Aviation Particle Emissions Workshop
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Proceedings of a conference sponsored by the
Ultra-Efficient Engine Technology (UEET) Project under the Vehicle Systems Program (VSP)
of the National Aeronautics and Space Administration (NASA)
Cleveland, Ohio
November 18–19, 2003

National Aeronautics and
Space Administration

Glenn Research Center

November 2004
**Foreword**

Aerosols have environmental effects ranging from degradation of local to regional visibility, contamination of lakes and ecosystems, damage in agricultural production, increased human mortality, and global climate change. Unfortunately, one of the least understood of the possible environmental effects from aircraft emissions is that of particles, both those emitted directly, which are mostly composed of soot, heavy hydrocarbons, and trace metals, and those resulting from emitted particle precursors such as water vapor, sulfur oxides, nitrogen oxides, and hydrocarbons.

The Aviation Particle Emissions Workshop was held November 18 to 19, 2003, at Cleveland, Ohio. It was sponsored by the Ultra-Efficient Engine Technology (UEET) Project under the Vehicle Systems Program (VSP) of the National Aeronautic and Space Administration (NASA). The workshop was organized with the objective of building a comprehensive research roadmap to strengthen partnership between U.S. stakeholders and research entities in understanding aviation particulate emissions.

Participants came from a broad spectrum of government agencies, aviation industries, and scientific and technical research communities. The workshop started with presentations of perspectives from the Federal Aviation Administration, the Environmental Protection Agency, NASA, and airports. It was followed by five interactive technical sessions: sampling methodology, measurement methodology, particle modeling, database, inventory and test venue, and air quality. Summaries of five sessions were presented by the session chairs to conclude the workshop.

This workshop achieved its objective of providing a sound foundation of the particulate research roadmap and a forum for discussions among all stakeholders and researchers.

Chowen Chou Wey  
NASA Glenn Research Center  
Cleveland, Ohio
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### November 18 and 19, 2003

**Tuesday, November 18, 2003**

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<th>Speaker/Chair</th>
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<tr>
<td>8:00–8:05 a.m.</td>
<td>Welcome</td>
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<tr>
<td>8:05–8:35 a.m.</td>
<td>EPA Perspective</td>
<td>Bryan Manning, EPA</td>
</tr>
<tr>
<td>8:35–9:05 a.m.</td>
<td>FAA Perspective</td>
<td>Julie Draper, FAA</td>
</tr>
<tr>
<td>9:05–9:35 a.m.</td>
<td>Airport Perspective</td>
<td>Ian Redhead, ACI-NA</td>
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<tr>
<td>9:35–10:05 a.m.</td>
<td>NASA Perspective</td>
<td>Joe Shaw, NASA</td>
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<tr>
<td>10:05–10:20 a.m.</td>
<td>Objective and Expected Outcomes</td>
<td>Chowen Chou Wey, NASA</td>
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<tr>
<td>10:50 a.m.–</td>
<td>Sampling Methodology—Current Understanding and Issues</td>
<td>Robert Howard, AEDC, and Bruce Anderson, NASA</td>
</tr>
<tr>
<td>–12:20 p.m.</td>
<td>Discussion</td>
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<td><strong>Break</strong></td>
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<tr>
<td>1:20 p.m.–</td>
<td>Measurement Methodology—Current Understanding and Issues</td>
<td>Phil Whitefield, UMR, and Doug Worsnop, ARI</td>
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<tr>
<td>–2:50 p.m.</td>
<td>Discussion</td>
<td></td>
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<td></td>
<td><strong>Break</strong></td>
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</tr>
<tr>
<td>3:20 p.m.–</td>
<td>Particle Modeling—Current Understanding and Issues</td>
<td>Rick Miake-Lye, ARI, and Med Colket, UTRC</td>
</tr>
<tr>
<td>–4:50 p.m.</td>
<td>Discussion</td>
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**Adjourn**
# Aviation Particle Emissions Workshop
## November 18 and 19, 2003

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<th>Time Min.</th>
<th>Topic</th>
<th>Speaker/Chair</th>
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<tr>
<td>8:30 a.m.–</td>
<td>Database, Inventory, and Test Venues—Current Understanding and Issues</td>
<td>Steve Baughcum, Boeing, and Gregg Flemming, DoT</td>
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<td>–10:00 a.m.</td>
<td>Discussion</td>
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<tr>
<td>10:30 a.m.–</td>
<td>Local Air Quality, Modeling, and Measurements—Current Understanding and Issues</td>
<td>Don Wuebbles, UI Urbana, and Wayne Miller, UCRiverside</td>
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<tr>
<td>–12:00 p.m.</td>
<td>Discussion</td>
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**Break**

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<th>Time Min.</th>
<th>Topic</th>
<th>Speaker/Chair</th>
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<tbody>
<tr>
<td>1:30–1:45 p.m.</td>
<td>Report of Session 1 Conclusion</td>
<td>Robert Howard, AEDC, and Bruce Anderson, NASA</td>
</tr>
<tr>
<td>1:45–2:00 p.m.</td>
<td>Report of Session 2 Conclusion</td>
<td>Phil Whitefield, UMR, and Doug Worsnop, ARI</td>
</tr>
<tr>
<td>2:00–2:15 p.m.</td>
<td>Report of Session 3 Conclusion</td>
<td>Rick Miake-Lye, ARI, and Med Colket, UTRC</td>
</tr>
<tr>
<td>2:15–2:30 p.m.</td>
<td>Report of Session 4 Conclusion</td>
<td>Steve Baughcum, Boeing, and Gregg Fleming, DoT</td>
</tr>
<tr>
<td>2:30–2:45 p.m.</td>
<td>Report of Session 5 Conclusion</td>
<td>Don Wuebbles, UI Urbana, and Wayne Miller, UCRiverside</td>
</tr>
<tr>
<td>2:45–3:30 p.m.</td>
<td>Recommendations and Next Step</td>
<td></td>
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</table>

**Adjourn**
PM$_{2.5}$
National Ambient Air Quality Standards

NASA Aviation Particle Emissions Workshop
November 18-19, 2003
Bryan Manning
Overview

• What and Why of the PM National Ambient Air Quality Standards (NAAQS)

• Review of the PM Standards

• Implementation of the PM$_{2.5}$ Standard
Particles: What Are They?

Airborne particles are a complex mixture of extremely small solids and liquid droplets.

Human Hair (70 μm diameter)

Hair cross section (70 μm)

PM$_{10}$ (10 μm)  PM$_{2.5}$ (2.5 μm)

M. Lipsett, California Office of Environmental Health Hazard Assessment
PM$_{2.5}$ or Fine Particles
Public Health Risks Are Significant

- Particles are linked to:
  - Premature death from heart and lung diseases
- Aggravation of heart and lung diseases
  - Hospital admissions
  - Doctor and ER visits
  - Medication use
  - School and work absences
Public Health Risks Are Significant (cont.)

- Particles possibly linked to:
  - Lung cancer deaths
  - Infant mortality
  - Developmental problems, such as low birth weight in babies or slower lung growth in children
Some Groups Are More at Risk

- People with heart or lung disease
- Older adults
- Children
Environmental Effects

- **Visibility impairment and regional haze**
  - Quality of life effects
- **Soiling effect**
  - Observable on both buildings and vehicles
  - Contributes to degradation of monuments & artwork
History of PM Standard

• 1971 TSP
  – In general <100 $\mu$ because of the sampling method

• 1987 PM-10
  – Equal to or less than 10 $\mu$

• 1997 PM$_{2.5}$ (Fine) plus PM-10
  – Equal to or less than 2.5 $\mu$, plus
  – Equal to or less than 10 $\mu$
Court Challenge to 1997 Standards

• Delayed Implementation

• Required split between fine and coarse
  – PM-fine < 2.5 \( \mu \)
  – PM-coarse 2.6 to 10 \( \mu \)

• Review of standards
  – Proposal 3/05
  – Final 12/05
PM NAAQS Review Milestones

- 4th draft Criteria Document: June 2003
- Draft Staff Paper & Risk Assessment: August 2003
- CASAC/public review of draft Staff Paper & Risk Assessment: Nov. 2003
- 2nd draft Staff Paper & Risk Assessment: April 2004
- Final Staff Paper and Risk Assessment: Sept. 2004
PM Staff Paper

• Released August 29, 2003
  – See http://www.epa.gov/ttn/naaqs/standards/pm/s_pm_cr_sp.html
  – Public comment period closed October 28, 2003

• Evaluates policy implications of key scientific and technical information in Criteria Document
  – Identifies critical elements for consideration in PM NAAQS review
  – These are staff judgments and recommendations and not EPA positions
Staff Recommendations

- Separate standards for fine and coarse particles,
- Replace current PM$_{10}$ standards with PM$_{10-2.5}$ standards
PM\textsubscript{2.5} Implementation
# PM$_{2.5}$ Implementation Program Timelines

<table>
<thead>
<tr>
<th>Action</th>
<th>PM$_{2.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA proposes implementation rule</td>
<td>Fall 2003</td>
</tr>
<tr>
<td>States/Tribes recommend designations</td>
<td>Feb. 2004</td>
</tr>
<tr>
<td>EPA finalizes implementation rule</td>
<td>Fall 2004</td>
</tr>
<tr>
<td>EPA finalizes designations</td>
<td>Dec. 2004</td>
</tr>
<tr>
<td>State plans due</td>
<td>Dec. 2007</td>
</tr>
<tr>
<td>Attainment dates</td>
<td>2009-2014</td>
</tr>
</tbody>
</table>
PM$_{2.5}$ Implementation Rule Topics

- Classifications and attainment dates
- Modeling and attainment demonstrations
- Precursor emissions coverage
- RACT/RACM
- RFP
- New source review
- Transportation and general conformity
- Contingency measures
- Innovative program mechanisms
- Policies for SIP credit
- PM$_{2.5}$ test methods
- Emission inventories
- Tribal issues
PM Implementation Issues

- **Classifications**
  - No classification categories based on design value
  - Possible “transport” classification

- **Attainment Dates**
  - within five years of designation (e.g., end of 2009/early 2010)
  - five year extension (e.g., end of 2014/early 2015)

- **Precursors are SO$_2$, NOx, VOC, and ammonia**
  - SO$_2$ should be addressed in all SIPs
  - NOx & VOC either in SIP or can be added
  - Ammonia new pollutant
PM Implementation Issues (cont.)

- RACT lowest emission limit considering technological and economic feasibility.
  - Options:
    - > 100 tpy of direct PM$_{2.5}$ or any secondary precursor
    - > 50 tpy of direct PM$_{2.5}$ or any secondary precursor
    - Required only to the extent it is needed for attainment.

- Example of RACM Measures
  - Diesel idling and retrofits
    - Watering/gravel on unpaved roads
    - Wood stove retrofit programs
    - Smoke management plans
PM Implementation Issues (cont.)

- Reasonable Further Progress (RFP): annual incremental reductions in emissions for purpose of ensuring progress toward attainment
PM$_{2.5}$ Designations
Counties With Violating Monitors for 8-hour Ozone and PM$_{2.5}$ Standards (based on 2000-2002 data)

Data Source: AQS 2003
EPA Preferred Timelines for PM$_{2.5}$ Designations and PM$_{2.5}$/RH Implementation Plans

<table>
<thead>
<tr>
<th>Date</th>
<th>PM$_{2.5}$</th>
<th>Regional Haze</th>
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<tbody>
<tr>
<td>December 2003</td>
<td>3-years data available for all monitored areas (2001-2003)</td>
<td></td>
</tr>
<tr>
<td>February 2004</td>
<td>Governors submit recommendations based on 2001-2003 data</td>
<td></td>
</tr>
<tr>
<td>December 2004</td>
<td>EPA publishes final designations</td>
<td></td>
</tr>
<tr>
<td>December 2007</td>
<td>Implementation plans due</td>
<td>Implementation plans due for all areas without regard to PM$_{2.5}$ designation</td>
</tr>
</tbody>
</table>
Non-volatile and Volatile PM

- The PM NAAQS is based on a consideration of both volatile & non-volatile PM.
- As a result, compliance with PM NAAQS is based on a measurement protocol that collects both types of PM in the ambient air.
- Similarly, the protocol for measuring PM from mobile sources other than aircraft (e.g., on-highway diesel trucks) also accounts for both volatile and non-volatile PM.
• Health effects are the concern for emissions on or near the ground in the vicinity of an airport or as a contribution to PM exposure in an urban area (local air quality).

• For health effects, the entire aerosol must be considered.

