NASA/CP—2004-213398

Aviation Particle Emissions Workshop

November 2004

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NASA/CP—2004-213398

Aviation Particle Emissions Workshop

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

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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

Contents

Aviation Particle Emissions Workshop
November 18 and 19, 2003

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

Aviation Particle Emissions Workshop
November 18 and 19, 2003

Wednesday, November 19, 2003		
Time Min.	**Topic**	**Speaker/Chair**
8:30 a.m.–	Database, Inventory, and Test Venues—Current Understanding and Issues	Steve Baughcum, Boeing, and Gregg Flemming, DoT
–10:00 a.m.	Discussion	
Break		
10:30 a.m.–	Local Air Quality, Modeling, and Measurements—Current Understanding and Issues	Don Wuebbles, UIUrbana, and Wayne Miller, UCRiverside
–12:00 p.m.	Discussion	
Lunch Break		
1:30–1:45 p.m.	Report of Session 1 Conclusion	Robert Howard, AEDC, and Bruce Anderson, NASA
1:45–2:00 p.m.	Report of Session 2 Conclusion	Phil Whitefield, UMR, and Doug Worsnop, ARI
2:00–2:15 p.m.	Report of Session 3 Conclusion	Rick Miake-Lye, ARI, and Med Colket, UTRC
2:15–2:30 p.m.	Report of Session 4 Conclusion	Steve Baughcum, Boeing, and Gregg Flemming, DoT
2:30–2:45 p.m.	Report of Session 5 Conclusion	Don Wuebbles, UIUrbana, and Wayne Miller, UCRiverside
2:45–3:30 p.m.	Recommendations and Next Step	
Adjourn		

U.S. Environmental Protection Agency

Office of Transportation and Air Quality

$PM_{2.5}$ National Ambient Air Quality Standards

NASA Aviation Particle Emissions Workshop

November 18-19, 2003

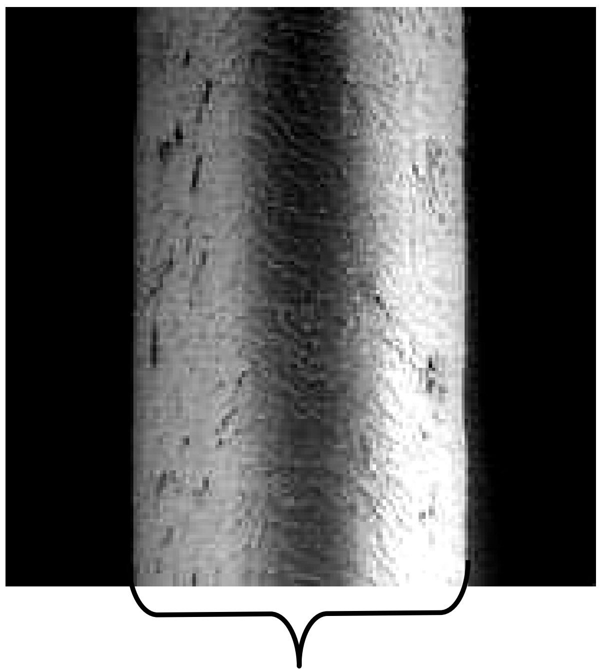
Bryan Manning

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

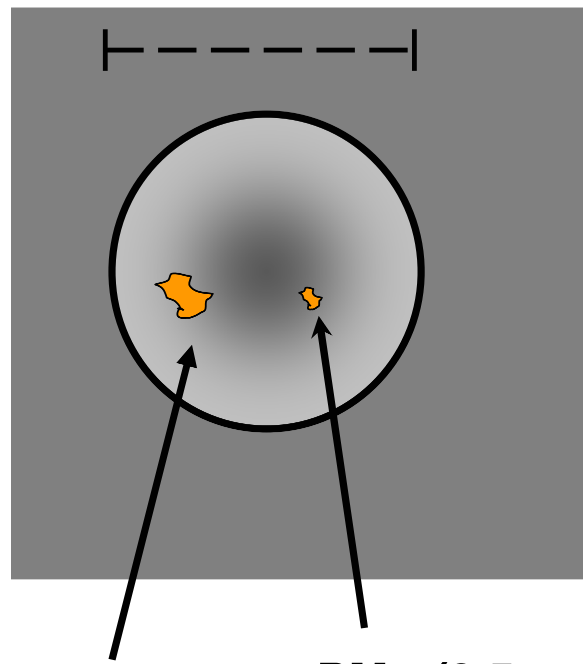
Particles: What Are They?

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



Human Hair (70 μm diameter)

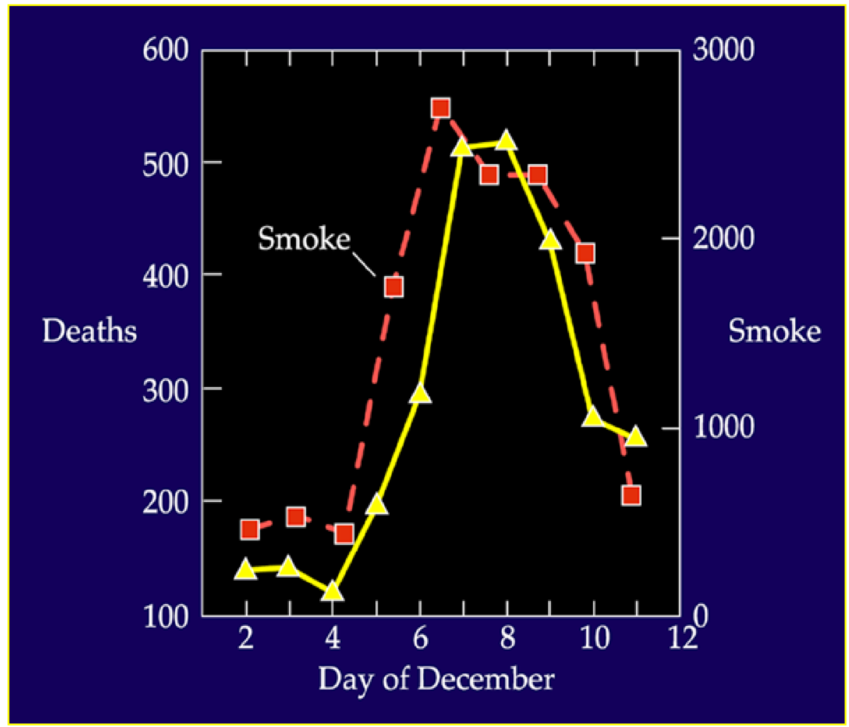
Hair cross section (70 μm)



PM_{10} (10μm) **$PM_{2.5}$(2.5 μm)**

M. Lipsett, California Office of Environmental Health Hazard Assessment

$PM_{2.5}$ or Fine Particles



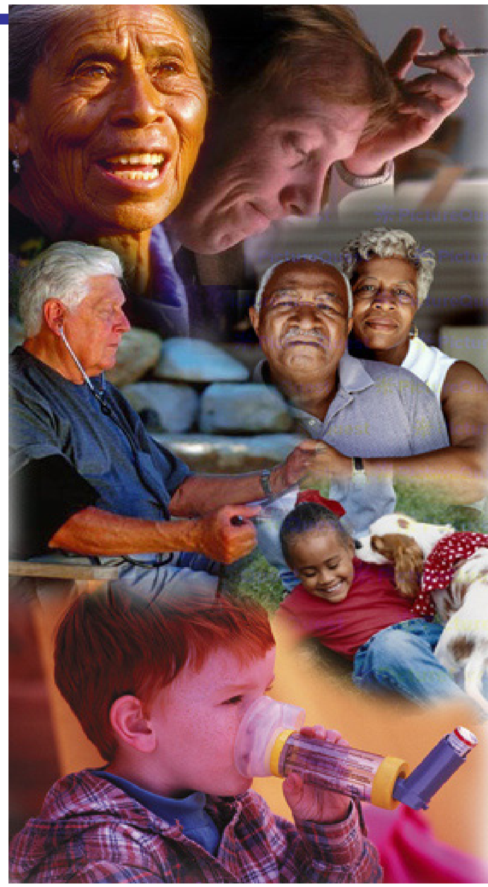
Public Health Risks Are Significant

- 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 μ because of the sampling method**
- **1987 PM-10**
  - **Equal to or less than 10 μ**
- **1997 $PM_{2.5}$ (Fine) plus PM-10**
  - **Equal to or less than 2.5 μ, plus**
  - **Equal to or less than 10 μ**

Court Challenge to 1997 Standards

- **Delayed Implementation**
- **Required split between fine and coarse**
  - **PM-fine < 2.5** μ
  - **PM-coarse 2.6 to 10** μ
- **Review of standards**
  - **Proposal 3/05**
  - **Final 12/05**

Review of the PM Standard

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
• Final Criteria Document	Dec. 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 $PM_{10\text{-}2.5}$ standards

$PM_{2.5}$ Implementation

$PM_{2.5}$ Implementation Program Timelines

Action	$PM_{2.5}$
EPA proposes implementation rule	Fall 2003
States/Tribes recommend designations	Feb. 2004
EPA finalizes implementation rule	Fall 2004
EPA finalizes designations	Dec. 2004
State plans due	Dec. 2007
Attainment dates	2009-2014

$PM_{2.5}$ 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.

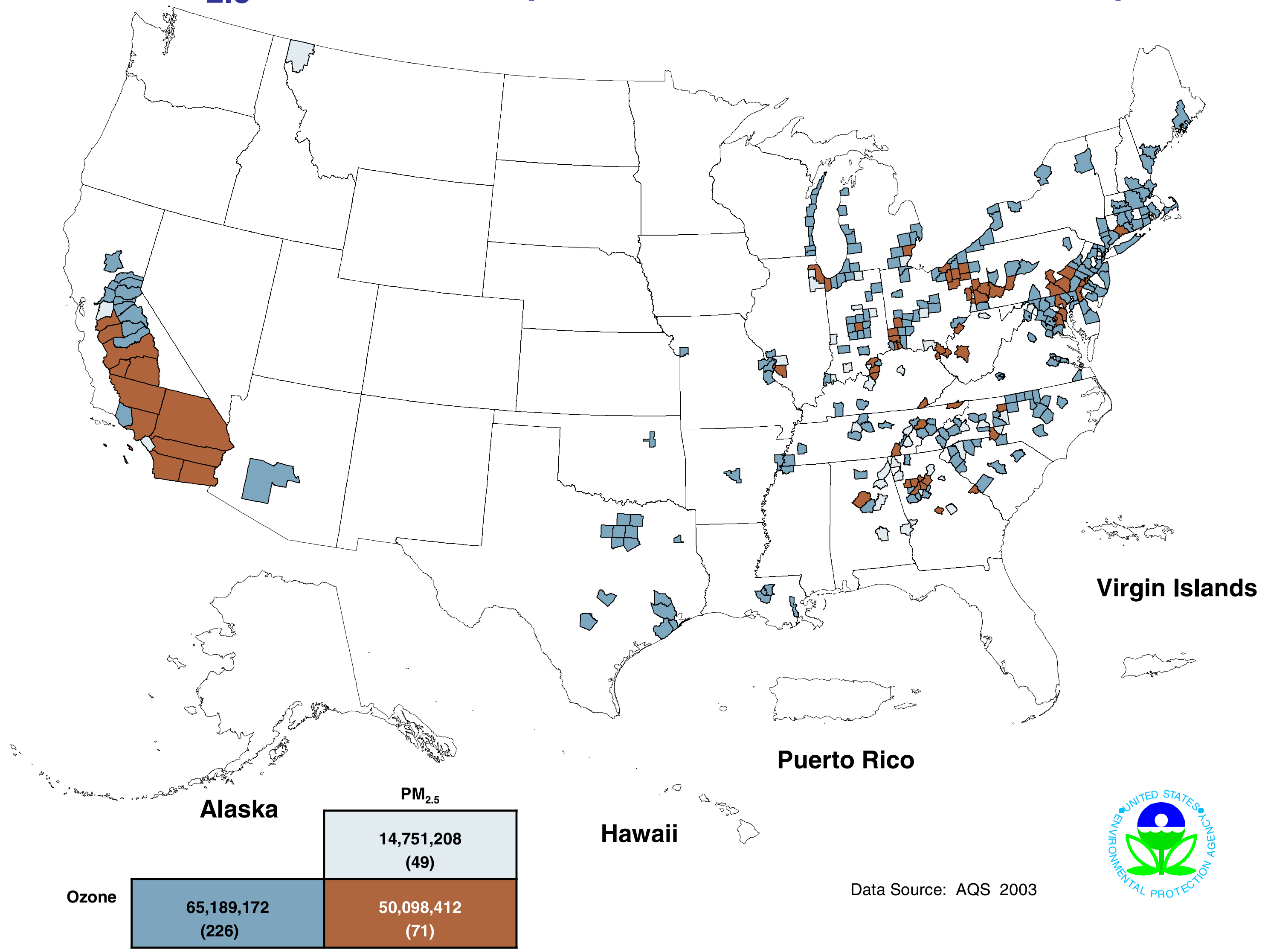
- Example of RACM Measures
  - Diesel idling and retrofits
  - – Watering/gravel on unpaved roads
  - – Wood stove retrofit programs
  - – Smoke management plans

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)



EPA Preferred Timelines for $PM_{2.5}$ Designations and $PM_{2.5}$/RH Implementation Plans

Date	$PM_{2.5}$	Regional Haze
December 2003	3-years data available for all monitored areas (2001-2003)	
February 2004	Governors submit recommendations based on 2001-2003 data	
December 2004	EPA publishes final designations	
December 2007	Implementation plans due	Implementation plans due for all areas without regard to $PM_{2.5}$ designation

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.

Non-volatile and Volatile PM (cont.)

- **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

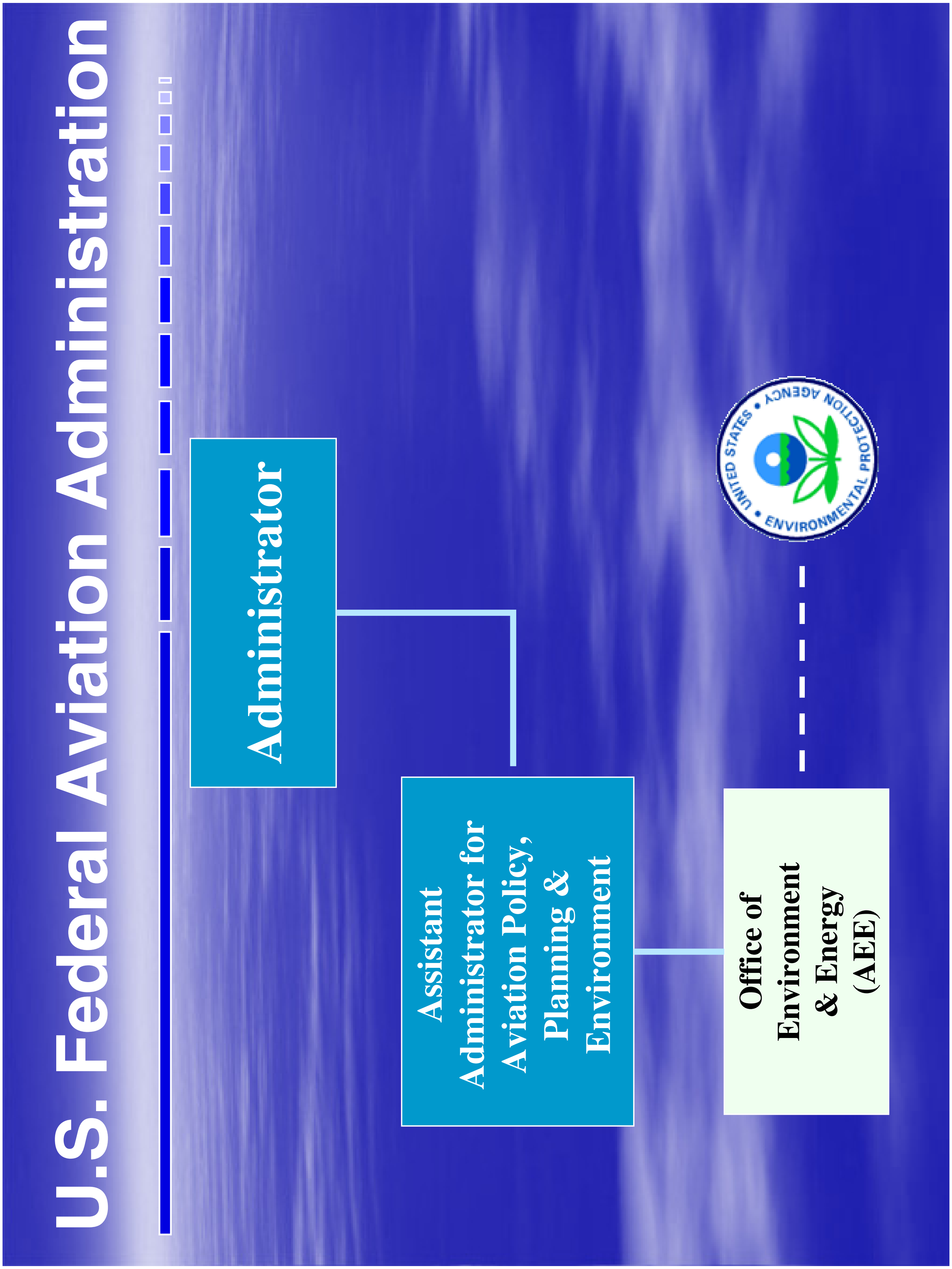
Julie Draper
Emissions Division
Office of Environment and Energy
Federal Aviation Administration

PM Workshop

18-19 November 2003, Cleveland, Ohio

Outline

- Context
- Current Status
- A Way Forward


U.S. Federal Aviation Administration
Administrator
Assistant Administrator for Aviation Policy, Planning & Environment
Office of Environment & Energy (AEE)
UNITED STATES • ENVIRONMENTAL PROTECTION AGENCY •

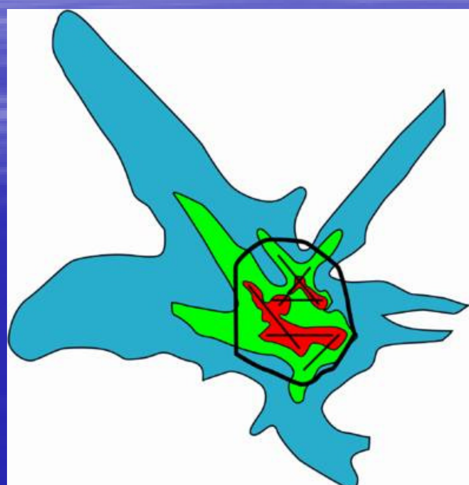
AEE Regulatory Responsibilities

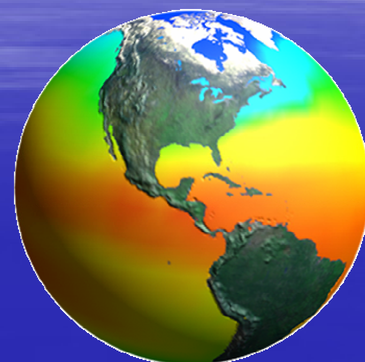
- Aircraft Noise
- Administers & Enforces EPA Established Clean Air Act Aircraft Engine Emissions Standards (part 34)
- Compliance Responsibility with NEPA & CAA*

* 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
INTERNATIONAL STANDARDS AND RECOMMENDED PRACTICES
ENVIRONMENTAL PROTECTION
ANNEX 16
TO THE CONVENTION ON INTERNATIONAL CIVIL AVIATION
This edition incorporates all amendments to Annex 16 adopted by the Council prior to 25 March 1993 and supersedes, on 11 November 1993, all previous editions of the Annex.
For information regarding the applicability of the Standards and Recommended Practices, see Foreword and the relevant clauses in each chapter.
INTERNATIONAL CIVIL AVIATION ORGANIZATION

