similarly to the number-based emission index and is higher at idle, exhibits a minimum at approach, and then rapidly increases to a maximum at takeoff.
- The JT8D number and mass emissions trends are consistent with behavior of the CFM56-2C1 engine studied in the APEX campaign.
- The two JT8D engines in this study have greater black carbon emission indices than any other engine tested in the APEX studies.
- The CF6 and PW2037 have a greater number-based emission index than the JT8D. At a given thrust condition and for a given fuel, the JT8D emits fewer but larger particles while engines designed to reduce smoke number certification measurements (those more recently developed) emit more numerous quantities of smaller particles.
- For thrust conditions near idle, the amount of volatile organic PM emitted by JT8D-219 engines decreases rapidly with increasing thrust, consistent with the thrust dependence of the emission index of UHC. This observation is consistent with nucleation/condensation of the least volatile UHC to form organic PM.

The LIDAR analysis gave similar qualitative trends for all of the engines studied, but the reliability of the system employed in this study was judged to be low for quantitative measurements.

Upon completion of the dedicated engine testing, the extractive sampling systems were positioned downwind of active runways. Exhaust plumes transported from source aircraft by the prevailing winds were continuously sampled and the source aircraft tail numbers logged. The tail numbers provided a unique method for correlating the plumes with specific aircraft and, hence, specific engines. In excess of 500 taxi and takeoff events were sampled during a three-day period.

The following general conclusions from the wind-blown plume analyses can be drawn:

- The combination of the PM and gas analysis of the transported plume provides unique identification of the engine operating condition generating the plume (i.e., idle, spool-up, maximum thrust, etc.).
- Much more volatile material converts to the particle phase during plume transport across the runway than is observed during dedicated engine tests.

- The black carbon component of the PM emissions detected in the transported plume varies among engine types as is observed at the exhaust nozzle.
- For all plumes sampled, the number-based emission index ranged from 3×10^{16} to 2×10^{17} particles/kg fuel and the mass-based emission index ranged from 0.1 to 0.35 g/kg fuel. These averages, based on measurements of PM emissions from in-service aircraft during normal operating conditions, give credence to the rough averages reported in the Intergovernmental Panel on Climate Change (IPCC) report. (Penner et al. 1999)

5.3 JETS-APEX2

The objective of the next APEX study, JETS-APEX2, was to develop TOG and PM speciation profiles for engines used in newer Boeing 737-type commercial aircraft burning standard Jet A fuel. These aircraft were specifically chosen since they represent greater than 70% of the aircraft currently in operation in the domestic commercial fleet.

The JETS-APEX2 study aimed to produce a comprehensive data set of emission factors for TOG and PM for older (CFM56-3) and newer (CFM56-7) CFM56-class engines. The study was successful in producing the first state-of-the-art measurements for PM physical characterization of in-service CFM56-type engines.

The major conclusions from the JETS-APEX2 study are as follows:

- The qualitative emissions trends observed are consistent with those measured for the CFM56-2C1 engine studied in the APEX1 campaign.
- At takeoff, the mass-based emission index for the -7B engines was significantly lower than that for the older technology -3B and -2C1 engines. At takeoff (typically 85% rated thrust at OAK), the -7B mass-based emission index was found to be four times less than that of the -3B.
- NO_X measurements were in good agreement with ICAO certification data, indicating that the engines were in good condition and lending credence to the assumption that the concomitant PM emissions are also representative of an engine in good condition.
- Most individual HC species decrease with increasing thrust in proportion to each other. As one of the most plentiful emitted hydrocarbons, formaldehyde is easily measured and provides a good standard for comparing the emissions of other less abundant trace hydrocarbons.
- The emission index of SO_2 increases directly with fuel sulfur content.
- Volatile particles are composed of both sulfate and organic materials, adding to the carbonaceous aerosol that is present already at the exhaust nozzle.
- The amount of sulfate emitted by the CFM56 engines increased with fuel sulfur content, as did the number of particles formed in the diluting exhaust gas in the 30-m (98-ft) and 50-m (164-ft) samples.
- The CFM56 engine exhaust did not contain substantial quantities of lubrication oil in the exhaust, even at high thrust. Lubrication oil contributed at most about 3mg/kg to the overall quantity of emitted organic PM.
- A significant fraction of the organic PM contained in CFM56 exhaust appears to be UHC. Unburned hydrocarbons constitute as much as 80% of the CFM56 organic PM emissions at idle and as much as 70% at climb-out/takeoff.
- The measured ratio of sulfate to organic PM was greater at high thrust (climb-out and takeoff) than at low thrust (approach and idle) by a factor of at least three. The observed thrust dependence is consistent with combustor efficiency (and, therefore, HC emissions) being more sensitive to thrust condition than conversion of fuel sulfur to condensible species (i.e., SO_3).
- The data from APEX1, Delta Atlanta-Hartsfield, and JETS-APEX2 indicate that PM emissions depend on engine/airframe.

Upon the completion of this study, the following recommendations for future aircraft emission characterization tests were made:

- Emissions studies of wider range of engines/airframes should now be performed (e.g., B747/CF6-80, etc.).
- The ideal testing conditions afforded by the GRE at OAK recommends the use of the GRE for future tests.
- Since the mix of transports routinely operating in and out of OAK will limit the range of engines/airframes that can be studied, for future studies where B747, B757, B767, and B777 and the larger Airbus transports A320, A340, etc. are anticipated test vehicles, it will be necessary to consider GREs located at other airports.
- In future tests, engine operating data (e.g., N1—fan rotor speed [rpm], N2—core rotor speed [rpm], EGT—exhaust gas temperature, fuel flow rate) should be recorded to facilitate interpretation of emissions data. Ideally, engine operating data will be recorded at high-frequency and made available in real time. Recording of engine data may be difficult for older airframes, but straightforward for newer additions to the commercial fleet that digitally record engine operating conditions.
- Engine-to-engine variability is difficult to estimate when the engine sample size is small (in this study ≤4 engines per model). The value of accurately estimating this parameter warrants the consideration of a longer period of study, allowing more engines of a given model to be studied.

JETS-APEX 2 was similar to the Delta Atlanta-Hartsfield study in that it included a second series of experiments focusing on emissions sampled during normal airport operations from plumes transported downstream of the active taxiway and runway. The results of these downwind studies continue to be analyzed, and the analysis to date has been summarized in two conference proceedings (Whitefield et al. 2007, Herndon et al. 2007). The major conclusions reported are broadly consistent with those from the Delta Atlanta-Hartsfield downwind studies. Specific conclusions include:

- As the plume expands and mixes with the ambient air, a large number of small particles are produced. These nucleation/growth mode particles are not present at the exhaust nozzle.
- The production of the small particles increases the number-based emission index by at least an order of magnitude relative to samples acquired at the exhaust nozzle.
- The nucleation/growth particles do not significantly contribute to the mass-dependent parameter values, and no significant changes in the mass-based emission index are observed.
- The -3B series takeoff mass-based emission indices were significantly greater than those for its taxi emissions and for both takeoff and taxi emissions for the -7B series. On average, the mass-based emission index for the -7B series, at both idle and takeoff is less than half that for the older technology -3B series.
- In some cases, because of the unique aircraft traffic patterns, sampling location, and prevailing wind direction at OAK, takeoff 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 de-convolved to yield single aircraft specific information and such analysis is currently underway.

5.4 APEX3

APEX3 is the most recent field study, and reporting on APEX3 data has not progressed as far as the earlier studies. Although most data are available through the FAA, it has not been interpreted and reported, as is the case for the previous APEX-type studies discussed in this document. Furthermore, the archived PM data have not been corrected for sample line loss, as was the case in the previous studies. Preliminary analyses were presented at the APEX3 conference held in November 2006 (Hagen et al. 2006) and these could be used to draw some qualitative results and intercomparisons. NASA may coordinate a final report, but that report was not available before publication of this ACRP document. For these reasons, any reference to APEX3 data in this report exclusively applies to Missouri S&T and ARI data available at press time.

CHAPTER 6

Gaseous and Particulate Matter Emissions Literature Review

This section focuses on collecting and summarizing relevant published articles, results of existing literature reviews, and available documentation that addresses the current issues and informational needs of the airport community on gaseous and particulate emissions at airports. The reader is encouraged to read Chapter 1, Primer on Particulate Matter Emissions from Aviation. Chapter 6 is intended to augment the information presented in Chapter 1.

6.1 Characteristics of Aircraft PM

As discussed in Chapter 1, aircraft PM is categorized either as primary PM or as contributing to secondary PM. Primary PM can be described as either volatile or non-volatile. Non-volatile PM has a size distribution that differs from the volatile PM generated by aircraft gas turbine engines. The diameters of non-volatile carbonaceous particles (soot) generated by aircraft gas turbine engines range from approximately 0.02 to 0.06 μm (20 to 60 nm) in diameter. The EPA classifies such PM as $PM_{2.5}$, which includes particles less than 2.5 μm in aerodynamic diameter. The diameter of volatile PM ranges from approximately 0.001 to 0.015 μm (1 to 15 nm), and also is classified as $PM_{2.5}$ (Lukachko et al. 2008).

Primary volatile PM is initially formed in the near-field plume (<1 min from emission). Volatile PM is composed of a variety of compounds whose emissions indices and relative contributions depend on a number of factors including ambient air conditions, thrust setting, and fuel sulfur content (Anderson et al. 2005). Research suggests volatile PM may be composed of the following compounds:

- **Sulfuric Acid.** Sulfuric acid (H_2SO_4) resulting from fuel sulfur nucleates as $(H_2SO_4)_n \bullet (H_2O)_m$, where n and m are small integers, to form volatile PM (Lukachko et al. 2008). H_2SO_4 molecules also condense onto preexisting aerosol surfaces (Lukachko et al. 2008).
- **Hydrocarbons.** Hydrocarbons may nucleate as independent PM sources but may play a more important role in contributing to volatile PM via uptake on existing particles (Wey et al. 2006).
- **Lubrication Oil.** Lubrication oil may also influence volatile PM composition, particularly during transient periods when engine thrust level is switched from one level to the next. APEX3 data indicated that up to 90% of the organic PM emitted by some engines may be lubrication oil (Timko, Onasch et al. 2008). For less efficient engines, lubrication oil makes up as little as about 10% of the total organic PM. In general, lubrication oil is least important in engines with low combustion efficiencies, and understanding of lubrication oil emissions continues to grow.

The total PM reported by EDMS as calculated using the FOA is an estimate of the non-volatile and volatile primary PM.

Secondary volatile PM forms on the timescale of minutes to days and may continue to form in air masses moving hundreds of kilometers (or miles) from the source. Nitrogen oxides, sulfur oxides, and HC emissions are important contributors to secondary volatile PM formation. After atmospheric processing, these species are absorbed into existing particles, some of which are non-volatile particles. Nitric acid (HNO_3) is produced by the photochemical processing of NO_2. Ammonium nitrate (NH_4NO_3) found in PM provides evidence that HNO_3 contributes to formation of secondary volatile PM. A regional-scale model is needed to calculate the quantities and composition of secondary volatile PM that is formed.

Several factors can alter aircraft PM properties. Engine technology influences particle size. Fuel sulfur content also influences primary volatile PM properties since volatile PM concentrations tend to increase with higher fuel sulfur content (Kugele et al. 2005). Organic emissions also contribute to primary volatile PM composition and mass. Secondary PM properties are influenced by coexisting pollutants emitted from other sources (U.S. EPA Jul 2004). Therefore, PM sourced to aircraft can change as emissions from other sources evolve.

To date, the studies conducted by Spicer et al. (1992, 1994) have been the primary source of hazardous air pollutant (HAP)

emission factors for aircraft. A commercial jet engine and a military jet engine were tested under varying thrust conditions, and the studies identified that formaldehyde and acetaldehyde are the two predominant HAPs contained in jet exhaust. These studies represent a thorough analysis of two jet engines, but also highlight the need for expanded measurements on a broader and more modern range of engine types.

6.2 Literature Reports on Aircraft PM

Particulate matter emitted within airport boundaries comes from many sources, such as aircraft engines, aircraft APU, tire and brake wear, GSE, vehicles that travel to and from the airport (ground access vehicles), dust from construction, boilers, and training fires for firefighters. The relative contributions of all of these sources are not well characterized, as there are limited data for some PM sources.

6.2.1 Relative Contributions from GSE and Aircraft Brakes/Tires

The relative contribution of GSE to total airport emissions depends on many factors, including the size of aircraft served and the length of flight. In addition, the fuel type of the GSE directly affects the PM emissions, especially in the case of electric GSE where the emissions are generated off-site and are therefore not included in the airport inventory. As a result of these factors, the relative contribution of GSE emissions is small (less than 20% of the airport total) at some airports and large (greater than 50% of the airport total) at others. An analysis of the mix of GSE equipment and its utilization is needed to properly quantify its contribution to emissions at a specific airport.

Tire wear rates are calculated both by experiment and by estimation from statistical information. For vehicles, wear rates are typically reported as milligrams per vehicle-kilometer (vkm) traveled (vkm takes into account the four tires on a typical vehicle). Wear rates vary depending on numerous factors, including the weight of the vehicle, tire composition, and driving conditions. Brake and tire wear rates typically are reported as mg/vkm and can vary greatly depending on braking conditions. For light-weight vehicles, the brake wear rates range from 8.8 mg/vkm to 20 mg/vkm (Legret and Pagotto 1999).

Aircraft tire and brake emissions are reported on a per LTO basis. Much like vehicles, aircraft tire and break emissions estimates contain large uncertainties and vary depending on the type of aircraft and the landing conditions. For six different aircraft listed in the Project for the Sustainable Development of Heathrow (PSDH) study (UK DfT 2007), the range of emission rates (tire and brake) was measured to be between 110,000 mg per landing (A321) and 780,000 mg per landing (B747-400). These values fall in line with a EUROCONTROL study (Kugele et al. 2005) that estimated the average tire and brake emission rates per LTO as 130,000 mg and 30 mg, respectively.

The percentage of emissions from tire and brake wear that become suspended and are classified as PM_{10} (or $PM_{2.5}$) is an area of current research. Little data are available for vehicles; none is available for aircraft. For tires, it is believed that less than 10% of emissions become PM_{10}, but studies have shown it can be as high as 30% (Boulter 2005). Nearly all tire wear emissions are larger than $PM_{2.5}$. For brakes, a study conducted by Sanders et al. (2003) observed that between 50% and 90% of brake emissions become airborne particles (mass mean diameter is 6 μm and the number-weighted mean is between 1 to 2 μm). The measurement brackets the United Nations Economic Commission for Europe (UNECE) estimate of 70% of brake lining becoming suspended matter (UK DfT 2007). Since aircraft experience more extreme braking conditions than vehicles do, the PSDH study uses the upper limits of 10% for tire wear and 100% for brake wear for estimates of PM_{10} emissions for aircraft.

6.3 Modeling PM Using EDMS

Researchers use an FAA-developed, EPA-approved tool known as EDMS to estimate PM emissions from aircraft main engines, GSE, on-road vehicles, and stationary sources. The required tool for assessing the changes to local air quality resulting from airport projects is EDMS.

The EDMS tool estimates primary PM emissions for ICAO-certified aircraft main engines with a smoke number using FOA 3.0a for U.S. airports and FOA 3.0 for airports outside the United States. The FOA 3.0 method is accepted by the Committee on Aviation Environmental Protection (CAEP), and FOA 3.0a has been approved by the EPA. Together, they represent the latest methods approved by these groups to approximate primary PM emissions from aircraft. The estimate of non-volatile PM emissions is based on smoke number, where the estimates of volatile PM are based on UHC and fuel sulfur content, and—in the case of FOA3a—lubricating oil. For jet and turboprop aircraft without smoke numbers, only the volatile contribution to primary PM is computed. EDMS does not estimate any PM emissions for piston aircraft (CSSI 2008). EDMS uses a standard, single fuel, sulfur level for each aircraft; the level of sulfur can be adjusted for scenarios and aircraft.