• For climate forcing impacts from aircraft emissions in flight, the non-volatile fraction of the emission aerosol has the predominant effect.
Summary

• Significant health effects from exposure to PM
  – Including death

• New PM review complete in 2005

• Implementation of PM$_{2.5}$
  – Proposal 2003
  – Final Fall 2004
  – Designations December 2004

• Volatile & non-volatile PM must be considered.
FAA Perspective on Particulate Matter Issues

Lourdes Q. Maurice
Chief Scientific & Technical Advisor
Office of Environment and Energy
Federal Aviation Administration

Julie Draper
Emissions Division
Office of Environment and Energy
Federal Aviation Administration

PM Workshop
18-19 November 2003, Cleveland, Ohio
Aircraft Noise
Administers & Enforces EPA
Established Clean Air Act Aircraft Engine Emissions Standards (part 34)
Compliance Responsibility with NEPA
&A CAA*

* Responsibility to comply with PM Standards without the means to do so (i.e., aircraft PM emission indices)
Related Responsibilities

ICAO
Committee on Aviation
Environmental Protection (CAEP)

- FAA Office of Environment & Energy Director is U.S. Representative in CAEP
- CAEP is Following SAE Activity
Aviation Environmental Research Interests

Global climate
Reduce the impact of aviation on global climate

Noise within airport boundaries
Constrain objectionable noise to within airport boundaries

Air Quality
Reduce impact of aviation on local air quality
NASA – aircraft noise and emissions exploratory research, early technology development, and physics based modeling

FAA - aircraft noise and aviation emissions analytical tools for regulatory process and aircraft certification and regulatory issues
Outline

✱✱ Context
✱ Current Status
✱ A Way Forward
### New EPA Standards

<table>
<thead>
<tr>
<th>Action</th>
<th>PM-2.5</th>
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<tbody>
<tr>
<td>Propose Implementation Rule</td>
<td>Fall 03</td>
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<tr>
<td>State/Tribes Recommend Designations</td>
<td>2/04</td>
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<tr>
<td>Promulgate Implementation Rule</td>
<td>Fall 04</td>
</tr>
<tr>
<td>Publish designations</td>
<td>12/04</td>
</tr>
<tr>
<td>State/Tribe Plans Due</td>
<td>12/07</td>
</tr>
<tr>
<td>Attainment Years</td>
<td>09-14</td>
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Air-Quality Issues That Are Major Concerns for Airports

- Growing demand for parking: 27
- Uncertainty about conformity with the Clean Air Act’s requirements: 22
- Difficulties offsetting increased air pollutant emissions: 19
- High number of auto trips to and from the airport: 16
- Road congestion limiting airport growth: 16
- Lack of resources for public transit: 11
- No credits for voluntary air pollutant emission reductions: 10
- All others: 13

### Environmental Issues That Most Concern Airports Currently and in the Future


<table>
<thead>
<tr>
<th>Issue</th>
<th>Number of Airports</th>
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</thead>
<tbody>
<tr>
<td>Noise</td>
<td>29</td>
</tr>
<tr>
<td>Water quality</td>
<td>12</td>
</tr>
<tr>
<td>Air Quality</td>
<td>16</td>
</tr>
<tr>
<td>Compatibility with nearby land uses</td>
<td>4</td>
</tr>
<tr>
<td>None applicable</td>
<td>2</td>
</tr>
<tr>
<td>Wetlands</td>
<td>0</td>
</tr>
</tbody>
</table>

Legend:
- **White** = Most serious problem currently
- **Gray** = Most serious problem in the future

**Number of Airports**

- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35
Emissions Issues - PM

Aircraft Particulate Matter

- Particulate matter (PM) represents a direct threat to public health and contributes to visibility degradation… NESCAUM, 2003
- Data on particulate matter emissions is not available for aircraft… GAO, 2003
- Reducing emissions of PM remains a crucial component of EPA's strategy for cleaner air and improved visibility… EPA, 2000
- In 1997, EPA strengthened its' health protection standards for PM by adding NAAQS for smaller-sized or "fine" particles with an aerodynamic diameter of 2.5 micrometers or less (PM$_{2.5}$)… EPA, 1997
- Aircraft engines emit “…relatively small numbers of particles of diameter greater than 0.24” micrometers… Battelle, 1988
- A new necessity for research in the field of particulate/aerosol emissions from the aircraft is well recognized… National Academies Research Associateship Program at NASA-Glenn
- 10 of the 50 Largest Public Use Airports in PM10 NAA/Maintenance Areas; Approximately 31 will be in PM2.5 areas… DOT ACARS Airport Database and EPA Green Book for Nonattainment Areas

![Graph showing PM10 NAA/Maintenance Airports and PM2.5 NAA/Maintenance Airports]

- PM10 NAA/Maintenance Airports: 80% Attainment, 20% NAA/Maintenance
- PM2.5 NAA/Maintenance Airports: 38% Attainment, 62% NAA/Maintenance
Impact of Contrails/Cirrus Clouds
Highly Uncertain

Contrails lead to cirrus cloud formation
Particulates play a role in cirrus cloud formation – but mechanism highly uncertain
Volpe reviewing and evaluating activities for the measurement and related computation of aircraft PM data, and developing recommendations on how to improve current approaches.

As part of this study, Volpe conducted literature review of past and current research, and developed a first-order approximation (FOA) for characterizing aircraft PM emissions.

The first-order approximation will form basis of future FAA guidance and EDMS enhancements in coordination with EPA.
Future Plans

- Coordinate approximation method with EPA, and refine as new data becomes available

- Work with Society of Automotive Engineers (SAE) on guidelines to sample and measure PM emissions from aircraft engines

- Work with NASA, DoD, Academia, and Industry to obtain PM measurements to provide a broader database of aircraft emissions

NEED DATA!
New FAA/NASA COE — Team of Equals Building on Collective Capabilities

Cover the Boston, Chicago, Miami “triangle of congestion and delay” as well as sensitive California & Western States

Extensive research record addressing aviation environmental issues

Combined history of 769 years training professionals in relevant subject areas

Strong, existing relationships with industry partners and Government agencies

PARTNER - Partnership for AiR Transportation Noise and Emissions Reduction
Emissions Measurements

Participants: Boise State, University of Missouri-Rolla, Florida International University, MIT, Stanford, University of Central Florida, Aerodyne, Boeing, GE, Pratt & Whitney, Rolls Royce

Objective: Collect particulate matter data using Light Detection and Ranging (LIDAR) to provide data to enhance dispersion analytical models

Universities shown in italics are not specifically funded due to budget limitations – but have capabilities to perform valuable research in subject area.
Future Needs

✱ Coordinated Research Activities – leading to:
  ✳ Agreement on what needs to be measured
  ✳ Standard Measurement methodology of PM from aircraft engines – SAE E-31 & ICAO
  ✳ Enhance understanding of how plume ages – including volatile component
  ✳ Clarify impact of particulates on global climate

Internationally accepted methodology

Recommends a strategic framework for assessing airport emissions.
Suggested Next Steps

**Under GAO Mandate – develop a national roadmap for addressing PM issues**

**Issues identified at this workshop (& timing to address)**

**Propose FAA develop draft national roadmap**

**Propose FAA-hosted meeting of key stakeholder in January to discuss draft roadmap (week of January 12th)**
National Roadmap

✱ Key stakeholders include Government, Industry, Academia, Public

✱ Clearly assigns roles/responsibilities and timelines (tied to EPA and ICAO/CAEP requirements)

✱ Establishes executive body to steer efforts
Sampling Methodology - Current Understanding & Issues

Robert Howard
Aerospace Testing Alliance
Arnold Air Force Base, TN

Aviation Particle Emissions Workshop
November 18-19, 2003

Air Force Materiel Command
Arnold Engineering Development Center
Arnold Air Force Base, TN 37389
**Sampling Methodology - Current Understanding & Issues**

Workshop Objectives

- Describe current particulate sampling methodology
- Define known sampling issues
- Evaluate current methodology assumptions and tradeoffs
- Identify improvements to mitigate sampling issues
- Identify experiments and processes for sampling methodology validation
- Take action toward standardized sampling methodology
**Sampling Methodology - Current Understanding & Issues**

Probe Hardware Design Considerations, Durability and Environment:

- Probes are designed to survive in a severe thermal environment recognizing that exhaust conditions (temperature and pressure, velocity, Mach number, particle loading, etc.) can vary widely from engine to engine, throttle position, flight condition, and spatially throughout the plume.

- Water-cooled probes were designed such that water-cooling does not interfere with the sampling process, either externally or internally.
  - Transpiration cooling, in which water is typically forced out of passages near the probe tip, was avoided.
  - Leakage between internal cooling passages and the sample tube must be avoided.
  - Massive cooling of the extracted sampling stream was avoided to minimize condensation within the probe and the sample transfer line.

- Particulate sampling probes allow for dilution of the sample stream to:
  - Maintain the integrity of the particulate matter, and
  - Reduce the particle number density to a range suitable for the particle analyzers.
Sampling Considerations

Minimize the loss or gain of particulates in the sample stream due to the effects of:

- Non-isokinetic sampling
- Thermophoresis
- Wall impaction
- Particle diffusion wall losses
- Dilution
**Isokinetic Sampling**

Isokinetic: Gas velocity at the probe tip equals the exhaust free-stream velocity.

Sub-Isokinetic: Gas velocity at the probe tip is less than the exhaust free-stream velocity; sample biased to large particles.

Super-Isokinetic: Gas velocity at the probe tip is greater than the exhaust free-stream velocity; sample biased to small particles.
Thermophoresis

- Particles suspended in a fluid with a temperature gradient, tend to move in the direction of decreasing temperature. Thermophoresis is the result of the differential momentum of gas molecules impacting the particle surface. On the hot side of the particle, the molecules arrive with a higher kinetic energy than on the cold side. A higher momentum change on the hot side of the particle results in a net force on the particle in the opposite direction of the temperature gradient – i.e. towards the cold side.

- If the sampling probe wall is cooler than the sample stream, smaller particles will be driven to the probe wall, where they may adhere, and thus not reach the particle analyzers.

Wall Impaction

- Larger particles can be lost in bends of sampling lines.
- This effect is “assumed” negligible for turbine engine exhaust
Sampling Methodology - Current Understanding & Issues

Dilution ...

- Minimizes particle-particle interactions.
- Minimizes gas-to-particle conversion.
- Helps quench chemical reactions.
- Reduces the particle concentration level for particle analyzer detection limits.
- Is introduced as close to the probe tip as possible.
- Ratio is quantified (or verified) by measurements of CO$_2$ in the sample stream with and without dilution.
**Sampling Methodology - Current Understanding & Issues**

Current Particulate Sampling Probe Tip Concept

- Adds diluent near the probe tip.
- Injects the diluent along the wall and parallel to the sample flow.
- Is water cooled.

![Diagram](image)
Sampling Methodology - Current Understanding & Issues

1/2 inch AB/Combustor Probes

- Dilution Gas Supply
- Cooling Water Supply
- Cooling Water Return
- Total Temperature
- Mach/Swirl MFA
- Gaseous Extraction
- Particulate Extraction
- Camera
- Quick Chemical Quench
- Blank, Contour Matches
- Rake Leading Edge

Probes also available in 1/4 inch and 1/8 inch sizes
NASA Water-Cooled Rake Arm with 12-Particulate Probes

Sample Tube within Diluent Tube
Components For Independent Diluent Supply

1/4 x .029 wall sample tube
1/4 x 3/8 Swagelok Reducing Union
1/2 x 3/8 Swagelok Reducer
1/2 Swagelok Union Tee
9/32 x .035 wall Probe Sample Extraction Tube
Annular Probe Diluent Supply
1/2 Diluent Supply Tube

2 7/8"
Independent Diluent Supply Tee Assembly
Sampling Methodology - Current Understanding & Issues

NASA-DERA
Reactive Species Probe
GAS EXTRACTION PIPE
21/2” XXS Stain. Stl.
OD 2.875”
Wall .522”
ID Glass Coated

Particulate Extraction Probe
1.0” Tube
.095” Wall

36”

18”R

NASA Particulate and Gas Extraction Probes
for the NASA EXCAVATE Test

Dilution Gas
Particulate Sample Transfer
Unrestricted Vent to Atmosphere
Probe & Support
Cooling Water

Non Cooled Support

Optional Particulate / Reactive Probe Ports

Water In  Water Out
For Inner Jacket Cooling

12" Blind Flange with 8" Center Hole & Inner Jacket Cooling

Water Inlets

NASA GRC-CE5 Inline Probe Installation With Flange
Miniature Rake Torch Test

Bench Test: Probe Water Cooling / Survivability
Remarks

- Probe penetration measurements performed at the University of Minnesota indicate good particulate transfer.
- UMR and NASA discovered that a single-control dilution supply for multiple probes limited the range of application.
- Probes redesigned to allow individual dilution supply control per probe performed well and expanded the range of applicability.
- Water-Cooled Probes and Rakes have excellent survivability, durability and can be applied to a wide variety of flow-field conditions.
Sampling Methodology - Current Understanding & Issues

Future Plans / Recommendations

• Collaboration effort led by UMR to develop a probe calibration facility:
  ‣ Simulate turbine and/or combustion exhaust aerodynamic conditions.
  ‣ Produce controlled and well-characterized particle streams as a source for probe penetration calibrations.

• Collaboration effort led by ARI and MIT to develop chemical quench probe criteria for aerosol precursor sampling.

• Refine the probe / sampling system design and methodology as required.

• Investigate further sampling effects on aerosol precursors and volatile aerosols.

• Collaborative effort to investigate a methodology for extracting exhaust into an environmentally controlled reaction/mixing chamber for standardized process formation and subsequent characterization of volatile and non-volatile aerosols.
Ambient Air

Exhaust Mixed With Entrained Ambient Air for volatile aerosol formation

Inlet Air

Ambient Air

Sea-Level Test Cell
Ambient Air

Inlet Air

Conditioned Air

To Instruments

Environmentally Controlled Mixing/Reaction Chamber

Ambient Air

Inlet Air

Conditioned Air

To Instruments

Environmentally Controlled Mixing/Reaction Chamber

Inlet Air

Ambient Air

Sea-Level Test Cell
Discussion Items

- Temperature of the probe tip and sample line:
  - A dilution ratio that prevents water condensation negates requirements for heated sample lines?
  - Can sample lines be heated sufficiently to prevent condensation of species that form aerosols?
  - Should sample lines be heated for consistency/uniformity in measurement methodology?
  - If water cooled, should the probe tip be “cooled” with heated water?
  - How should an optimal probe and sample line temperature be determined?

- Is the current probe rake system design a gross over-kill for particulate sampling at commercial engine exit plane conditions?
**Sampling Methodology - Current Understanding & Issues**

Discussion Items (cont.)

- Probe tip and sample line penetration:
  - How do volatile and non-volatile aerosol penetrations compare?
  - Probe penetration calibrations should be performed at simulated aerodynamic and thermodynamic engine exhaust conditions?

- Pressure discontinuity/disturbance in front of the probe tip has a negligible effect on the sampled particulate matter?

- “Due to the small size of turbine engine exhaust particles, this or that effect is negligible and can be ignored.” Is this a generalization that fosters complacency and produces biased measurement results?

- Tradeoffs due to practical design considerations tend to be dismissed?