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-FAA Environmental R&D Roles

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
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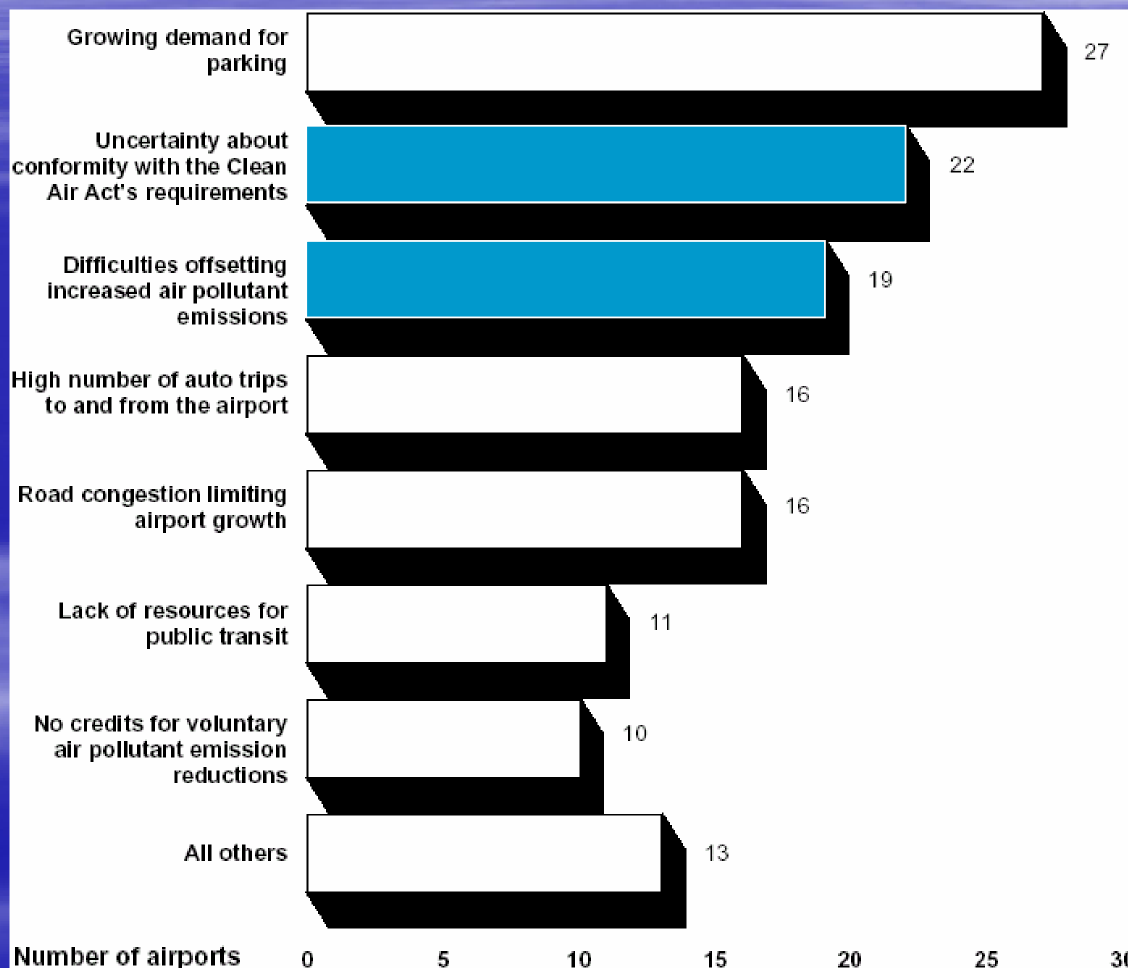
* A Way Forward

New EPA Standards

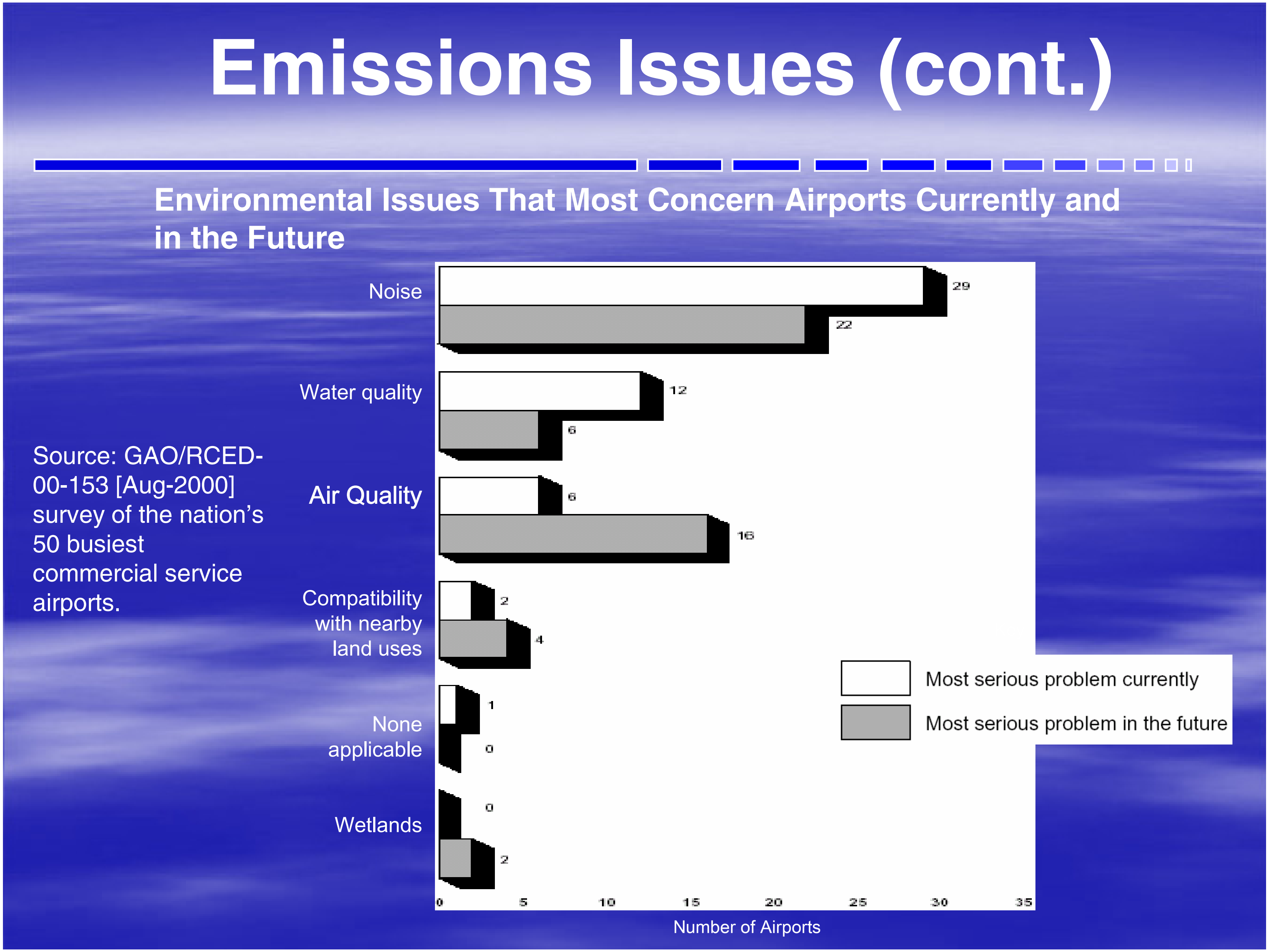
Action	PM-2.5
Propose Implementation Rule	Fall 03
State/Tribes Recommend Designations	2/04
Promulgate Implementation Rule	Fall 04
Publish designations	12/04
State/Tribe Plans Due	12/07
Attainment Years	09-14

Emissions Issues

Air-Quality Issues That Are Major Concerns for Airports



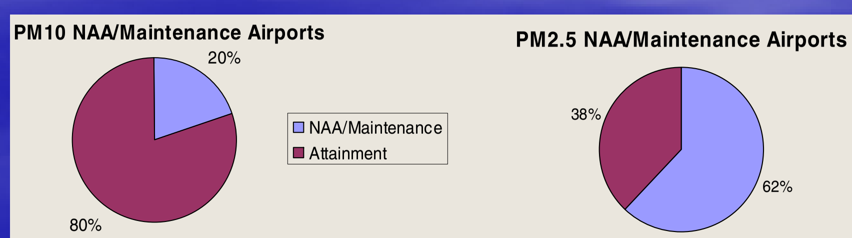
Source: GAO/RCED-00-153 [Aug-2000] survey of the nation's 50 busiest commercial service airports.


Emissions Issues (cont.)
Environmental Issues That Most Concern Airports Currently and in the Future
Source: GAO/RCED-00-153 [Aug-2000] survey of the nation's 50 busiest commercial service airports.
Noise
Water quality
Air Quality
Compatibility with nearby land uses
None applicable
Wetlands
29
22
12
6
6
16
2
4
1
0
0
2
0 5 10 15 20 25 30 35
Number of Airports
Most serious problem currently
Most serious problem in the future

Emissions Issues - PM

Aircraft Particulate Matter

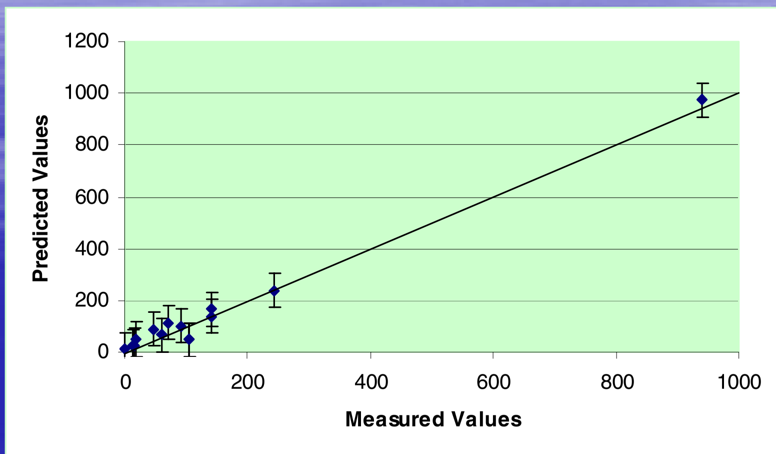
- Particulate matter (PM) represents a direct threat to public health and contributes to visibility degradation… NESCAUM, 2003
- Data on particulate matter emissions is not available for aircraft… GAO, 2003
- Reducing emissions of PM remains a crucial component of EPA's strategy for cleaner air and improved 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 ACAIS Airport Database and EPA Green Book for Nonattainment Areas



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

FAA Particulate Matter Study



- 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

The Society Of Automotive Engineers

* 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
BOISE STATE UNIVERSITY
University of Central Florida
Massachusetts Institute of Technology
PENNSTATE
PURDUE UNIVERSITY
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

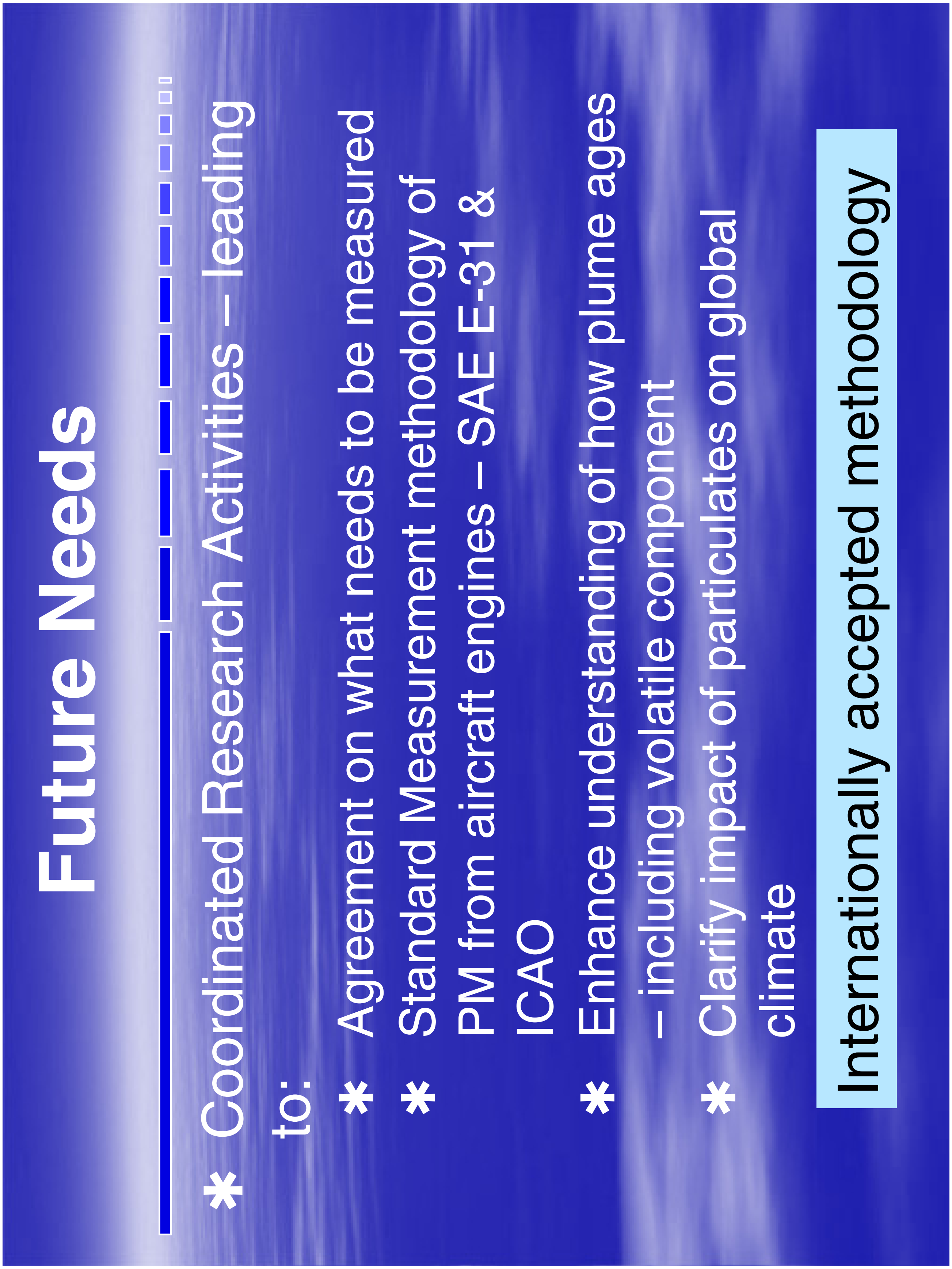
COE PARTNER First Projects

- **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

Outline

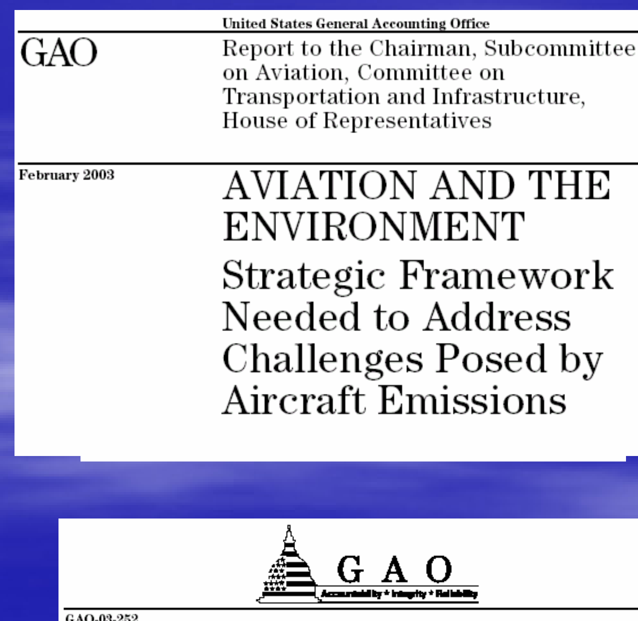
* Context
* Current Status
* A Way Forward


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

GAO Recommendation

U.S. General Accounting Office, Feb. 2003

Recommends a strategic framework for assessing airport emissions.


United States General Accounting Office

GAO

Report to the Chairman, Subcommittee on Aviation, Committee on Transportation and Infrastructure, House of Representatives

February 2003

AVIATION AND THE ENVIRONMENT

Strategic Framework Needed to Address Challenges Posed by Aircraft Emissions

GAO

GAO-03-252

Suggested Next Steps

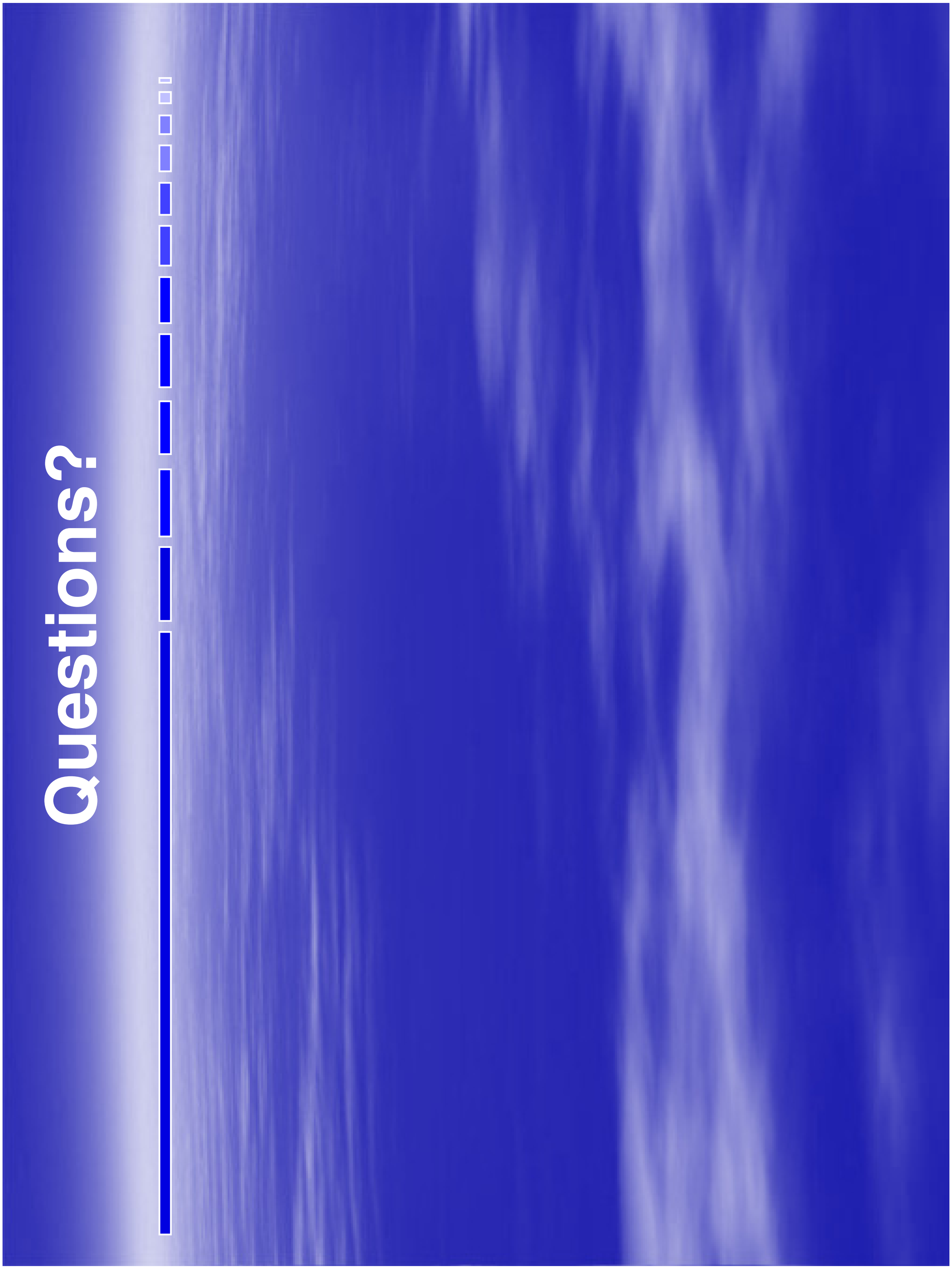
Recommendation for Executive Action

We recommend that the Secretary, DOT, direct the Administrator of FAA, in consultation with the Administrator of EPA and Administrator of NASA, to develop a strategic framework for addressing emissions from aviation-related sources. In developing this framework, the Administrator should coordinate with the airline industry, aircraft and engine manufacturers, airports, and the states with airports in areas not in attainment of air quality standards. Among the issues that the framework should address are

- 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


Questions?