EDMS models PM from ground support equipment using EPA's NONROAD model and PM from on-road vehicles using EPA's MOBILE model. The EPA's NONROAD model can also be used outside of EDMS to estimate the PM emissions from construction equipment engines, but not from other PM sources, such as fugitive dust, that can result from earthmoving activities. Airport modelers must account for these emissions separately.

6.4 Current Model Limitations

Particle diameter is influenced by throttle setting, but all operating modes produce particles less than 2.5 μm in diameter ($PM_{2.5}$). Particle chemical composition also varies with thrust setting (Lobo, Whitefield et al. 2007).

Accurately estimating throttle setting is important to account for changes in engine conditions that influence PM emission indices. For certification, throttle setting is specified for the LTO cycle describing aircraft operation to a height of approximately 900 m (2,953 ft) by regulation. Over the LTO cycle, ICAO specifies generic time in mode and thrust assumptions for aircraft engine certification with four discrete settings: taxi/idle (26.0 min, 7% throttle), takeoff (0.7 min, 100% throttle), climb (2.2 min, 85% throttle), and approach (4.0 min, 30% throttle) (ICAO 1993).

The certification prescribed LTO cycle is not necessarily representative of actual flight procedures. This affects resulting estimates of total PM emissions (Fleuti and Polymeris 2004). This question was addressed by APEX1, which looked at PM emissions at 11 thrust settings: 4, 5.5, 7, 15, 30, 40, 60, 65, 70, 85, and 100% to understand trends at intermediate thrusts and below the prescribed idle setting. Particulate matter emissions trends below 7% vary by PM component. In general, non-volatile PM (black carbon) emissions are relatively small at low thrust settings. However, volatile PM components exhibit more complex behavior as precursor gases condense downstream (Wey et al. 2006).

Typically, when modeling airport activity using EDMS, the user assumes that once an aircraft has pushed back from the gate, the APU is turned off and the main engines are used to provide power to the aircraft. In reality, however, anticipated delays prompt pilots to shut off main engines and run the APU to conserve fuel. Recommended warm-up and cool-down times are dependent on design parameters for each specific engine type, and influence a pilot's decision to shut off main engines (ICAO 2000). Although airlines have individual operating procedures, the ultimate decision rests with the pilot (ICAO 2000). Assuming that the aircraft main engines remain operating at 7% thrust throughout the taxi/queue portion of the LTO is conservative, but may not accurately represent the actual operation of the aircraft.

6.5 Mitigation

Although there are many sources of PM emissions at airports, only a few of the sources are under the direct control of the airport. Stationary sources, GSE, and some aircraft operational characteristics are the most likely to be influenced through airport policy. Examples of mitigation for PM from each of those sources is as follows:

- For stationary sources like emergency generators, incinerators, power turbines, and oil-fired boilers, particle traps can be installed on exhaust stacks to control PM emissions.
- Ground support equipment PM emissions can be mitigated by using an ultra-low sulfur diesel fuel. Keeping the engines properly maintained and tuned is important for minimizing particle emissions as well. Working with tenants to promote the use of alternative fuels can also be beneficial. This might include supplying alternative, lower emission fuels. Working with airlines to install chargers in the ramp area for electric GSE may encourage greater use of zero-emission electric vehicles.
- Installing electrical power and preconditioned air at each gate can provide the airlines with the power and ventilation they need without running APU.
- Many airports have changed from using Jet A or diesel fuel to propane or other cleaner burning fuels in their firefighter training. This change in fuels reduces smoke and soot emissions from about 1,000 lbs/1,000 gal for jet fuel to about 120 lbs/1,000 gal for propane (FAA and USAF 1997).
- Controlling ground operations to minimize delays reduces aircraft emissions. Establishing airport policies to promote fuel conservation practices among airlines and other tenants can reduce airport emissions. Such a policy might recommend single-engine taxiing, de-rated takeoff, enhancing GSE maintenance, and using ultra-low sulfur diesel in GSE and other vehicles.
- On the landside, airports do not have any regulatory authority over passenger vehicles. However, many airports have worked with local taxi companies to encourage, or even mandate, use of low-emission taxis as a requirement for serving the airport. For example, all taxicabs permitted to pick up passengers at Seattle Tacoma International Airport are required to use compressed natural gas. Through fees and licenses, some airports have taken strides to reduce the frequency of circulating through the airport by hotel, parking, and car rental vans. Similarly, the use of cell phone waiting areas allows vehicles to remain nearby with their engines off until passengers are ready to be picked up.
- Providing ultra-low sulfur diesel or other reduced-sulfur fuel for use in GSE, boilers, emergency generators, etc., can reduce particulate emissions. A new generation of alternative fuels, known as synthetic paraffinic kerosene, which in their pure form contain no sulfur, show promise in reducing PM emissions from the aforementioned sources and turbine-powered aircraft (Hileman et al. 2008).

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APPENDIX A

Details of Measurement Campaigns

Mission	Dates	Location	Operator	Airframes	Engines
Dedicated Engine Tests					
APEX1	April 2004	NASA Dryden Flight Research Center	NASA	DC-8	CFM56-2C1
Delta Atlanta-Hartsfield (UNA-UNA)	September 2004	Atlanta, GA	Delta Airlines	MD-88	JT8D-219
			Delta Airlines	B767-300	CF6-80A2
			Delta Airlines	B767-400ER	CF6-80C2B8F
			Delta Airlines	B757-200	PW2037
JETS APEX2	August 2005	Oakland, CA	Southwest Airlines	B737-300	CFM56-3B1
				B737-700	CFM56-7B22
APEX3	November 2005	Cleveland, OH	NASA	LearJet 25	CJ610
			Continental Airlines	B737-300	CFM56-3B1
			Continental Express	ERJ 135/145	AE3007A
			FedEx	A300-600	PW4158
			Continental Airlines	B757	RB211-535E-4B

Mission	Dates	Location	Operator	Airframes	Engines
Advected Plume Studies (Airport Tests)					
Delta-Atlanta Hartsfield (UNA-UNA)	September 2004	Atlanta, GA	Multiple	ATR72	PW127
				A340	CFM56
				B717	BR715
				B737	CFM56
				B757	PW2037
				B767	CF6-80/PW4060
				B777	TRENT 892B
				CL-600	CF34
				DC-9	JT8D
				MD-88	JT8D
JETS APEX2	August 2005	Oakland, CA	Multiple	A300	CF6-80
				A320	V2527
				B727	JT8D
				B737	CFM56
				CL-600	CF34

APPENDIX B

Glossary of Terms

Advected plume—wind-transported exhaust plume, subjected 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.

Classical aerodynamic diameter[1]—the 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 attaching to other particles.

Elemental carbon—the refractory carbon found in combustion-generated particulate matter; 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 the EPA to regulate. For the complete list of pollutants see Appendix C: The Clean Air Act Amendments of 1990 List of Hazardous Air Pollutants found on the EPA website: http://www.epa.gov/ttn/atw/orig189.html.

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 of the logarithm of a random variable.

Mass-based emission index—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.

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 $f(x) = (1/(\sigma\sqrt{2\pi}))e^{(-1/2[(x-\mu)/\sigma]2)}$ 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.

Non-volatile 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—often abbreviated 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.

Parameterization—expression in terms of statistically representative characteristics.

Parts per million (ppm)—the unit volume concentration of a gas per million unit volumes of the gas mixture of which

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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 by Merriam-Webster, Incorporated.

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

it is part; also applicable to mass measurements as referred to as ppmm.

Photochemical—the interaction of atoms, molecules, and light.

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

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

Refractory—resistant to heat: non-volatile.

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. These particles form on the timescales of minutes to days and may continue to form in air masses moving hundreds of kilometers from 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—often abbreviated as SN, the dimensionless term quantifying smoke emission and is determined using the SAE Aerospace Recommended Practice–1179. 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.

Soluble mass fraction—the fraction of the aerosol mass that is soluble in water.

SUMMA canister—an airtight, stainless-steel vessel whose internal surface has been passivated using a SUMMA process, which combines an electro-polishing step with chemical deactivation, to produce a surface that is chemically inert.

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 1.0 μm.

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

APPENDIX C

Bibliography for the Literature Survey

Aksit, I. M. and J. B. Moss, "Model fuels to reproduce the sooting behavior of aviation kerosene." ***Fuel*****. 84. Jan-Feb 2005.**

Researchers designed model fuels which exhibited similar sooting behavior to that of aviation kerosene.

Aristotle University. ***PARTICULATES. Characterisation of Exhaust Particulate Emissions from Road Vehicles. Deliverable 8: Measurement of Non-exhaust Particulate Matter,*** **Laboratory of Applied Thermodynamics. 2004. http://lat.eng.auth.gr/particulates/downloads.htm**

This report is part of the 3-year PARTICULATES project, launched in April 2000, which aimed to collect and analyze PM in a scientific and technical manner. This portion of the report focused on non-exhaust PM, including: tire wear, brake wear, clutch wear, road surface wear, corrosion of vehicle body/components, and corrosion of street furniture/signs/etc.

Barbosa, S., et al., ***Air Monitoring Study at Los Angeles International Airport*****. South Coast Air Quality Management District. Oct 1999.**

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, S., et al., ***Air Monitoring Study of Felton and Lloyd Schools*****. South Coast Air Quality Management District. Sep 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.

Boulter, P. G., ***A Review of Emission Factors and Models for Road Vehicle Non-Exhaust Particle Matter*****. Published Project Report PPR065. TRL Limited. 2005. http://www.airquality.co.uk/archive/reports/reports.php?action=category&section_id=8**

A detailed report conducted by TRL Limited investigating non-exhaust PM from road traffic. The goal is to improve prediction methods for emissions and air pollution. The report is broken down into five phases: a literature review, emission model development and application, initial air quality model development and application, further air quality model development and discussion of abatement options.

Broughton, M., "Check in for carbon trading." ***Engineer*** **(London). 293(16). Jan 15-28, 2007.**

Editorial arguing the attention and criticism which Aviation gets for polluting is disproportionate to its percentage contribution to total emissions.

Bruno, T. J. and B. L. Smith, "Improvement in the measurement of distillation curves. 2. Application to aerospace/aviation fuels RP-1 and S-8." ***Industrial & Engineering Chemistry Research*****. 45(12). Jun 7, 2006.**

Demonstrated new measurement method and applied it to two common types of fuel.

Camp Dresser & McKee, Inc. ***LAX Master Plan—Technical Report Deposition Monitoring*****. Mar 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 implicates

freeway traffic for high daytime concentrations; copper composition data indicates that a small fraction of the total deposition seen in the daytime is potentially from aircraft braking.

Chan, C. Y., et al., "Characteristics of vertical profiles and sources of $PM_{2.5}$, PM_{10}, and carbonaceous species in Beijing." *Atmospheric Environment*. 39(28). Sep 2005.

Fugitive dust from construction adds to the particulate matter problems of Beijing but gives no clear values as to the role of construction compared to other emission sources. Construction PM tends to be larger than $PM_{2.5}$.

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

Gerilla, G. P., K. Teknomo, and K. Hokao, "An environmental assessment of wood and steel reinforced concrete housing construction." *Building and Environment.* July 2007.

Article provides a comparison of the life-cycle costs of wooden housing to steel reinforced concrete. The work compared the life-time emissions for construction through useful life of both types of construction using a hybrid input-output model to capture the PM emissions. This research did not attempt to measure PM (or any emissions) directly and used a model to capture the emissions of the components of each method of construction.

Goldman, A., "Soot and Odor," KM Chng Environmental Inc. *Airport Air Quality; Approaches, Basics & Challenges*. Institute of Transportation Studies. University of California, Berkeley. 2005.

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.

Granell, J., C. Ho, et al. *Analysis of MOBILE 6.2's PM Emission Factor Estimating Function.* 13th International Emission Inventory Conference. June 8-10, 2004. http://www.epa.gov/ttn/chief/conference/ei13/

This paper summarizes the difference between the EPA's older PART5 model, released in 1995, and their new MOBILE6.2 model, released in 2004. Both models are used to estimate exhaust, brake wear, and tire wear particulate matter emissions.

Green, J. E., "Civil aviation and the environment—the next frontier for the aerodynamicist." *Aeronautical Journal*. 110(1110). 2006.

In addition to the work being done to reduce emissions through optimization of engines, progress towards a cleaner fleet could be done through the improvement of the aerodynamic properties of aircraft. This is mostly done through optimizing the aircraft for fuel efficiency.

Green, J. E., "Future aircraft—greener by design?" *Meteorologische Zeitschrift*. Aug 2005.

This paper considers what might be achieved within the next 50 years by advances in aircraft and engine technology and by a shift in design priority from minimizing costs to minimizing environmental impact of air travel. In U.K. Air Travel—Greener by Design initiative is the response of the civil aviation community to this environmental challenge. There are substantial research programs in Europe and the United States aimed at low NOx combustor technology (mostly focused on emissions near the airports). Trade Off: Increased pressure ration → Low fuel burn and high NO_x. This constitutes a tradeoff between NO_x emissions and CO_2 emissions (which vary with fuel burn). The evidence to date suggests that success is more likely at the medium pressure ratios of small engines than at the high pressure ratios of the large engines typical of long-range aircraft.

Hoffnagle, G., *Community Impact of Aircraft Particle Emissions*. TRC Environmental Corp. 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.

Karcher, B., "Aviation-produced aerosols and contrails." *Surveys in geophysics*. 20(2). 1999.

Review of "current" (1998) knowledge about aerosols and contrails.

Kinsey, J., K. Linna, W. Squier, G. Muleski, and C. Cowherd Jr., "Characterization of the fugitive particulate emissions from construction mud/dirt carryout." ***Journal of the Air and Waste Management Association.*** **54(11). Nov 2004.**

Cars driving over the mud/dirt carryout from construction can be a source of construction-related PM as cars re-suspend particles from this dirt. The measurements of PM_{10} are within the EPA current emission factors, but $PM_{2.5}$ was found to be lower than expected. In these test areas, the $PM_{2.5}$ emissions are overshadowed by car exhaust rather than the mud carryout.

K. M. Chng Environmental Inc. ***Summary of Two Logan Soot Studies.*** **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.

Kugele, A., F. Jelinek, and R. Gaffal, ***Aircraft Particulate Matter Emission Estimation Through All Phases of Flight.*** **Eurocontrol Experimental Centre. EEC/SEE/2005/0014, 2005.**

A study of PM emitted by aircraft broken down into three "work packages": literature review, review and development of a method to estimate PM emissions from aircraft through all phases of flight, implementation of the method into an MS–Access-based module linked to EUROCONTROL's AEM III.

Langley, I. D., et al., "Using NO_x and CO monitoring data to indicate fine aerosol number concentrations and emissions factors in three U.K. conurbations." ***Atmospheric Environment*****, 39(28). Sep 2005.**

The authors' work determined that NO_x and CO is heavily correlated with PM emissions through a series of equations. These equations can be adjusted to reflect the uniqueness of the NO_x and CO monitoring situations. Using these correlations, the authors suggested potential road transport PM emissions factors though the PM factors may need to be evaluated and changed to consider seasonal variations.

Lee, D. S., et al., "Aviation emissions: Present-day and future." ***Meterologische Zeitschrift*****. 11. 2002.**

Paper compared two different methods of estimating emissions. The methods concentrated on measuring emissions based on fuel consumption.

Method one: ANCAT/EC2 1991/92 inventory construction → ANCAT/EC2 2015 inventory forecast. Construction: Aircraft movements database, a representation of the global fleet in terms of aircraft and engines, a fuel flow model, calculation of emissions at altitude from fuel flow, and landing and takeoff emissions data. Forecast: Global air fleet forecast by the U.K. Department of Trade and Industry. Use past development trends to forecast future engines/aircraft. Applied trends in fuel efficiency. Emission performance of the forecast fleet was determined by the response to an assumed regulatory scenario: Results: Drop in NPX emissions.