- Non-isokinetic sampling
- Thermophoresis
- Wall impaction
- Particle diffusion wall losses
- Dilution
Factors to Consider in Designing Aerosol Inlet Systems for Engine Exhaust Plume Sampling

Bruce Anderson

Atmospheric Sciences

NASA Langley Research Center
Processes Influencing Particle Size and Concentration

- Inertial Effects
- Thermophoretic Effects
- Loss in Bends
- Turbulent Deposition
- Coagulation
- Gravitational Settling

ENGINE → Thermophoretic Effects → Loss in Bends → Coagulation → Turbulent Deposition → Gravitational Settling → INSTRUMENTS
Thermophoretic and Gravitational Losses

Deposition Velocity (cm/sec)

Diameter (nm)

300 K/mm
Thermophoretic Velocity
Settling Velocity

NASA/CP—2004-213398
Particle Losses in 0.25" Elbow

Penetration vs. Diameter (nm)

- 20 LPM
- 10 LPM
- 50 LPM

Diameter (nm)
Coagulation for EI=5e15/kg

15 m pipe @ 10 LPM

Initial

2 Seconds Later

Nf/No=0.28
Coagulation for \( EI = 5\times 10^{15} / \text{kg} \) w/10 Fold Dilution

15 m pipe @ 10 LPM

Initial

2 Seconds Later

\( \frac{N_f}{N_0} = 0.87 \)
Impact of Dilution on EI

Sample CO
- 3200 ppm (Blue)
- 1600 ppm (Red)
- 800 ppm (Black)

Engine Power vs. (X 1.E15)
Coagulative Growth for EI=5e15/kg

15 m pipe @ 10 LPM

No Dilution

10-Fold Dilution

Count Mean Diameter (nm)

Time (seconds)
Coagulative Losses for E=5e15/kg

10X Dilution

No Dilution
Coagulation + Diffusion Losses for $EI = 5 \times 10^{15}$ kg

- No Dilution
  - 0.25" Tube
    - $EI = 8.5 \times 10^{14}$

- 10X Dilution
  - 0.5" Tube
    - $EI = 2.4 \times 10^{15}$
Relative Humidity of Sample
100 % Power Setting

Relative Humidity (%) vs. Sample Temperature (K)
- No Dilution
- 2:1
- 4:1
- 8:1

Sample Temperature (K): 285 to 310
Relative Humidity (%): 0 to 240
Condensation of Volatile Species

FSC 1820 ppm, 1.3 epr, 1m

University of Minnesota

20 C

300 C
Pressure Drop Across 20 m Tube

Pressure Drop (Torr) vs Mass Flow (LPM)

- 0.25"
- 0.375"
- 0.5"
- 0.625"
- 0.75"

NASACP—2004-21398
Measurement Methodologies
Non-volatile Aerosols

Phil Whitefield
Director UMRCOE
“There is general consensus that the regulations regarding the emission of visible smoke for aircraft engines, which have been in place for decades, do not address and are not relevant to the measurement of particles responsible for health effects and environmental impacts.”

“ICAO, USEPA, USFAA, USDoD Environmental Research Programme of the European Commission Directorate General for Research German Association of Engineers (VDI) have all expressed interest in specifying measurement technology relevant to these present concerns.”

“Working Group 3 of the ICAO Committee on Aviation Environmental Protection (CAEP) has asked the SAE E-31 committee and European Commission AERONET Group for technical assistance in developing appropriate particulate characterization techniques for routine certification of aircraft turbine engines.”
**Development of Recommended Practices for Particulates –**

This position paper outlines the motivation and foundation for the SAE E-31 committee to develop a set of measurement recommendations for particle emissions.

The process of developing these recommendations is being initiated in response to expressed interest from a variety of regulatory and certification agencies.

The scope of these recommendations includes:

- Measurements at the engine exit plane
- Characterization of non-volatile particles
- Exclusion of the characterization of volatile particles

Volatile aerosols have not yet formed when the exhaust leaves the engine and depend sensitively on ambient environmental conditions. Measurement of condensable precursor gases that contribute to volatile aerosol formation and particle growth is a separate and distinct measurement issue and will not be included in the present activity.
Aircraft gas turbine engines emit small particles (<<10 µm) as a result of the combustion of hydrocarbon fuels.

mostly solid carbon particles and metals.
(Soot encompasses all primary carbon-based particle products from incomplete combustion in an engine and may include both pure (optically black) carbon and non-volatile (gray) organic compounds.
Metal particles result from engine erosion and the combustion of fuels containing trace metal impurities or metal particles that enter the exhaust from the fuel.
Metal particle concentrations are several orders of magnitude smaller than those for soot).

aerosols of sulfur compounds and hydrocarbons are formed as the engine exhaust cools.
**Present Controls** - Emissions from aircraft gas turbines are presently regulated for emissions of:
- Oxides of nitrogen (NO and NO2)
- Carbon monoxide
- Total unburned hydrocarbons
- Carbonaceous particulates (soot) as correlated to visible smoke

**PM Regulations** – Smoke Number (SAE ARP 1179, 1997) acquires a sample of the emitted particles on a filter, which is then assayed for an optical smoke stain measurement. The reflectivity of the filter spot is related to the deposited total particle mass by an empirical relationship.

Soot and any aerosols resulting from condensed hydrocarbons or sulfur that are quantified by a smoke number are currently regulated.

“This method has proven to be a useful means of quantifying the visible smoke emissions and, by using this metric, aviation engines have become virtually smoke-free.”
The spot filtration (Smoke Number) method of measuring smoke does not:

discriminate particle size, type, or size distribution,

the measured particles do not represent all of the particles that are important to health or environmental impacts,

The sizes of particles that most strongly affect visible smoke are significantly larger than the particles of consequence for health and environmental effects.

More specific methods of measuring particulates are now required.
How should aviation particles be characterized?

Mass Number concentration  Size and size distribution  Composition

An agreement is required to determine which fraction of the exhaust aerosol becomes subject to regulatory rule. Refractory carbonaceous particles make up the most stable fraction of the exhaust aerosol. The volatile nanoparticle mode is highly variable and depends strongly on the sampling conditions.

Conditions for sampling and considered particle size ranges have to be described very carefully to define the object of measurement unambiguously.

BUT............
Current regulatory interest in stationary source particle emissions is framed by total mass measurements, especially regarding particles that are smaller than 2.5 microns (µm) in classical aerodynamic diameter (EPA PM-2.5; Ref 2.2.a).

**National Ambient Air Quality Standards**

**Particulate (PM 10)**  *Particles with diameters of 10 micrometers or less*

- Annual Arithmetic Mean 50 µg/m³ Primary & Secondary
- 24-hour Average 150 µg/m³ Primary & Secondary

**Particulate (PM 2.5)**  *Particles with diameters of 2.5 micrometers or less*

- Annual Arithmetic Mean 15 µg/m³ Primary & Secondary
- 24-hour Average 65 µg/m³ Primary & Secondary
Accurate particle measurement is susceptible to a number of experimental difficulties:

Requires careful instrument design, calibration, and operation. Reference standards are required and stable absolute references are difficult to maintain.
Sample handling is very important, since small particles can be created downstream of the source by gas-to-particle conversion.
Particle characteristics can be changed by coagulation and condensation effects.
Particles can be lost from the sampled flow due to diffusional, thermophoretic, inertial, and electrical effects which cause deposition on surfaces.

Quantitative interpretation of particle measurements requires carefully specified measurement instrumentation and protocols.
Existing particle measurement techniques for stationary emissions sources have been used for measuring aircraft engine emissions.

**USEPA’s Method 5 (USEPA, 40 CFR 62-297.415)** applied to the emissions from the exhaust stack of an aircraft engine test facility.

- uses a heated line, filter, and ice bath impinger train to collect particles.
- provides a total mass measurement of the particle emission
Advantages:

Method 5 provides a methodology already in practice for stationary sources and thus allows a comparison between aircraft emissions and those of stationary sources.

Disadvantages:

Method 5 will not determine the size, quantity, or size distribution of the particles it entraps. Thus, it cannot characterize particle emissions in the way now required to control impacts on health and environment.

Method 5 applied to aviation sources needs source to be installed in a test house and operated solely for the purposes of emission testing unlike stationary sources, where a Method 5 test could be carried out during routine operation.

Method 5 typically takes hours to acquire the full complement of sample, which requires maintaining a single engine operating condition during that time. Dedicated engine testing using Method 5 would exceed manufacturers typical engine testing times and would be very expensive.
Disadvantages Continued:

Method 5 measures the emissions from the engine and test house in toto. Particles associated with the test facility and the background air used to operate the engine in the test house all contribute to the emissions and can constitute an appreciable fraction of the emissions measured, particularly at the large size end of the emission spectrum. While corrections can be made for some of these effects, they add to the costs and uncertainties of measurement.

Method 5 collects solid soot particles and some fraction of the aerosols from condensed gases, but without distinguishing between the two, and as a result provides an over-estimate of the true particle emissions at the engine exit. Regulatory issues may continue to evolve requiring the distinction between emitted solid particles and exhaust gases which may form secondary pollutants as additional particles through gas-to-particle conversion some time after emission. Method 5 measures a mixture of these two types of emissions that is difficult to quantify precisely.

EPA method 5 is unsuitable for the measurement of particulates from aircraft gas turbines.
What methodologies are currently available or in development:

Nonvolatile PM measurement methods can be divided into two general approaches.

Mass measurement

Particle number density and size measurement
Direct measurement of mass?

Direct measurement of number concentration?

Direct measurement of size and size distribution?

Mass indirectly (mass = f(number conc., size, density))?
Mass measurement includes methods that measure the total mass of emitted particles, without distinguishing size or number of particles emitted.

One technique samples the exhaust stream and collects particle matter on a filter, which is then analyzed for the collected particle mass. Another probes the exhaust flow optically to quantify the scattering material in situ without requiring the exhaust to be sampled and transported to the measurement system.

The amount of particulate matter emitted from aircraft engines can be quantified in terms of mass of particles per volume of gas. Typical units are mg m\(^{-3}\) or \(\mu g m^{-3}\). Reference conditions for the gas volume have to be specified, e.g., \(T = 273.14\) K, \(p = 1013.25\) hPa for Standard Temperature and Pressure (STP) conditions or \(T = 288\) K, \(p = 1013.25\) hPa for Sea Level Static (SLS) conditions. Unless stated otherwise, the particle mass concentration does not refer to a specific range of particle sizes.
<table>
<thead>
<tr>
<th>Measurement Method</th>
<th>Measurement</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric analysis</td>
<td>Total particulate matter, total mass</td>
<td>off line, filter samples</td>
</tr>
<tr>
<td>Combustion of filter samples and CO₂ detection</td>
<td>Total carbonaceous mass, TC</td>
<td>off line, filter samples</td>
</tr>
<tr>
<td>Combustion analysis including OC/EC separation</td>
<td>Organic carbon (OC), elemental carbon (EC)</td>
<td>off line, filter samples</td>
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<tr>
<td></td>
<td>OC + EC = TC</td>
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<td>Optical absorption photometry</td>
<td>Black carbon (BC)</td>
<td>on line, filter samples</td>
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<td></td>
<td>BC = EC</td>
<td>time resolution ≥ 1 min</td>
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<tr>
<td>Laser induced incandescence</td>
<td>Black carbon (BC)</td>
<td>on-line, in situ</td>
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<tr>
<td>Transmissometry</td>
<td>Opacity</td>
<td>on-line, in situ</td>
</tr>
<tr>
<td>Light scattering</td>
<td>Forward scattering</td>
<td>on-line, in situ</td>
</tr>
<tr>
<td>Microbalance</td>
<td>Total particulate mass</td>
<td>on-line, extractive</td>
</tr>
</tbody>
</table>
**Particle temperature**

\[ T \approx 4000 \text{K} \]

**Laser pulse**

\[ t \approx 50 \text{ ns} \]

**Camera gate**

**Incandescence signal**

**Exhaust plume**

**Engine**

**1064-nm pulsed laser**

**Beam dump**

**Camera**

**Beam-directing optics**

**Test cell**

**Laser room**

**Translation Stage**

**Detection unit**

**Power setting**

**Soot mass**

**Average soot concentration (mg/m³)**

**Max**

**Idle Lo-cruise Hi-cruise**

**Soot concentration vs. Power setting**

**Power setting**

**Time (seconds)**

**Soot mass**

**Maximum power**

**s (mm)**

**1064-nm pulsed laser**

**Beam-directing optics**

**Pass-through**

**Laser Induced Incandescence**

**NASA/CP—2004-213398**
Particle number density and size measurement distinguishes the size and number of individual particles.

This type of measurement provides a number density and a particle size distribution derived from a sampled exhaust stream.

The measurement of these parameters can be used, with a value of particle density and information on the particle morphology, to estimate the total mass of the particles.

This approach offers considerably more information about the emitted particles, but it comes at the expense of a more complex and costly measurement system.

The techniques for measuring number and size distribution have been used extensively in atmospheric research and have been refined for use in measuring aircraft engine exhaust.

Particles emitted from combustion sources like an aircraft engine are usually significantly smaller than 1 µm in diameter. Size distributions reported from either aircraft engine test rig experiments or in-flight studies show a modal diameter of 0.03 - 0.06 µm with an average lognormal geometric standard deviation of 1.6. A second but weaker mode was found at a modal diameter of 0.15 – 0.2 µm.
widely used and accepted by academia, industry and government organizations for the characterization of particulate exhaust from diesel and turbine engines. Organizations using these techniques include:

- University of Missouri-Rolla (UMR)
- University of Minnesota
- Air Force Research Laboratory (AFRL)
- NASA Glenn Research Center
- Southwest Research Institute (SwRI)
- United Technologies Research Center (UTRC)
- German Aerospace Center (DLR, Germany)
- Paul Scherrer Institute (PSI, Switzerland).
- Rolls Royce (Derby, UK)
A typical size and number sampling system schematic
Typical TCN trace UMR data points no. 260-264 Eng No. 074613 Power setting 4 Fuel +100 (02N21 545p TCNA - T.xls)

\[ \langle \text{TCN} \rangle = (3.8 \pm 0.1) \times 10^6 \] (1σ) 102 data pts in 230 secs, sample rate = 0.46 Hz
115

NASA/CP—2004-213398

Number

Surface Area and Mass
Particle Measurement Methodology

Douglas Worsnop
Aerodyne Research

Aviation Particle Emissions Workshop
West Olmstead, OH

November 18-19, 2003
Atmospheric Aerosol Sources and Effects

- Polar Stratospheric Cloud (PSC)
- Stratospheric Ozone Depletion
- Junge (Sulfate) Layer
- Contrail and Cirrus Formation
- Soot, Sulfate
- Direct Climate Effect
- Indirect Climate Effect
- Cloud Condensation Nuclei
- Indirect Effect
- Urban/Industrial Pollution (Soot, Smog)
- Health Effects
- Secondary Aerosol Formation/Growth
- Acid Deposition
- Marine Aerosols
- Rain
- Visibility Reduction
- Regional Aerosol

NASA/CP—2004-213398
Aerosol Size and Composition

Goal: Size Resolved Chemical Composition of Ambient Aerosol
Air Quality Suspended Particulate Regulation

1970’s   TSP   Total Suspended Particulate
          “Equivalent to Smoke Number”

1980’s   PM10  Inhalable particulate Mass < 10 micron diameter

1990’s   PM2.5  Fine particulate Mass < 2.5 micron diameter

2000’s   PM1.0  ??  Nanoparticles ??