Sampling Methodology - Current Understanding & Issues

Robert Howard
Aerospace Testing Alliance
Arnold Air Force Base, TN

Aviation Particle Emissions Workshop
November 18-19, 2003

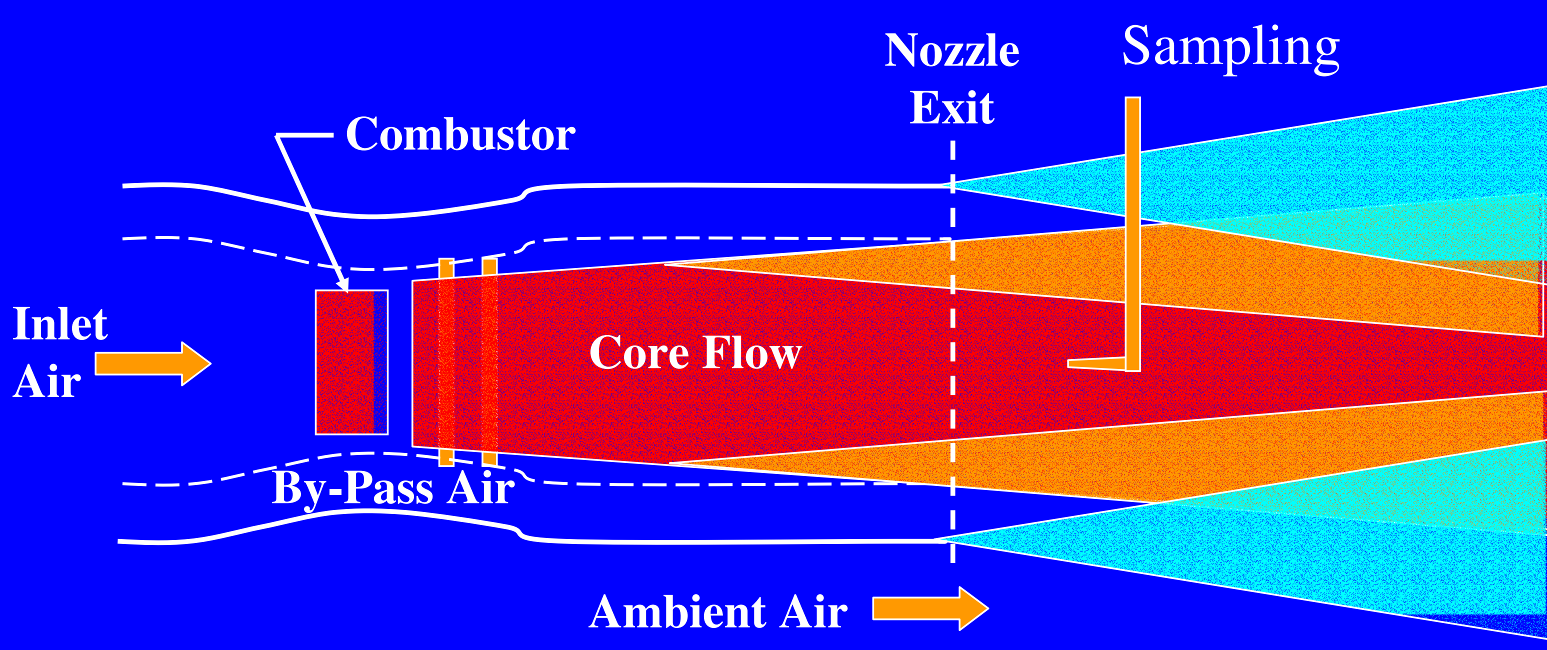
Air Force Materiel Command
Arnold Engineering Development Center
Arnold Air Force Base, TN 37389

Sampling Methodology - Current Understanding & Issues

Workshop Objectives

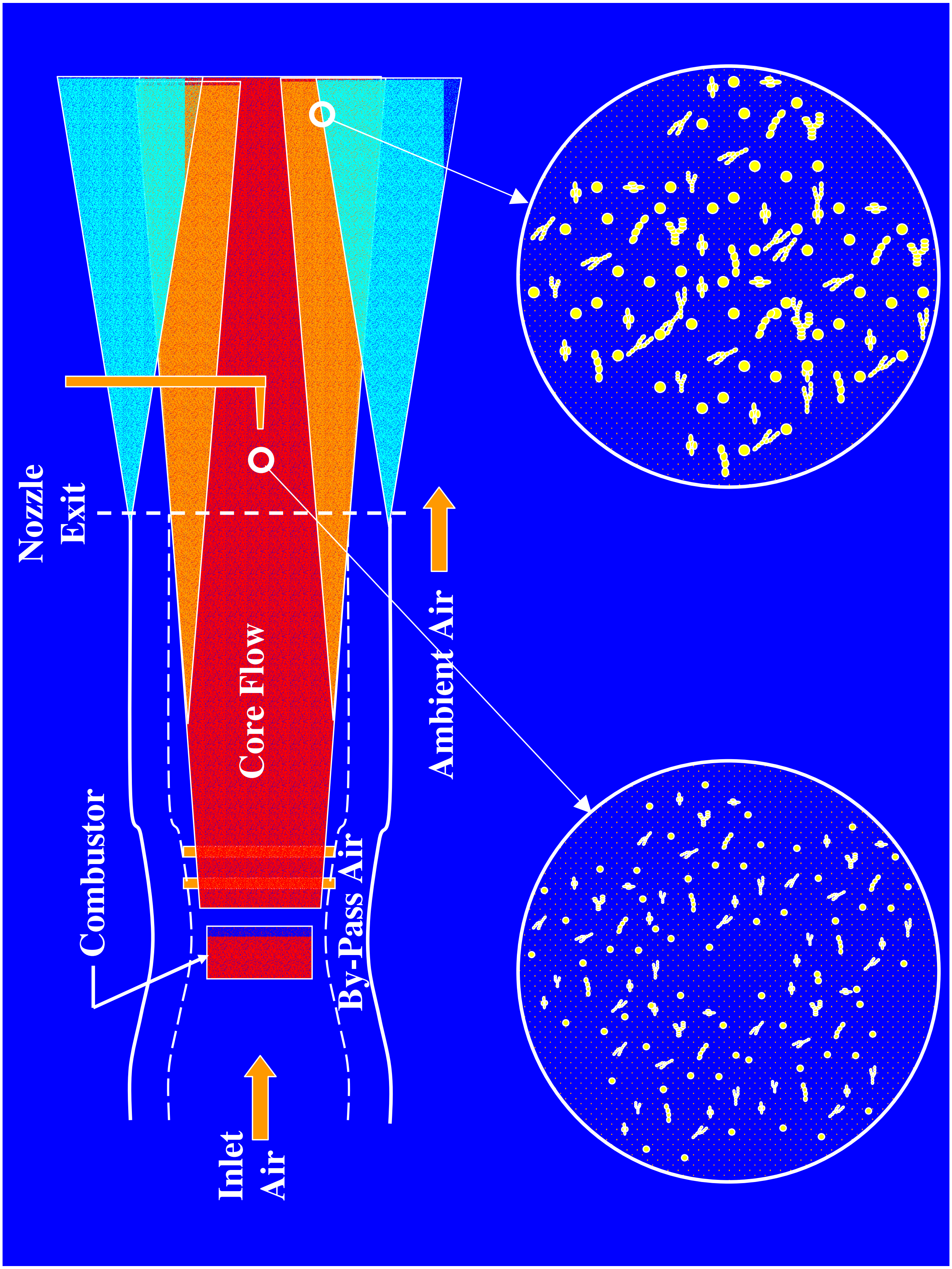
- Describe current particulate sampling methodology
- Define known sampling issues
- Evaluate current methodology assumptions and tradeoffs
- Identify improvements to mitigate sampling issues
- Identify experiments and processes for sampling methodology validation
- Take action toward standardized sampling methodology

Sampling Methodology - Current Understanding & Issues



Particulate Matter (size, chemistry, ...)
Aerosol Precursors
NO, NO_X, CO, CO_2, HC
Other Trace Gaseous Species
Temperature, Pressure, Velocity, ...

→ Radial and Axial Variations


Nozzle
Exit
Combustor
Core Flow
Ambient Air
By-Pass Air
Inlet
Air

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.

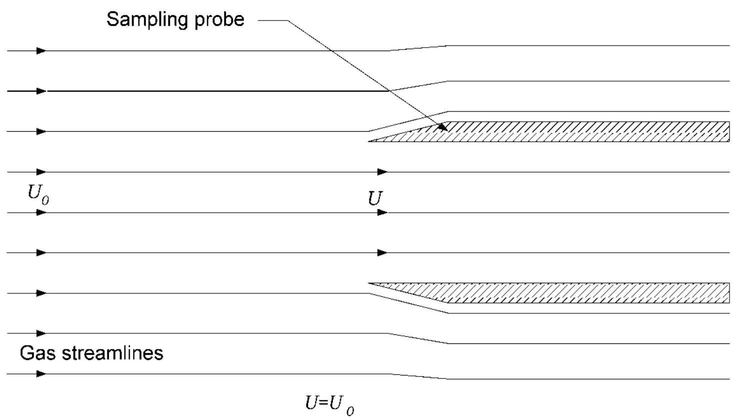
Sampling Methodology - Current Understanding & Issues

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

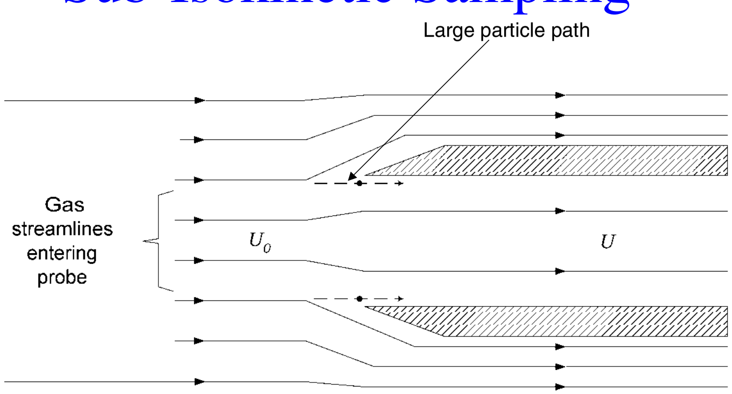


Isokinetic: Gas velocity at the probe tip equals the exhaust free-stream velocity.

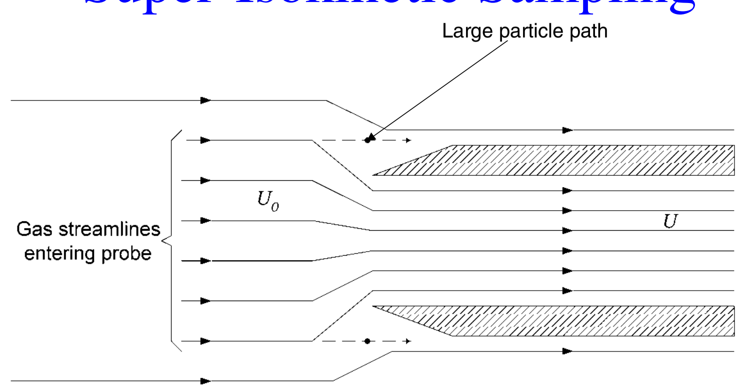
Sub-Isokinetic: Gas velocity at the probe tip is less than the exhaust free-stream velocity; sample biased to large particles.

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

Sub-Isokinetic Sampling



Super-Isokinetic Sampling



Sampling Methodology - Current Understanding & Issues

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

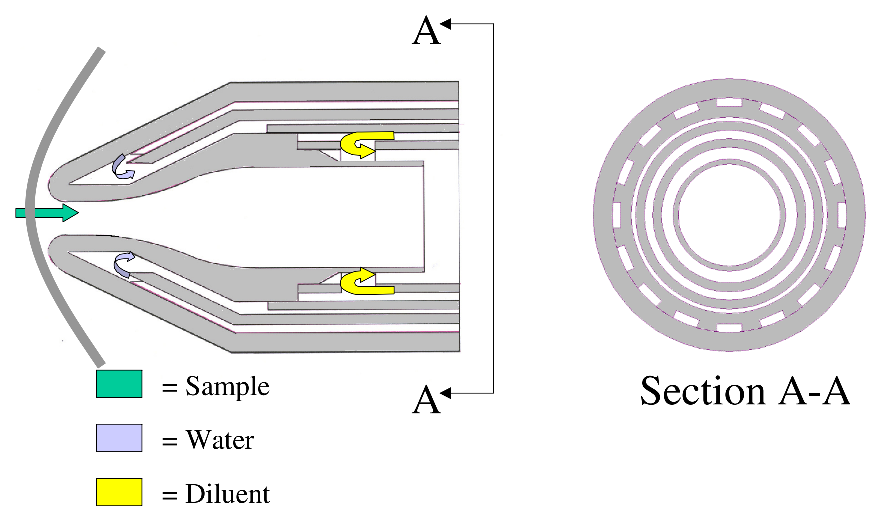
Dilution ...

- 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

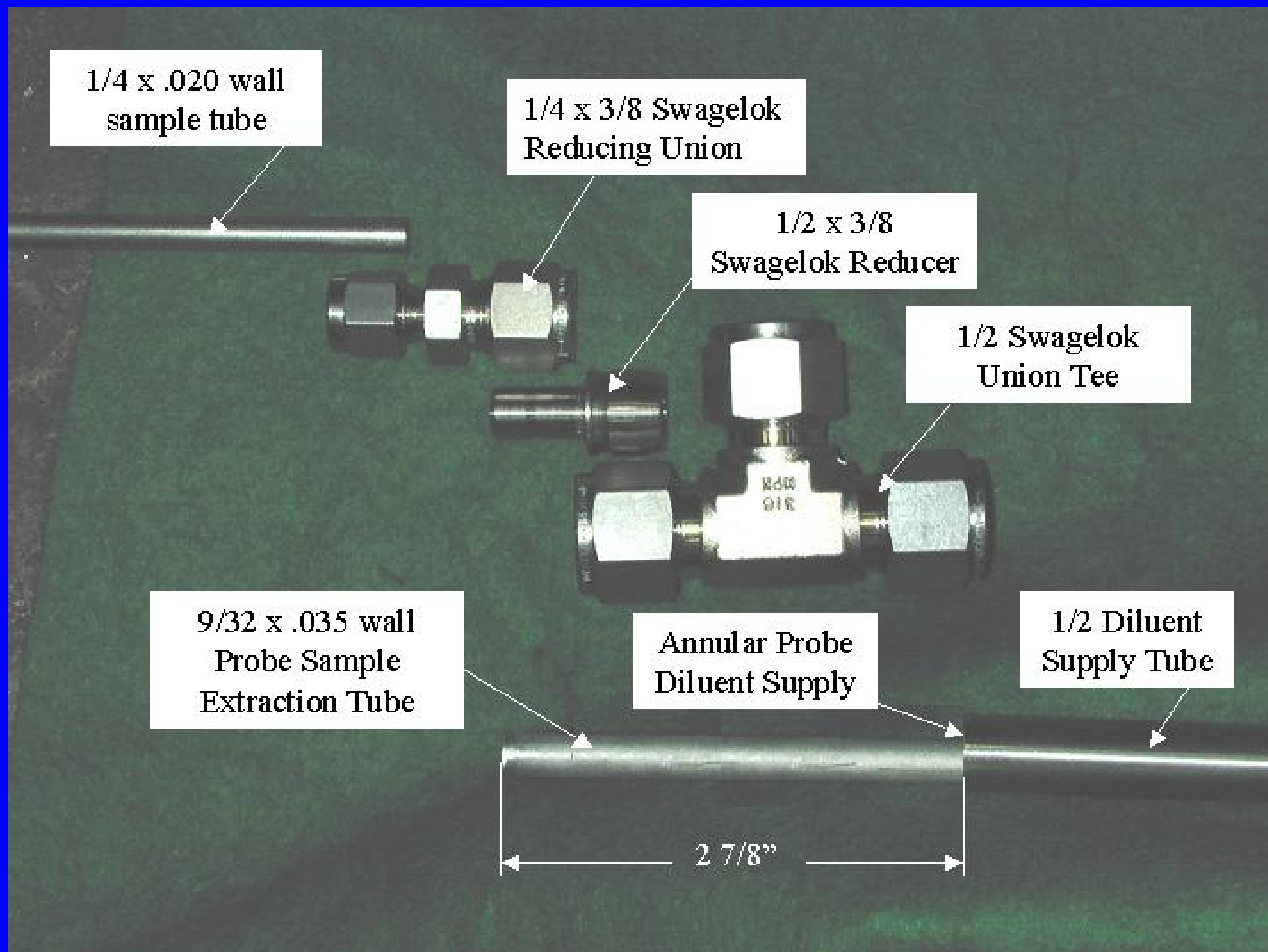
- Adds diluent near the probe tip.
- Injects the diluent along the wall and parallel to the sample flow.
- Is water cooled.