Method two: The FESG 2050 Aircraft Emission Scenarios. Compared their original results to the results found by other researchers using this technique.

Method one and two have comparable results.

Lee, J. J., S. P. Lukachko, I. A. Waitz, and A. Schafer, ***Historical and Future Trends in Aircraft Performance, Cost, and Emissions*****. 2000.**

Emissions per aircraft reduced by 3.3%; air traffic is increasing by 5.5%. E in MJ/RPK (mega joules/revenue passenger kilometer) is forecast to decline by 1.2%–2.2% a year in the future.

Legret, M. and C. Pagotto, "Evaluation of pollutant loading in the runoff waters from a major rural highway." ***The Science of Total Environment*****. 235:143–150. 1999.**

This study examined the pollutants found in runoff water from a 275-m (902-ft) motorway during a 1-year study, consisting of approximately 50 rain events. Included in this study is a comparison of estimation of pollutant emission from vehicle traffic, which includes tire and brake emission estimates.

Metcalfe, J. L., G. W. Fischer, et al., ***Auckland Air Emissions Inventory: 2004.*** **Auckland Regional Council. Technical Publication 292. 2006. http://www.arc.govt.nz/arc/publications/technical-publications/arc-technical-publications.cfm.**

This report estimates the emissions in the Auckland area from four major sources: transportation, domestic, industry, and biogenic. The study puts an emphasis on ambient air pollutants: PM_{10}, NO_x, CO, VOCs.

Metts, T. A., S. A. Batterman, G. I. Fernandes, and P. Kalliokoski, "Ozone removal by diesel particulate matter." ***Atmospheric Environment*****. 39(18). Jun 2005.**

Examined the ozone removal capacity of fresh diesel soot particles. Diesel soot is expected to remove only a small portion of O_3 from urban/tropospheric and indoor air.

Muleski, G., C. Cowherd Jr., and J. Kinsey, "Particulate emissions from construction activities." ***Journal of the Air and Waste Management Association.*** **55(6). June 2005.**

The emissions factors for heavy construction have remained unchanged since their publication in 1975. Using construction sites in Kansas, the authors measured the PM (PM_{10} and $PM_{2.5}$) emissions of construction activities. The work focused on earthmoving machines as their use constitutes 70% to 90% of the PM emissions associated with construction. PM_{10} measurements were significantly higher than AP-42 would have estimated and the effects of mud carryout were lower than expected. There was less $PM_{2.5}$ than expected. The dirt path of the loaded and empty earthmover is the portion of construction with the highest PM emissions. A lower portion of the emissions are based in the diesel exhaust when compared to loading and unloading.

National Environmental Technology Centre (Netcen), ***Gatwick 2010 Baseline Emission Inventory*** **(Public Access Version). Reference: AEAT/ENV/R/1791/Issue 1. 2006. http://www.gatwickairport.com/portal/page/LGW%5EAbout+BAA+Gatwick%5EPublications/**

This report provides a forecast of atmospheric emissions from London Gatwick airport in 2010, the year the European Union will begin to limit values for NO_2 for its member states. This study is similar to the 2002/03 emission inventory except results are forecast predictions.

National Environmental Technology Centre (Netcen), ***Gatwick Emission Inventory 2002/3*** **(Public Access Version). Reference: AEAT/ENV/R/1569/Issue 2. 2006. http://www.gatwickairport.com/portal/page/LGW%5EAbout+BAA+Gatwick%5EPublications/**

This report provides the methodology and data used to generate an inventory of emissions at London Gatwick airport for the period spanning June 1, 2002 to May 31, 2003. This study focuses primarily on NO_x and PM_{10} emission from the following sources: aircraft in the landing and takeoff phase, airside vehicles/plant, road vehicles on landside airport roads (and surrounding network), car parks and taxi queues, heating plant, and fire-training ground.

Rakopoulos, C. D., D. T. Hountalas, and D. C. Rakopoulos. "Comparative environmental evaluation of JP-8 and diesel fuels burned in direct injection (DI) or indirect injection (IDI) diesel engines and in a laboratory furnace." ***Energy & Fuels.*** **18(5). 2004.**

In recent years, NATO and U.S. military forces have decided to implement a single fuel (JP-8) for all land-based military aircraft, vehicles, and equipment during war and peace times. Substituting JP-8 for diesel oil No-2. Primary goal of paper is to contrast emissions of two emissions that were comparable for both fuels.

Ruijgrok, G. J. J., ***Elements of Aircraft Pollution.*** **IOS Press. 2005.**

Book about aircraft pollution. Attention has been concentrated on emissions at ground level near the airport (CO and unburned hydrocarbons which appear to be dominating at low thrust setting) with great success. Considerable efforts to lower emissions were made by changing the combustion process.

Sanders, P., N. Xu, T. Dalka, and M. Maricq, "Airborne brake wear debris: Size distributions, composition, and a comparison of dynamometer and vehicle tests." ***Environmental Science and Technology.*** **37:4060–4069. 2003.**

This paper summarizes the findings of two experiments on brake emissions. Three experiments were conducted: one using a brake dynamometer, another using a wind tunnel, and another on a test track. This study expands on a previous study conducted by the same authors by providing data on particle size distributions, analyzing the brake wear debris composition, and comparing the dynamometer results to the wind tunnel and test track results.

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

Stolzenbach, K. D., 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 K. Schiff, et al., Southern California Coastal Water Research Project. Sep 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. Aug 31–Oct 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.

Unal, A., et al., "Airport related emissions and impacts on air quality: Application to the Atlanta International Airport." *Atmospheric Environment.* 39(32). 2005.

The emissions estimation focused on $PM_{2.5}$ using FOA1.0 for each mode of aircraft operation. The authors also speciated the PM emissions into elemental carbon (66%), organic carbon (29%), sulfate (4.6%), and nitrate (0.32%). They determined that the ground support equipment (GSE) was more influential in local air quality than the aircraft even though the GSE emitted less pollution. The approximation method used in the research affected the results dramatically. By using FOA1.0 in a mode-specific manner and spatially distributing the emissions, the final conclusion was that aircraft are not the driver for PM problems in the Atlanta area. The study evaluated traffic for select days in August 2000.

United Kingdom, Department for Transport, *Project for the Sustainable Development of Heathrow—Air Quality Technical Report.* June 2007. http://www.dft.gov.uk/pgr/aviation/environmentalissues/ secheatrowsustain/

A collection of findings from technical panels set up by the Department for Transport in 2004 to find ways to improve the air quality around Heathrow Airport. The three technical panels were assigned to investigate dispersion modeling (Panel 1), monitoring of air pollution (Panel 2) and emission source data (Panel 3).

Venkatesan, M. I., *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, K.E., 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 values for urban locations.

Whellens, M. W. and R. Singh, "Paper 7111: Propulsion System Optimization for Minimum Global Warming Potential." *Proceedings of ICAS 2002 Congress*, Toronto, Canada. 2002.

Analysis of how turbofan engines would be designed if they were optimized for the environment rather than fuel consumption. The results of the study show that, with the given relationship between emissions and global warming potential, a turbofan engine optimized for minimum cruise global warming potential is characterized by lower operating pressures and temperatures than those found in a turbofan optimized for minimum cruise SFC (specific fuel consumption). Although this makes it a fuel-inefficient solution, it is also shown that a better SFC performance can be retained by choosing solutions that are close, but not coincident, to the mathematical optimum for global warming potential.

Yan, S. H., E. G. Eddings, A. B. Palotas, R. J. Pugmire, and A.F. Sarofim, "Sooting tendency of HC liquids in diffusion flames." *Energy and Fuels.* 19(6). Nov-Dec 2005.

Discusses methods for predicting soot emissions of particular fuels.

Zanini, G., et al., "Concentration measurement in a road tunnel as a method to assess 'real-world' vehicle exhaust emissions." *Atmospheric Environment.* 40(7). 2006.

Authors ran buses for 8 hours in a closed tunnel with different fuels to measure PM changes over time and driving conditions outside a laboratory environment. Other pollutants were measured as well.

Zannis, T. C. and D. T. Hountalas, "DI diesel engine performance and emissions from the oxygen enrichment of fuels with various aromatic content." ***Energy & Fuels.*** **18(3). 2004.**

Paper examines effect of fuel oxygen enhancement with various aromatic content on pollutant emissions. Result: Fuel oxygen addition appears to be more effective in the reduction of soot CO and HC emissions (higher NO_x emissions when oxygenated additives).

Zervas, E., X. Montagne, J. Lahaye, ***Influence of Fuel and Air/Fuel Equivalence Ratios on the Emission of Hydrocarbons from a SI Engine. Experimental Findings, Formation Pathways and Modeling of Combustion Processes.***

For this paper, researchers tested emissions for fuels with varying air/fuel equivalence ratios.

The emissions of all hydrocarbons generally decrease with the addition of oxygenated compounds except sometimes in the case of methane, ethane, and cyclohexane. Under rich conditions the relative increase of exhaust methane and benzene is more important than the other saturated hydrocarbons. Some hydrocarbons are correlated with the physical properties of the fuel and other exhaust pollutants.

APPENDIX D

Additional Supporting Material for Chapter 5: Review of the Data from Measurement Campaigns

D.1 PM Data Review Summary

D.1.1 ICAO Smoke Number Database

The ICAO Smoke Number Database (ICAO 2008) does not provide adequate quantitative parameterization of PM characteristics suitable for local air quality applications. The ICAO smoke number was developed as a metric for plume visibility and is measured for all engines in the commercial fleet. It is not a fundamental PM characterization parameter and can only be applied to dispersion models if correlated with fundamental PM characterization parameters such as number, size, and mass. Attempts at such correlations have met with limited success (Paladino 1997; Whitefield et al. 2001; Society of Automotive Engineers 2004; Wayson et al. 2006; FAA Jul 2007).

D.1.2 Essential Fundamental PM Characterization Parameters

The essential fundamental PM characterization parameters required for local air quality applications are the following:

- Number (number-based Emission Index, EI_n);
- Size distribution;
- Mass (mass-based Emission Index, EI_m);
- Composition.

D.1.3 Confidence in Fundamental Parameter Measurement

When the APEX series of campaigns was initiated, measuring fundamental properties of aircraft gas turbine PM was a new challenge. Since no comparable data existed on aircraft PM, the experiments contained two separate internal checks to ensure data accuracy: (1) measurement redundancy and (2) gas-phase measurements. State-of-the-art PM measurement instruments were deployed during all of the APEX campaigns, and new instrumentation developments were incorporated in the measurement suite as the campaigns evolved. Particle size distributions were measured with no fewer than three different instruments (DMS500, SMPS, and EEPS); particle count was measured to determine EI_n using several different model condensation particle counter instruments (CPC); EI_m was measured using real-time instruments (DMS500, SMPS, TEOM) and filter samples: black carbon soot mass was measured using two different types of instruments (MAAP and PSAP); particle composition was measured by two real-time instruments (AMS and PAS—for polycyclic aromatic hydrocarbon content) and complemented by filter samples. Additionally, the measurement suites deployed by the various teams intentionally overlapped so that multiple measurements of the same PM characteristics could be made in parallel. The built-in redundancy helped ensure that operator errors could be identified and removed from the data set.

Gas-phase data were used to build additional confidence in the measurement approach and in the maintenance state of the gas turbines tested. Any given engine emission can be considered representative if its measured primary combustion gas profiles (NO_X, CO, and HC) match those calculated from certification data in the ICAO databank. The gaseous emissions of the APEX engines exhibited the anticipated trends with respect to engine power condition and the measured values were similar to the ICAO certification values (see Section D.2 for more details on the gas-phase measurements). Therefore, the extractive sampling dilution system was judged to be operating properly and the condition of the APEX engines was judged to be characteristic of typical in-use engines representative of the fleet.

D.1.4 Data Reproducibility

During the campaigns, PM emissions data were collected at over 1,200 stable conditions (i.e., the power setting/fuel flow was stable at the desired set point). Table D1.1 lists all of

Table D1.1. PM instruments deployed in APEX missions.

Instrument	Species Detected	Detection Limit	Sampling Frequency	Campaign(s) Deployed
Combustion DMS500	Size distribution	5 nm	1 sec	APEX1,2,3, Delta-ATL
TSI SMPS	Size distribution	15nm	30 sec	APEX1,2,3, Delta-ATL
TSI CNC	Total particle concentration	7nm	1 sec	APEX1,2,3, Delta-ATL
Aerodyne Aerosol Mass Spectrometer	Volatile PM composition and size distribution (sulfate and organic)	>30 nm >100 ng m^{-3}	>3 sec	APEX1, 2, 3
Thermo MAAP	Black carbon soot mass	>5 μg m^{-3}	1 sec	JETS APEX2, APEX3

the PM species measured during the APEX campaigns, along with the instruments used to make the measurements. State-of-the-art instruments were used for the measurements, and the quality of the instruments is reflected by their fast time responses and low detection limits.

During an emissions test, the airplanes remained grounded and chocked during all tests while the engine thrust was varied to simulate operation at ground idle (4%), idle (7%), taxi (30%), climb-out (85%), take-off (93%), and intermediate power conditions including 15%, 45%, and 65% rated thrust. The power cycle during a typical experiment was as follows: (1) the engines were allowed to warm up for roughly 5 to 10 min; (2) measurements commenced as the engines were operated at ground idle; (3) the test continued as the power was increased in a step-wise fashion (e.g., 4% to 7% to 15%, etc.) up to either take-off power or climb-out power; (4) the power was directly reduced to either idle or ground idle; (5) after several minutes at idle, the power was increased directly to either take-off or climb-out; (6) the test concluded as the power was reduced step-wise back to ground idle.

PM samples were taken continuously throughout the entire experiment and each stable point lasted for 2 to 5 min. Sampling was performed both at 1 m [3 ft] from the engine exit plane and further downstream of the engine (15 m, 30 m, 45 m, or 50 m [49 ft, 98 ft, 148 ft, or 164 ft] depending on the size of the engine). During each engine test, EI measurements were made at a given thrust rating both as the engine thrust was increased and as it was decreased to the set point.

Table D1.2 lists EI number and EI mass data for all of the engines studied in the APEX series of campaigns. Idle/taxi (either 7% or 8% depending on the engine), approach (30%), and climb-out (85%) power conditions are emphasized in Table D1.2 since these are the set points used in ICAO certification data.

EIs for take-off power conditions are only available in certain cases due to the difficulty in operating stationary aircraft at full-rated thrust. Each EI reported in Table D1.2 is the average of all available replicate points taken at a given set of conditions for measurements made at 1 m [3 ft]. (For a given airframe/engine combination, duplicate measurements are those made at the same downstream distance and engine power condition.) Accurate estimation of the measurement uncertainty is critical to the proper use of the APEX data set. Typically, each EI reported is the average of between 3 and 6 replicate measurements. Experimental uncertainties were estimated by setting the uncertainty in each EI equal to the standard deviation of all available EI data points at a given set of conditions. These data handling procedures ensure that reported errors accurately represent experimental reproducibility. Sources of systematic error are considered later in this section.

D.1.5 Measurement Reliability and Sources of Systematic Error for PM

In addition to reproducibility, absolute measurement accuracy is also important. Two measurement uncertainties contribute to overall uncertainty in the EIs determined in these studies. They are related to the detection limits and the systematic errors associated with the measurement of (1) the CO_2 concentration, and (2) the PM differential concentration. Systematic errors for PM EIs arise from particle line loss, sample dilution, flow rate, and particle density measurements.

A detailed discussion for PM error analysis, using electric mobility methodology, can be found in Schmid et al. 2004, where derived relative uncertainties (%) for EI_n and EI_m are 20% and 30%, respectively.

D.1.6 Sample Sources

These studies focused on engine specific emissions and their downstream evolution.

- Dedicated aircraft
  - Close to exit plane (≤1 m [≤3 ft]);
  - Near field plume (~10 m, ~15 m, ~30 m, and ~50 m [~33 ft, ~49 ft, ~98 ft, and ~164 ft]).