Health effects (and visibility)
push science (regulation?) to smaller particles

New (cleaner) technology push combustion emissions to
smaller (nano-???) particles (e.g. diesel)
Outline

• Air Quality Emissions Inventories
  – *Measurement Challenges:* *Particles* *(and gases)*

• Size Resolved Chemistry
  – *Nano:* <10nm  *ultrafine:* <100nm  *fine:* <1 µm  *coarse:* >1 µm
  – Black carbon  semi-volatile organics  sulfate  metals

• Physical and chemical measurements
  – *Real time:*  *seconds to minutes*
    – AMS: bulk chemistry vs aerodynamic diameter
    – SMPS: number density vs mobility diameter
    – Nephelometer, PSAP: Black Carbon
    – TEOM: total mass
  – *Collected particles:*  *hours*
    – “complete” chemical analysis (PM2.5, EC/OC, air toxics, limited sizing)

• Measurement examples
  – Portable Lab ground-based measurements
  – EXCAVATE (Langley), JFK, Logan runway experiments  ➔ *Dryden, LAX*?
Mass Distribution: Urban Site  New York City (SUNY Albany)

Primary vs Processed Organic Aerosol
Aircraft Particle Size Distribution

\[ \text{dN/dlogD [kg]} \]

\[ 10^{18} \]

\[ 10^{17} \]

\[ 10^{16} \]

\[ 10^{15} \]

\[ 10^{14} \]

\[ 1 \]

\[ 10 \]

\[ 100 \]

\[ N_0 = 2.4 \times 10^{17} \]

\[ \text{sigma} = 1.55 \]

\[ D_{\text{mean}} = 1.8 - 7 \text{ nm} \]

\[ \text{Environmental Variability} \]

\[ \text{Condensation Growth} \]

\[ \text{ATTAS} \]

\[ \text{B-737} \]

\[ 2.6 \text{mg/kg} \]

\[ \times \text{ATTAS} \]

\[ 118 \text{mg/kg} \]

\[ \circ \text{ATTAS} \]

\[ 2700 \text{mg/kg} \]

\[ \text{F. Schroeder et al., JGR 105, 19,941-19,954, 2000.} \]
Measurement Challenges

- Real-time Platform for (Gases and) Particles
- Sub-micron size and composition
- Engine Emissions measurement
- Test cell
- On-Wing: Evolution of plume away from engine
- Airport
- Downwind of runway
- Circling of Airport
- Connect engine exit to local/regional air quality
EXCAVATE

Sampling Probe

Aerosol Chemistry of Commercial Aircraft Emissions NASA EXCAVATE Experiment
Switched between sampling at 1 and 25 meters

10 and 35 (with plane forward)
“In-plume” sampling indicated by above-ambient CO₂ levels

Gas or Particle Signal

Time

CO₂ (ppm)

Emission perturbed level

Ambient background level

ΔCO₂

ΔSignal

Emission Ratio = \frac{\Delta \text{Signal}}{\Delta \text{CO₂}}
Organics µg m⁻³

Sulphates µg⁻³

Eng. Power (EPR)

January 26, 2002

Probe (m)

NASA/CP—2004-213398
Evolution of Particles: 1 to 25 meters

Figure 2: Variation of average aerodynamic diameter of sulfate and organics at 1 and 10 M for engine power of 1.3, 1.4, and 1.5 EPR.

Sulfate
Volatile
Organic primarily oil

Observed Growth: condensation of semi-volatile vapors
EXCAVATE Emission Indices (g/kg Fuel)

**Engine power**

- **Sulfate**
  - 5mg/kg fuel

- **Volatile Organic**
  - 20-60 mg/kg fuel

**Probe distance**

- **Sulfate**
  - 5mg/kg fuel

- **Volatile Organic**
  - 20-60 mg/kg fuel
Aerosol Chemistry:  *Steady State Operation of B757*

- Black carbon dominates at high power
- EC/OC higher than diesel at aircraft steady state
Aerosol Number (UMN) and Mass (ARI) at 35 meter behind 757 at 1.4 EPR

**UMN Nano-DMA**

**ARI AMS**

Sulfate (x10)  Organic C
MASS Distributions – B757 at 1.3-1.5 EPR

Fuel Sulfur = 1050 ppm
Probe Distance = 25 m
EPR = 1.30, 1.40, 1.50

SMPS
physical size

AMS chemical
organic / sulfate

25 meters
**MASS Distributions – B757 at 1.3-1.5 EPR**

Fuel Sulfur = 1050 ppm  
Probe Distance = 25 m  
EPR = 1.30, 1.40, 1.50

- **SMPS**
- **Organics**
- **Sulfate**

**25 meters**

- **Black carbon**
- **Small sulfate**
- **Sulfate coating**
- **Organic (oil) coating**
Transient high mass loadings (~5000 μg m⁻³) occurred during engine start-up and shut down.
Mass loadings during steady conditions ranged from 1-30 μg m⁻³.
Organics size distribution during transient periods

Engine power down  Engine power up

Average vacuum aerodynamic diameter ~ 40-60 nm

x100 increase in organic (oil/fuel) loading for minutes
ARI Mobile Lab at JFK

Scott Herndon, John Jayne et al
Simultaneous Gas and Particle Monitoring

Scot Herndon (ARI)

Particle Mass

Gases
NO\textsubscript{x}, NH\textsubscript{3}, CH\textsubscript{2}O

Air Toxics (PTRMS)

Logan Airport, Boston
Outline

- Air Quality Emissions Inventories
  - Measurement Challenges: Particles (and gases)

- Size Resolved Chemistry
  - Nano: <10nm    ultrafine: <100nm    fine: <1 µm    coarse: >1 µm
  - Black carbon   semi-volatile organics   sulfate   metals

- Physical and chemical measurements
  - Real time: seconds to minutes
    - AMS: bulk chemistry vs aerodynamic diameter
    - SMPS: number density vs mobility diameter
    - Nephelometer, PSAP: Black Carbon
    - TEOM: total mass
  - Collected particles: hours
    - “complete” chemical analysis (PM2.5, air toxics, limited sizing)

- Measurement examples
  - Mobile Lab, ground-based measurements
  - EXCAVATE, JFK runway experiments
Summary

• Size Resolved Chemistry
  – **Nano**: <10 nm **ultrafine**: <100 nm **fine**: <1 µm **coarse**: >1 µm
  – Black carbon semi-volatile organics sulfate metals

• Physical and chemical measurements
  – **Real time**
    – Size and (limited) chemistry
    – Transients – engine cycle
    – **Exit Plane (< 1 meter behind engine)** ⇒ **Plume (> 20 meter)**

  – Comprehensive (PM2.5) Chemical analysis of collected particles (hours)
    – “complete” chemical analysis (limited size resolution)
    – Air toxics

• Test cell ⇒ on wing ⇒ runway/airport ⇒ local air quality (model)

• Intensive (few engines/planes) ⇒ Commercial aircraft fleet
Summary

Detailed chemistry and microphysics

⇒ Comprehensive (PM2.5) Chemical analysis

Test cell ⇒ on wing ⇒ runway/airport ⇒ local air quality (model)

Intensive (few engines/planes) ⇒ Commercial aircraft fleet

Research / Certification ⇒ Regulation / Monitoring

Engine technology ⇒ Air Quality

• Analogy to evolution of both measurement and technology of diesel engines
Summary

Airport Measurement of Gas and Sub-Micron Particle Emission

input to local / regional air quality model

Aerosol number nanoparticles?

Sub-micron volatile mass
Outline

• Air Quality Emissions Inventories
  – Measurement Challenges: Particles (and gases)

• Size Resolved Chemistry
  – Nano: <10nm  ultrafine: <100nm  fine: <1 \( \mu \text{m} \)  coarse: >1 \( \mu \text{m} \)
  – Black carbon  semi-volatile organics  sulfate  metals

• Physical and chemical measurements
  – Real time: seconds to minutes
    – AMS: bulk chemistry vs aerodynamic diameter
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    – TEOM: total mass
  – Collected particles: hours
    – “complete” chemical analysis (PM2.5, air toxics, limited sizing)
MIT-CAM-ARI
Field Measurement Campaign

Aerodyne Mobile Lab
MCMA 2003

AMS
Aerosol Mass Spec
Size Resolved Composition
30 nm - 2 μm
NO$_3^-$, SO$_4^{2-}$, NH$_4^+$
Organic Carbon

Relative Humidity
Pressure
Temperature
Velocity

TDL
Tunable Diode Lasers
NO$_2$, HCHO

PTR-MS
Proton-Transfer Mass Spec
Selected VOCs

QCL
Quantum Cascade Laser
NH$_3$ 1 s rms ~ 500 ppt

Aethlometer
PM 2.5

NO$_y$
Chemiluminescence

NO$_x$
Chemiluminescence

CO
N.D. IR Absorption

SO$_2$
Fluorescence

O$_3$
UV Absorption

PeroxylAcetyl/Nitrate
LC. Fluorescence

CO$_2$
Lcor N.D. IR

NO$_y$ converter

Roof
Sun Photometer
Anemometer
GPS

Cyclone < 2.5 μm

sokinetic sample splits

Rear Roof Inlet

Videoc Camera
Aircraft Plume Analysis (take-off turbine engine)

Take-off

Take-off Taxi

NO + NO₂ (ppb)

CO₂ (ppm)

390
380
370
360

9.8 ppb NOₓ ppm⁻¹ CO₂

30 g NOₓ kg⁻¹ Fuel

21:15 8/2/2001

Preliminary Results: NO\textsubscript{x} Emission Ratios by Aircraft State

Emissions one aircraft at a time, taxi and take-off

<table>
<thead>
<tr>
<th>Mass NO\textsubscript{x} Emission Index (g NO\textsubscript{x} kg\textsuperscript{-1} Fuel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Aircraft Plumes</td>
</tr>
<tr>
<td>Turbine Engine Aircraft</td>
</tr>
<tr>
<td>Taxiway Idle</td>
</tr>
<tr>
<td>Taxiway Acceleration</td>
</tr>
<tr>
<td>Runway Take-Off</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Molar NO\textsubscript{x} Emission Ratio (ppb ppm\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0  2  4  6  8  10  12  14  16</td>
</tr>
</tbody>
</table>

08/02/01 19:34:48

08/02/01 20:41:34
Particle Modeling -
Current Understanding and Issues:
Post combustor particle processes

Prepared by
R.C. Miake-Lye
Aerodyne Research, Inc.,
Billerica, MA 01821-3976 USA
Regimes

- Ambient
- Combustor ➾ Med’s talk
- Turbine/Nozzle
- Plume/Wake
- Far-Wake/Corridors
- Ambient

- Probes

Aerodyne Research, Inc.
Processes

- **Chemistry**
- Nucleation
  - Heterogeneous on existing particles
  - Homogeneous (binary or multi-component)
- Condensational growth
- Coagulation
- Impact of ions (versus recombination)
Particle Evolution Stew

- Gas Phase Chemistry
  - Homogeneous Nucleation
  - Coagulation and Condensation
  - Mixing and Dilution

Aerodyne Research, Inc.
What we do know

- Carbonaceous non-volatile particles (soot)
- Volatile particles
  - Sulfate plays an important role
  - Condensable organics’ role is significant but still being defined and understood (especially at low sulfur levels)
    - UHCs
    - Lubricating oil
- Emitted particle size distribution(s)
  - Bimodal
  - Non-volatile and volatile components
- Ions are present and affect particle processes
What we do know (cont’d)

- Models now include the primary particle processes
- Comparisons between existing models and measurements demonstrate basic thermodynamics and kinetics represent the observations
Measured Particle Size Distribution


*Aerodyne Research, Inc.*
What we don’t know

◆ What is important?
  ■ For environmental impact (global and regional)
  ■ For health effects/local air quality
  ■ What will be regulated?

◆ Lacking quantitative comparison between model parameters and specific observations
  ■ Ion impacts not fully quantified
  ■ Relative role of sulfates and condensable organics indeterminate
  ■ Which organics are important (fuel versus oil?)

