

# Chemical Properties of Aircraft Engine Particulate Exhaust Emissions

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The chemical properties of the particulate exhaust emissions from an in-use commercial aircraft engine were characterized in April 2004 as part of the Aircraft Particle Emissions Experiment. The test aircraft was the NASA DC-8 equipped with CFM56-2-C1 engines and the test matrix included 11 different engine throttle levels, three fuel compositions, and three sampling distances. The variations in particle emissions number, size, mass, and chemical composition were measured using a suite of instruments, including an aerosol mass spectrometer. The particle emissions were characterized by a trimodal size distribution. The largest mode was dominated by ambient accumulation mode particles mixed into the plume. The middle mode consisted of carbon soot with sulfate and organic coatings. The smallest mode was completely volatile and consisted of sulfate and organic components. The soot emission indices increased with power from 2–120 mg/kg fuel. The semivolatile components increased with distance and decreased with power from 33–5 mg/kg fuel. The sulfate emissions increased with distance and fuel sulfur content. The emissions under low power were dominated by organics, and the high-power conditions were dominated by soot. The CFM56 engine was less efficient at the low thrust levels typically used on the ground at an airport.

## Introduction

EMISSIONS from aircraft are coming under increasing scrutiny. Although airplanes consume only a few percent of fossil fuel currently being used (8% of petroleum fuel products [1]), they may be significant local contributors of emissions to urban airsheds [2–5] and at altitudes [6–8]. With the continued growth of commercial air traffic, aviation emissions are anticipated to make an increasing contribution to pollution on local, regional, and global scales [9,10].

Particulate matter (PM) emissions have become the focus of much international attention as anthropogenic particles have been observed to impact human health and atmospheric processes locally and regionally as well as affecting global climate change [11,12]. Combustion-generated inorganic carbon soot particles directly absorb solar radiation, are implicated in climate forcing [13], and may indirectly affect cloud properties by activating into cloud droplets [14,15]. Specific open issues relating to aircraft particulate emissions include the quantification of particles that are emitted on the ground at airports and at altitude during flights and an understanding of the role of emitted aerosol precursors in particle nucleation, growth, and particle activation [10]. Relatively little is known about the chemical speciation and sources (e.g., contributions of lubricating oils to volatile particulate matter [10]) of the emissions of particles and aerosol precursor gases from aircraft engines, and so a number of recent studies [e.g., Atmospheric Effects of Aviation Project study, Experiment to Characterize Aircraft Volatile Aerosol and Trace

Species Emissions (EXCAVATE), NASA/QinetiQ, PartEmis (measurement and predictions of the emission of aerosols and gaseous precursors from gas turbine engines), SULFUR 1–7] have been directed at improving understanding of these emissions and how they may contribute to particles in the atmosphere [16–20].

The Aircraft Particle Emissions Experiment (APEX) was conducted on 23–29 April 2004 at NASA Dryden Flight Research Center (DFRC) at Edwards Air Force Base, CA to characterize the particulate emissions of an in-use aircraft, the NASA DC-8 with four CFM56-2C1 engines [21]. With the airplane chocked in place on the ground, the inboard right engine (or engine #3) was sampled over a range of operating conditions from ground idle (4%) through full takeoff power (nominally 100%, actually 93%). The exhaust emissions were sampled at three distances downstream (1, 10, and 30 m) in an attempt to characterize the emissions near the engine exit plane (relevant to engine technology and certification testing) and downstream after the exhaust has diluted and cooled significantly (relevant to local airport environments). In addition to varying the engine power, three different aviation fuels (JP-8 fuel with moderate sulfur and aromatic contents, a high-sulfur JP-8 fuel, and a high-aromatic Jet-A fuel) were employed during APEX to begin exploring how fuel properties affect the resulting particle emissions.

Aerodyne Research, Inc. deployed its mobile laboratory in collaboration with multiple research groups including (not exclusive list) NASA, the University of Missouri–Rolla (UMR), and the U.S. Environmental Protection Agency. The Aerodyne mobile laboratory housed state-of-the-art instrumentation for measuring trace gas species and aerosol particle properties [22]. Gas phase measurements obtained in the mobile laboratory are reported elsewhere [23–25]. The physical and chemical properties of the particulate exhaust emissions (particle number, size, mass, and chemistry) were measured as a function of engine thrust, probe distance, and fuel type.

This paper focuses on the chemical composition and mass of the aircraft particulate exhaust measured during APEX. The particulate compositions were speciated using an aerosol mass spectrometer, filter-based refractory carbon soot absorption instruments, and a combination of heated and unheated scanning particle mobility sizers

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