Table D1.2. EI number and EI mass data for all of the engines studied in the APEX series of campaigns.

Engine Model/Tail Number	Engine Location	EI_n (10^{15} particles/kg fuel burned)*			EI_m (g/kg fuel burned)*		
		7%	30%	85%	7%	30%	85%
CFM56-2C1 / N817NA	stbd	0.44±0.146	0.45±0.198	1.92±0.367	0.0048±0.0035	0.0067±0.00340	0.13±0.0370
CFM56-3B1 / N353SW	stbd	1.08±.0.565	1.17±0.499	4.20	0.0043±0.00086	0.0060±0.00003	0.254
	port	1.20±0.58	1.09±0.358		0.0045±0.00085	0.0060±0.00096	No Data
CFM56-3B2 / N695SW	stbd	1.15±0.784	1.64±0.323	2.57	0.0062±0.00211	0.016±0.00111	0.249
	port	40.1±23.8	35.9±49.6		0.054±0.0186	0.021±0.0208	No Data
CFM56-7B22 / N435WN	stbd	0.50±0.104	0.50±0.173	1.12	0.0090±0.00298	0.0079±0.000923	0.0614
	port	0.51±0.147	0.38±0.120		0.0083±0.0033	0.0055±0.000829	No Data
CFM56-7B22 / N429WN	stbd	0.28±0.184	0.26±0.249	1.09	0.0021±0.00171	0.0023±0.00180	0.073
	port	0.065	0.098		0.00046	0.00098	No Data
JT8D-219 / 908DL	stbd	2.145±1.47	0.85±0.43	11.2±0.32	0.0042±0.00298	0.0014±0.000315	0.22±0.0395
JT8D-219 / 918DL	stbd	8.81±1.78	0.58±0.02	10±0.69	0.042±0.0174	0.0013±0.000133	0.18±0.0106
CFM56-3B1 / N14324	stbd	0.18±0.0977	0.20±0.0919	1.44±0.120	0.0033±0.00099	0.0057±0.00172	0.13±0.00990
CFM56-3B1 / N70330	stbd	0.39	0.25	1.16	0.0063	0.0042	0.0837
RB211-535E4-B / N75853	stbd	0.34	1.26±0.145	1.48	0.013	0.072±0.0112	0.475
RB211-535E4-B / N74856	stbd	0.38±0.202	0.66	1.31±0.0665	0.013±0.0056	0.035	0.36±0.0177
PW4158 / N729FD	stbd	10.5±21.89	6.79±16.234	1.89±0.316	0.27±0.487	0.048±0.102	0.16±0.0122
AE3007-A1E / N11193	stbd	3.39±3.23	0.62±0.0988	0.68±0.0299	0.059±0.0631	0.016±0.00170	0.043±0.00150
	port	1.36±0.238	0.68±0.0436	1.03±0.0609	0.029±0.00206	0.016±0.000909	0.080±0.00655
AE3007-A / N16927	stbd	0.93±0.581	0.76±0.340	0.72±0.0125	0.022±0.00493	0.020±0.00223	0.057±0.00313
CJ6108A / N616NA	stbd	0.49±0.162	3.07±1.11	8.53±0.660	0.0078±0.00259	0.071±0.00257	0.298±0.0541

Note: Idle/taxi (either 7% or 8% depending on the engine), approach (30%), and climb-out (85%) power conditions are emphasized since these are the set points used in ICAO certification data.

*All available 1-m data.

- Advected plumes from aircraft operating under normal landing and take-off (LTO) conditions
  - Taxi;
  - Take off;
  - Approach.

To address the impact of PM emission on local air quality it is necessary to obtain both exit plane and downstream PM emission data. The emission products at the exit plane depend exclusively on the engine design and operating conditions. They evolve in the downstream plume. This evolution is greatly influenced by atmospheric conditions. The PM observed in the downstream plume is a complex mixture of the emissions from the engine, the results of plume processing, and the background ambient PM.

D.1.7 General PM Emission Trends

When sampling at or close to the exit plane (within 1 m [3 ft]), emitted particles were log-normally distributed within a single size mode and ranged from a few nanometers (nm) to 300 nm in diameter (Figure D1.1).

D.1.7.1 PM Characteristics Change with Engine Operating Conditions for a Given Engine Type

D.1.7.1.1 All engines. At ≤1 m [≤3 ft],

i. Particle mass and black carbon emission indices (EI_m and EI_m-soot respectively) were a minimum at low powers

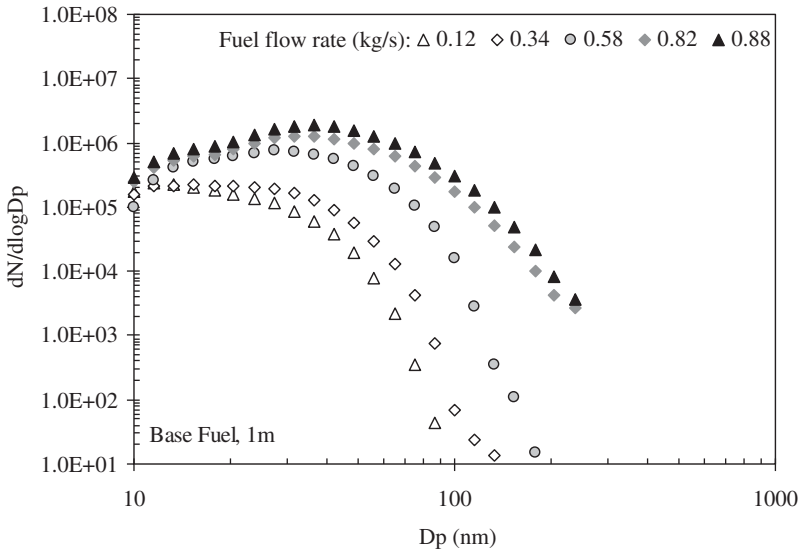

Figure D1.1. Typical particle size distributions. Source: **Lobo, Hagen, Whitefield, and Alofs, "Physical Characterization of Aerosol Emissions from a Commercial Gas Turbine Engine."** ***Journal of Propulsion and Power,*** **2007, *23* (5), p. 922.**

and increased with power, reaching values more than 0.3 g-particle/kg-fuel at power levels higher than 65%.

ii. The mean particle diameter increased linearly with power, ranging from around 15 nm at idle to about 40 nm at maximum power (at engine exit).

iii. Primary (non-volatile) particle EI_n varied from 0.16 to 3×10^{15} particles/kg-fuel, and were greatest at idle and take-off thrust settings and a minimum at power levels corresponding to approach.

iv. EI_m values were nonlinearly dependent on engine power and typically less than 20 mg-particle/kg-fuel over the 4% to 65% engine power range and greater than 200 mg-particle/kg-fuel at and above 85% power level.

v. The PM composition is primarily non-volatile:
   - Temperatures high enough to suppress formation of volatile species.
   - Validated by measurements at APEX1, JETS APEX2—not APEX3.
   - No dependence on fuel composition, specifically sulfur, and aromatics. Fuel composition was systematically investigated in APEX1. JETS APEX2 and APEX3 provide further determinations of the dependence of 1-m PM characteristics on fuel properties.

For downstream locations (>30 m [>98 ft]) and advected plume data,

i. Measured particle distributions typically exhibited two distinct modes, one corresponding to non-volatile particles and peaking at roughly the same diameters observed in the 1-m [3-ft] samples, and the other occupied by freshly nucleated sulfur and organic particles peaking at <12 nm.

ii. At high engine powers, particle mass emissions were dominated by non-volatile PM.

iii. Volatile PM number and mass concentrations are dependent on fuel sulfur concentrations.

iv. Non-volatile particle size as well as EI_n and EI_m were independent of fuel properties or downstream sampling distance (plume age).

v. From the advected plume data, on any given day the engine-engine variability within a given class is less than 5% for mass- and number-based emission indices (see Figures D1.2 and D1.3).

vi. From the advected plume data, the day-to-day variability for a given engine class ranged from 10% to 30% for mass-based and 10% to 80% for number-based emission indices (see Figures D1.2 and D1.3).

vii. Changes in ambient atmospheric conditions are likely to impact PM emissions. Advected plume data indicate that EI_n is more sensitive to ambient conditions than EI_m, consistent with EI_n being dominated by volatile nucleation/growth mode particles and EI_m dominated by non-volatile soot particles. Table D1.3 summarizes the daily and day-to-day changes in atmospheric conditions during this study.

The observations discussed in items v to vii above provide powerful tools for assessing aircraft operations on airport

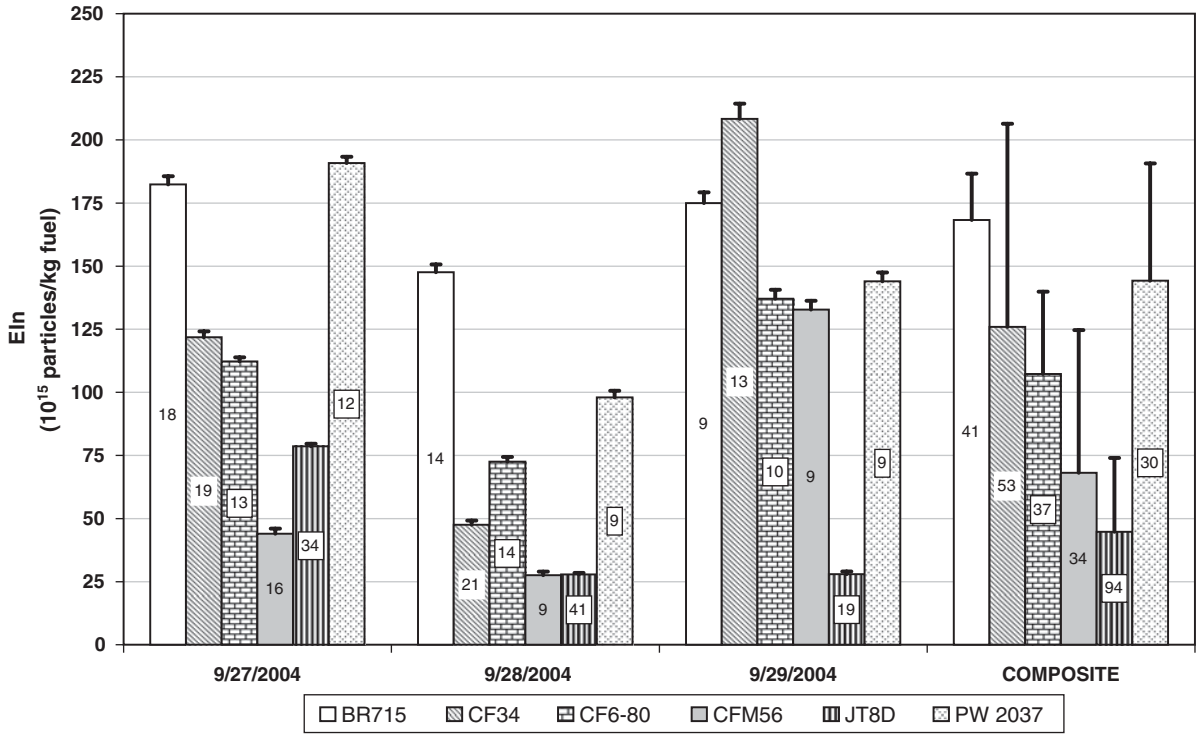

Figure D1.2. Average number-based emission indices at take-off measured for six aircraft engine families during the Delta-Atlanta Hartsfield Study.

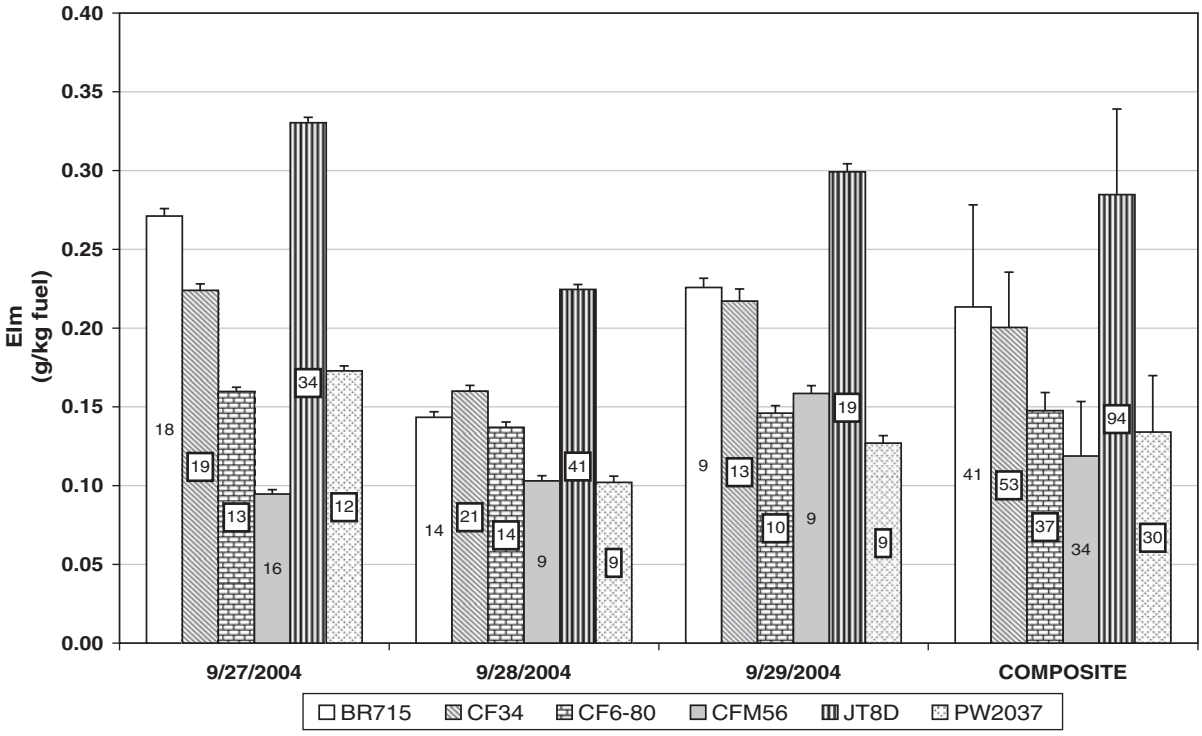

Figure D1.3. Average mass-based emission indices at take-off measured for six aircraft engine families during the Delta-Atlanta Hartsfield Study.

Table D1.3. Summary of the daily and day-to-day changes in atmospheric conditions during the Delta Atlanta-Hartsfield Advected Plume Study.

Date	Ambient condition	min	max	avg	std dev	% Deviation
9/27/2004	Temperature (°C)	19.1	20.4	19.5	0.2	1.1%
	Rel. Humidity (%)	91.7	100.0	99.0	2.0	2.0%
9/28/2004	Temperature (°C)	21.5	27.5	24.8	1.3	5.2%
	Rel. Humidity (%)	53.0	76.9	64.8	6.3	9.7%
9/29/2004	Temperature (°C)	19.9	28.5	24.2	2.2	8.9%
	Rel. Humidity (%)	34.6	78.1	54.7	12.9	23.6%

local air quality but were drawn from only one study (Lobo et al. 2008). Their potential value warrants further advected plume studies of this type.

D.1.7.1.2 The CFM56 studies. The engine type most extensively studied in these campaigns is the CFM56, which is the most prevalent engine type operating in the commercial fleet. The CFM56 common to all four campaigns and the CFM56 data provide the most insight into the engine-to-engine variability issue. Furthermore, the data provide a unique opportunity to examine the variability within sub-classes of the engine, specifically: -2C1, -3B1, and -7B22.