Aerodyne Research, Inc.
What we don’t know (cont’d)

◆ Volatile component on “non-volatile” particles
  ■ Sulfur or organics or both
  ■ Partitioning of volatile species between volatile particles and condensed matter on non-volatile cores
  ■ Relative mass of volatile component on non-volatile core

◆ Particle evolution in turbine/nozzle not well understood (NASA/QinetiQ versus Partemis)
What we don’t know (cont’d)

◆ How to sample exhaust with condensable gases: particle processes in probes
◆ Relationship between combustor particle emissions, their engine exit properties, and particles deposited in the atmosphere
NASA Workshop on Aviation Particle Emissions
November 18, 2003
United Technologies Research Center
Med Colket and Dave Liscinsky

Carbonaceous Particulates from Combustors
Particulate Issues

**PM 2.5 is Primary Threat**

**Combustor** (chemical reactions)
- Fuel $\rightarrow$ CO$_2$, H$_2$O
- PAH, soot (at power)
- UHC (idle)
- fuel vapor (shut down, start up)
- Fuel S $\rightarrow$ SO, SO$_2$
- Air N2 $\rightarrow$ NO, NO$_x$

**Turbine** (quench)
- H$_2$O, soot
- PAH $\rightarrow$ condensed particulates
- fuel vapor
- SO, SO$_2$
- NO $\rightarrow$ HONO

**Near field** (quench, nucleation)
- H$_2$O soot
- fuel vapor
- SO$_3$ $\rightarrow$ H$_2$SO$_4$

**Far field** (absorption, condensation)
- nuclei
- particulates, condensed particulates, aerosols, droplets

**Plume Evolution & Growth**
- Smoke & Soot Particulates (PM-2.5)
Other PM matter

*Carbonaceous soot is only part of problem*

- Sulfur/sulfates
- Partially burned HCs
- Unburned Jet fuel (start-up/shutdown)
- Lubricating oils
- Tires (landings)
- Metals

- Uncertainties w.r.t. hydrophobic characteristics of non-volatiles
**Soot Formation/Oxidation in Aeroengines**

*Avoid E.R. > 1.6 for formation and T < 1600-1700K for quench*

---

**Fuel decomposition => soot formation => soot oxidation**

![Diagram of fuel decomposition and soot formation](image)

**Formation of Soot:**

\[
\frac{d\text{ (soot mass)}}{dt} = R_{\text{inception}} + R_{\text{surface growth}} - R_{\text{oxidation}}
\]

**Inception:**

\[
R_{\text{inception}} = k_{\text{inception}}[\text{aromatic}][C_2H_2]
\]

**Surface Growth:**

\[
R_{\text{surface growth}} = k_{\text{growth}} \frac{3m}{r} [C_2H_2]
\]

**Oxidation: \(O_2\) and \(OH\):**

\[
R_{\text{oxidation}} = R_{O_2}(NSC) + k_{OH} \frac{3m}{r} [OH]
\]

---

**Unoxidized Soot => Visible Smoke Emissions**

**Soot Formation**

**Soot Oxidation**

---

**Temperature (K)**

![Temperature vs. Equivalence Ratio Graph](image)

**Equivalence Ratio**

0 1 2 3

**Lean** => **Fuel rich**

---

**C_{12}H_{23}** spray, vaporization

**C_{x}H_{y}** Alkylated - aromatics

**C_{2}H_{2}** naphthenes

**PAH** Gas -phase kinetics

**C_{2}H_{2}** PAH oxidation products

---

**Inception**

\[
R_{\text{inception}} = k_{\text{inception}}[\text{aromatic}][C_2H_2]
\]

**Surface Growth**

\[
R_{\text{surface growth}} = k_{\text{growth}} \frac{3m}{r} [C_2H_2]
\]

**Oxidation: \(O_2\) and \(OH\):**

\[
R_{\text{oxidation}} = R_{O_2}(NSC) + k_{OH} \frac{3m}{r} [OH]
\]
Particle Size Statistics

- Lognormal distributions describe most particle data
  - Polydisperse, size range generally > two orders of magnitude
  - Only carbonaceous material

- Statistical properties
  - Median - nm
  - Mean - nm
  - Concentration
    - $\frac{dN}{d\log dp}$ (#/cm$^3$)
      - $dN$ is concentration over size range
      - Log scale covers wide size range
  - Volume – nm$^3$/cm$^3$
  - Convert to mass with assumed density

Note that reductions using +100 presented here have not been repeated.
Normalized Distributions at 200 psia and 500F
Following Harris and Maricq (2003)

\[ m = \frac{dn}{d(\ln(d_p))}/N \]

- JP-8, f/a=0.032
- JP-8, f/a=0.040
- JP-8, f/a=0.044
- JP-8+100, f/a=.032
- JP-8+100, f/a=.040
- JP-8+100, f/a=.044

Harris and Maricq
H&M, \sigma=1.8
Sizing by Electron Microscopy (TEM) – Old engine technology

Significant agglomeration observed – engine or sampling artifact?

Soot collected by impact on a TEM grid in SBIF III from behind an F16 (primary particle diameter = ~ 40 nm)

Soot collected by impact on filter paper from an engine (primary particle diameter ~ 60 nm)

Elwood, P&W
Aircraft Carbonaceous PM Measurement Challenges

• Needs and Standards
  – No standard methodology or instrumentation established
  – No standard quantification unit established
    • EPA uses mass-based, engine manufacturers likely to use EI
  – Not clear which parameters are of interest to agencies regulating aircraft emissions (e.g., #, mass, or size)

• Particulates Probe
  – Difficult to characterize probes at realistic engine conditions
    • Very high exhaust temperature and velocity flows
    • High inertia of exhaust PM and potential leaks in dilution flow through probe tip result in inaccurate measurement
  – Probe axial location
    • Near engine: primary (carbonaceous) particles formed in engine
    • Far engine: plus secondary particles (volatiles) to study atmospheric impacts
  – Probe design
Aircraft PM Measurement Challenges

- Particulate Matter Sampling
  - Most turbine engine PM emissions are nanometer diameter size
  - Small particles can stick to walls of probe and transport lines
    - leading to loss and measurement uncertainty
  - Effects of sample conditioning
  - Particles may undergo change from sampling point to instrument
  - Gas-to-particle conversion, Coagulation, Thermophoresis, Condensation/ evaporation
    - Sample dilution near sampling point believed to alleviate most of these problems

- Fuel chemical composition will impact PM emissions
  - Aromatic and sulfur content
**Schematic of Particulate Sampling System**

*Dilution is used to minimize particle coagulation and condensation*

- **Combustor**
- **Heater**
  - Particle free N2 (20-50 slpm)
- **Impactor**
- **Smoke meter**
  - Exhaust
- **Cyclone cascade**
- **Electrostatic classifier**
- **CN Counter**
- **Gas Emissions (CO₂ & O₂)**
  - Diluted sample
- **Gas Emissions (THC, NOₓ, CO, CO₂ & O₂)**
  - Undiluted sample
  - Cell wall
  - Heated lines
- **Sample should be diluted at probe entrance**

Dilution is used to minimize particle coagulation and condensation.

Sample should be diluted at probe entrance.
Correlation of Smoke Number

Independent of soot particle size – but ~ factor of two uncertainty

Smoke No. - Mass Correlations

Smoke No. measured and soot mass computed from measured particle size distribution and number density (DMA/CNC) assuming particle sphericity and known density.
Photographs of filters from Anderson Impactor

Andersen Impactor
Particle Loading for
JP-8 at f/a = 0.044,
P3 = 200 psia and T3 = 500 F
SEM Photomicrographs of Particles using Andersen Impactor

*Particles are ~ 70-100 nm for all stages (exceptions)*

Some rogue particles, but majority are 70-100 nm
- rogues may be sampling line artifacts

Stage 4 (4.4 - 2.8µm)  Stage 7 (0.88 - 0.60µm)  Stage f (< 0.60µm)

Note large particles were targeted

SEM Photomicrographs of Andersen Impactor Filters at 10,000x
(JP-8 at f/a = 0.044, P3 = 200 psia, T3 = 500 F)
SEM Photomicrographs of Particles using Andersen Impactor

Particles are ~ 70-100 nm, even for Stage 4 (2.8µm at 30kx magnification)
Concerns (unranked)

- Role of sulfur/aromatics on non-volatile emissions for advanced engines
- Size range of particles as function of engine operating conditions
- Level of agglomeration
- Hydrophobic vs. hydroscopic character
- Non-volatiles as nucleation site for HC
- Speciation
- Control of emissions via combustor design (and trade-off between volatile and non-volatile emissions)
- Relative role of non-volatile PM vs. total PM inventory
- Relative health effects of different PM
- Probe/turbine effects
- Mass vs. # vs. size
Modified F119 - Mean Particle Diameter Reduced with +100
Other Results on JP-8+100

Confusion persists

- NAVAIR – no change
- AFRL – reduction, but time effect observed
- Southwest Research Institute
  - Reduction
  - Including information on PAH

NAVAIR

Test Data For All Non-Afterburning Engines Operation Power Settings

- Average of No Additive Data
- No Additive Data (247 Cycles)
- Average of Additive Data
- Additive Data (150 Cycles)

Reduction in Particulate Mass Emission Index with JP-8+100

- Negligible impact on particulate emissions at two hours of operation with additive
- Significant reductions with continuous use of additive
- Highest impact at low power
- Potential for much greater improvements
- Second tests planned to verify results

FUEL & ADDITIVE EFFECTS ON PARTICLE SIZE DISTRIBUTION (PSD)

- 4 to 5 consecutive scans in each data set show repeatability
- Fuel and Additive effects apparent; changes did not affect mean size
Database and Inventory - current understanding & issues

Steven L. Baughcum
Boeing Company

NASA Aviation Particle Emissions Workshop
November 19, 2003
Outline

• Background
  – How do we currently calculate gas phase emission inventories?
  – What do we need to calculate for particulate inventories?

• Approach to particulate inventories

• Data needs
Gas Phase Emissions Data

Standard ICAO emissions databank data for CFM56-2-C5
Landing/Takeoff (LTO) data - Standard Day Conditions Sea level static

<table>
<thead>
<tr>
<th>Mode</th>
<th>Power Setting</th>
<th>Time (minutes)</th>
<th>Fuel Flow (kg/s)</th>
<th>EI(HC)</th>
<th>EI(CO)</th>
<th>EI(NOx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff</td>
<td>100%</td>
<td>0.7</td>
<td>0.985</td>
<td>0.04</td>
<td>0.9</td>
<td>18.5</td>
</tr>
<tr>
<td>Climbout</td>
<td>85%</td>
<td>2.2</td>
<td>0.819</td>
<td>0.05</td>
<td>0.9</td>
<td>16.0</td>
</tr>
<tr>
<td>Approach</td>
<td>30%</td>
<td>4</td>
<td>0.311</td>
<td>0.08</td>
<td>4.2</td>
<td>8.2</td>
</tr>
<tr>
<td>Idle</td>
<td>7%</td>
<td>26</td>
<td>0.128</td>
<td>1.83</td>
<td>30.7</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Non-standard conditions:

- Calculated from engine thermodynamical cycle data combustor inlet temperature/pressure (T3/P3) data (Proprietary data)

- Calculated using empirical fuel flow method data based on T3/P3 analyses (e.g., Boeing Method 2 or DLR method)
Gas Phase Emission Inventories

- Airport vicinity
  - Departure/Landing data (number of flights by airplane/engine/combustor type)
  - Combine “time in condition” data with appropriate ICAO LTO emissions data

- Global inventories of cruise emissions (gridded)
  - Flight schedule data (departure city, arrival city, airline, airplane type)
  - Match airline data to determine engine and combustor type on airplane
  - Fly each mission (e.g., great circle route) using airplane performance data
    - Altitude increases as airplane uses fuel and gets lighter
    - Fuel burn rate changes as airplane gets lighter
  - Calculate emissions using fuel flow method at each point along the mission
    - Comprehensive database of emissions from ICAO
  - Combine data for all airplane/engine/combustor combinations
2020 Airplane Market Projections

- Fleet Mix Projections
- Regional Growth Projections

2020 City-Pair Level Flight Schedule

2020 Aircraft Performance Characteristics
- Performance Characteristics of Future Aircraft
- Performance Characteristics of Existing Aircraft

2020 Aircraft Emissions Characteristics
- Emissions Characteristics of Future Aircraft
- Emissions Characteristics of Existing Aircraft

Global Atmospheric Emissions Code (GAEC)

2020 Scheduled Fleet 3-Dimensional Emission Scenario
What is Needed for Particulates?

- Which particulate emissions?
  - Soot?
  - Sulfate aerosols?
  - Organic aerosols?

- What properties?
  - Total mass?
  - Total number of particles?
  - Surface Area?
  - Particles within some size range?

- Where?
  - Airport vicinity (sea level static)?
  - Regional?
  - Global (cruise conditions)?
Smoke number has decreased with time

Max Smoke Number Historical Trend

- Smoke number measurements reported in ICAO databank for all certificated engines
  - For many engines, only peak smoke number is reported
Can smoke number characteristics of different engines have similar functional forms?

Smoke Number forms

Analysis by Doug DuBois
How well does the NOX data collapse for the different variants of the CFM56?

ICAO Emissions Databank NOx for CFM56

- Considering only single annular combustors

Analysis by Doug DuBois
Does the Smoke Number data collapse for the different variants of the CFM56?

**ICAO Emissions Databank SN for CFM56**

- Considering only single annular combustors

Analysis by Doug DuBois
Approaches to Soot Inventories

- Zero order
  - Scale fuel burn with a single scalar [e.g., 0.04 grams/(kg fuel burned) (Döpelheuer, 1997)] to estimate mass loading
  - Use for scoping studies with atmospheric models to understand relative importance compared to other soot sources (e.g., ongoing GMI studies)
  - Doesn’t account for technology

- First order
  - Develop representative characteristics for different generations of engines/combustors to account for technology changes
  - Need data on modern engines/combustors
  - Different approaches to combustor design (e.g., lean versus rich) will be important
Approaches to Soot Inventories (cont.)

- Detailed calculations
  - Similar to our approach with NOx inventories
  - Need methodology to calculate soot at different ambient and engine (T3/P3/Fuel air ratio?) conditions (single mission)
    - Can combustor soot modeling provide insights?
  - Need empirical methodology equivalent to a fuel flow methodology for practical inventory calculations
  - Need detailed data to develop methodologies
  - Need extensive data to build inventory
Sulfate Aerosol Inventories

- Sulfate aerosol production
  - Sensitive to fuel sulfur levels
    - Maximum jet fuel sulfur level is 3000 ppm
    - Typical level is 400-500 ppm
    - Varies with fuel source and refinery technology (e.g., hydro treating)
    - Varies with other demands on refinery output
      - Pressure to reduce sulfur in diesel will change jet fuel sulfur loading
      - Unclear whether it will increase or decrease
  - Thus, will vary regionally and seasonally
  - Limited fuel sulfur data available
  - Most fuel sulfur will be emitted as $\text{SO}_2$
Sulfate Aerosol Inventories (cont.)

- Sensitive to engine operating conditions and design
  - $\text{SO}_2 \rightarrow \text{SO}_3$ conversion in engine (~2-3%) (Arnold et al.)
  - Research issue (MIT/Aerodyne/DLR)
  - How much does this vary with
    - Power setting?
    - Ambient conditions?
    - Combustor design?
    - Engine?

- Plume Evolution
  - Sensitivity to ambient temperature/humidity
  - Other factors?

- Is this a local airport issue or a global issue or both?
Organic Aerosols

- Essentially no data now (from an inventory perspective)
  - Steady state versus transients?
  - Primarily an airport vicinity issue?

- Are these a subset of the total hydrocarbon measurements now made?