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

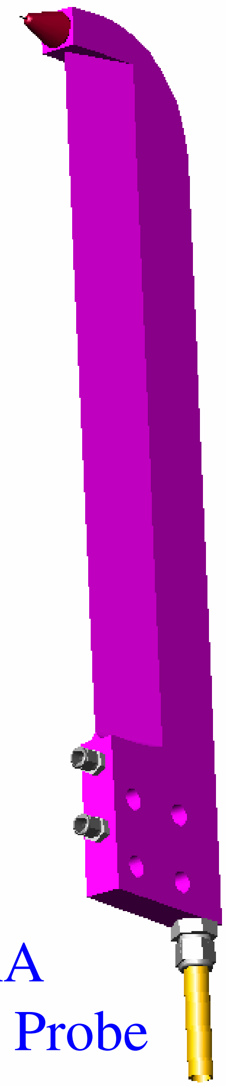
NASA Water-Cooled Rake Arm with 12-Particulate Probes

Components For Independent Diluent Supply

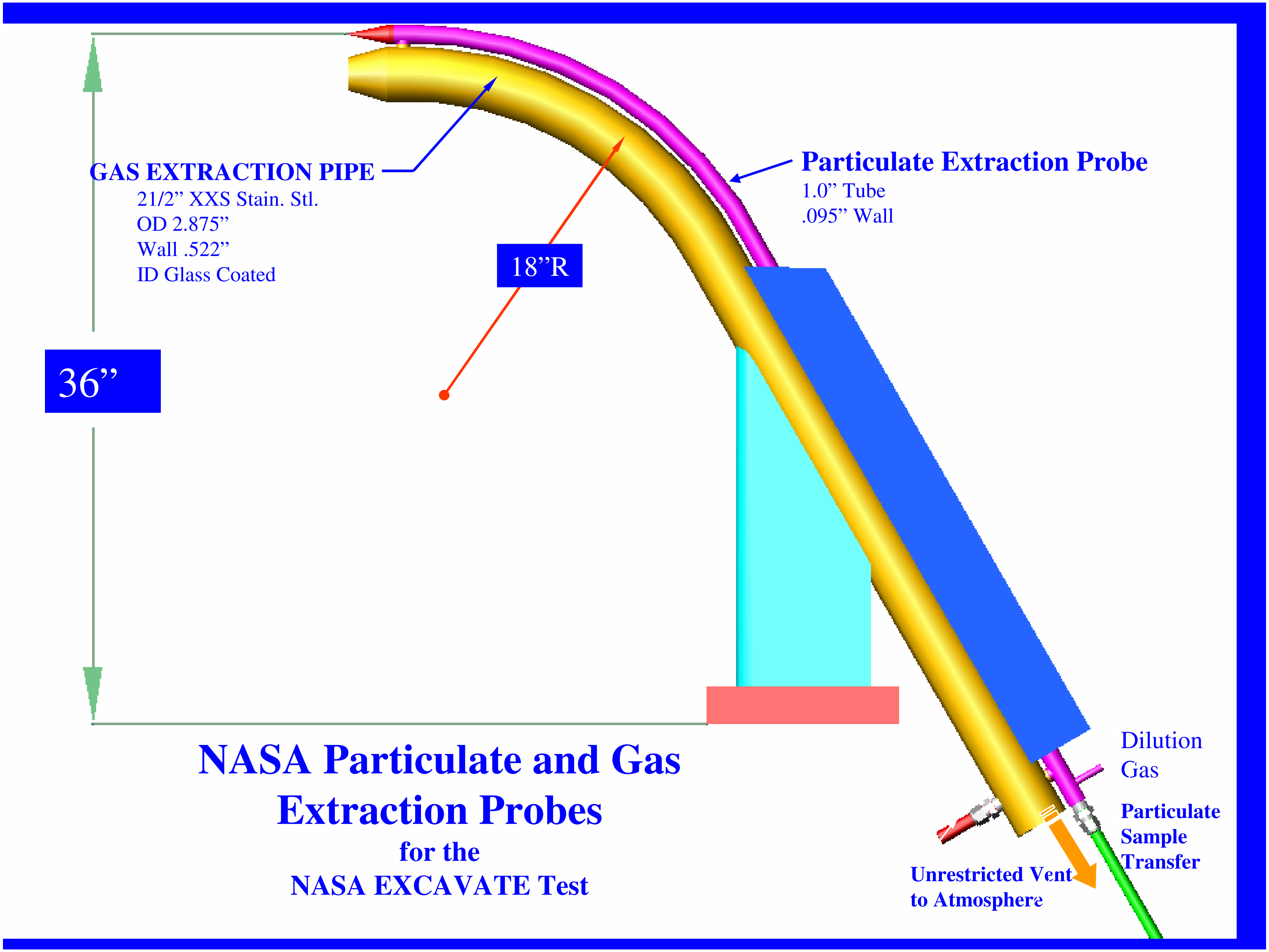


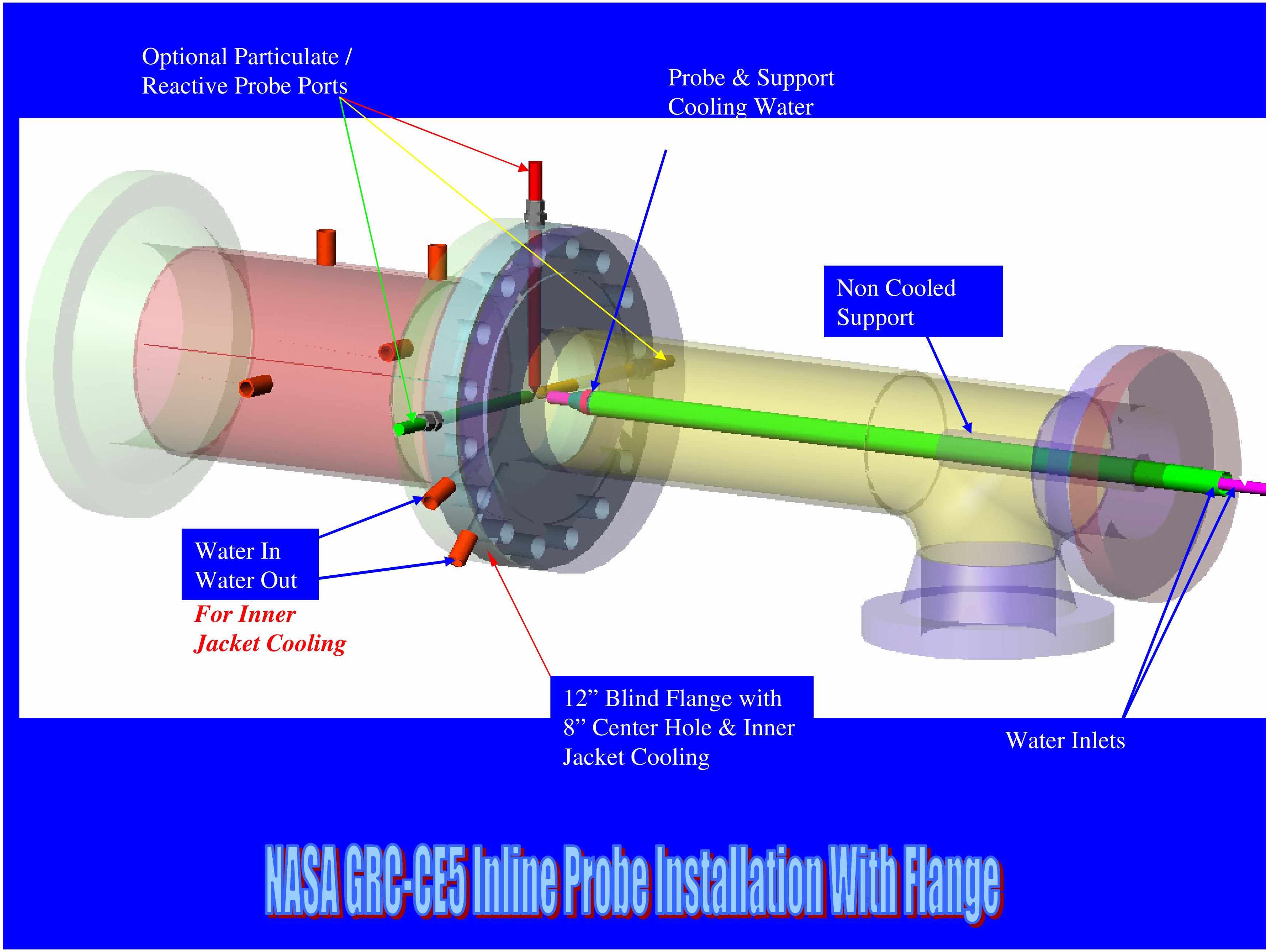
Independent Diluent Supply Tee Assembly

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
18”R
36”
Particulate Extraction Probe
1.0” Tube
.095” Wall
Dilution
Gas
Particulate
Sample
Transfer
Unrestricted Vent
to Atmosphere
NASA Particulate and Gas
Extraction Probes
for the
NASA EXCAVATE Test


Optional Particulate /
Reactive Probe Ports
Probe & Support
Cooling Water
Non Cooled
Support
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

Sampling Methodology - Current Understanding & Issues

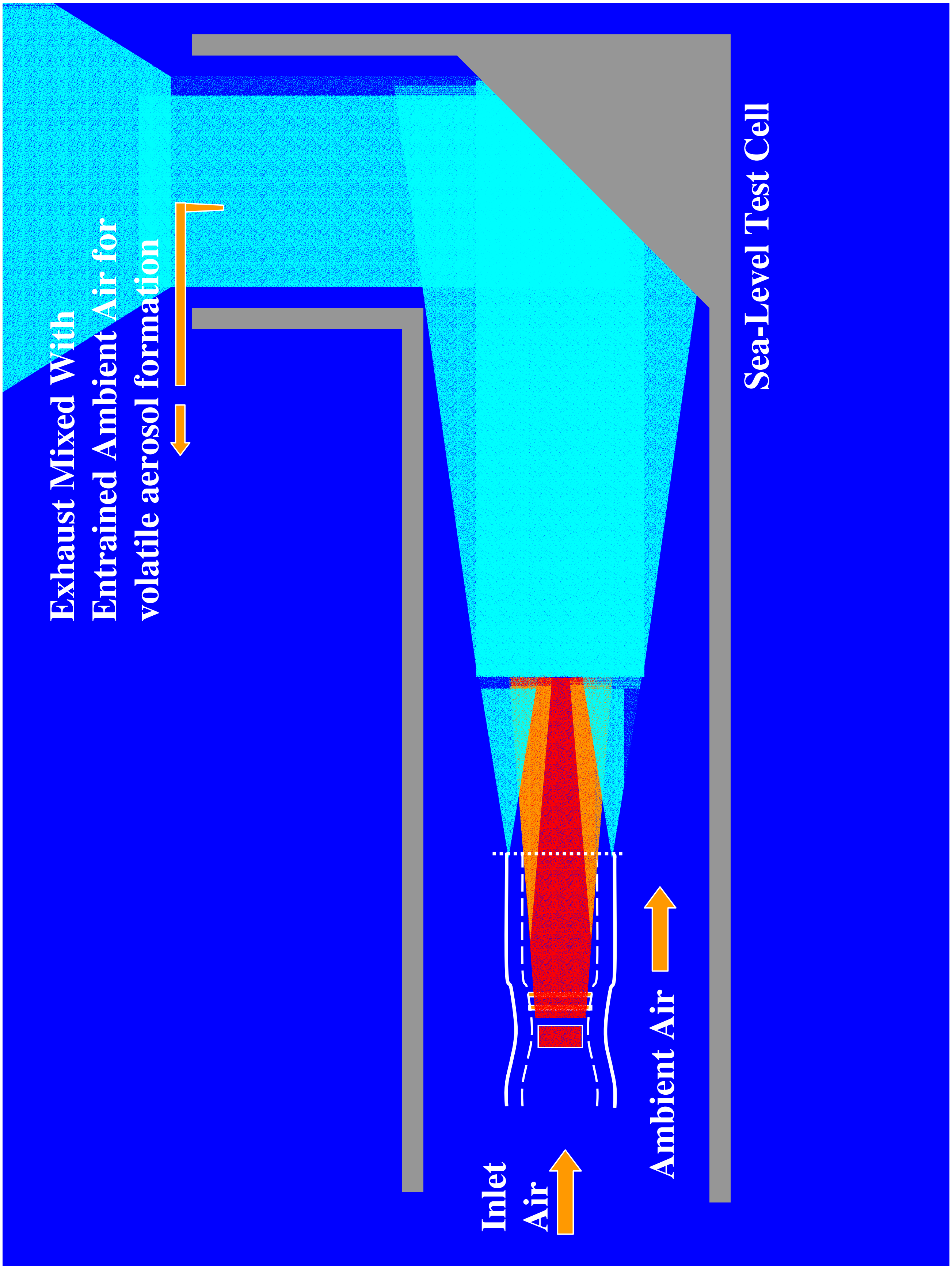
Remarks

- Probe penetration measurements performed at the 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.

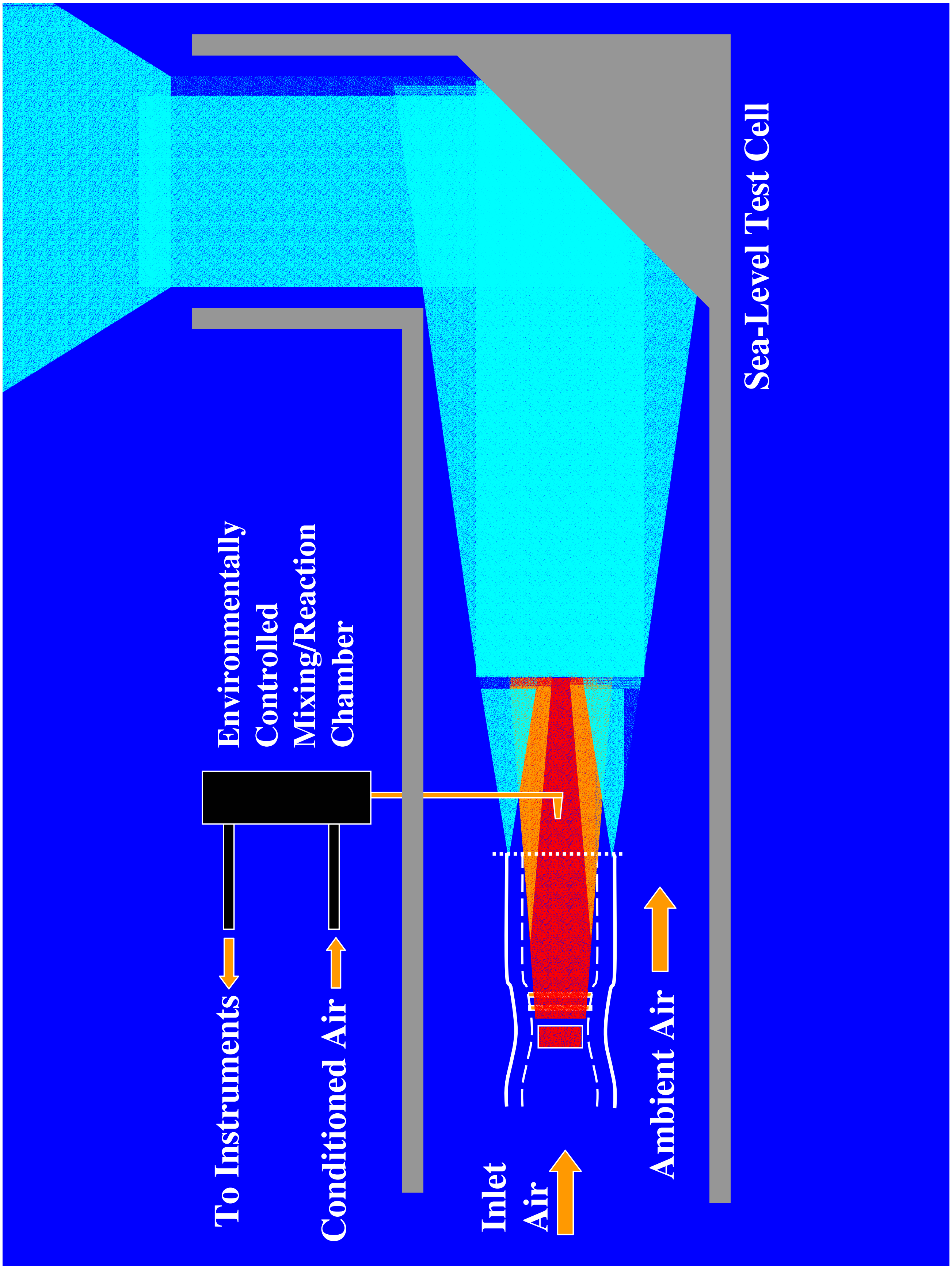
Sampling Methodology - Current Understanding & Issues

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.



Exhaust Mixed With
Entrained Ambient Air for
volatile aerosol formation
Sea-Level Test Cell
Inlet
Air
Ambient Air



Sea-Level Test Cell
Environmentally
Controlled
Mixing/Reaction
Chamber
To Instruments
Conditioned Air
Inlet
Air
Ambient Air

Sampling Methodology - Current Understanding & Issues

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.)

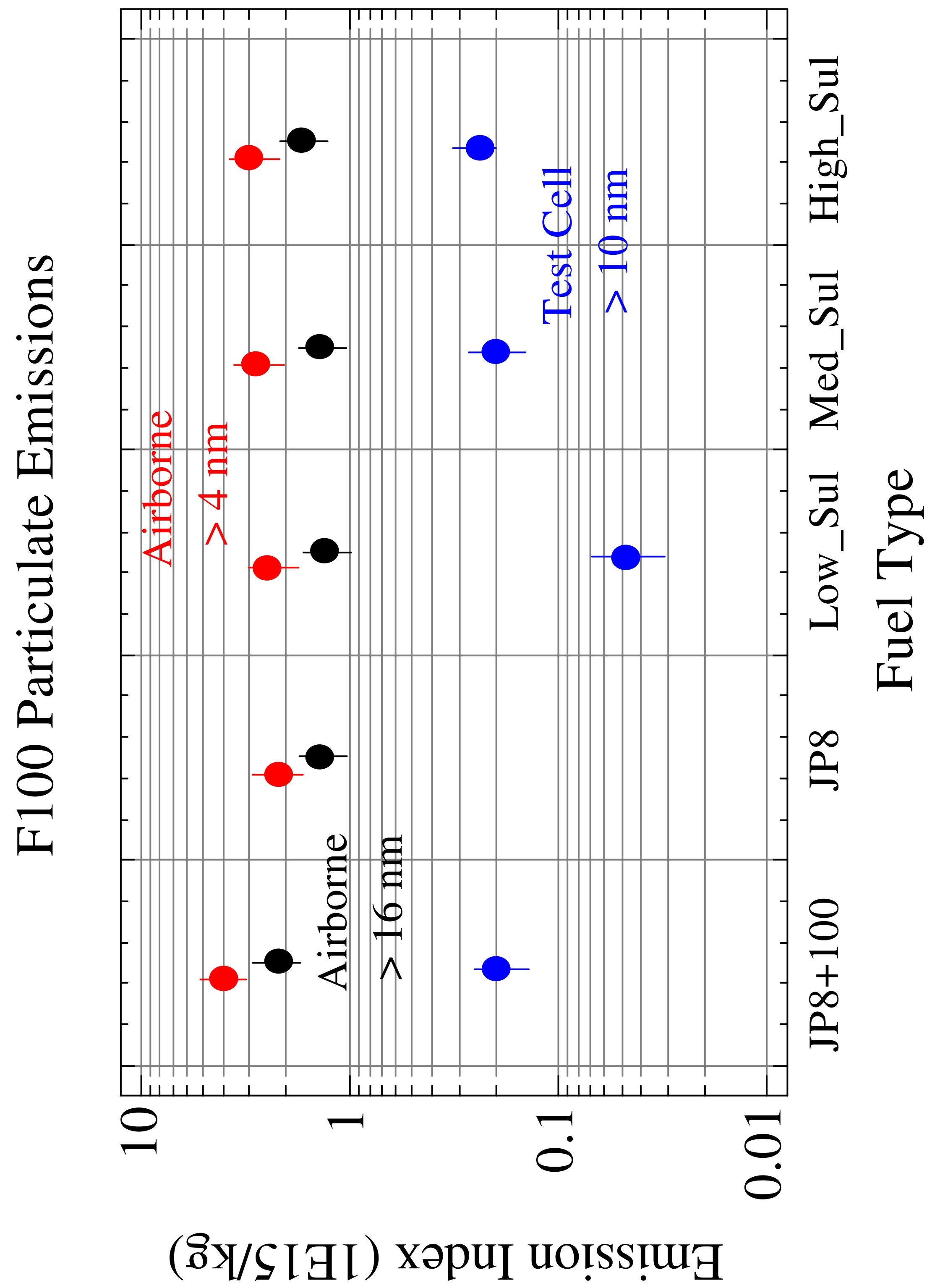
- Probe tip and sample line penetration:
  - How do volatile and non-volatile aerosol penetrations compare?
  - Probe penetration calibrations should be performed at simulated aerodynamic and thermodynamic engine exhaust conditions?
- Pressure discontinuity/disturbance in front of the probe tip has a 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