At ≤1 m [≤3 ft] (see Figure D1.4):

- For all CFM56 sub-classes, mean particle diameter increases with increasing engine power. No statistically significant difference between the particle number diameter of the PM emitted by the various CFM56 technologies is discernable due to measurement variability (i.e., real engine-to-engine variability) and measurement uncertainty.
- Both the -3B1 and -7B22 engine sub-classes demonstrate a minimum number-based emission index (EI_n) at ~20% power. The newer technology -7B22 engines produced fewer particles per kilogram of fuel burned than did the older -3B1 engines. Averaged across all powers, the -7B22 engines exhibited a 79 ± 12% reduction in number-based emissions normalized to fuel flow relative to the -3B1. EI_n for the -2C1 engine fall between those of the -3B1 and -7B22 series.
- The mass-based emission index (EI_m) increased with increasing power. The trend is stronger for the older engine technology (-3B1). At 85% power, EI_m for the 7B22 engines is 72% less than the -3B1 engines. A statistically significant decrease is also observed for the CFM56-2C1 engine compared to the -3B1.

At ≥30 m [≥98 ft]:

The onset of gas-to-particle conversion was apparent at downstream locations for low to medium powers as the formation of new particles. At high powers, gas-to-particle conversion resulted in formation of a coating on the soot particles. In the ≥30-m [≥98-ft] data, non-lognormal size distributions were often observed. The ≥30-m number-based emission indices were 10 to 100 times greater than those measured at 1 m [3 ft] due to the appearance of a large quantity of particles smaller than 15 nm in diameter. The <15 nm particles present in the ≥30-m [≥98-ft] samples were attributed to nucleation of condensable materials as the hot exhaust gases cooled. Since the <15 nm particles do not contribute significant mass, EI_m and related parameters did not vary strongly with sampling position. Because the coating layer was thin (<1 nm), the volatile coatings on the soot particle did not alter the soot particle size distribution.

D.1.7.2 PM Characteristics Also Change between Engine Types

At both the ~1-m and ≥30-m (~3-ft and ≥98-ft) locations:

The mean particle diameter (Figure D1.5), number-based emission index (Figure D1.6), and mass-based emission index (Figure D1.7), depend on engine type for all PM parameters measured as follows:

- All engines have comparable minima and
- Significant variation is observed between the maxima.

D.1.7.3 PM Characteristics Change during Engine Warm Up

The number-based emission indices, EI_n, for a given operating power were observed to decrease with engine on-time following a cold start. For example, in the case of a CFM56-7B22 engine sampled at 50 m [164 ft], EI_n decreased by about 60% after the engine warmed up. The effect was observed for other engine types where cold starts were studied.

D.1.8 Chemical Composition of Aviation Particles

As a complement to aviation particle physical characterization, the APEX studies included measurements of particle

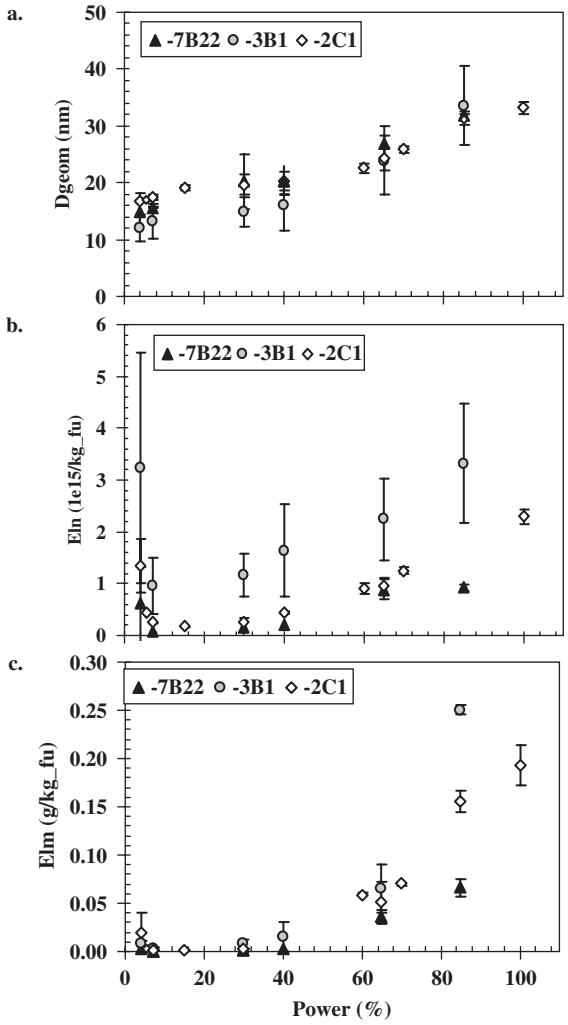

Figure D1.4. Mean particle diameter, number-based emission index, and mass-based emission index as a function of engine power for the -2C1, -3B1, and -7B22 models of the CFM56 class of engines.

chemical composition. Just like particle mass, number, and size, the chemical composition is likely to play an important role in potential human health and environmental impacts. The aerosol mass spectrometer (AMS) was one of the instruments used to measure particle chemical composition during APEX. The AMS is a powerful instrument that obtains size-resolved particle chemical data. The operation of the AMS has been described elsewhere in detail (Jayne et al. 2000; Canagaratna et al. 2007; Drewnick et al. 2005; DeCarlo et al. 2006). Briefly, a specially designed inlet focuses particles in a sample gas at the expense of the gas-phase molecules. The focused particles enter a high vacuum chamber and are accelerated to their vacuum terminal velocity. Since larger particles travel more slowly than smaller particles, they become size separated during their travel through the vacuum chamber. At the end of their travel, the particles strike a heater which is usually held at 600°C. Volatile components become vaporized and are ionized by collision with high energy electrons. The resulting ions are extracted into a mass spectrometer which separates them based on the ratio of the molecular mass to ionic charge. Individual ions give rise to an electronic signal which is converted via a series of internal amplification stages and external calibration standards to a mass concentration. The experimental measurements provide size resolved chemical information for a collection of particles.

The AMS can detect and quantify any species that is vaporized at 600°C. The AMS identifies particle-bound ammonium, chloride, nitrate, sulfate, water (though only partially due to its high vapor pressure), and various organic species in ambient air samples. On some occasions, it has detected certain metal species including lead, lead oxides, zinc, and zinc oxides. A wide range of organic materials have been identified in ambient air (Dzepina et al. 2007) and vehicle exhaust (Canagaratna et al. 2004). Aviation PM contains appreciable amounts of organic material and sulfate. The sulfate originates directly from sulfur compounds present in the jet fuel. The combustion process converts fuel sulfur compounds into SO_2 quantitatively. Post-combustion, about 0.5% to 5% of the SO_2 becomes oxidized to SO_3 (Lukachko et al. 2008) within a fraction of a second. In the presence of water, SO_3 condenses as H_2SO_4 on the time scale of seconds to minutes for ground level emissions. The composition of the organic material is more complex. Detailed studies (Timko, Onasch et al. 2008) have identified engine oil and partially burned hydrocarbons as the two primary types of organic materials in aviation PM. All engines studied during the APEX missions have emitted engine oil. Engine oil is a larger fraction of the total organic PM at high powers, when efficient combustion drives the emission of unburned hydrocarbons (UHCs) to near zero. Engine oil constitutes about 50% of the organic PM at high power, though for some engines the figure is closer to 90%. At low power, engine oil constitutes roughly 20% of the organic PM. Understanding that the organic content of aviation PM is divided between engine oil and partially burned hydrocarbons should aid future engine design efforts to reduce PM. Likewise, the potential human health and environmental impacts of partially burned hydrocarbon particle contributions are likely to be different from those of engine oil.

Circumstantial evidence suggests that the organic and sulfate components are internally mixed in aviation PM—in other words, each individual particle contains roughly the same fraction of sulfate and organic material as the next. The evidence for internally mixed particles comes in the form of size-resolved chemical data which show that the size distributions for organic and sulfate materials occur over

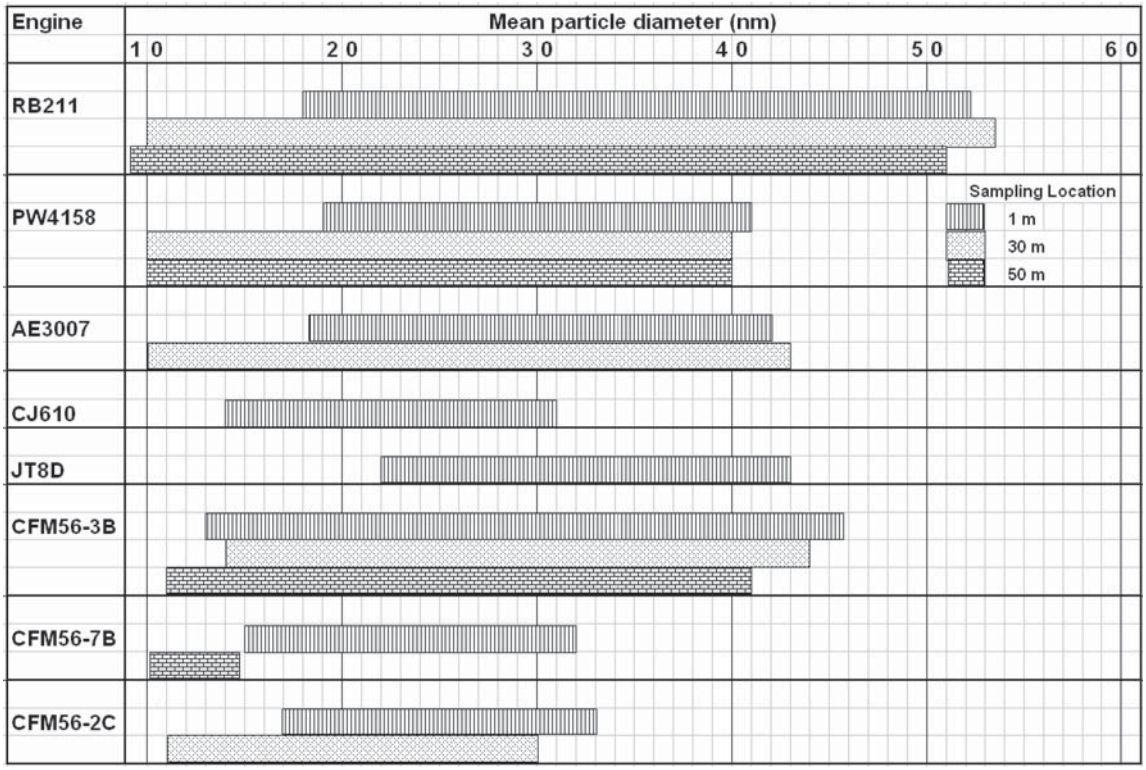

Figure D1.5. Ranges of measured mean particle diameter for engines emissions sampled in the near field plume.

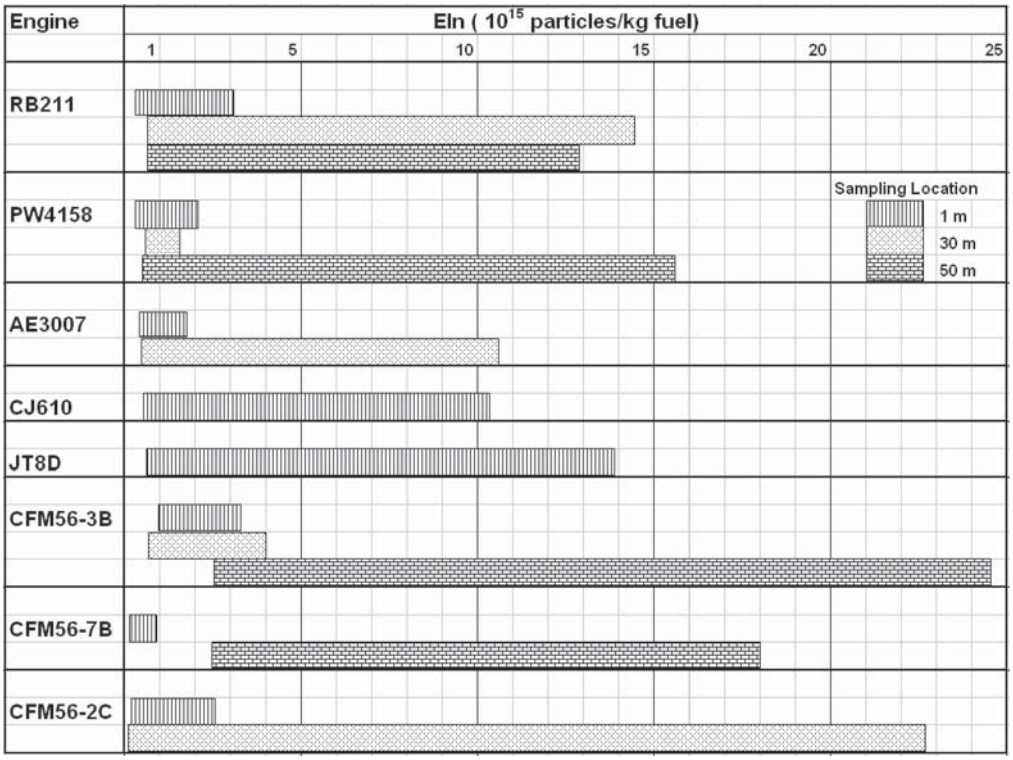

Figure D1.6. Ranges of measured number-based emission index for engines emissions sampled in the near field plume.

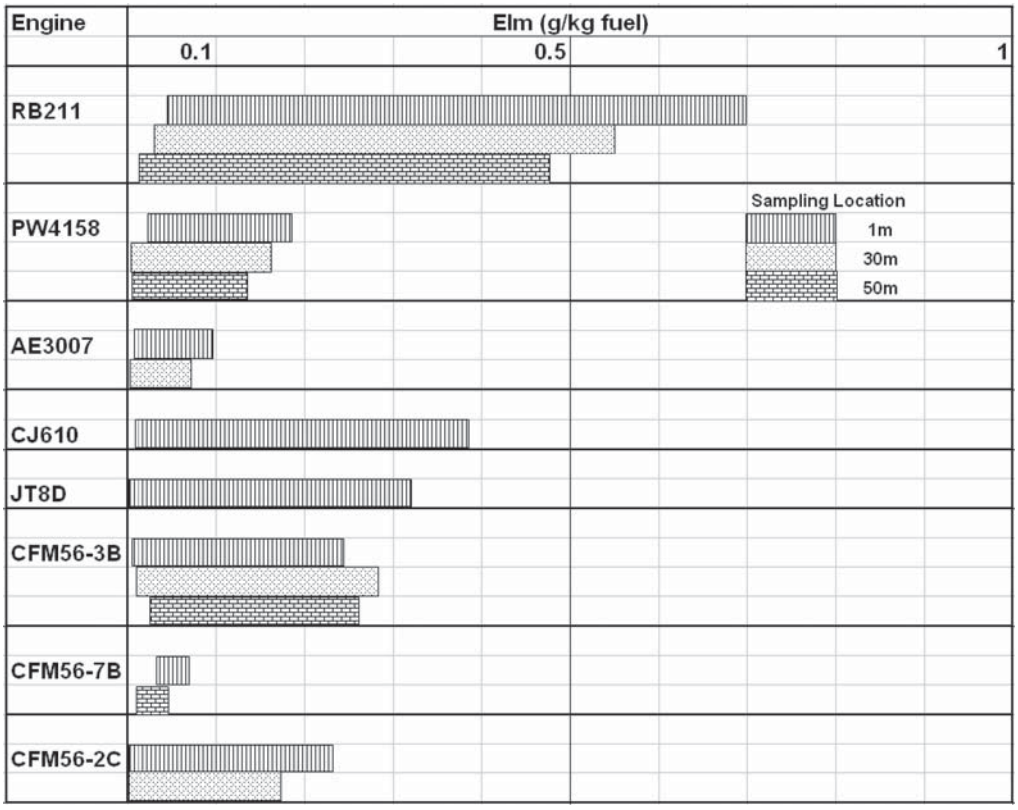

Figure D1.7. Ranges of measured mass-based emission index for engines emissions sampled in the near field plume.

the same size range and have similar shapes (Onasch et al. 2008).