- Which organic aerosols will persist as aerosols and which will evaporate relatively quickly?

- What is the composition of these aerosols?
  - Organic aldehydes/ketones/acids?
  - Large chain hydrocarbons?
  - Unburned fuel?
  - How does it change with power setting?
The Path Forward

?
Aviation-Related Particulate Matter Databases and Test Venues

Gregg G. Fleming
Roger L. Wayson
Volpe Center Air Quality Facility
Environmental Measurement and Modeling Division
and
Julie Draper
Federal Aviation Administration
Motivation

- EPA and others have identified PM as a significant health issue.
- Federal regulations require an environmental assessment be conducted to assess significant actions at airports, e.g., new/extended runways, etc.
- Related air quality, including PM emissions, must be estimated and shown to be in compliance with the National Ambient Air Quality Standards (NAAQS) or in conformity with the SIP.
Current Situation

- Regulations must be met today – the “reality”.
- A standard methodological approach is required to ensure equitable comparability from project to project (i.e., airport to airport).
- Standardized PM measurement techniques do not exist.
- Two parallel development tracks:
  - Existing PM Databases.
  - PM Measurement Methodologies – E-31 lead.
- Stakeholders: NASA, FAA, EPA, SAE, ICAO, Academia (UMR COE and FAA COE), and Industry.
Existing PM Databases

- Current practices for estimating mass-based emissions differ.
  - Many issues remain, e.g., in probe-based, probe characteristics,
    mass-based PM data are most desirable to meet regulatory
    requirements, but very little exist.
    Development of a from-scratch measurement-based database in
    the near term is not a realistic expectation.
Existing PM Databases

- ICAO Emissions Database is the most complete PM-related databank – contains smoke number (SN).
- Not complete for all commercial aircraft.
- Sometimes lacks modal differences.
- SN does not always correlate well with mass emissions of PM, which is what’s required under EPA regulations.
Existing PM Databases

- Much more complete than any other existing database.
- Allows for assessment of changes in PM mass emissions due to changes in fleet mix and aircraft modes.

Recognizing this...

- Led to a comprehensive FAA/Volpe review of past research in the area of aviation-related PM (FAA’s First-Order Approximation).
**Objective:** To allow for an informed decision to be made on a possible first-order approximation to predict mass of PM emissions in lieu of a suitable measurement methodology, which is likely to be several years out.

- Based on all data currently available.
- A combination of methodologies put forward primarily by the University of Missouri Rolla and the German Aerospace Center, DLR.
- Allows for an approximation of the mass emissions for most aircraft engine types as well as accounting for fleet changes and mode.
- Consistent with the approach used for other pollutants.
Development of FOA

- The derived mass-based factor should be more accurate than those that have been used in the past.
- Testing against existing independent data indicate that the derived FOA would provide reasonable emission rates for use by airport operators.
- The FOA will continue to evolve as more data becomes available, and until new measurement techniques become available.
- Example future enhancements include smoke number behavior, effects of additives and/or impurities in the fuel, and inclusion of the volatile components, which is currently very difficult to quantify.
Residual Findings of FOA Study

- Small PM is considered to be a health concern.
- Most PM emitted by modern transport aircraft has an aerodynamic diameter of less than 2.5 μms (μm), i.e., important considering the EPA health-based standards for PM$_{2.5}$ and PM$_{10}$.
- PM is irregular in shape and often coagulate.
- PM include both volatile and non-volatile components.
- Soot is the most prevalent, non-volatile component.
- Metals are emitted, but in extremely small amounts.
Residual Findings of FOA Study

- Effects on PM emission indices include fuel flow, engine design / operating conditions, altitude, and fuel composition.
- Deposition measurements near airports have shown the impacts of aircraft activity on particulate matter concentrations to be minimal.
- EPA Method 5 testing could be used to quantify particulate matter from the jet turbine engine exhaust, but is cost prohibitive and raises some technical questions on applicability to aircraft.
• Dryden Measurements.
  - Douglas DC-8-72 (4-engine aircraft).
  - Re-engined in April 1986 (CFM56-2C).
• Airline/Airport Measurements.
  - First half 2004.
  - 2 to 4 aircraft in a controlled environment.
  - Many in-situ aircraft (old and new technology, differing environmental conditions, etc.).
Measurement Studies/Test Venues

- Probe-based measurements:
  - Well understood.
  - "Gold" Standard.
  - Time-consuming, expensive process.
  - Different measurement techniques and hardware.
- LIDAR-based measurements (feasibility study):
  - Mass-based measurements, using light backscatter.
  - Time-efficient method of measurement.
  - Large sample capability.
  - New methodology requiring development.
  - Requires sensitivity/calibration.
Effects of Particles from Airports on Air Quality: Issues and Uncertainties

Don Wuebbles

Department of Atmospheric Sciences
University of Illinois, Urbana, IL

November, 2003
Conflicting Messages in the Media

(Chicago) December 19, 1999 - The City of Chicago today released two air quality studies that show that O'Hare International Airport has a minimal impact on air quality in the area around the airport, compared to other sources such as motor vehicle traffic and industrial operations. Further, the studies show the airport and its airline tenant have significantly reduced aviation contributions to local and regional pollutant emissions.

O'HARE RANKS AS MAJOR POLLUTER: "LIKE HAVING A POWER PLANT AS A NEIGHBOR"
NRDC (1996)

EPA (2000)
Near O'Hare: Emissions from the airport have an impact on air quality of adjacent communities, but those levels are not higher than those found in typical urban environments throughout the U.S.
Smoke Number

- Existing controls on aircraft particle emissions based on smoke number
  - Dominated by largest soot particles collected onto a filter
  - Sampling particles smaller than 300 nm too inefficient
    - Most soot particles being emitted from current engines much smaller than this
Relative Cancer Risks

Based on ARB monitoring data 1995 - 1997

Chicago: 30 mile cancer risk
Cancer risks due to airport emissions exceed the EPA's limit of 1 per million in 98 communities

Acceptable cancer risk by EPA standards
2x acceptable cancer risk
5x acceptable cancer risk
10x acceptable cancer risk
100x acceptable cancer risk

Source: City of Park Ridge, Illinois
# U.S. Particle Standards

<table>
<thead>
<tr>
<th>Particle Size</th>
<th>Level</th>
<th>Averaging Time</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$</td>
<td>15 $\mu$g/m$^3$</td>
<td>Annual</td>
<td>3-year arithmetic average, spatial averaging</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>65 $\mu$g/m$^3$</td>
<td>24-hour</td>
<td>3-year average of 98th percentile at each monitor</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>50 $\mu$g/m$^3$</td>
<td>Annual</td>
<td>3-year arithmetic average – no spatial averaging</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>150 $\mu$g/m$^3$</td>
<td>24-hour</td>
<td>3-year average of 99th percentile at each monitor</td>
</tr>
</tbody>
</table>
Sources of Ambient PM2.5

Combustion-generated air pollution encompasses all key air issues

- Stationary and mobile sources
- Non-anthropogenic sources

Non-Combustion Sources

CFCs
Stratospheric Ozone Depletion

Ecosystem Effects

Global Warming

Acid Rain

PM2.5/Visibility

Health Effects

HAPs/Toxics

Smog

SO₂

NOₓ

SO₃

NH₃

H₂O

HCl, HAPs

SVOC

Metals soot

The majority of ambient PM2.5 is formed in the atmosphere from precursors which are not particles at the emission point.

Relative contribution of different sources?
PM 2.5 In Ambient Air - A Complex Mixture

Primary Particles (Directly Emitted)

Secondary Particles (From Precursor Gases)

- Carbonaceous
- Other
- Crustal
- Secondary Organics
- Ammonium Sulfate
- Ammonium Nitrate
- NOx
- Ammonia
- SO2
- VOC

June 2000 / tgp
Ambient Particle Size Distribution

Particle Aerodynamic Diameter (µm)

Relative Concentration

PM 0.1
PM 2.5
PM 10
TSP

PM 10
PM 2.5
PM 0.1

Sulfate, Nitrate, Ammonium, Organic & Elemental Carbon, Heavy Metals, Clays

Geological Material, Pollen

Carbon

ultrafine

Accumulation

Coarse

Watson et al., 1998
PM$_{2.5}$ and 8-hour Ozone Standards Attainment

- Based on available 1999-2000 PM$_{2.5}$ data, 173 counties nationwide are likely to exceed the fine particle standard.

- Currently 82 million people live in 173 counties with projected concentrations greater than 15 ug/m$^3$ (the annual fine particle standard).

*1997-1999 Ozone
1999/2000 PM$_{2.5}$—preliminary depiction based on two years of data. Three years of complete data are required for attainment demonstrations.
PM2.5 Ambient Composition

Note: PM-2.5 mass concentrations are determined using at least 1 year of monitoring at each location using a variety of sampling methods. They should not be used to determine compliance with the PM-2.5 NAAQS.
PM2.5 from Aircraft

- Modern aircraft produce PM with aerodynamic diameters less than 2.5 µm.
- PM emissions are affected by fuel flow, engine design, operating conditions, altitude, fuel composition, etc.
- PM is composed of both volatile and non-volatile components. The non-volatile components are more prevalent.
- Coagulation of particles over time results in a bi-modal distribution.
Aerosol Chemistry: *Steady State Operation of B757*

Black carbon dominates at high power

EC/OC higher for than diesel at aircraft steady state
PM from O’Hare Airport?

PM$_{10}$ at Chicago, IL; 1995 - 1999

PM2.5 Aerosols
Surface Layer – Accumulation Mode

PM from O’Hare Airport?

PM$_{10}$ at Chicago, IL; 1995 - 1999

PM2.5 Aerosols
Surface Layer – Accumulation Mode

June 1, 1996 12:00:00
Min= 0.007 at (33,37), Max= 13.877 at (24,37)

<table>
<thead>
<tr>
<th>Airport</th>
<th>FAA Code</th>
<th>1990 LTOs</th>
<th>2010 LTOs</th>
<th>Growth for 20-year period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hartsfield</td>
<td>ATL</td>
<td>287,080</td>
<td>388,728</td>
<td>35.4%</td>
</tr>
<tr>
<td>Logan</td>
<td>BOS</td>
<td>114,282</td>
<td>137,137</td>
<td>20.0%</td>
</tr>
<tr>
<td>Douglas</td>
<td>CLT</td>
<td>119,990</td>
<td>215,726</td>
<td>79.8%</td>
</tr>
<tr>
<td>Midway</td>
<td>MDW</td>
<td>65,135</td>
<td>66,510</td>
<td>2.1%</td>
</tr>
<tr>
<td>O’Hare International</td>
<td>ORD</td>
<td>347,653</td>
<td>500,767</td>
<td>44.0%</td>
</tr>
<tr>
<td>George Bush Intercontinental</td>
<td>IAH</td>
<td>181,214</td>
<td>337,080</td>
<td>86.0%</td>
</tr>
<tr>
<td>Hobby</td>
<td>HOU</td>
<td>55,770</td>
<td>61,621</td>
<td>10.5%</td>
</tr>
<tr>
<td>Burbank</td>
<td>BUR</td>
<td>26,129</td>
<td>30,607</td>
<td>17.1%</td>
</tr>
<tr>
<td>John Wayne</td>
<td>SNA</td>
<td>28,291</td>
<td>33,043</td>
<td>16.8%</td>
</tr>
<tr>
<td>Long Beach</td>
<td>LGB</td>
<td>12,984</td>
<td>14,790</td>
<td>13.9%</td>
</tr>
<tr>
<td>Los Angeles International</td>
<td>LAX</td>
<td>212,041</td>
<td>312,976</td>
<td>47.6%</td>
</tr>
<tr>
<td>Ontario</td>
<td>ONT</td>
<td>40,323</td>
<td>53,445</td>
<td>32.5%</td>
</tr>
<tr>
<td>Kennedy</td>
<td>JFK</td>
<td>94,382</td>
<td>111,360</td>
<td>18.0%</td>
</tr>
<tr>
<td>La Guardia</td>
<td>LGA</td>
<td>154,700</td>
<td>158,209</td>
<td>2.5%</td>
</tr>
<tr>
<td>Newark</td>
<td>EWR</td>
<td>134,124</td>
<td>183,381</td>
<td>36.7%</td>
</tr>
<tr>
<td>Philadelphia International</td>
<td>PHL</td>
<td>107,646</td>
<td>123,177</td>
<td>14.4%</td>
</tr>
<tr>
<td>Sky Harbor International</td>
<td>PHX</td>
<td>121,024</td>
<td>179,265</td>
<td>48.1%</td>
</tr>
<tr>
<td>Dulles</td>
<td>IAD</td>
<td>60,787</td>
<td>105,888</td>
<td>73.9%</td>
</tr>
<tr>
<td>Washington National(^{21})</td>
<td>DCA</td>
<td>96,931</td>
<td>97,268</td>
<td>0.3%</td>
</tr>
</tbody>
</table>
EDMS Model

- **Emissions and Dispersion Modeling System (EDMS)**
  - Combines emissions and dispersion modeling to assess impact of airport emissions, including:
    - Aircraft
    - Ground support equipment (aircraft tractors, baggage handling equipment; service trucks)
      - Treated either (a) assigned to aircraft per LTO, or (b) counted and allocated to gates
    - Ground Access Vehicles
    - Stationary sources

- EDMS required for airport air quality analyses (FAA) and is approved by EPA
EDMS Overview

- Emissions modeling
  - ICAO exhaust emissions databank (certification data)

- Dispersion modeling
  - EPA Gaussian dispersion models
  - EPA AERMOD dispersion model

\[ C = \frac{Q}{2\pi \sigma_x \sigma_y \sigma_z} \exp \left[ -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right] \exp \left[ -\frac{1}{2} \left( \frac{z-H}{\sigma_z} \right)^2 \right] + \exp \left[ -\frac{1}{2} \left( \frac{z+H}{\sigma_z} \right)^2 \right] \]
Disadvantages of Gaussian Plume Models

- Inaccurate in regions with complex terrain
- Inaccurate in rapidly changing conditions
- Inaccurate in calm conditions or low wind speeds
- Generally have trouble treating dry and wet deposition accurately
- Generally have insufficient treatments of chemical, physical and microphysical processes
Regional Air Quality Model: Focus on Chicago Region

Domains:
D1  30 km
D2  10 km
D3  2 km
The nested global-regional modeling system: its components and their interactions.
### Hartsfield’s Emissions in Current Inventory

#### Daily emissions (tons/day)

<table>
<thead>
<tr>
<th></th>
<th>SO$_2$</th>
<th>VOC</th>
<th>CO</th>
<th>NH$_3$</th>
<th>NOx</th>
<th>PM$_{10}$</th>
<th>PM$_{2.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1.30</td>
<td>2.78</td>
<td>14.26</td>
<td>0</td>
<td>13.45</td>
<td>1.37</td>
<td>0.95</td>
</tr>
</tbody>
</table>

#### Composition of PM$_{2.5}$ emissions (%)

<table>
<thead>
<tr>
<th></th>
<th>EC</th>
<th>OC</th>
<th>SO$_4$</th>
<th>NO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>65.87</td>
<td>29.21</td>
<td>4.60</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Diurnal Profile of emissions

---

T Odman et al. (2003)
GIT: Preliminary Assessment of Hartsfield’s Impact

- The impact of Hartsfield’s emissions during the August 11-20, 2000 period was assessed using the “brute-force” approach.