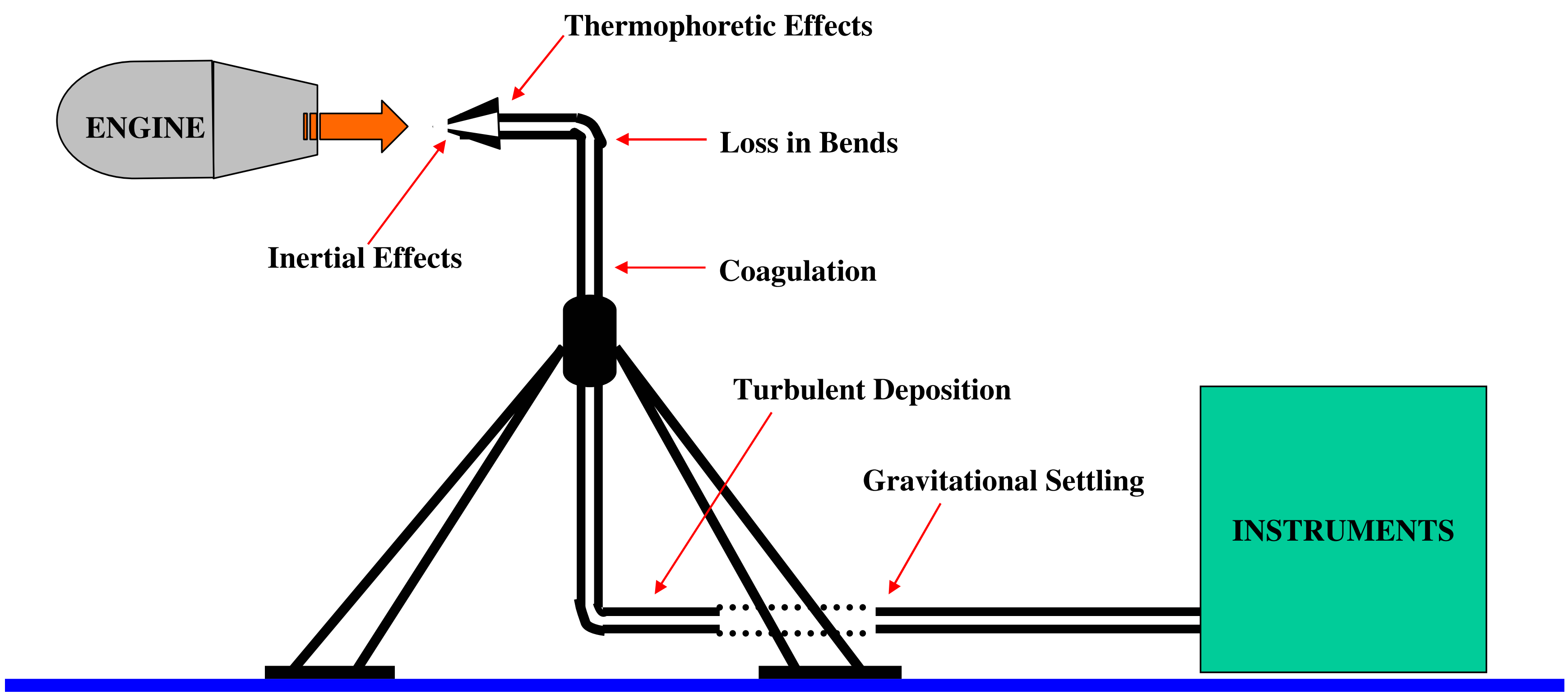
Bruce Anderson

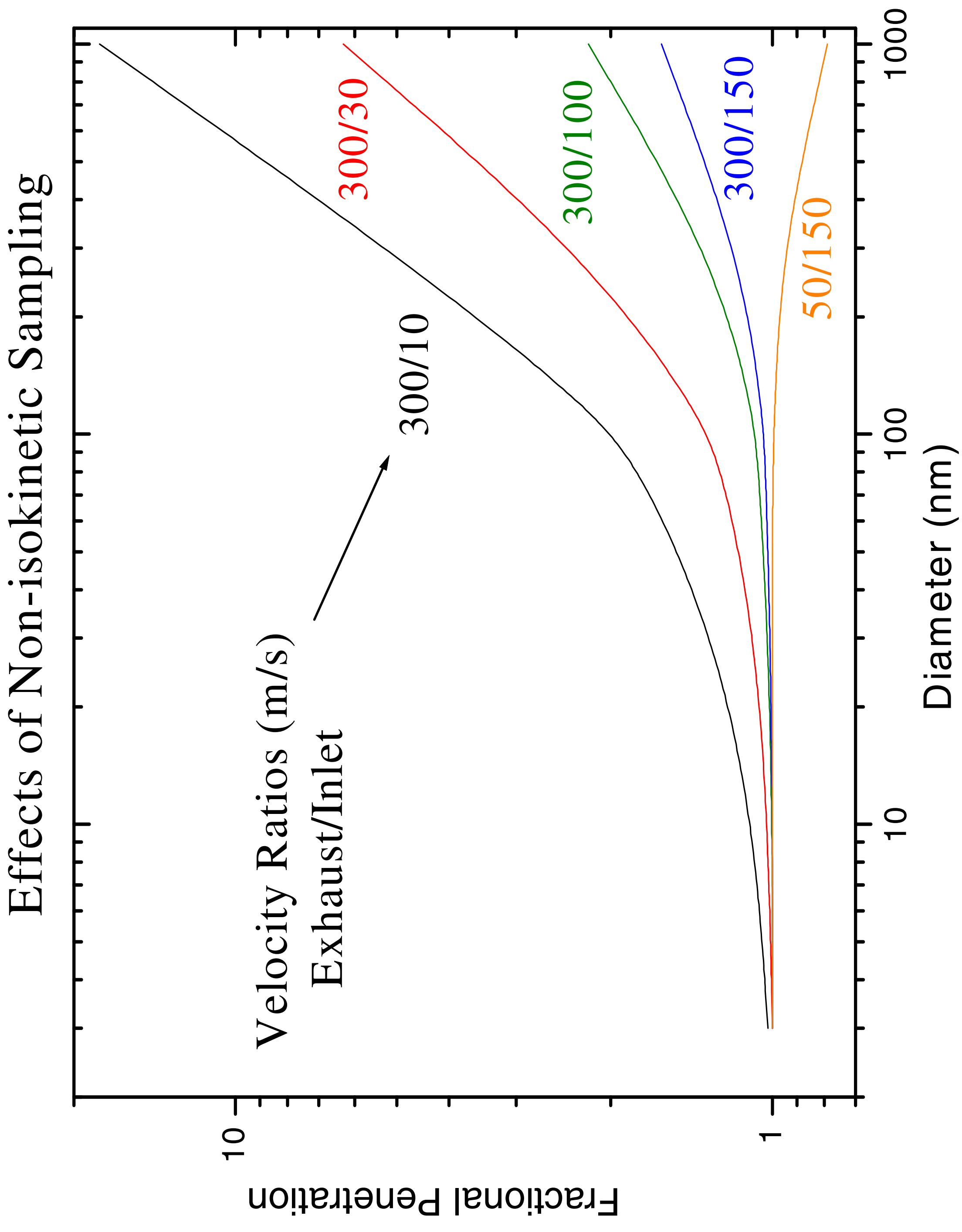
Atmospheric Sciences

NASA Langley Research Center

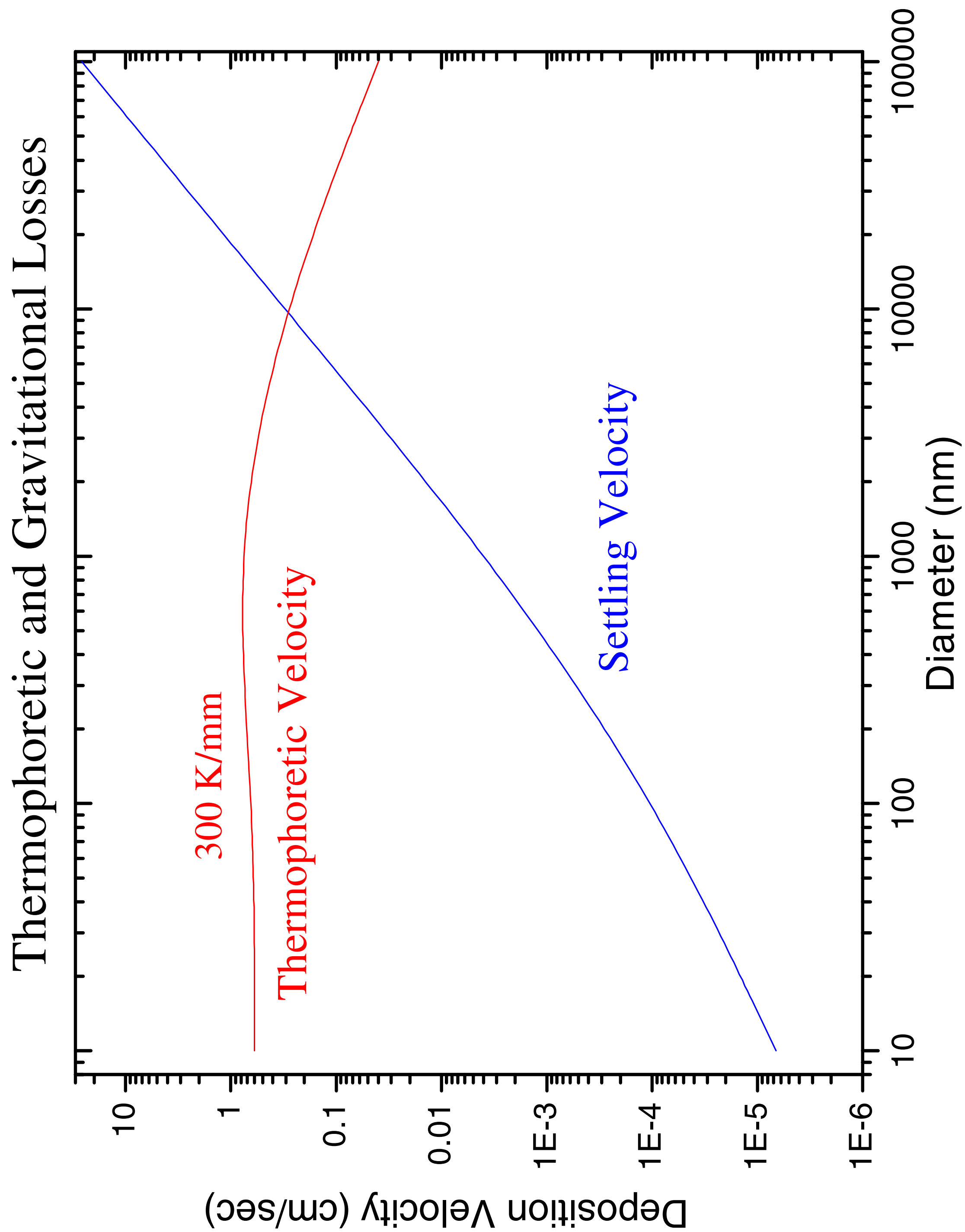

F100 Particulate Emissions
Emission Index (1E15/kg)
10
1
0.1
0.01
JP8+100
JP8
Low_Sul
Med_Sul
High_Sul
Fuel Type
Airborne
> 4 nm
Airborne
> 16 nm
Test Cell
> 10 nm

Processes Influencing Particle Size and Concentration

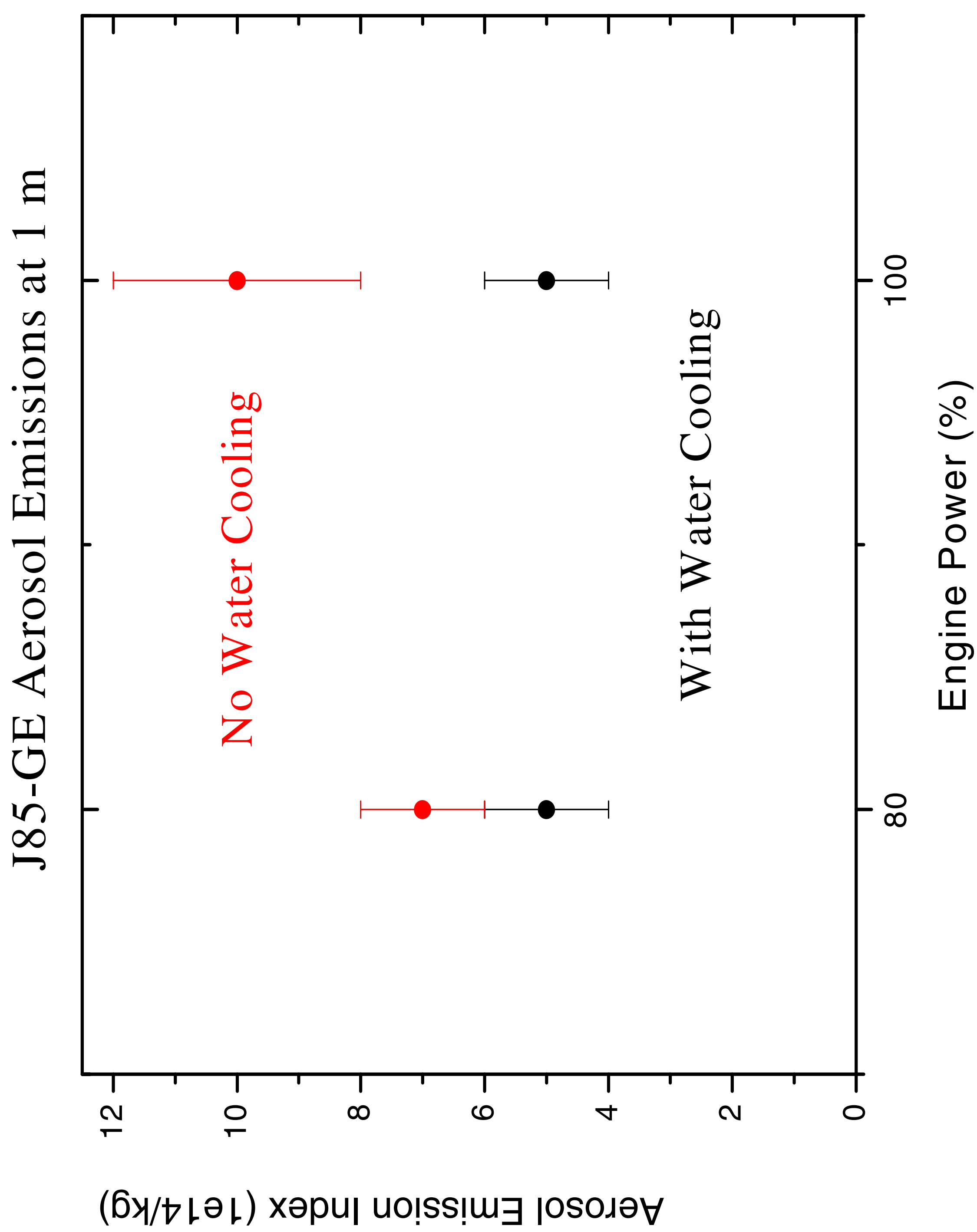


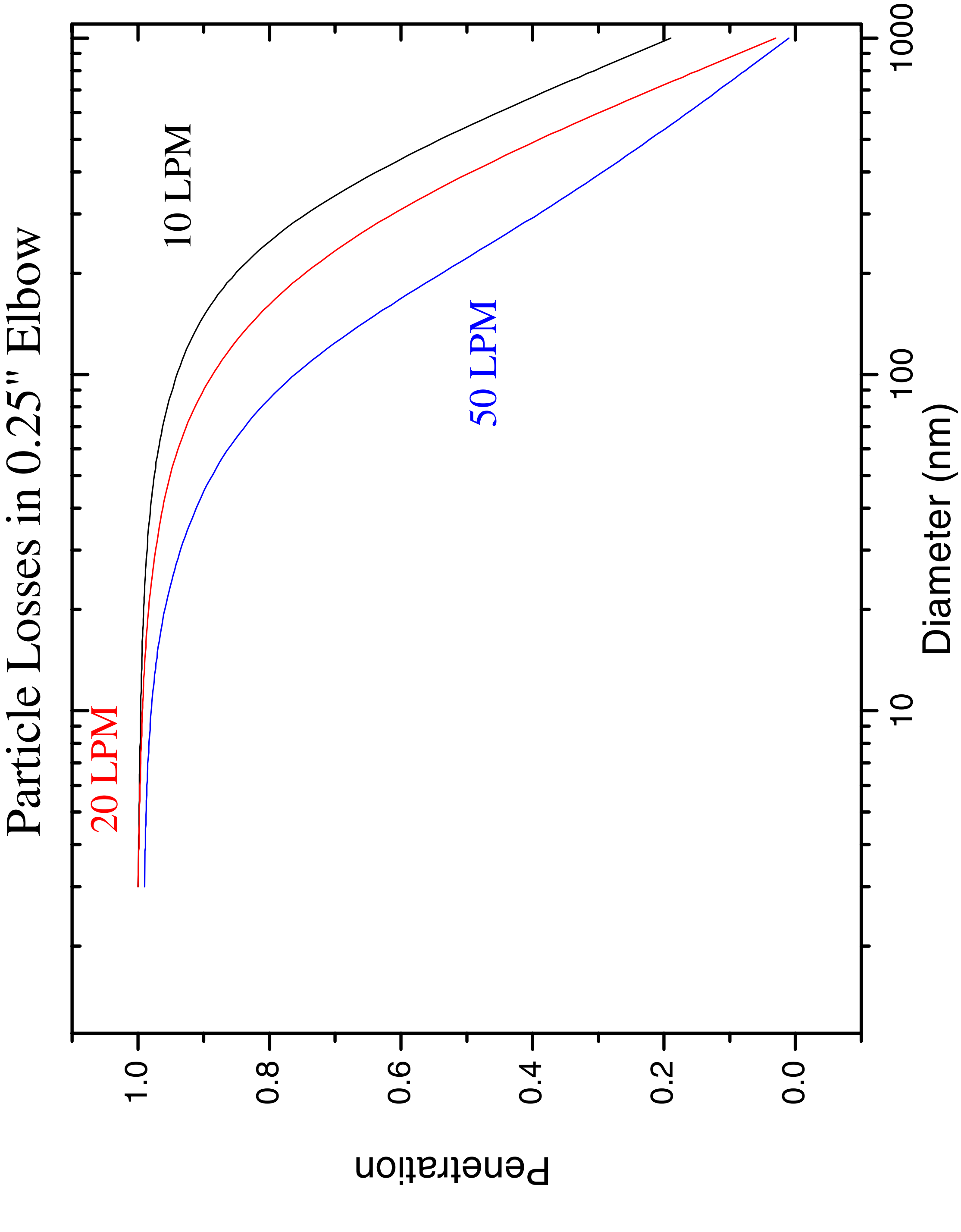


Effects of Non-isokinetic Sampling
Velocity Ratios (m/s)
Exhaust/Inlet
300/10
300/30
300/100
300/150
50/150
Fractional Penetration
10
1
Diameter (nm)
10
100
1000