Engine operating condition (Timko, Onasch et al. 2008) and fuel sulfur content (Timko, Onasch et al. 2008; Onasch et al. 2008) influence the chemical composition of aviation PM. At idle, aviation PM seems to be predominantly organic material, a result of the relatively lower combustor efficiencies at low power conditions. At climb-out and take-off, combustor efficiency is greater than 99%, very little UHC exits the engine, and the particles contain roughly equal amounts of sulfate and organic material. As stated previously, much of the organic material emitted at climb out/take-off appears to be due to engine oil, which has nothing to do with the combustor. APEX1 provided an excellent opportunity to understand the effects of fuel sulfur content on aviation PM chemical composition. As might be expected, increasing fuel sulfur content increases the mass of sulfate particles emitted (Onasch et al. 2008). The effect of fuel sulfur content on sulfate emissions is also seen in the JETS APEX2 and APEX3 data (Timko, Onasch et al. 2008). More surprisingly, increasing fuel sulfur content also increases the amount of organic PM emitted. The organic material contained in nucleation/growth mode particles is more sensitive to fuel sulfur content than that coated onto soot. It seems likely that condensed sulfate acts as nucleation sites for conversion of organic materials to the particle phase.

D.1.9 PM Measurement Methodology Development

The campaigns provided the opportunity to improve aircraft PM characterization methods, resulting in a more accurate PM emissions data. The APEX campaigns occurred over a 2-year period and afforded much insight into sampling methodology and diagnostic techniques for aircraft PM characterization. The general approach had been defined in such previous studies as Howard et al. 1996; SUCCESS (Hagen et al. 1997); SONEX/POLINAT (Hagen et al. 1999; Schlager et al. 1997); EXCAVATE (Anderson et al. 2005); and NASA QinetiQ (Whitefield et al. 2002). A detailed description of the basic methodology can be found in Schmid et al. 2004. The same methods were employed throughout the campaigns but were continuously improved as a result of lessons learned from each campaign. The lessons learned have led to subsequent focused studies sponsored by the FAA, NASA, and DoD to refine further the methodology employed in the APEX studies. These studies are being used extensively by the SAE E-31 committee (aircraft exhaust emissions measurements) to develop standards for measuring PM emissions from aircraft gas turbine engines. SAE E-31 also interacts strongly with the ICAO Committee on Aviation Environmental Protection (CAEP) to ensure that all standards for

aircraft emission measurements are developed for international application.

D.2 Gas-Phase Data Review Summary

In addition to the PM measurements described in Section 6.1, the APEX studies included a variety of gas-phase emissions measurements. The purpose of the gas-phase measurements was to complement the existing ICAO emissions databank. Whereas ICAO certification requires reporting of total UHCs and total NO_X emissions, the APEX measurements provide much more in-depth chemical-level detail. Potential health and environmental implications depend critically on the properties of the emitted compounds, and the APEX measurements contain more chemical information than the ICAO databank. Using the APEX data should therefore improve the completeness of local air quality models used for airport emissions, and may potentially improve understanding health effects.

The APEX gas-phase measurements can be divided broadly into two classes: nitrogen oxides and hydrocarbons. Other gas-phase emissions are carbon dioxide, water vapor, and sulfur dioxide. Hydrocarbon emissions decrease with increasing engine thrust (and are most important at low power, e.g., idle/taxi), whereas nitrogen oxide emissions are highest at high power (take-off), though are important both at low power and high power. Nitrogen oxides (NO_X) are emitted primarily as NO and NO_2. Unlike many other combustion-based engines, jet engines emit a substantial fraction of total NO_X as NO_2, at least at idle. A third nitrogen oxide species, HONO, is also emitted in smaller quantities (Wormhoudt et al. 2007). Aviation engines emit a wide range of hydrocarbons, the most prevalent being ethylene (C_2H_4) and formaldehyde (HCHO). Benzene, toluene, styrene, acetaldehyde, methanol, and naphthalene are some of the other UHCs that are emitted by aircraft engines and were measured during the APEX measurement campaigns. Figure D2.1 shows representative gas-phase EIs measured for a CFM56-3B1 engine during APEX3. Some features of EIs are well known: at idle, EI CO dominates, while EI NO_X (defined as the sum of EI NO and EI NO_2) dominates at take-off. The exceptional aspect of Figure D2.1 is the degree of chemical detail which far exceeds that available in ICAO certification data.

Separate measurement of all hydrocarbon species emitted by gas turbines to certify commercial aviation engine models would be a daunting task. Fortunately, one of the useful findings of the APEX studies is that emission of the various hydrocarbon species scale with one another, regardless of engine type or thrust setting. Even when the absolute magnitudes change by an order of magnitude or more (due to changes in engine power condition, for instance), the ratio of one hydrocarbon to the next remains constant.

In addition to greater chemical detail, the APEX studies provide data on the effects of two important operational variables which impact aviation emissions: (1) the ambient temperature, and (2) emissions at power conditions other than ICAO idle (7%), approach (30%), climb-out (85%), and take-off (100%). To remove variability and provide a common baseline, the ICAO emissions databank tabulates data at standard day conditions (15°C, 760 torr, 60% R_H). Deviations from standard day conditions are common during normal airport operations, and the APEX data can help link actual ambient conditions to emissions performance. Likewise, aircraft engines operate at power conditions not tabulated in the ICAO databank. In fact, the runway studies conducted at Atlanta-Hartsfield airport (Herndon et al. 2008) suggest infrequent use of ICAO power—especially 7% idle. The APEX studies measured emissions at a number of additional power conditions, including a low-power idle (4%) and several intermediate power conditions (15%, 40%, and 65%). Use of the more complete data set should enable generation of more accurate airport emissions inventories. Moreover, the emissions effects of potential operational changes (e.g., reduced-thrust take-off, minimized idling times) can be calculated using the APEX data so that alternative scenarios can be explored before policy changes are instituted.

This section begins with a description of the reproducibility of the gas-phase APEX measurements and—when possible—direct comparisons to ICAO certification data. Experimental details are provided to explain how the measurements were made. Representative gas-phase data are presented to provide a better understanding of the range of data available. Following the general discussion of the data, several potential sources of systematic error are presented. The next two sections describe the hydrocarbon and nitrogen oxide in greater detail. The final section provides two examples of how the APEX data can be used: (1) effects of reduced thrust take-off and extended idle time on NO_X emissions, and (2) estimating uncertainties in hydrocarbon emissions due to ambient temperature effects and uncertain power condition.

D.2.1 Gas-Phase Data Reproducibility and Comparability to ICAO

During the APEX campaigns (i.e., the combined APEX1, JETS APEX2 and APEX3 campaigns) emissions data were collected at over 1,200 stable conditions (i.e., the power setting/fuel flow was stable at the desired set point) for 21 gas-phase species. Table D2.1 lists all of the gas-phase species measured during the APEX campaigns, along with the instruments used to make the measurements. State-of-the-art instruments were used for the measurements, and the quality of the instruments is reflected by their fast time responses and low detection limits.

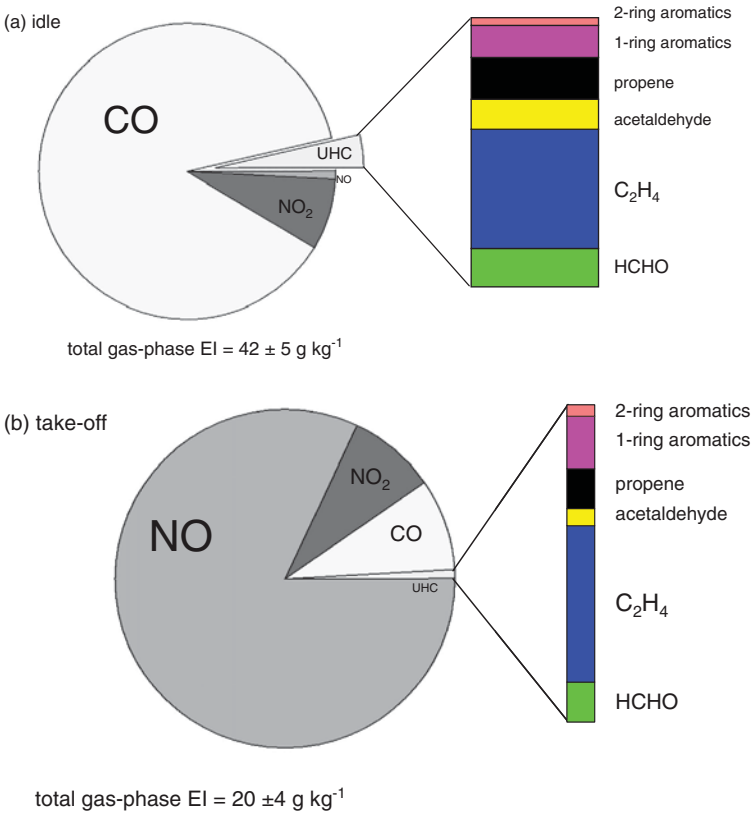

Figure D2.1. Gas-phase emissions measurements for a CFM56-3B1 (N14324, APEX3) at (a) idle and (b) take-off powers. Area corresponds to the mass-based EI. All data meaured at 30 m [98 ft]. Total gas-phase pollutant EIs provided in figure. Benzene, toluene, styrene, and phenol are the 1-ring aromatics included in this figure. Naphthalene, methylnaphthalene, and dimethylnaphthalene are the 2-ring aromatics included. The level of chemical detail provided by the APEX measurements far exceeds that available from ICAO certification data, which should lead to improved understanding of the potential impacts of airport operations on air quality.

During an emissions test, the airplanes remained grounded and chocked during all tests while the engine thrust was varied to simulate operation at ground idle (4%), idle (7%), taxi (30%), climb-out (85%), take-off (93%), and intermediate power conditions including 15%, 45%, and 65% rated thrust. The power cycle during a typical experiment was as follows: (1) the engines were allowed to warm up for roughly 5 to 10 min; (2) measurements commenced as the engines were operated at ground idle; (3) the test continued as the power was increased in a step-wise fashion (e.g., 4% to 7% to 15%, etc.) up to either take-off power or climb-out power; (4) the power was directly reduced to either idle or ground idle; (5) after several minutes at idle, the power was increased directly to either take-off or climb-out; (6) the test concluded as the power was reduced step-wise back to ground idle. Exhaust gas samples were taken continuously throughout the entire experiment and each stable point lasted for 2 to 5 min. Sampling was performed both at 1 m [3 ft] from the engine exit plane and further downstream of the engine (15 m, 30 m, 45 m, or 50 m [49 ft, 98 ft, 148 ft, or 164 ft] depending on the size of the engine). During each engine test, EI measurements were made at a given thrust rating both as the engine thrust was increased and as it was decreased to the set point. With a notable exception, no systematic biases or hysteresis effects were found; EI CO for the RB211-535E4-B engines was 18 g kg^{-1} when the power was rapidly decreased from climb-out or take-off to ground idle, as compared to 35 g kg^{-1} when ground idle power was approached gradually in step-wise fashion. EI CO for the RB211-535E4-B did not exhibit hysteresis at power settings other than 4%, though the power was never rapidly

Table D2.1. Gas-phase instruments deployed in APEX missions.

Instrument	Species Detected	Detection Limit	Time Resolution	Campaign(s) Deployed
LICOR IR Gas Analyzer (models 6262 and 820)	CO_2	3 ppm	1 sec	APEX1,2,3
Siemens (Ultramat 23)	CO CO_2 O_2	<25 ppm <500 ppm <2,500 ppm	1 sec	APEX1,2,3
Multi-Gas Analyzer (MGA) (AFR-2010)	N_2O, CH_4, HCHO, C_2H_4, CH_3OH, HCOOH, Jet Fuel, SO_2, H_2O, CO_2, CO, NO	species dependent ranging from 0.1 (HCOOH, C_2H_4) to 85 (H_2O)	1 sec	APEX1,2,3
QCL-TILDAS[a]	NO_2 C_2H_4 CO HCHO	0.5 ppb 2 ppb 5 ppb 1 ppb	1 sec 1 sec 1 sec 1 sec	APEX2,3 APEX2,3 APEX2,3 APEX3
TILDAS[b]	HCHO NO HONO	0.5 ppb 1 ppb 1 ppb	1 sec 1 sec 1 sec	APEX1,2,3 APEX3 APEX1
Eco-Physics (CLD 700 EL ht)	NO NO_X	>50 ppm >50 ppm		APEX1,2,3
NO_x Chemi-luminescence Analyzer	NO	0.2 ppb	1 sec/20 sec	APEX2,3 APEX2,3
ThermoElectron model 42C	NO_Y[c]	0.2 ppb	20 sec	
Signal (300 HM)	UHC	>40 ppm	1 sec	APEX1,2,3
PTR-MS[d]	acetaldehyde, propene, benzene, toluene, styrene, C_2-benzene[e], phenol, naphthalene, methylnaphthalene, dimethylnaphthalene	5 ppb	8 sec	APEX1,2,3

[a] quantum-cascade tunable infrared laser differential absorption spectrometer (Nelson et al. 1998) (Aerodyne Research, Inc.).
[b] tunable infrared laser absorption spectrometer (Nelson et al. 2002) (Aerodyne Research, Inc.).
[c] NO_Y implies NO + NO_2 + RNO_2 + RONO. In practice, NO_Y = NO_X = NO + NO_2 for these experiments.
[d] proton-transfer reaction mass spectrometer (Hansel et al. 1995).
[e] C_2-benzene implies *o*-xylene,*m*-xylene, *p*-xylene, and ethylbenzene.

dropped from take-off or climb-out to any powers except ground idle. The RB211-535E4-B EI HCHO and some of the particulate measurements (e.g., total number count) followed similar trends as EI CO. None of the other APEX engines exhibited the engine warm-up/cool-down hysteresis effect and the extent of the phenomenon is unknown.

Table D2.2 lists EI CO, EI NO_X, and EI HCHO (a hydrocarbon shown to be representative for most hydrocarbon emissions) for all of the engines studied in JETS APEX2 and APEX3. The EI data presented in Table D2.2 are reproduced from a similar table originally provided by Timko, Onasch et al. (2008). Idle/taxi (either 7% or 8% depending on the engine), approach (30%), and climb-out (85%) power conditions are emphasized in Table D2.2 to facilitate comparison to ICAO certification data. EIs for take-off power conditions are only available in certain cases due to the difficulty in operating stationary aircraft at full-rated thrust. Relative humidity can influence NO_X emissions, and the EI NO_X reported in Table D2.2 have been corrected for this effect (Wey et al. 2006). Each EI reported in Table D2.2 is the average of all available replicate points taken at a given set of conditions. (For a given airframe/engine combination, duplicate measurements are those made at the same downstream distance and engine power condition.) Accurate estimation of the measurement uncertainty is critical to the proper use of the APEX data set. Typically, each EI reported is the average of between 3 and 6 replicate measurements. Experimental uncertainties were estimated in two ways. In the first method, the uncertainty was set equal to the standard deviation of all available data points at a given set of conditions. In the second, the uncertainties in each of the experimental quantities which define an EI (e.g., uncertainty in the CO_2 and pollutant concentrations in the ambient air and exhaust gas) were propagated as a Taylor series expansion following a standard method. The larger of these two estimates of the uncertainty are reported here. These data handling procedures ensure that reported errors accurately represent

Table D2.2. Summary of EIs measured for some gas-phase species during APEX.