- A simulation was conducted without Hartsfield’s emissions and its results were compared to the base case simulation (with Hartsfield’s emissions).

T Odman et al. (2003)
GIT: Impact on PM$_{2.5}$

- The maximum impact on PM$_{2.5}$ is 4 – 39 mg/m$^3$ within a 5-km radius;
- Greater than 1 mg/m$^3$ within a 20-km radius.
GIT: Composition of PM$_{2.5}$ Impact

- PM$_{2.5}$ is largely in the form of EC and OC (primary)

Elem. Carbon

![Elem. Carbon Map](Image)

Organic Carbon

![Organic Carbon Map](Image)

T Odman et al. (2003)
Summary

- Modeling studies underway to investigate the impact of aircraft emissions from Chicago O’Hare and Atlanta Hartsfield airports on regional air quality, especially PM$_{2.5}$.
- Preliminary analysis shows significant impact of Hartsfield on EC and OC in Atlanta metro counties.
- Dispersion models (like use din EDMS) are useful but have limitations in air quality analyses.
- Significant uncertainties remain in airport emissions and in accurate representation of these emissions into local/regional models.
NCEP Reanalysis Data sets

ADP Surface station data

Upper Air Sounding ROABS

Grid level FDDA

Hourly Dynamic Fields

MM5 V3.4

Observation FDDA

Met observations from local sources, such as EPA monitoring stations

TERRAIN

3-D GRID
EPA NEI Inventory (1999)

Surrogate ratios generated for the domain using ArcInfo

MM5 generated Dynamic fields

BEIS3.0

MOBILE 6.2

Hourly gridded emission data
CMAQ-4.3

HOURLY GRIDDED EMISSIONS

HOURLY DYNAMIC FIELDS

CMAQ-4.3

INITIAL AND BOUNDARY CONDITIONS

1.25 HRS FOR 1 DAY CALCULATION USING 16 NODES ON A LINUX CLUSTER (JAZZ AT ANL) FOR A 90X80X28 GRID

HOURLY GAS AND AEROSOLS MIXING RATIOS FOR ALL GRID LOCATIONS
CMM5 Skill: Daily Fluctuations

Midwest States daily-mean precipitation variation during 1983 JFMA

Midwest States daily-mean precipitation variation during 1983 MJJA

Midwest States daily-mean precipitation variation during 1983 SOND
CMM5 Skill: Daily Fluctuations

Cascade Range daily-mean precipitation variation during 1983 JFMA

Cascade Range daily-mean precipitation variation during 1983 MJJA

Cascade Range daily-mean precipitation variation during 1983 SOND
Local Air Quality: Connecting the Dots

NASA’s 2003 Aircraft Particle Emissions Workshop
North Olmsted, Ohio
November 18 & 19, 2003

Wayne Miller
University of California, Riverside
Bourns College of Engineering
Center for Environmental Research and Technology
Outline

• What is known?
  – Criteria pollutants
  – Conformity
  – Case Study: South Coast AQMD’s 2003 Air Quality Management Plan

• What issues are fuzzy or unknown?
• Looking Beyond Current Requirements
State Implementation Planning Process
## Ambient Air Quality Standards*

<table>
<thead>
<tr>
<th>Air Pollutant</th>
<th>California Standard</th>
<th>Federal Primary Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concentration Averaging Time</td>
<td>Concentration Averaging Time</td>
</tr>
<tr>
<td>Ozone</td>
<td>0.09 ppm, 1-hr. avg. &gt;</td>
<td>0.12 ppm, 1-hr avg. &gt;</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>9.0 ppm, 8-hr avg. &gt;</td>
<td>9 ppm, 8-hr avg. &gt;</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>0.25 ppm, 1-hr. avg. &gt;</td>
<td>0.053 ppm, ann. avg. &gt;</td>
</tr>
<tr>
<td>Sulfur Dioxide</td>
<td>0.04 ppm, 24-hr avg. &gt;</td>
<td>0.03 ppm, ann. avg. &gt;</td>
</tr>
<tr>
<td>Suspended Particulate Matter ($PM_{10}$)**</td>
<td>30 µg/m$^3$, ann. geometric mean &gt;</td>
<td>50 µg/m$^3$, ann. arithmetic mean &gt;</td>
</tr>
<tr>
<td>Suspended Particulate Matter ($PM_{2.5}$)**</td>
<td>50 µg/m$^3$, 24-hr average &gt;</td>
<td>150 µg/m$^3$, 24-hr avg. &gt;</td>
</tr>
<tr>
<td>Sulfates</td>
<td>25 µg/m$^3$, 24-hr avg. ≥</td>
<td>15 µg/m$^3$, ann. arithmetic mean &gt;</td>
</tr>
<tr>
<td>Lead</td>
<td>1.5 µg/m$^3$, 30-day avg. ≥</td>
<td>1.5 µg/m$^3$, calendar quarter &gt;</td>
</tr>
<tr>
<td>Visibility-Reducing Particles</td>
<td>Extinction coefficient is greater than 0.23 inverse kilometers (to reduce the visual range to less than 10 miles) at relative humidity less than 70 percent, 8-hour average (10am - 6pm)</td>
<td></td>
</tr>
</tbody>
</table>

*Concentration appears first; e.g. "0.12 ppm, 1-hr avg. >" means 1-hr avg. > 0.12 ppm.

** ARB adopted new and stricter state standards of a PM$_{10}$ annual average of 20 µg/m$^3$ and a PM$_{2.5}$ annual average of 12 µg/m$^3$. 
What is Conformity?

- A Federal agency is required to determine if their action “conforms” to the applicable SIP, by ensuring that the action does not:
  - Cause or contribute to new violations of any NAAQS,
  - Increase the frequency or severity of existing violations of any NAAQS,
  - Delay the timely attainment of any NAAQS or any required interim emission reductions or milestones.

- Two categories of conformity actions: transportation and general.
  - Transportation conformity actions required for highway or transit projects in all non-attainment and maintenance areas with FHA/FTA funds.
  - Most Federal actions at airports are general conformity actions. The general conformity rule contains established net annual emissions threshold rates and exemptions from and presumptions of conformity.

SCAQMD has jurisdiction over an area of approximately 10,743 square miles where 15 million people live.


New plan updates the attainment demonstration for the federal standards for ozone and particulate matter (PM$_{10}$).

Incorporates significant new scientific data, primarily in the form of updated emissions inventories, ambient measurements, new meteorological episodes and new air quality modeling tools.
South Coast Air Basin Compared to Major U.S. Metropolitan Areas

Percent of Federal Standard

- Ozone
- Carbon Monoxide
- PM10
- Nitrogen Dioxide
- Sulfur Dioxide

STANDARD
South Coast Air Basin Compared to Other Air Basins in California

Percent of Federal Standard

South Coast | San Joaquin Valley | Sacramento Valley | San Diego | San Francisco | South Central Coast
---|---|---|---|---|---
Ozone | Carbon Monoxide | PM10 | Nitrogen Dioxide | Sulfur Dioxide

Center for Environmental Research and Technology
Percent of Days Exceeding Federal Standards at Most Affected Locations

Percent of Days Exceeding

- Any Standard Basin-Day
- Ozone (1-Hour)
- Carbon Monoxide (8-Hour)
- PM10 (24-Hour)
- PM2.5 (24-Hour)

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%

1985
1990
1995
2001
NO DATA
Annual Average $\text{PM}_{10}$ Concentration for 2001
Annual Average PM$_{2.5}$ Concentration for 2001
Annual Average PM Emissions

- TSP: 700 tons per day
- PM10: 500 tons per day
- PM2.5: 300 tons per day

PM Composition:
- PM 0.1: Geologic Material, Pollen
- PM 2.5: Sulfate, Nitrate, Ammonium, Organic & Elemental Carbon, Heavy Metals, Clays
- PM 10: Ultrafine
- TSP: All PM sizes

Graph shows relative concentration of PM sizes.
Annual Average PM Emissions by Source Category in 2020
Annual Average PM Emissions for Miscellaneous Category in 2020
Annual Average PM Emissions in 2020
Without Miscellaneous Source Category

On-Road Motor Vehicles
Other Mobile Sources
Industrial Processes
Fuel Combustion
Pet. Refine & Market
Waste Disposal
Cleaning and Surface Coatings
Solvent Evaporation

tons/day

TSP
PM10
PM2.5
Annual Average PM$_{2.5}$ Emissions in 2020 Without Miscellaneous Source Category

Total On-Road = 15.5 tons/day
Total Other Mobile = 15.9 tons/day
• What issues are fuzzy or unknown?
• Looking beyond current requirements
SCAQMD: “Uncertainties Associated with the 2003 Air Quality Management Plan”

- Demographic and Growth Projections

- Input Elements to Air Quality Models
  - Ambient Air Quality Monitoring Data
  - Meteorological Measurements
  - Emissions Inventory

- Air Quality Models
## EPA’s AP-42 Emission Factors - Small Diesel Engines

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emission Factor (lb/HP-hr) (power output)</th>
<th>Emission Factor (g/kW-hr) (power output)</th>
<th>Emission Factor (lb/MMBtu) (fuel input)</th>
<th>Emission Factor Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>0.031</td>
<td>18.85</td>
<td>4.41</td>
<td>D</td>
</tr>
<tr>
<td>CO</td>
<td>6.68E-03</td>
<td>4.06</td>
<td>0.95</td>
<td>D</td>
</tr>
<tr>
<td>SOx</td>
<td>2.05E-03</td>
<td>1.25</td>
<td>0.29</td>
<td>D</td>
</tr>
<tr>
<td>PM10</td>
<td>2.20E-03</td>
<td>1.34</td>
<td>0.31</td>
<td>D</td>
</tr>
<tr>
<td>CO2</td>
<td>1.15</td>
<td>699.20</td>
<td>164</td>
<td>B</td>
</tr>
<tr>
<td>Aldehydes</td>
<td>4.63E-04</td>
<td>0.28</td>
<td>0.07</td>
<td>D</td>
</tr>
<tr>
<td>TOC</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>E</td>
</tr>
<tr>
<td>Exhaust</td>
<td>2.47E-03</td>
<td>1.50</td>
<td>0.35</td>
<td>D</td>
</tr>
<tr>
<td>Evaporative</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>E</td>
</tr>
<tr>
<td>Crankcase</td>
<td>4.41E-05</td>
<td>0.03</td>
<td>0.01</td>
<td>E</td>
</tr>
<tr>
<td>Refueling</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>E</td>
</tr>
</tbody>
</table>
Issue: Measured PM$_{2.5}$ Emission Factors are much less than AP-42 (gen sets)

AP-42 = 1.34 g/kWhr

<table>
<thead>
<tr>
<th>Bug ID Number</th>
<th>PM (g/kWhr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.12</td>
</tr>
<tr>
<td>11C</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>0.17</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
</tr>
<tr>
<td>9</td>
<td>0.22</td>
</tr>
<tr>
<td>9C</td>
<td>0.25</td>
</tr>
<tr>
<td>12</td>
<td>0.28</td>
</tr>
<tr>
<td>10</td>
<td>0.30</td>
</tr>
<tr>
<td>10C</td>
<td>0.33</td>
</tr>
<tr>
<td>4</td>
<td>0.35</td>
</tr>
<tr>
<td>5</td>
<td>0.37</td>
</tr>
<tr>
<td>2</td>
<td>0.39</td>
</tr>
<tr>
<td>6</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Issue: How to Measure PM$_{2.5}$
Issue: Mass of PM$_{2.5}$ Differs with Test Method

![Graph showing the comparison of Total PM gm/bhp-hr for Cat 3406 B (Vandenberg) with test methods M5 and ISO at 50%, 75%, and 100% efficiency.](image-url)
Issue: Mass of PM$_{2.5}$ Differs with Test Method

![Graph: DDC 8083-7405 (Vandenberg)](image)

- **Total PM gm/bhp-hr**
- **Impinger Organic**
- **Impinger Inorganic**
- **Filter**

**Legend:**
- M5 50%
- ISO 50%
- M5 75%
- ISO 75%
- M5 100%
- ISO 100%
Issues: How do you measure low PM emissions and what do filters really measure?*

- For standard vehicle tests, gravimetric PM mass using filters show hydrocarbon artifacts at low PM levels when compared to particle instrument data
  - With 3-way catalyst: Gravimetric PM mass is very low and $\approx$ mass calculated from size dist of ELPI/SMPS
  - Without catalyst: Gravimetric PM mass $>>$ calculated mass
- Suggests that without catalyst semi-volatile HCs in exhaust adsorb onto filter. FID shows $<\text{HC after filter}$ (Hochgreb & Kayes)

*Reference: From work of Dr. Matti Maricq, Ford Motor Co.
Issue: Where Risk is High, Air Toxic Control Measures will be Implemented.

