Measurement and simulation of volatile particle emissions from military aircraft

WP 1625, WP-1626, WP-1627

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Measurement and simulation of volatile particle emissions from military aircraft

Presented at the Partners in Environmental Technology Technical Symposium & Workshop, 29 Nov – 1 Dec 2011, Washington, DC. Sponsored by SERDP and ESTCP. U.S. Government or Federal Rights License

Many military airfields are located in nonattainment areas for fine particulate matter (PM2.5) but the contribution of aircraft emissions to local and regional PM2.5 concentrations is not well understood. Aircraft directly emit particles, but the vast majority of the emissions are gases and vapors, some of which undergo gas-to-particle conversion in the atmosphere. Primary particulate matter is defined as directly emitted particles plus any material that condenses into the particle phase without undergoing chemical reactions. This latter component is often referred to as volatile particulate matter. Secondary particulate matter is formed from oxidation of gas-phase species such as sulfur dioxide and organics. To develop effective control strategies one must understand the overall contribution of military aircraft emissions to ambient particulate matter? both direct particle emissions and particulate matter formed in the atmosphere. To assist the Department of Defense in meeting the current and future regulations related to PM2.5 concentrations, SERDP initiated a research program in 2007 to investigate volatile particulate matter emissions. Three projects were funded within this program; the lead organizations of these programs were Aerodyne Research Inc., Carnegie Mellon University, and Oak Ridge National Laboratories. The projects included experiments to measure the formation and atmospheric evolution of volatile particulate matter, the development volatile emission models, and the evaluation of new instrumentation and experimental techniques. This presentation will summarize the major findings of the SERDP volatile particulate matter program, including the contribution of lubricating oil and atmospheric oxidation to volatile particulate matter emissions.
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
MEASUREMENT AND SIMULATION OF VOLATILE PARTICLE EMISSIONS FROM MILITARY AIRCRAFT

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Many military airfields are located in nonattainment areas for fine particulate matter (PM$_{2.5}$), but the contribution of aircraft emissions to local and regional PM$_{2.5}$ concentrations is not well understood. Aircraft directly emit particles, but the vast majority of the emissions are gases and vapors, some of which undergo gas-to-particle conversion in the atmosphere. Primary particulate matter is defined as directly emitted particles plus any material that condenses into the particle phase without undergoing chemical reactions. This latter component is often referred to as volatile particulate matter. Secondary particulate matter is formed from oxidation of gas-phase species such as sulfur dioxide and organics. To develop effective control strategies one must understand the overall contribution of military aircraft emissions to ambient particulate matter—both direct particle emissions and particulate matter formed in the atmosphere.

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What is volatile PM?

(Wey et al. NASA/TM—2006-2143822006)
Engine

Elm
(mg/kg-fuel)

DR ~ 1
T ~ 500°C

EC

Non-volatile PM

(Kinsey et al. EST 2011)
Engine

$E_{Im}$ (mg/kg-fuel)

1 m

DR ~ 1
T ~ 500°C

30 m

DR ~ 40
T ~ 40°C

Non-volatile PM

Volatile PM

EC

SO4

NH4

OC

EC

(Kinsey et al. EST 2011)
How does volatile PM evolve in the atmosphere?

- Dilution of exhaust
- Photochemical aging

**Spatial / Temporal Scales**

- Near Plane (< 1 km & min)
- Urban/Regional (10+ km, hrs to days)
SERDP Volatile PM Projects

**Oak Ridge National Lab Team (WP-1627)**
- Measurement Systems
  - Thermodenuder
  - Dilution sampler & aging chamber
- Measurements of gas turbine engine emissions

**Aerodyne Team (WP-1625)**
- Microphysical Kinetic Model for Plume
- Contributions of lube oil
- Laboratory studies of specific HCs and Sulfate
- Combustor system studies

**Carnegie Mellon University Team (WP-1626)**
- Measurement of PM in engine exhaust
- Aging in “smog” chamber
- Modeling of gas-particle partitioning and SOA production

**OH**
**O₃**

**NO₃**

0 → 2 km

0 → 1 km

0.1 → 50 km
Microphysical Modeling of Near-Field Evolution of Volatile PM

WP-1625

~ 1 km
Predicted evolution of nucleation mode
Predicted Particle Composition in Aircraft Plume

Findings:
- Highly Dynamic Systems
- Nucleation driven by sulfuric acid and water
- Hydrocarbons critical for growth

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Staged Testing

Mobile Laboratory

CFM56-2B Engine

KC-135T Stratotanker

Smog Chamber

Heated Transfer Line

Rake Inlet

WP-1626
Engine

1 m
DR ~ 1
T ~ 500°C

250 m
DR ~ 200

Isothermal Dilution at $T_{amb}$

Elm (mg/kg-fuel)

Dilution Ratio

Apex Data

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Elm (mg/kg-fuel)

**Engine**

1 m
- DR ~ 1
- T ~ 500°C

250 m
- DR ~ 200
- T ~ 20°C

**Isothermal Dilution at T_{amb}**

**Apex Data**

**Dilution Ratio**

Presto et al. AE 2011 WP-1626
Engine

1 m
DR ~ 1
T ~ 500°C

250 m
DR ~ 200
T ~ 20°C

Elm
(mg/kg-fuel)

Dilution Ratio

Apex Data

OC

Volatile PM

Non-volatile PM

EC

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Amount of volatile PM emissions vary with atmospheric conditions
What are effects of photo-chemical aging?

Taking off the chamber cover
Primary PM in Chamber

Miracolo et al. ACP 2011
Secondary aerosol production overwhelms primary emissions

Ave [OH] $\sim 6 \times 10^6$ molec/cm$^3$
At every engine load
Effect of Fuel Composition on Secondary Aerosol

![Graph showing emission factor (mg/kg fuel) for different fuel compositions: JP-8, Blend, and FT. The graph compares secondary and primary aerosol emissions.]
Modeling Secondary Aerosol Formation

Parameterizing Yields

Predicted Evolution Yields

Secondary PM dominant at urban and regional scales
Instrumentation development

Dilution sampler

New Thermodenuder

- Low particle losses
- Portability
- Turnkey
Lubrication Oil and Volatile PM

Findings:
The emission of lubrication oil varies significantly among the aircraft engines with different designs.

Contribution from oil can be dominant in organic PM emission in some cases.
Key findings SERDP Volatile PM

- Volatile PM highly dynamic system in atmosphere
- Secondary volatile PM production very significant
- Lube oil important constituent of volatile PM
- New tools:
  - Detailed microphysical kinetic model for plume soot, sulfate, and organic
  - Volatility basis set model for gas-particle partitioning of primary organic aerosol and production of secondary organic aerosol (SOA) in atmosphere
  - Dilution sampler, thermodenuder, and smog chamber techniques
- Archival Papers: 7 published, 4 near submission, others in process
Primary PM Emissions

CFM56 with Engine Load

T63 with Fuel Composition

Presto et al. AE 2011