Engine Model/ Tail Number	Engine Location[j]	π_{00}[a]	F_{00}[b] (kN)	EI CO[c] (g kg^{-1})			EI NO_X[d] (g kg^{-1})			EI HCHO[e] (mg kg^{-1})		
				7%	30%	85%	7%	30%	85%	7%	30%	85%
CFM56-2C1[f]/N817NA	stbd[m]			36±5	5±0.5	1.6±0.2	3.8±0.6	8.2±0.6	16.0±0.6	380±140	80±20	15±10
CFM56-3B1 (ICAO)		22.44	89.41	34.4	3.8	0.95	3.9	8.3	15.5	2,280	80	50
CFM56-3B1/N353SW	stbd[m]			30±1	3.6±0.5	1.0±0.3	2.8±0.6	7.0±0.4	17±1	164±6		1.7±0.5
	port			28±2[h]	3.7±0.1[h]		3.4±0.1[h]	7.8±0.3[h]		283±17[h]	ND[g]	
CFM56-3B1/N14324	stbd[m]			34±1	4±1	1.4±0.1	3.3±0.2	6.8±0.4	14±1	540±170		22±3
CFM56-3B1/ N70330	stbd[m]			40.0±0.8	5.1±0.3	1.6±0.1	2.99±0.07		13.2±0.7		ND[g]	ND[g]
CFM56-3B1/N695SW	stbd[m]			27±1	4.1±0.5	1.5±0.3	2.9±0.4	6.5±0.6	17±2	528±39	11.5±0.8	0.5±0.4
	port			28±1[h]	3.8±0.3[h]		3.2±0.1[h]	7.0±0.7[h]		410±30	ND[g]	
CFM56-7B22 (ICAO)		24.41	100.97	22.8	2.50	0.60	4.50	10.00	19.00	2,500	100	100
CFM56-7B22/N435WN	stbd[m]			24±7	1.9±0.7	0.40±0.03	4.3±0.3	9.5±0.6	19±4	270±40	15±8	7.3±0.5
	port			23.3±3.1[h]	1.71±0.05[h]		4.2±0.8[h]	11±1[h]		380±60[h]	12±7[h]	
CFM56-7B22/N429WN	stbd[m]			19±4	1.2±0.1	0.6±0.2	4.2±0.3	10.1±0.5	24±5	280±50	2.5±0.8	1.8±0.2
	port				1.5±0.05[h]			9.1±0.3			4.3±0.7	
RB211-535E4-B[l] (ICAO)		27.9	191.7	18.24	2.43	0.26	4.58	8.65	19.3	140	5	0
RB211-535E4-B[l]/N75853	stbd[m]			18±8	2.9±1.4	0.22±0.08	5±1	9.3±0.8	24±5	80±2	ND[g]	11±3
RB211-535E4-B[l]/N74856	stbd[m]			19±1	2.1±0.2	0.20±0.03	5.0±0.6	10±1	23.9±0.7	219±9	ND[g]	ND[g]
PW4158 (ICAO)		30.7	258.0	20.99	1.88	0.54	4.8	11.8	23.7	1,780	140	2
PW4158[k]/ N729FD	stbd[m]			39±3	2.2±0.5		3.5±0.3	9.6±0.8	22.4±2	1,010±70	ND[g]	
AE3007-A1E (ICAO)		19.06	37.16	37.97	5.63	0.64	4.26	7.42	14.91			
AE3007-A1E[i]/N11193	stbd[m]			29±12	3±1	0.267±0.004	3.7±0.7	7.7±0.5	13.2±0.6	400±100	12±1	ND[g]
	port			35±1	4.4±0.1	0.30±0.01	3.43±0.09	7.3±0.2	12.1±0.7	660±20	ND[g]	ND[g]
AE3007-A (ICAO)		18.08	33.73	33.73	17.35	3.28	3.83	7.79	17.47			
AE3007-A[i] /N16927	stbd[m]			32.8±0.7	4.0±0.4	0.33±0.03	3.4±0.3	6.7±0.5	10.4±0.8	520±20	ND[g]	17.1±1.2
CJ6108A[i,j]/N616NA	stbd[m]			140±7	45±7	21±2	2.4±1.6	3.2±0.5	4.6±0.3	2,500±500	400±130	47±11

[a] π_{00} = pressure ratio.
[b] F_{00} = rated thrust (kN).
[c] EI-CO measurements averaged over all available downstream sampling locations.
[d] EI-NO_X measurements averaged over all available sampling locations. EI-NO_X equals the sum of EI-NO_2 and EI-NO, both in units of mass of NO_2.
[e] EI HCHO reflects average value of all available 1-m data. ICAO values are for UHCs—EI-UHC. ICAO does not speciate hydrocarbon data.
[f] The CFM56-2C1 engine was mounted on a NASA airframe not used in the commercial fleet. No ICAO data are available for this engine.
[g] ND indicates that the species concentration was less than the detection limits of the instrument. Blank spaces indicate missing data.
[h] Measurements made at 1-m sampling location used for this data point— no downstream data available.
[i] The 7% thrust setting was not studied for this engine—data measured at 8% rated thrust.
[j] The CJ6108A thrust is lower than the ICAO certification limit. No ICAO data are available for this engine.
[k] The 85% thrust condition was not studied for this engine—data measured at 80% thrust.
[l] The RB211-535E4-B engines studied during the APEX missions were equipped with the Phase V combustor.
[m]The abbreviation "stbd" refers to the "starboard" engine. Likewise, "port" is the port engine.
Data excerpted from Timko, Herndon et al. 2008.

experimental reproducibility. Sources of systematic error are considered later in this section.

A number of internal and external consistency checks were used to help build confidence in the gas-phase data. Specifically, when multiple instruments were used to measure the same quantity (i.e., NO_X), the various measurements typically agreed to within the specified limits of instruments uncertainty. Moreover, data measured for multiple examples of the same engine technology agree within the limits of experimental reproducibility. When such comparisons are possible, the APEX data are in good general agreement with ICAO certification data. These two comparisons establish the quality of the APEX data. More details on the two comparisons are provided in the following two paragraphs.

Qualitatively, the EIs behave as expected. As engine power increases, so too do combustor efficiency and EI NOx, whereas EI CO and EI HCHO decrease. Quantitatively, EI CO and EI NO_X data for the 4 CFM56-3B1 engines agree nearly to the limits of experimental uncertainty. EI CO for the CFM56-3B1/N70330 engine is an apparent outlier. Similarly, duplicate measurements of EI CO and EI NO_X for the other engines agree reasonably well when such data are available. EI HCHO measured for different examples of a given engine type, however, is much more variable than EI CO or EI NO_X. For example, EI HCHO takes values ranging from 164±6 (N353SW, starboard) to 540±170 mg kg^{-1} (N14324, starboard) for CFM56-3B1 engines at 7% rated thrust. Ambient temperature is the likely source of much of the EI HCHO variability, and this topic is discussed in the section on hydrocarbon emissions. At high powers, the concentration of HCHO was frequently lower than the detection limits of the instrument (about 0.5 ppb). The abbreviation "ND," short for "not detected," indicates that the concentration was below the detection limits. (Table D2.1 lists detection limits of the various instruments.) EI NO_X is generally highest for the larger engines (i.e., PW4158 and RB211-535E4-B), which is expected as the certification process makes allowances for maximum rated thrust. EI CO does not follow the engine size trend and ranges from about 20 g kg^{-1} (RB211-535E4-B) to about 30 to 40 g kg^{-1} (CFM56) for the turbofan engines at 7% thrust. The single turbojet engine that was tested (CJ6108A/N616NA) has the lowest EI NO_X and the highest EI CO, by a factor of about 2. It has the highest EI HCHO by about a factor of 5. The low fuel efficiency and inlet combustor temperature of the turbojet CJ6108A accounts for the high EI CO and EI HCHO and low EI NO_X. The good agreement for EIs measured for different examples of the same engine technology (e.g., CFM56-3B1) indicates that the quality of the data is good and can be trusted for calculations. The CJ6108A is an older engine technology; newer turbojets may perform differently.

Comparison of measured EIs to ICAO certification data helps understand the quality of the APEX data. ICAO EIs for the APEX engines are provided in Table D2.2 for comparison with the data collected during the measurement campaigns. The APEX data set generally agrees with ICAO EIs. The good overall comparison between APEX data and ICAO certification data further underlines that the experimental data are high quality. Some important exceptions and qualifiers are required, as follows:

- Field measurements of EI CO agree with the ICAO values within the limits of experimental uncertainty for most of the engines, though the variability in the data is large enough (generally about 25%) to obscure small differences.
- Discrepancies between APEX EI CO and ICAO EIs generally occurred only when the actual fuel flow rate deviated from the ICAO value. Measurements of EI CO for the AE3007 engines were higher than ICAO EI CO, but the experimental fuel flow rate was lower than the ICAO value.
- Measured EI NO_X is generally lower than the ICAO value by about 10%. Given known experimental uncertainties and biases, 10% can be considered to be good agreement.
- EI NO_X increases monotonically for all engines in the APEX data set.
- Discrepancies between APEX EI NO_X and ICAO EIs generally occurred only when the actual fuel flow rate deviated from the ICAO value.

D.2.2 Gas-Phase Measurement Reliability and Sources of Systematic Error

In addition to reproducibility, absolute measurement accuracy is also important. Instrument detection limits are typically on the order of 1 ppb to 10 ppb. Typical measured concentrations are on the order of 10 ppb to 1,000 ppb. Therefore, the uncertainties of EIs less than about 0.05 g kg^{-1} are greater than experimental variability. The uncertainty is imposed by detection limits, such as hydrocarbons (especially at high thrust conditions) and HONO. Additionally, we have identified several other sources of systematic errors, as follows:

1. EI CO is lower when measured at the engine exit plane than when measured "downstream" by much as 20% at "ground" idle conditions (4% power) and by as much as 10% at "ICAO" idle (7%). Two likely mechanisms have been identified: (1) errors in the fitting procedure used to convert absorbance signals into concentrations for highly concentrated samples (>5,000 ppb). The fitting error is estimated to be no more than 5%, which is not sufficient to explain the observed discrepancies by itself; (2) oxidation of CO into CO_2 in the 1-m probe used to sample engine exit plane gases. NO_2, OH, O, and HO_2 are likely CO oxidants either in the gas-phase or on the heated metal surfaces in the 1-m probe. The apparent loss of CO at the engine exit

plane is most notable in the APEX3 data, consistent with the fact that the 1-m sample rake was not cooled during this mission, unlike the others. Because of the uncertainties in the engine exit plane CO measurements, only downstream CO measurements are included in Table D2.2.

2. Certain organic acids, namely formic and acetic acids, have been observed at downstream sample rakes. The presence of organic acids is due to chemical reactions which occur in the downstream probe and are not indicative of actual engine emissions. EIs for organic acids are not reported here.
3. NO_2 may be converted to NO in the 1-m probe, especially at idle conditions. The NO_2/NO transformation in the 1-m probe may be chemically coupled to the CO/CO_2 conversion mentioned previously. Thus, NO_2 may indirectly serve as the oxidant for conversion of CO into CO_2. Furthermore, evidence suggests that NO may be converted into NO_2 in the exhaust plume with a reaction time scale on the order of seconds (Wood et al. 2008). The two conversion effects may partially balance one another making quantitative speciation of NO_X into NO and NO_2 challenging when measured at the engine exit plane. Just as with EI CO, the deviation between engine-exit-plane and downstream EI NO_2 data is most pronounced for measurements made with the uncooled 1-m probe used during APEX3. Also, HONO may either be formed or destroyed in the 1-m sampling probe and this chemistry is poorly understood.
4. Butanol is used for certain particle size measurements. During transitions from one power to the next, butanol can be ingested into the internal transfer lines and carried from the particle instruments to the gaseous instruments. Butanol in the internal transfer lines gives rise to a false signal in the hydrocarbon measurement instrumentation (specifically a m/z = 57 signal in the PTR-MS) that prevents quantification of the important pollutants, butadiene and acrolein. Efforts are underway (Knighton et al. 2007a) to discriminate between butanol, butadiene, and acrolein.

D.2.3 NO_2, NO, and Total NO_X Emissions

Most combustion sources emit NO_X primarily in the form of NO (Heywood 1988). Gas turbine engines operating at low power conditions are an exception, as they emit a substantial amount of NO_X as NO_2. Figure D2.2 plots the nitrogen oxide EIs for a RB211-535E4-B (a turbofan) and a CJ6108A (a turbojet). Figure D2.2a is representative of all of the turbofan engines considered in the APEX missions. Figure D2.2b is shown for contrast and the data may be relevant for general aviation engines. Some general features are apparent in the NO_X data:

- For the turbofan, NO_2 is a significant fraction of the total NO_X at low thrust (idle) conditions. In fact, 99% of the

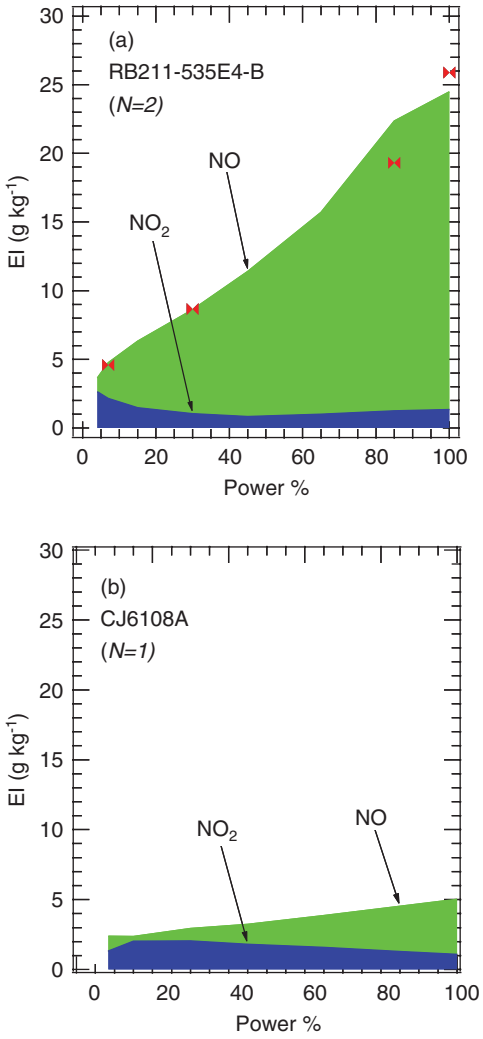

Figure D2.2. NO_x speciation for (a) RB211-535E4-B and (b) CJ6108A engines. ICAO data points (⋈) are shown for reference, when available. The CJ6108A thrust is below the ICAO threshold for certification, and no ICAO data are available for this engine. Both EI NO and EI NO_2 are plotted in units of NO_2 mass equivalents for direct comparison with ICAO EI-NO_X. The data shown in this figure are representative of the entire data set. The experimental data agree with ICAO EI NO_X for all engines except the AE3007s at high thrust. The data are not corrected for ambient humidity, though this effect was found to be small (<6%). *N* denotes the number of engines studied.

NO_X emitted from certain CFM56 engines was in the form of NO_2 at ground idle (4% rated thrust).
- EI NO_2 steadily decreases and EI NO steadily increases as power is increased for the turbofan engines. Less than 10% of the total NO_X is emitted as NO_2 at high power conditions for the turbofan engines.
- The turbojet engine, which is shown for contrast, emits a substantial fraction of the NO_X as NO_2 at all power conditions.

Wormhoudt et al. (2007) provide more details on APEX1 NO_X data, including HONO data. Wood et al. (2008) describe APEX2 and APEX3 NO_X data, both as measured during dedicated engine tests and from advected plume studies.

D.2.4 Speciated Hydrocarbon Emissions

The APEX data set includes EIs for a number of hydrocarbons including formaldehyde, ethylene, acetaldehyde, benzene, and styrene (see Table D2.1 for a complete list). The major conclusions that can be drawn from the hydrocarbon data are described below:

- Hydrocarbon EIs are highest at low thrust conditions and each individual EI falls to values below 0.1 g kg^{-1} at thrusts above 15%.
- Qualitatively, EI HCHO follows the same trends with respect to engine thrust as does EI CO.
- Formaldehyde and ethylene are the most prevalent hydrocarbons emitted from gas turbine engines on an EI basis.
- The sum of all measured hydrocarbon EIs is within about 10% to 20% of the value of UHC EIs measured by the ICAO flame-ionization detection method (FID). The quantitative agreement between the speciated measurements and the FID indicate that many of the UHCs have been included in the speciated analysis, yet the direct comparison is difficult since the FID is not equally sensitive to all HCs (aldehydes are under quantified) and not all HC species were separately quantified.
- Hydrocarbon EIs decrease by a factor of 100 or more as the power condition is adjusted from idle to take-off. Over almost the entire range, hydrocarbon EIs vary in proportion to one another. Therefore, accurate measurement of one hydrocarbon EI may allow quantification of all other hydrocarbon EI, provided a consistent speciation profile. The mutual scaling may not hold when the EIs fall below 0.1 g kg^{-1}, though this distinction has little bearing on emissions inventories.
- Ambient temperature strongly influences hydrocarbon EIs. A 20°C decrease in ambient temperature resulted in a 10-fold HCHO increase (when power setting is used as the scaling variable) or a 3-fold HCHO increase (when fuel flow rate is used as the scaling variable).