Relative Cancer Risks

Based on ARB monitoring data 1995 - 1997
### Issue: Data from U.S. EPA National Toxics Inventory (Ranked in Order)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Total Emission (Tons/Year)</th>
<th>Percent of Total</th>
<th>Cumulative Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formaldehyde</td>
<td>6,408</td>
<td>42.3</td>
<td>42.3</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>1,969</td>
<td>13.0</td>
<td>55.3</td>
</tr>
<tr>
<td>Benzene</td>
<td>1,184</td>
<td>7.8</td>
<td>63.1</td>
</tr>
<tr>
<td>Toluene</td>
<td>1,174</td>
<td>7.7</td>
<td>70.8</td>
</tr>
<tr>
<td>Acrolein</td>
<td>938</td>
<td>6.2</td>
<td>77.0</td>
</tr>
<tr>
<td>1,3-Butadiene</td>
<td>824</td>
<td>5.4</td>
<td>82.5</td>
</tr>
<tr>
<td>Xylene</td>
<td>702</td>
<td>4.6</td>
<td>87.1</td>
</tr>
</tbody>
</table>

Issue: Looking Beyond Today and Control of PM$_{2.5}$ Components (SCAQMD data)

(a) Predicted Annual Average (29 ug/m$^3$)

New controls likely for NO$_3$, NH$_4$, OC and EC

(b) Predicted Maximum 24-Hour Average (97 ug/m$^3$)
Issue: EPA’s PM Measurement Workshop (1998)

“The goal of this Workshop is to identify the key components and design parameters for a comprehensive measurement program to characterize ambient particulate matter and important co-pollutants in a way that optimizes information for multiple disciplines, including source apportionment; modeling, health and exposure study; and risk assessment.”

Aim for cross-cutting research with multiple disciplines and stakeholders involvement.
Issues

- What are the major science questions/hypotheses?
- What is to be measured? … to be modeled?
- Where are the measurements to be made? … models to be developed?
- When will the measurements/models be made?
Figure 1. Air Quality Assessment Process for Airports and Air Bases - Part 1

Figure 2. Air Quality Assessment Process for Airports and Air Bases - Part 2
Session 1:
Sampling Methodology
Current Understanding & Issues

Discussion Summary

Aviation Particle Emissions Workshop
Nov 18-19, 2003
**NASA Objective**
Quantification and mitigation of sampling affects to provide quantitative scientific research turbine exhaust flow-field characterization measurements.

**Current NASA Sampling Probe Hardware Concept**
- Probes were designed to survive in severe thermal and aerodynamic environments of turbine engine combustor and engine exhaust for a wide variety of flow-field conditions.
- The water cooling and diluent addition design prevents massive cooling of the probe tip allowing the sample tube wall to equilibrate at a temperature intermediate to that of the sample and cooling water.
- Dilution gas is added close to the probe tip and parallel to the sample flow stream.
- Diluent ratio is quantified (or verified) by measurements of CO₂ in the sample stream with and without diluent flow.
- A water cooled rake structure can house up to 12 independent particulate probes for spatial sampling.
Discussion Items

**Consensus Measurement Criteria**
- Turbine exhaust flow-field measurements must include the nozzle exit plane.
- Gas sampling probes are considered inadequate for detailed particulate matter sampling until validation measurements are performed.
- Particulate matter number density and size distribution measurements are required for NASA objectives.

**Identified Sampling Issues**
- Non-isokinetic sampling
- Thermophoresis
- Wall impaction
- Particle diffusion wall losses
- Coagulation

**Dilution**
- Dilution is required to help mitigate condensation, particulate losses, coagulation and volatile aerosol formation in the sample line.
- Dilution should be introduced at the probe tip.
Discussion Items

**Probe tip and sampling line/system temperature**

- Dilution prevents water condensation and coagulation, but
- Uncooled-probe-tip and line heating are still preferred
  - To reduce thermophoretic effects and condensation of UHC
  - For measurement methodology standardization to be immune to the ambient temperature.

**Probe and Sampling Line Design Criteria**

- Parametrically quantify sampling affects
  - Simulate exhaust flow-field thermodynamic and aerodynamic conditions, if possible, with known particulate matter.
  - Perform measurements while systematically varying probe temperature, line temperature, diluent ratio, probe and line diameter, probe and line surface material, and other relevant parameters.
  - Use non-intrusive diagnostics as appropriate.
- Develop a computer simulation model to complement limited measurement studies and assess particulate affects to sampling system design criteria.
**Discussion Items**

**Dilution**
- Dilution is required to help mitigate condensation, particulate losses, coagulation and volatile aerosol formation in the sample line.
- Dilution should be introduced at the probe tip.

**Comments**
- Sampling at one meter behind modern commercial aircraft engine should not require probe-rake cooling for survivability.
- Velocities are so high (~Mach 1 gas velocity at takeoff power) that particle size losses in sample lines cannot be ignored.
- High dilution through sample lines can have inertia problems.
- Modeling that accounts for and integrates chemistry and all loss mechanisms is required to adequately address sampling system issues; and this model must be verified by careful parametric measurement studies.
Session 2: Measurement Methodology Report
(APEW Meeting Cleveland 18-19 Nov 03)

Need to measure mass, size and number and to have a measurement methodology that achieves mass balance between components (volatile, non-volatile etc…).

Measurement techniques are available with demonstrated applicability to aircraft measurements. In some cases techniques need modification for aircraft measurements.

EPA Method 5 is not practical for aircraft emissions measurements for mass (time, cost…) and provides no information on particle microphysics (size, number).

Speciation of volatile component – cf. established (EPA) methods since typical loadings will require long sampling times.
  (lubricating oil. ?: (partially oxidized) fuel, PAHs, metals …)

Connect to SAE E31 Committee.
Measurements need to be made at both the exit plane and out in the expanding plume and the relationship between the two measurement locations need to be understood.

Sampling issues more complex at exit plane than in plume.

Methods for transients need to be developed.

(cold start, hot start, throttle shifts..., engine cycle)

Variation of non-volatile / volatile components with engine power?

Plane to plane variability requires multiple test venues using established techniques – Can (novel) off runway techniques be used to explore this variability?

There are a small number of off runway studies, although not particle specific; these studies need to be reviewed for lessons learned.
Needed modeling elements for a research roadmap

Over all goal of modeling efforts:

*Develop numerical modeling tools to establish an understanding of particulate formation and destruction and the relationship between combustor particle emissions, their engine exit properties, and particles deposited in the atmosphere*

1. **Probe effects modeling**
   - Begin development of modeling capability representing sampling exhaust with condensable gases: understanding of particle processes in probes
   - Applications to combustors, engine exit, and plume/wake

2. **Combustor Modeling**
   - Quantitative predictions of non-volatile carbonaceous particulates (number, size, and mass, properties) (advanced engines)
   - Effects of fuel aromatics (quantities and properties)
   - Effects of fuel sulfur (quantities and properties)
   - **Hydrophilic/hydrophobic characteristics**
   - Changes due to engine operating conditions
     - **combustor pressure effects**
   - Oxidation
   - Agglomeration levels
   - Effects of humidity on particle formation
   - Uncertainty/sensitivity analyses
     - **use on existing tools**
   - Quantitative predictions of volatile hydrocarbon precursors
     - For environmental impact (global and regional)
     - For health effects/local air quality
Good validation data sets
- Internal combustor data
- Combustor exit data
- Characterization of existing fleets
- What data should be provided by experimentalists

3. Post combustor Modeling

◆ What is important? Continued connection to Stakeholders
  ■ For environmental impact (global and regional)
  ■ For health effects/local air quality
  ■ What will be regulated?
◆ Continued interaction with measurement programs to obtain comparisons between model parameters and specific observations
  ■ Ion impacts not fully quantified
  ■ Relative role of sulfates and condensable organics indeterminate
  ■ Which organics are important (fuel versus oil?)
◆ Quantitative understanding of condensation of volatiles onto non-volatile particles: model studies and comparison to measurements
  ■ Sulfur or organics or both
  ■ Partitioning of volatile species between volatile particles and condensed matter on non-volatile cores
  ■ Relative mass of volatile component on non-volatile core
◆ Obtained detailed understanding of processes that affect particle evolution in turbine/nozzle (NASA/QinetiQ versus Partemis)
  ■ Sensitivities to operational parameters
    ■ Use existing tools
Session 4: Database, Inventory, and Test Venue Summary Report
(APEW Meeting Cleveland 18-19 November 2003)

Needs for airport inventories:

- A measurement methodology which results in repeatable data within an "acceptable" uncertainty limit.
- A definition for an acceptable level of uncertainty.
- Detailed data taken under a wide range of engine operational conditions.
- A clear understanding of the behavior of the detailed data and accuracy requirements leading to…
- A simplified data set which describes the range of operational conditions of an engine, leading to a database for ICAO and modeling community.

Additional needs for global inventories:

- Methodology to adjust/correct simplified (sea level) data to cruise conditions.

Other:

- Must be applicable to a wide range of aircraft/engine combinations, including various engine/combustor technologies.
Session 5: Effects of Particles from Airports on Air Quality: Session Summary

Don Wuebbles
Wayne Miller

November, 2003
The Issues with Particles

- Measuring the State of the Problem
  - Emissions Inventory
  - Aircraft and ground activities (mobile, point sources)
- Modeling the State of the Problem
Measuring the State of the Problem

- **Existing measurements**
  - Focus on total mass

- **Uncertainties needing to be resolved**
  - Are measurements being made in the right places? With sufficient accuracy?
  - Should observations also give size and number distribution?
  - To what degree is speciation needed (organic aerosols)?
  - Better understanding of precursors and air toxics
  - How do health effects affect what should be measured?
Emissions Inventory

- **Existing inventories**
  - Complex analysis to develop inventory (SMOKE)
  - Aircraft emissions
    - Old data (AP42)
    - Smoke number inadequate for PM2.5
      - Also based on maximum power setting

- **Uncertainties needing to be resolved**
  - New source data needed
    - Different measurement techniques giving different emissions
    - By engine, by fuel flow, by operating conditions, fuel composition, etc., speciation for particles, precursors
  - How well are ground equipment treated?
  - Are take-offs/landings being treated properly (capturing all emissions in the boundary layer)
  - Improved predictive capabilities
Modeling the State of the Problem

• Existing
  – Dispersion models
    • Fast to calculate, but has major limitations
  – Grid models
    • Current resolution: roughly 2 km (future: 1 km or less)
    • Particles only added in recent years; limited treatment of relevant processes

• Uncertainties needing to be resolved
  – Representation of meteorology and other physics
  – To what degree do effects of buildings need to be better resolved?
  – To study airport effects, do emissions need to be better resolved within the airport?

• Models can only be as good as the inputs
Session 5: Effects of Particles from Airports on Air Quality: Session Summary

Don Wuebbles
Wayne Miller

It is important scientifically to understand the effects of airports on local air quality. One of the potentially major issues relate to the effects of emissions of particles and particle precursors. This summary is divided in three parts. Each part has an objective plus priorities for research.

Measurements

Existing measurements of particles near airports only focus on measuring total mass. These measurements are insufficient to adequately characterize particles from aircraft and from other airport related sources.

The objective is to establish atmospheric measurement capabilities that can fully characterize airport-related particle. The more general objective extends this to capabilities to fully characterize particles affecting overall air quality.

Research Priorities

- Confirm total mass with new EPA Method 5/202 methods.
- Measure particle size and number with several methods that are based on independent scientific principles.
  - Compute and compare mess to first bulleted priority to establish a new methodology.
- Determine particle speciation – measure organic particles and toxics.
- Interact with health experts to determine key measurement priorities for toxics on particles.
- Develop improved plan (relative to existing measurement programs) for determining best locations to measure the airport contributions to local air quality.

Emissions Inventory

Existing emissions inventories in the vicinity of airports are based on inadequate measurements of the emissions. For aircraft, the emissions are estimated based on smoke number (or on old data for some aircraft), which is totally inadequate for the PM2.5 particles of particular concern. For airports, these emissions are summarized using the EDMS model, which also has well known limitations. The emissions for the region are typically then characterized onto a grid through use of the complex SMOKE model.

The objective is to establish more accurate atmospheric emissions inventories for the emissions associated with aircraft and with airports.
**Research Priorities**

- Make sure accurate measurements are made and used in inventories for all airport related sources. For aircraft this means emissions as a function of engine, fuel flow, operating conditions (including transients), fuel composition and other factors.
- Develop improved representation of take-offs/landings to make sure all emissions in the boundary layer are accurately represented. Make sure these emissions can be adequately represented in the grid structures of 1 km or less that will be available in next generation numerical models used to study air quality.
- Similar concerns about representing emissions from airport mobile and fixed emissions sources.
- Develop improved predictive capabilities for future emissions.

**Air Quality Modeling**

The existing approach to understanding local and regional air quality is to use either dispersion models or grid models. Dispersion models have the advantage of requiring little computational power (therefore allowing many runs to be done on personal computers), but have major limitations in accuracy under a variety of atmospheric conditions. Grid models can much more fully represent the chemistry and physics affecting air quality but are also much more computationally intensive.

*The objective is to develop enhanced capabilities for understanding the effects of airports on local and regional air quality.*

**Research Priorities**

- Improved emissions inventories are key to improving air quality studies.
- Likewise the improved measurement capabilities are key to verifying modeling capabilities, to provide “ground truth” for air quality analyses and predictions.
- The analyses of airport effects would be enhanced by improved modeling capabilities aimed particularly at better representation of:
  - particle physics and chemistry processes,
  - local and regional meteorology,
  - the effects of buildings on air quality transport and deposition
## Participant List

**Aviation Particle Emissions Workshop**  
**November 18-19, 2003**

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Aviation Particle Emissions Workshop

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The Aviation Particle Emissions Workshop was held on November 18–19, 2003, in Cleveland, Ohio. It was sponsored by the National Aeronautics and Space Administration (NASA) under the Vehicle Systems Program (VSP) and the Ultra-Efficient Engine Technology (UEET) Project. The objectives were to build a sound foundation for a comprehensive particulate research roadmap and to provide a forum for discussion among U.S. stakeholders and researchers. Presentations included perspectives from the Federal Aviation Administration, the U.S. Environmental Protection Agency, NASA, and United States airports. There were five interactive technical sessions: sampling methodology, measurement methodology, particle modeling, database, inventory and test venue, and air quality. Each group presented technical issues which generated excellent discussion. The five session leads collaborated with their members to present summaries and conclusions to each content area.