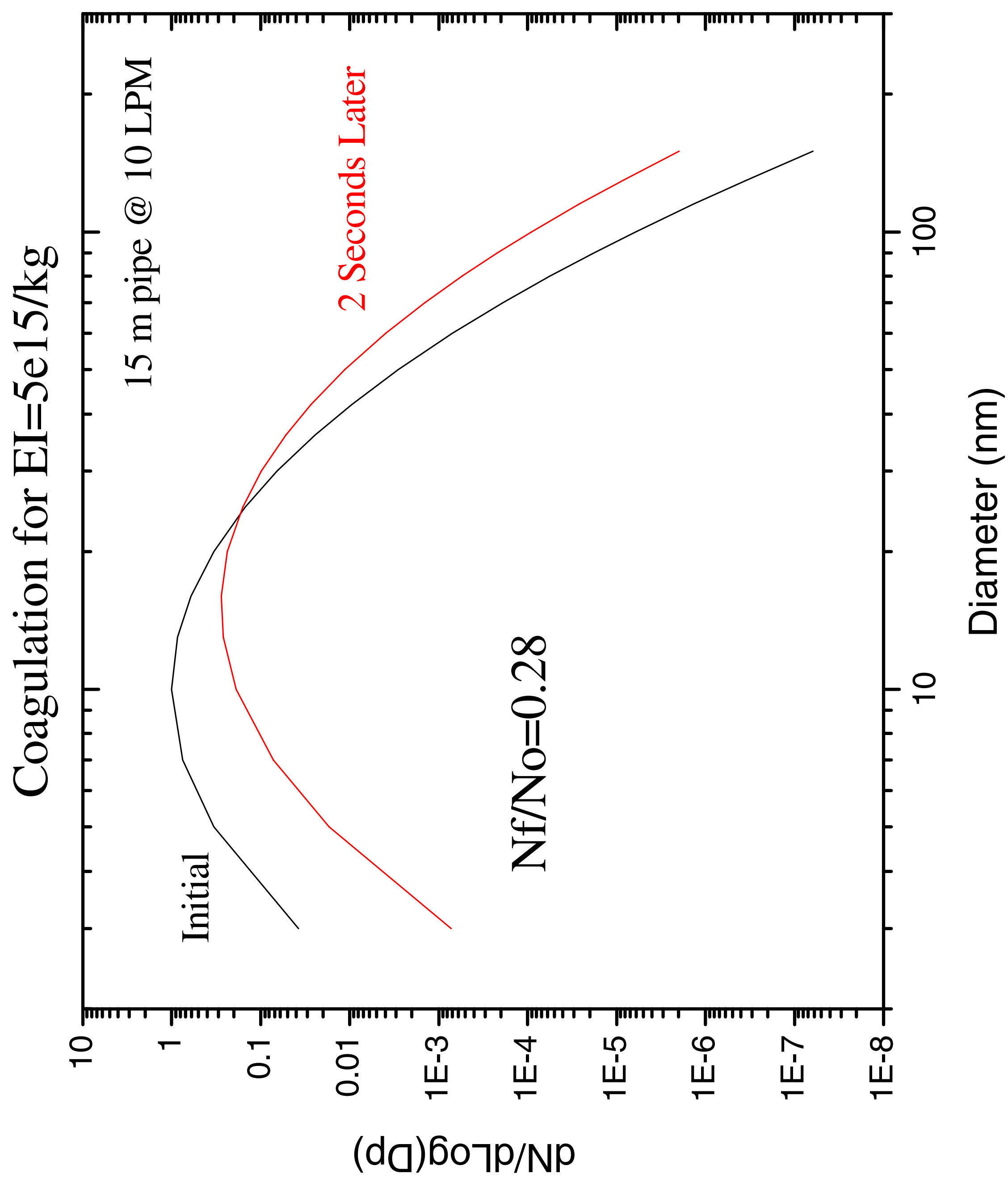


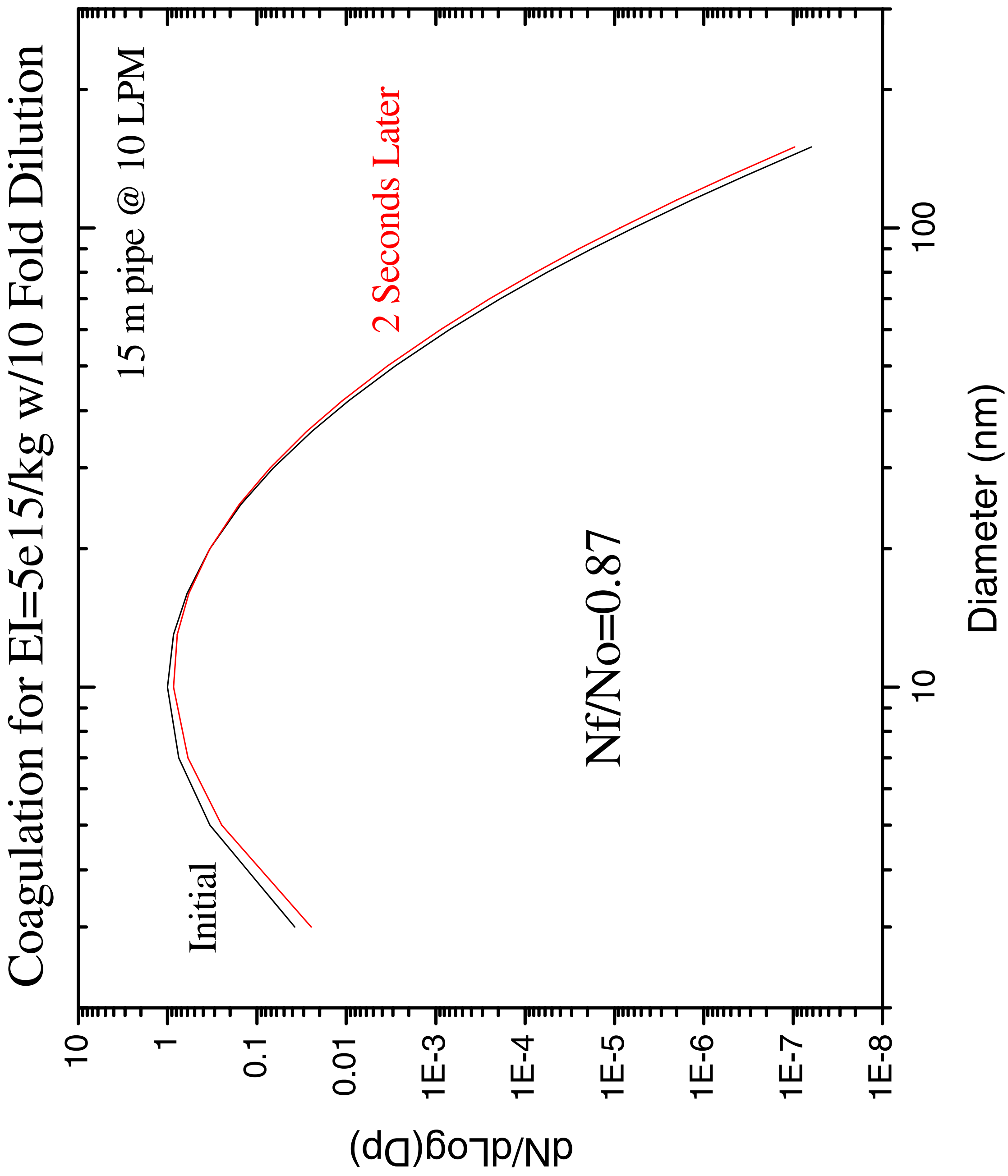
Thermophoretic and Gravitational Losses
300 K/mm
Thermophoretic Velocity
Settling Velocity
Deposition Velocity (cm/sec)
Diameter (nm)
10
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
10
100
1000
10000
100000


J85-GE Aerosol Emissions at 1 m
No Water Cooling
With Water Cooling
Engine Power (%)
Aerosol Emission Index (1e14/kg)
0
2
4
6
8
10
12
80
100

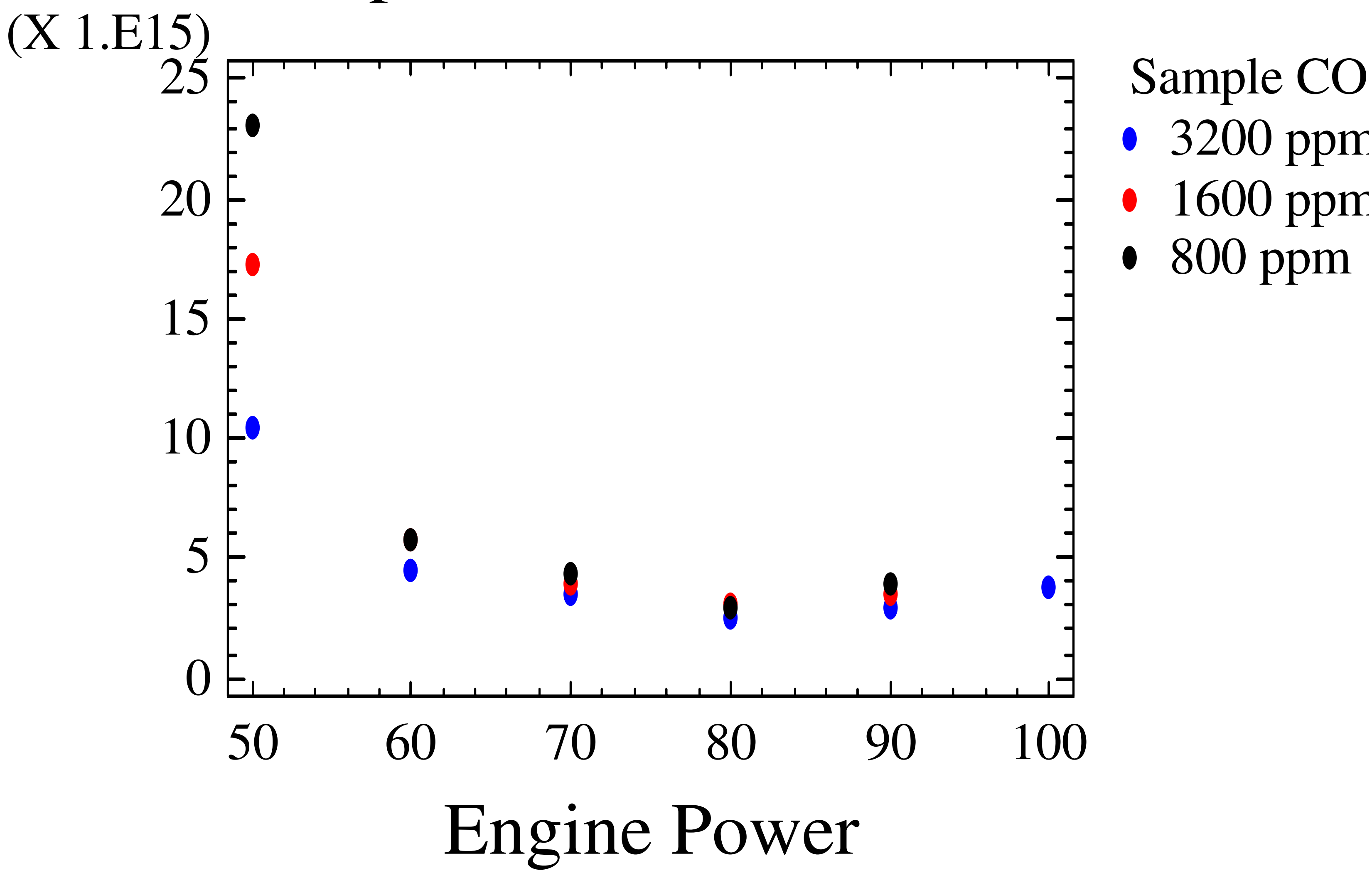


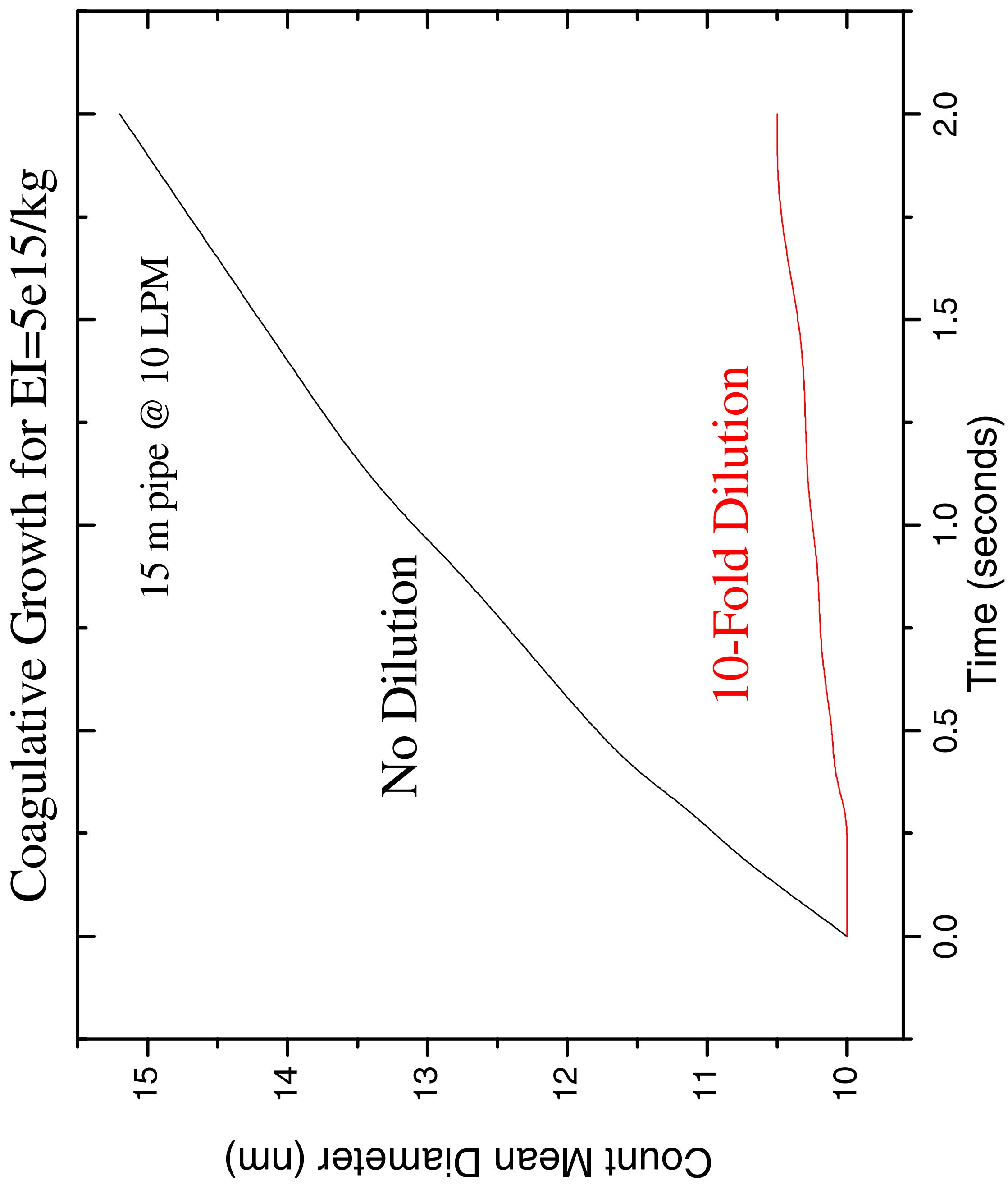
Particle Losses in 0.25" Elbow
10 LPM
20 LPM
50 LPM
Penetration
1.0
0.8
0.6
0.4
0.2
0.0
Diameter (nm)
10
100
1000


Coagulation for EI=5e15/kg
15 m pipe @ 10 LPM
2 Seconds Later
Initial
Nf/No=0.28
Diameter (nm)
dN/dLog(Dp)
10
100
10
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8

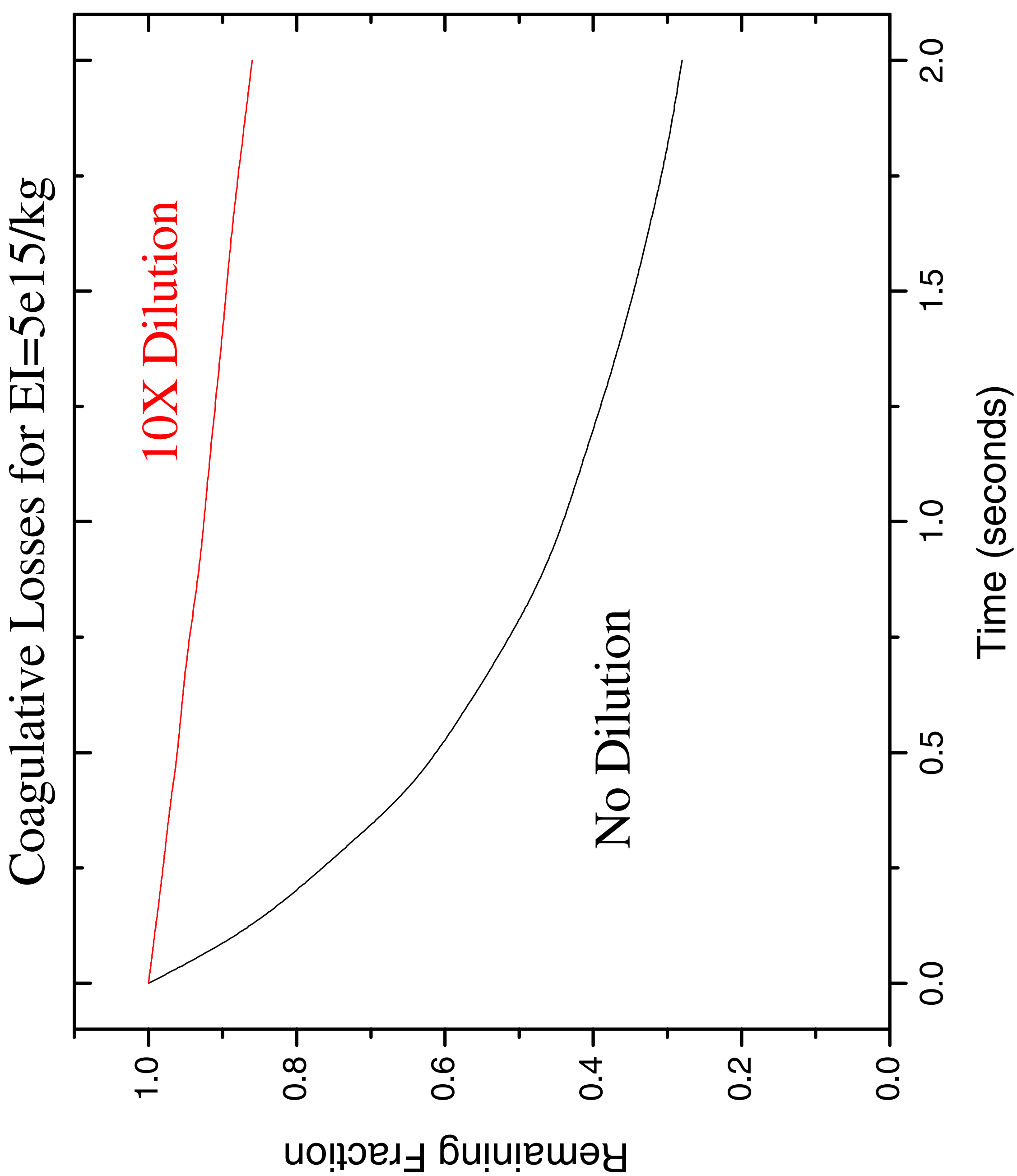

Coagulation for EI=5e15/kg w/10 Fold Dilution
15 m pipe @ 10 LPM
2 Seconds Later
Initial
Nf/No=0.87
Diameter (nm)
dN/dLog(Dp)
10
100
10
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8