The final two points are especially important and are described in more detail in the following sections.

Mutual scaling of the hydrocarbon EIs. One of the major findings of the APEX series of experiments is the mutual scaling of the various hydrocarbon EIs. As power conditions and/or ambient conditions change, all of the hydrocarbon EIs change in concert so that the ratios of the hydrocarbon EIs with respect to one another are constant. Typically, HCHO is used as a reference, a selection originally made because HCHO is measured by a separate instrument than the majority of the hydrocarbons (see Table D2.1). Figure D2.3 contains plots of APEX1 measurements of EI HCHO and EI benzene as functions of percent rated thrust for several engine conditions and a correlation plot of EI benzene versus EI formaldehyde for all available engine conditions (Knighton et al. 2007b). Spicer et al. (1994) performed measurements of hydrocarbon EIs and their data is shown for comparison. The highly correlated benzene-formaldehyde plot shows that, even though the individual measurements have substantial variability (e.g., due to changes in ambient temperature), the ratio of benzene to formaldehyde remains constant.

The relationships depicted in Figure D2.3 suggest that measurement of one hydrocarbon EI might be used to determine the EIs of other unmeasured hydrocarbons. The scaling law depicted in Figure D2.3 applies to all hydrocarbons which are measured during a standard APEX experiment (see Table D2.1). Due to the sensitivities of the hydrocarbon instruments deployed during the APEX missions, alkane EIs have not yet been measured in gas turbine exhaust and we cannot confirm if alkane EIs obey the "universal" scaling law. Measurements made by Spicer et al. (1994) suggest that the overall contribution of alkanes to the total hydrocarbon EI is less than roughly 10%. Likewise, an analysis performed by Yelvington et al. (2007) suggests that the alkane contribution to the total UHC EI is minor. In that treatment, the individual gas-phase EIs were summed on a per carbon atom basis to yield a total hydrocarbon EI which was within about 10% to 20% of that measured using the standard ICAO FID method (Yelvington et al. 2007). Therefore, the alkane contribution to the total hydrocarbon EI is likely to be less than about 10%; however, precise numbers are not available because the FID UHC number may not represent a total HC measurement due to its non-uniform sensitivity.

The effect of ambient temperature on hydrocarbon EIs. Ambient temperature strongly influences hydrocarbon EIs (but much less so NO, NO_2, or CO). During APEX1, a 20°C decrease in ambient temperature (from 35°C to 15°C) resulted in a 3-fold increase in EI HCHO. (The same change in ambient temperature results in a 10-fold increase in EI HCHO when

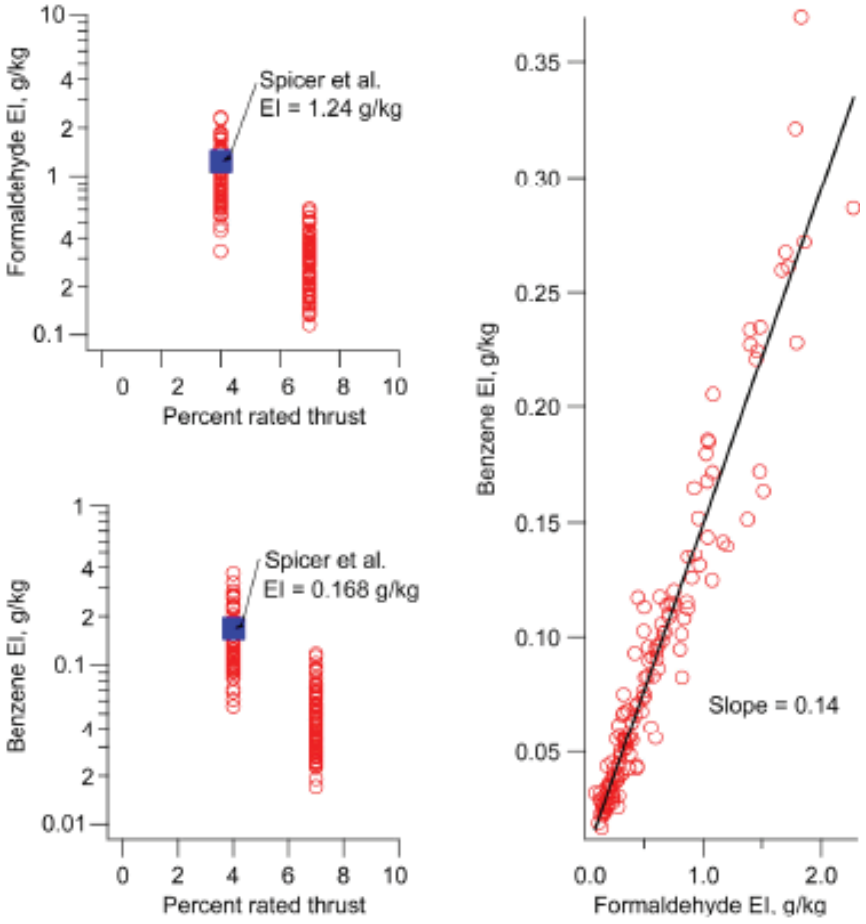

Figure D2.3. Formaldehyde and benzene EI data measured during APEX1 (CFM56-2C1). (a) EI HCHO as a function of power condition; (b) EI benzene as a function of power condition; (c) EI benzene as a function of EI HCHO. The individual hydrocarbon EIs vary by about a factor of 10 at a given power condition (either 4% or 7%), and by more than that between the two power conditions shown here. The apparent variability in individual EIs is captured as a strong correlation in the scatter plot. All hydrocarbons measured thus far vary in proportion to one another—benzene/HCHO provides a representative example. Comparison data provided by Spicer et al. (1994).

power setting, rather than fuel flow rate, is held constant. In other words, lower ambient temperatures require lower fuel flow rates to achieve a desired power setting. EI HCHO increases with decreasing fuel flow rate. The relationship between fuel flow rate and EI HCHO accounts for about one-third of the observed dependence of EI HCHO on ambient temperature.) Figure D2.4 is a plot of EI HCHO measured during APEX1. By virtue of the hydrocarbon scaling law, Figure D2.4 is representative of all hydrocarbon emissions. The variability in the EI versus thrust plots depicted in Figure D2.3 is due to the temperature sensitivity. APEX1 was unique among the APEX series of missions as a single test engine that was studied over a wide range of ambient temperature. Quantifying the effect of ambient temperature in the APEX data set is more challenging, though some data are consistent with the APEX1 results. For instance, the effect of ambient temperature may be reflected in the EI HCHO comparison between N14324/CFM56-3B1 (540 mg kg^{-1} at 7%, 8°C) and N353SW/CFM56-3B1 (160 mg kg^{-1} to 280 mg kg^{-1} at 7%, 13°C). Likewise, the two RB211-535E4-B engines studied during APEX3 may show a temperature effect: EI HCHO for N75853 equals 80 mg kg^{-1} (17°C) while that of N74856 (10°C) is 219 mg kg^{-1}. Yelvington et al. (2007) show that temperature variability of fuel flow rate accounts for about 1/3 of the observed variability in hydrocarbon EIs and suggest that relative humidity effects and/or instrument/sampling variability account for the rest. The likely emissions ramifications of the ambient temperature effect are clear: failure to account for the ambient temperature

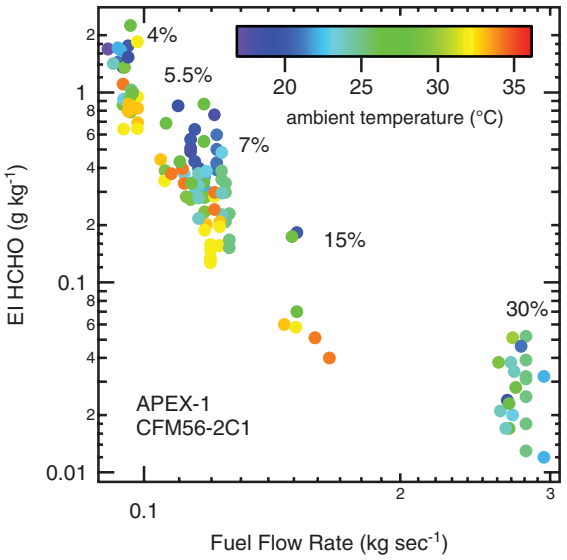

Figure D2.4. Formaldehyde emission index (EI) as a function of fuel flow rate measured during APEX1 for a CFM56-2C1 engine. Power condition is indicated directly on the graph.

effect may lead to estimated EIs which are inaccurate by a factor of 10 or more.

The effect of ambient temperature is clear—decreasing ambient temperature by 20°C results in a 10-fold increase in EI-HCHO. Data for power conditions >30% are omitted as the EIs are small (<0.01 g kg^{-1}) and noise in the measurment sometimes exceeds the absolute value.

D.2.5 Potential Use of APEX Data and the ICAO LTO Cycle to Generate Emissions Inventories

The APEX data can be used in conjunction with airport operations data to generate airportwide emissions inventories. The depth of chemical information and the wider range of operational conditions included in the APEX data set allow it be used to generate more comprehensive emissions inventories than is possible with ICAO data. Wood et al. (2008) demonstrate the use of APEX data for estimating emissions during LTO cycles, and the Wood approach is adopted here. Table D2.3 contains the results of a sample calculation for the nitrogen oxide emissions of a CFM56-3B1 engine calculated over the standard ICAO LTO cycle. Several observations can be made:

- APEX data and ICAO data yield similar estimates for total NO_X emissions;
- Almost 20% of the total NO_X is emitted as NO_2;
- Most of the NO_2 is emitted during idle;
- About half of the total NO_X is emitted during climb-out.

In addition to applying the APEX data set to standard LTO cycles, the emissions of various pollutants in hypothetical scenarios can be calculated. In Table D2.4, the total NO_X, NO_2, CO, and HCHO emitted during several hypothetical LTO cycles are listed for a CFM56-3B1 engine. The first two rows of Table D2.4 present data for the standard ICAO LTO cycle, using either ICAO or APEX EIs. The final NO_X/NO_2 figures presented in Table D2.3 can be compared directly to the first two rows of Table D2.4. The difference in APEX and ICAO estimates of CO emissions is due to a discrepancy in the EIs at 7% (28.1 g/kg for APEX compared to 34.4 g/kg for ICAO). Each row subsequent to the second lists emission estimates with one LTO parameter changed from the default.

- *Row 3: Reduced power idle.* HCHO emissions increase by about 40% and CO by nearly 20%.
- *Row 4: Prolonged idle.* Doubling the idle time to 52 min increases NO_X emissions by only 20% but increases NO_2 emissions by 67%. HCHO and CO emissions roughly double.

APEX data also capture variability in emissions data. Depending on the application and on the analysis technique used to interpret the data, real emissions variability data can be very useful for understanding the range of emissions that can realistically be expected during the course of normal operations. Primary sources of variability may include experimental errors, engine age and maintenance history, and ambient conditions.

Table D2.3. Emission indices and engine parameters used to calculate the total NO_2 and NO_x emissions from a CFM56-3B1 engine during a standard landing take-off cycle.

LTO Phase	Time in Mode (min)	Fuel Flow Rate (kg/s)	NO_X EI (g/kg)	NO_2 EI (g/kg)	Total NO_X (kg)	Total NO_2 (kg)
Approach	4	0.306	6.9	0.98	0.51	0.072
Idle	26	0.114	2.98	2.98	0.53	0.39
Take-off	0.7	0.953	16.8	1.2	0.67	0.048
Climb-out	2.2	0.886	15.1	1.15	1.77	0.13
				Totals		
				APEX	3.5	0.64
				ICAO	3.6	n/a

Table D2.4. CFM56-3B1 NO_x, CO, and HCHO emissions for different operating scenarios.

Row #	Scenario	Total NO_x (kg)	Total NO_2 (kg)	Total CO (kg)	Total HCHO (kg)
1	ICAO base case (ICAO times, thrust, and EIs)	3.6	n/a	6.5	n/a
2	Base case (ICAO times and thrust levels, APEX EIs)	3.5	0.64	5.5	0.082
3	4% idle, 26 min	3.6	0.59	6.4	0.13
4	7% idle, 52 min idle time	4.3	1.1	10.6	0.16

For the current stage of measurement development and for the number of engines tested, discerning one potential source of variability from the next is not always possible. As APEX style measurements become more routine, experimental variability will be reduced so that engine-to-engine variability can be isolated. In the meantime, the effects of ambient conditions, especially ambient temperature, and power conditions are clear. Figure D2.5 captures data variability graphically for total UHC emissions. In Figure D2.5, the UHC emission rate (i.e., mass of hydrocarbons emitted per second) is plotted over the course of a standard LTO (where the idle time has been reduced from 26 min to 22 min). The area under the curve is proportional to the total quantity of emitted UHC. The variability in the UHC emissions has been calculated based on variability in ambient temperature (here, a 20°C range has been considered) and to account for reduced power idle (4% compared to 7%). Readily apparent is that aircraft engines emit most—almost 90%—of the hydrocarbons during idle, a consequence of both the EI and the time in mode. The APU hydrocarbon emissions are shown for comparison and are clearly negligible compared to those of the aircraft engines. Also apparent is the high degree of variability for the estimated idling emissions. The errors bars in the diagram represent an estimate of the uncertainty in the true UHC emissions rate which is greatly impacted by ambient temperature and the actual thrusts used. Detailed analyses which take into account this real emissions variability will provide more realistic emissions inventories for use in chemical dispersion models.

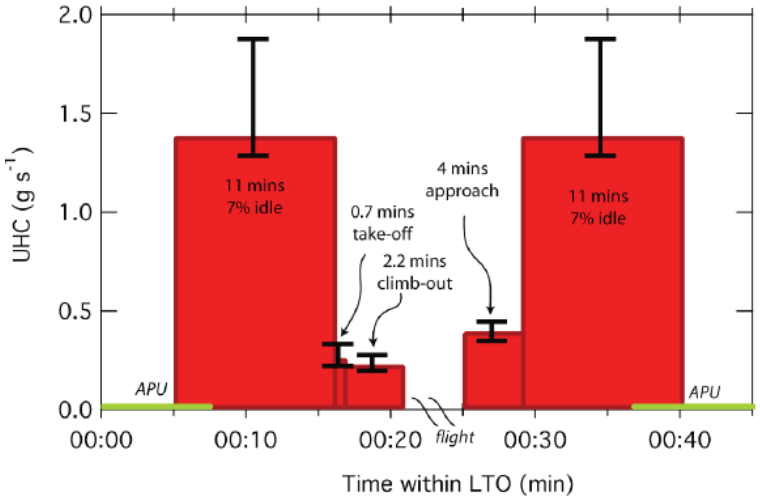

Figure D2.5. Total UHC emission rates plotted as a function of time in mode during LTO cycle. The area under the curve (i.e., the area of the "boxes") is proportional to the total amount of UHC emitted during a portion of the cycle. About 90% of the UHCs are emitted during idling. The error bars are an estimate of the range of the emission rate and account for uncertainties in the true thrust values used (e.g., 4% idle vs. ICAO 7%) and uncertainties in the influence of ambient temperature on hydrocarbon EIs (see Figure D2.4).

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