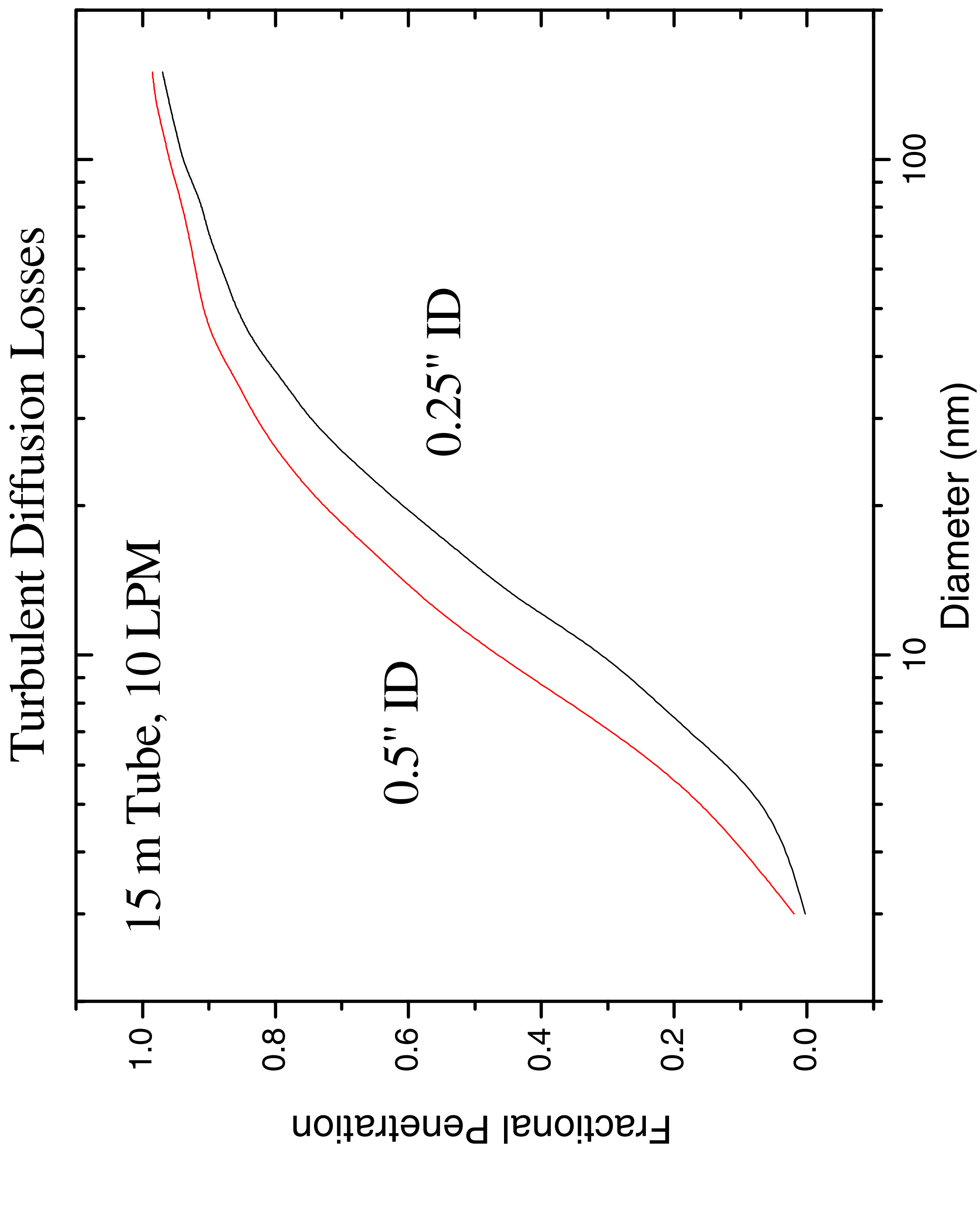
Impact of Dilution on EI

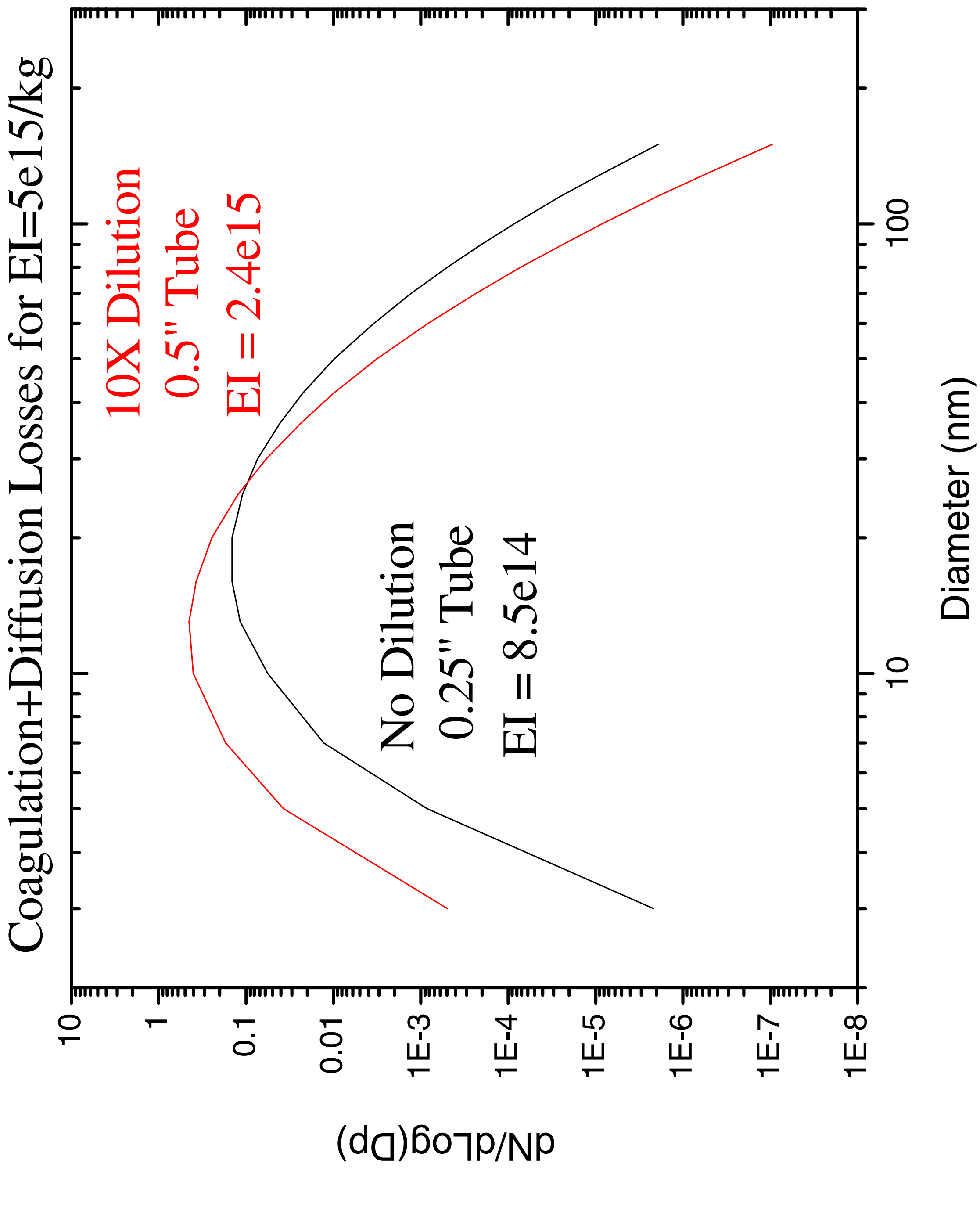




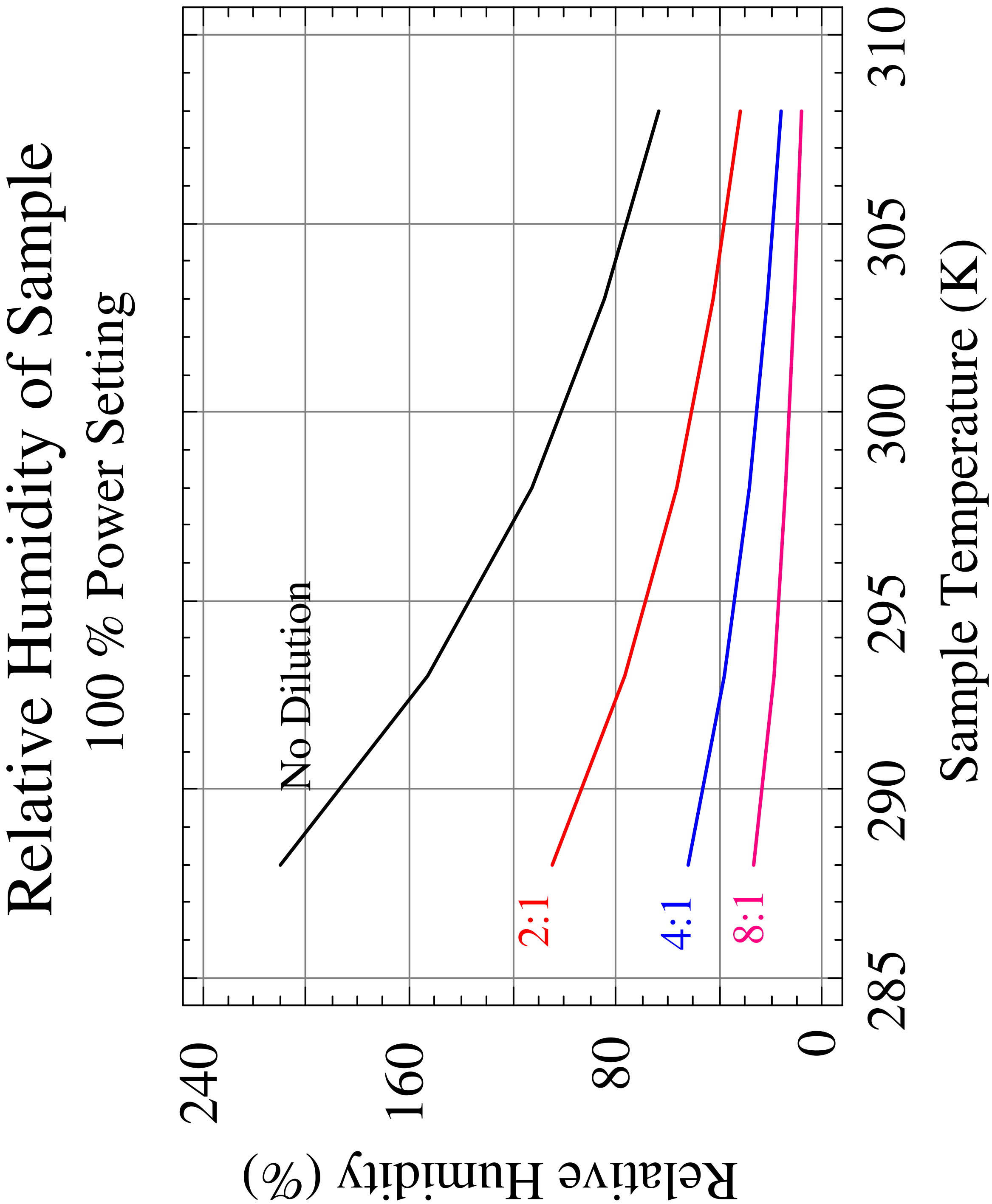
Coagulative Growth for EI=5e15/kg
15 m pipe @ 10 LPM
No Dilution
10-Fold Dilution
Count Mean Diameter (nm)
Time (seconds)
10
11
12
13
14
15
0.0
0.5
1.0
1.5
2.0


Coagulative Losses for EI=5e15/kg
10X Dilution
No Dilution
Remaining Fraction
Time (seconds)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0

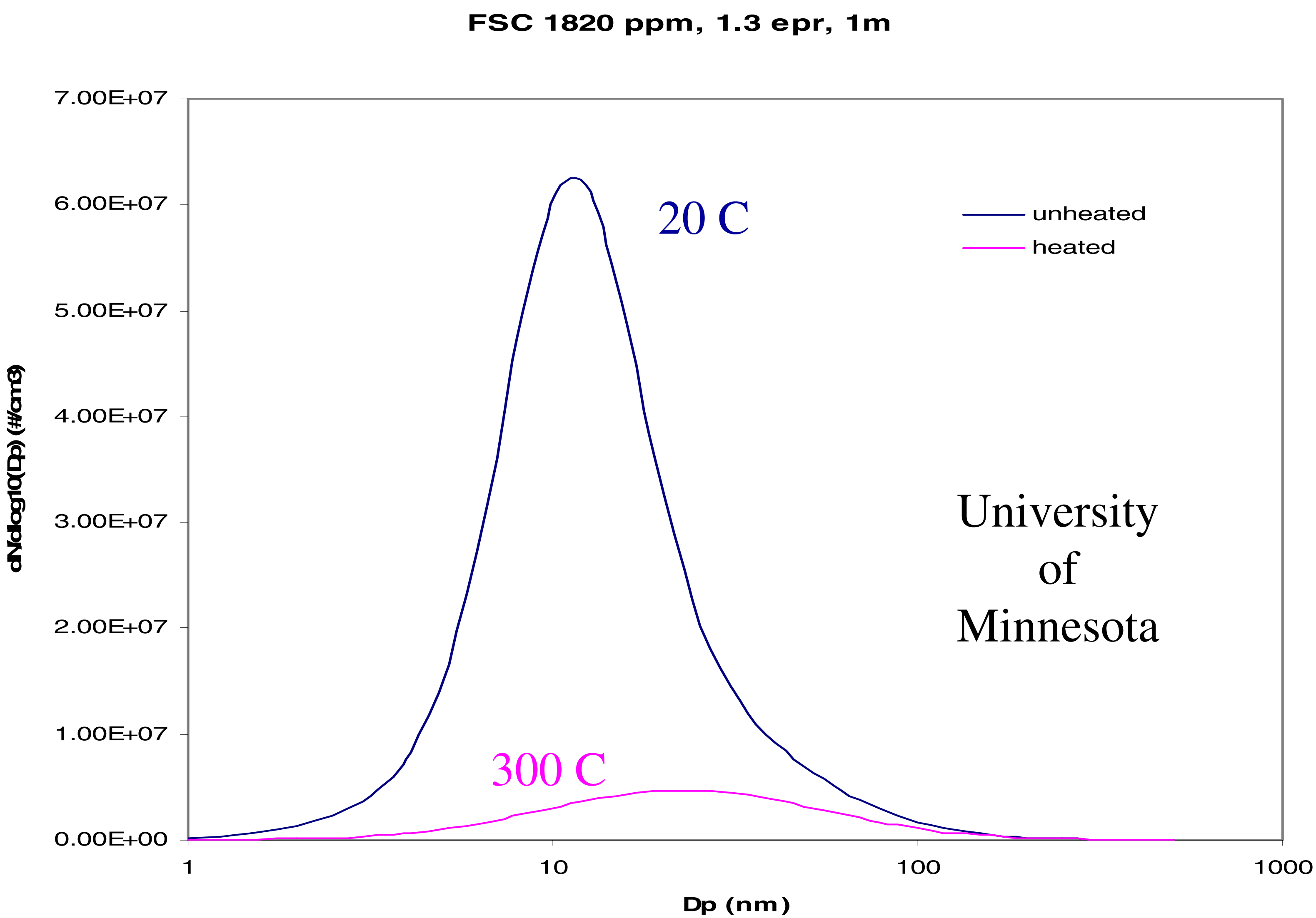

Turbulent Diffusion Losses
15 m Tube, 10 LPM
0.5" ID
0.25" ID
Fractional Penetration
1.0
0.8
0.6
0.4
0.2
0.0
Diameter (nm)
10
100

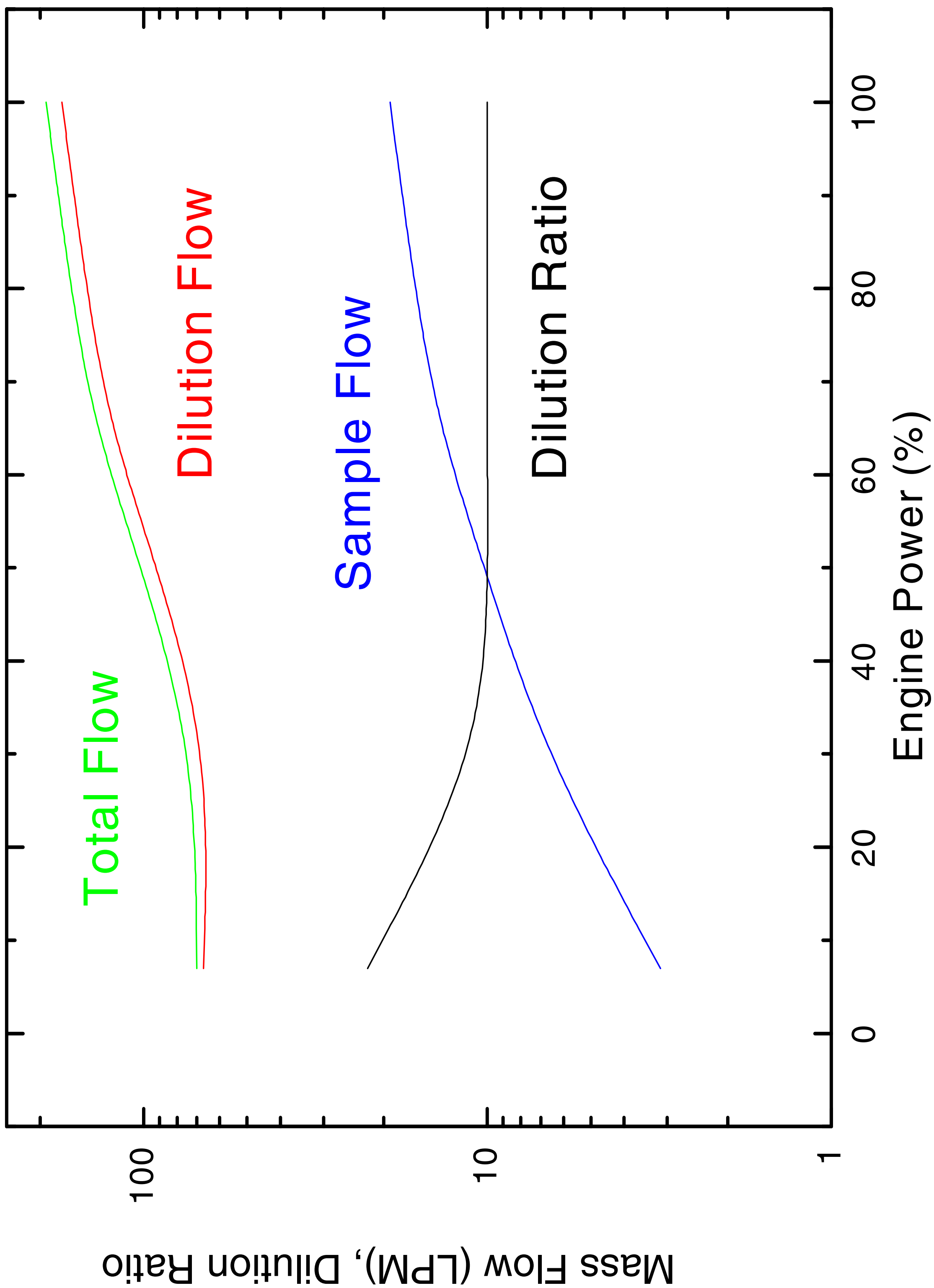


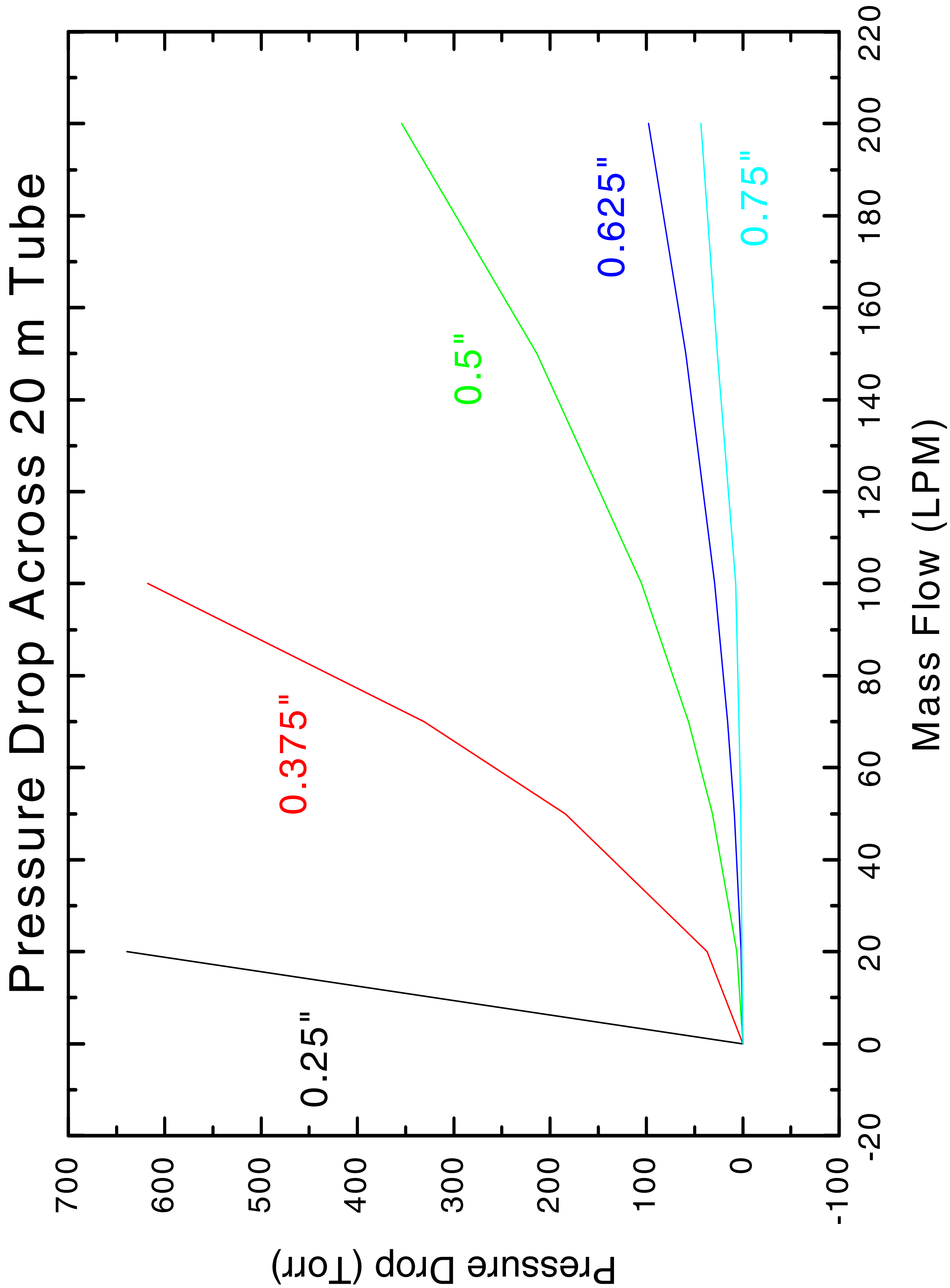
Coagulation+Diffusion Losses for EI=5e15/kg
10X Dilution
0.5" Tube
EI = 2.4e15
No Dilution
0.25" Tube
EI = 8.5e14
Diameter (nm)
10
100
dN/dLog(Dp)
10
1
0.1
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8


Relative Humidity of Sample
100 % Power Setting
No Dilution
2:1
4:1
8:1
Relative Humidity (%)
240
160
80
0
Sample Temperature (K)
285
290
295
300
305
310

Condensation of Volatile Species



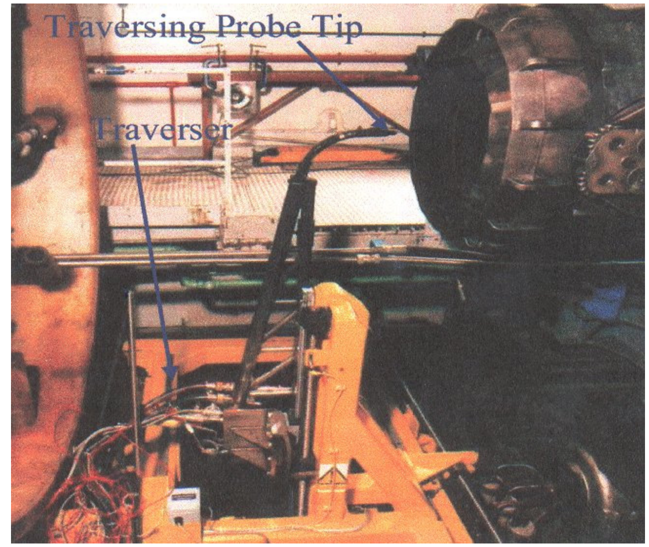

Total Flow
Dilution Flow
Sample Flow
Dilution Ratio
Engine Power (%)
Mass Flow (LPM), Dilution Ratio
0
20
40
60
80
100
1
10
100


Pressure Drop Across 20 m Tube
Mass Flow (LPM)
Pressure Drop (Torr)
0.25"
0.375"
0.5"
0.625"
0.75"
-20
0
20
40
60
80
100
120
140
160
180
200
220
-100
0
100
200
300
400
500
600
700

Aviation Particle Emissions Workshop
Cleveland, 18-19 November 2003

Measurement Methodologies Non-volatile Aerosols

Phil Whitefield
Director UMRCOE



SAE E-31 Position Paper
On Particle Matter Measurements April 2002

"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/m^3	Primary & Secondary
24-hour Average	150 µg/m^3	Primary & Secondary
Particulate (PM 2.5)	*Particles with diameters of 2.5 micrometers or less*	
Annual Arithmetic Mean	15 µg/m^3	Primary & Secondary
24-hour Average	65 µg/m^3	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.

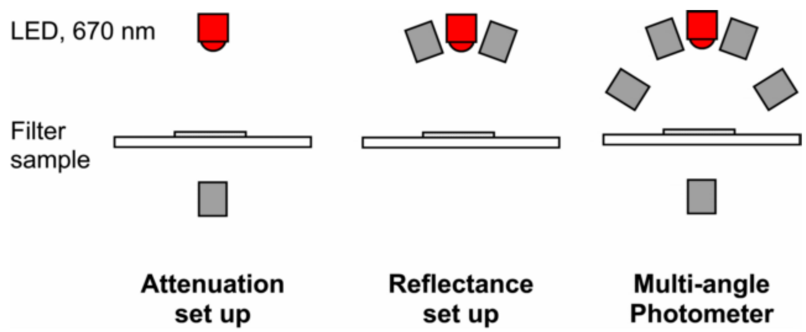
One technique samples the exhaust stream and collects particle matter on a filter, which is then analyzed for the collected particle mass.

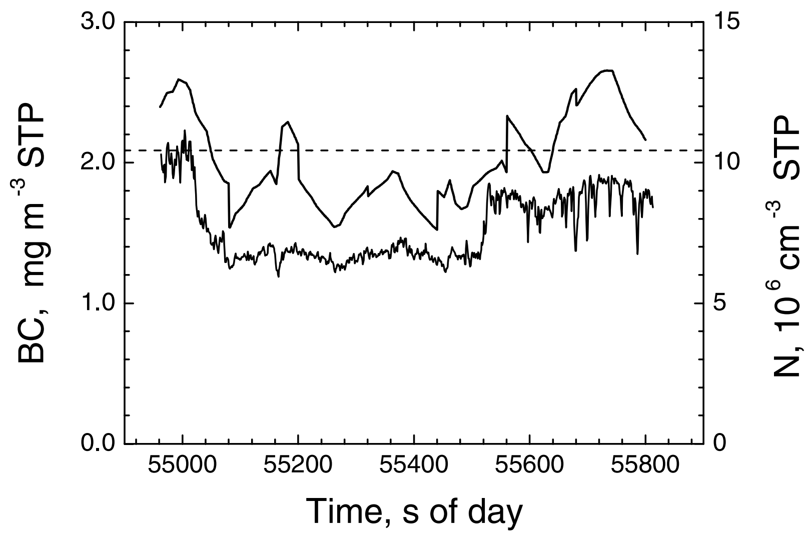
Another probes the exhaust flow optically to quantify the scattering material in situ without requiring the exhaust to be sampled and transported to the measurement system.

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 μg 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.

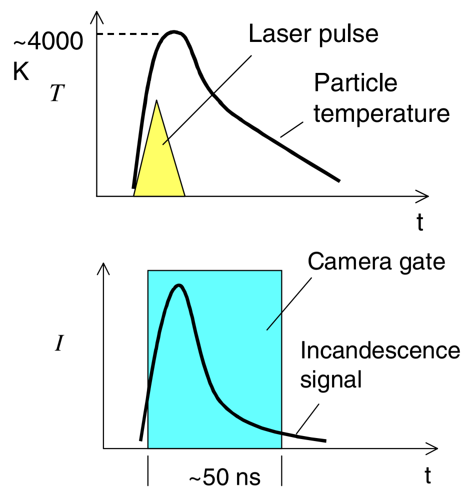
Measurement Method	Measurement	Analysis
Gravimetric analysis	Total particulate matter, total mass	off line, filter samples
Combustion of filter samples and CO_2 detection	Total carbonaceous mass, TC	off line, filter samples
Combustion analysis including OC/EC separation	Organic carbon (OC), elemental carbon (EC) $OC + EC = TC$	off line, filter samples
Optical absorption photometry	Black carbon (BC) $BC \cong EC$	on-line, filter samples time resolution $\geq$ 1 min
Laser induced incandescence	Black carbon (BC)	on-line, in situ
Transmissometry	Opacity	on-line, in situ
Light scattering	Forward scattering	on-line, in situ
Microbalance	Total particulate mass	on-line, extractive

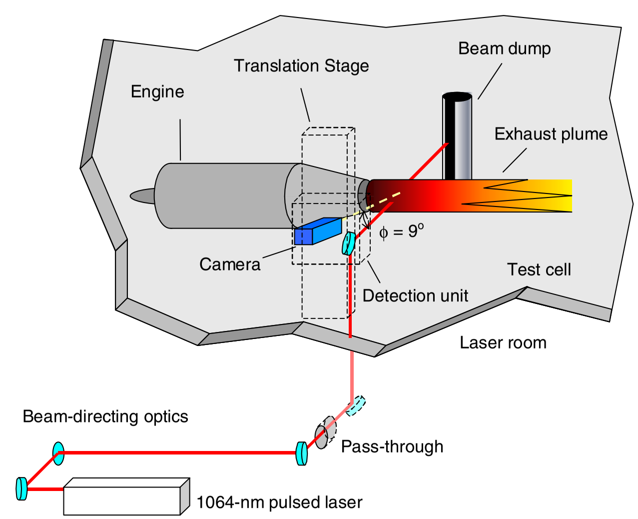
Optical Methods

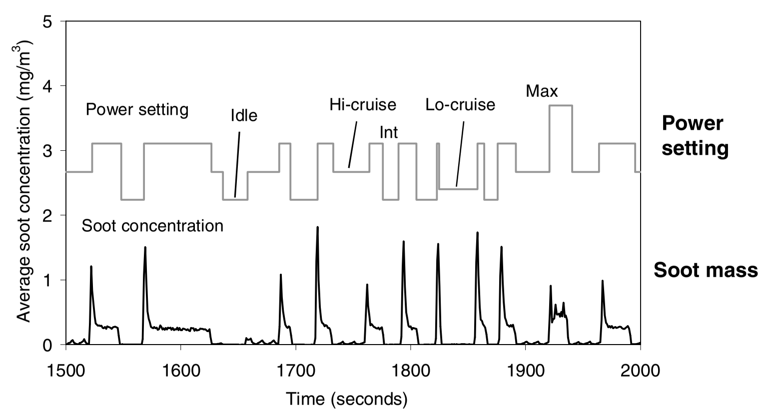


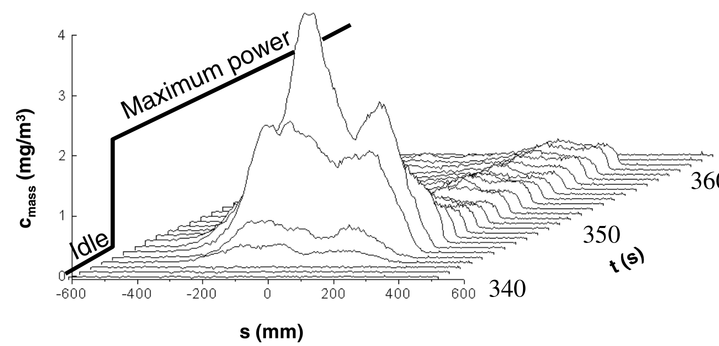


Laser Induced Incandescence









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.

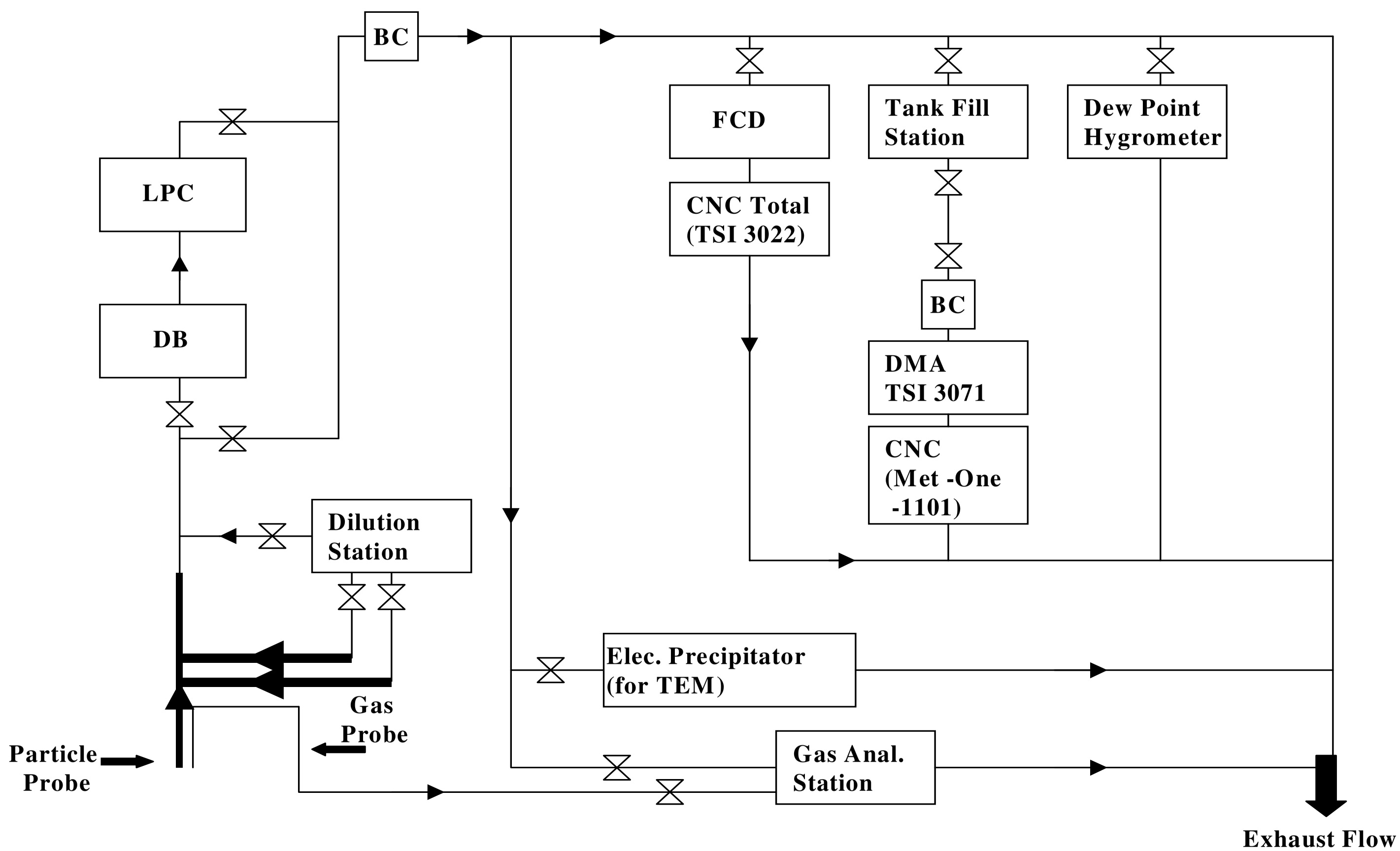
The techniques for measuring number and size distribution have been used extensively in atmospheric research and have been refined for use in measuring aircraft engine exhaust

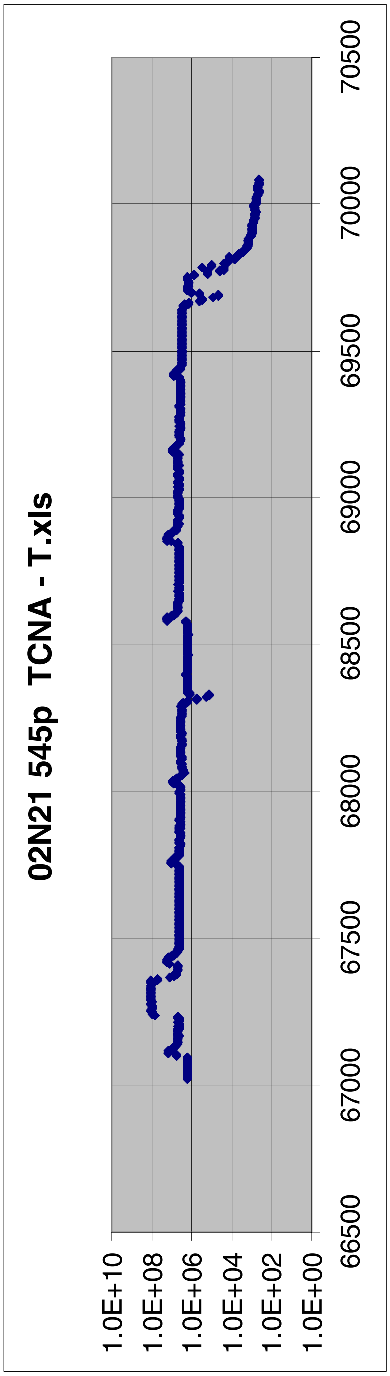
Particles emitted from combustion sources like an aircraft engine are usually significantly smaller than 1 μm in diameter. Size distributions reported from either aircraft engine test rig experiments or in-flight studies show a modal diameter of 0.03 - 0.06 μm with an average lognormal geometric standard deviation of 1.6. A second but weaker mode was found at a modal diameter of 0.15 – 0.2 μm.

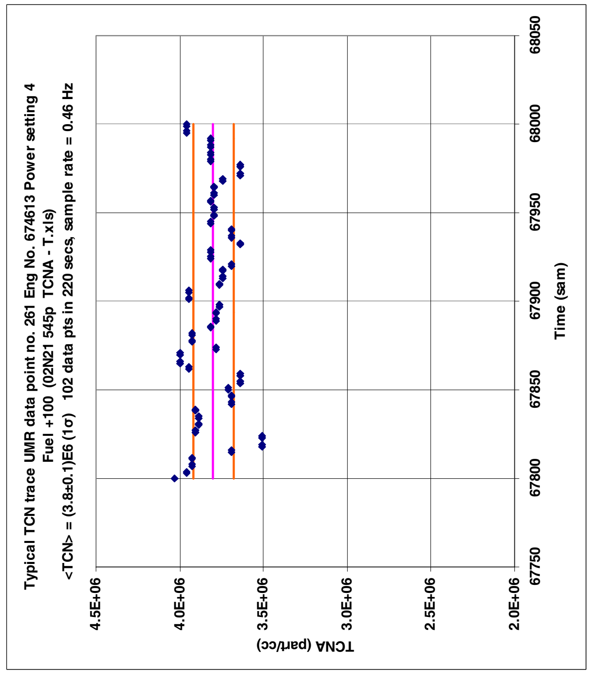
widely used and accepted by academia, industry and government organizations for the characterization of particulate exhaust from diesel and turbine engines. Organizations using these techniques include:

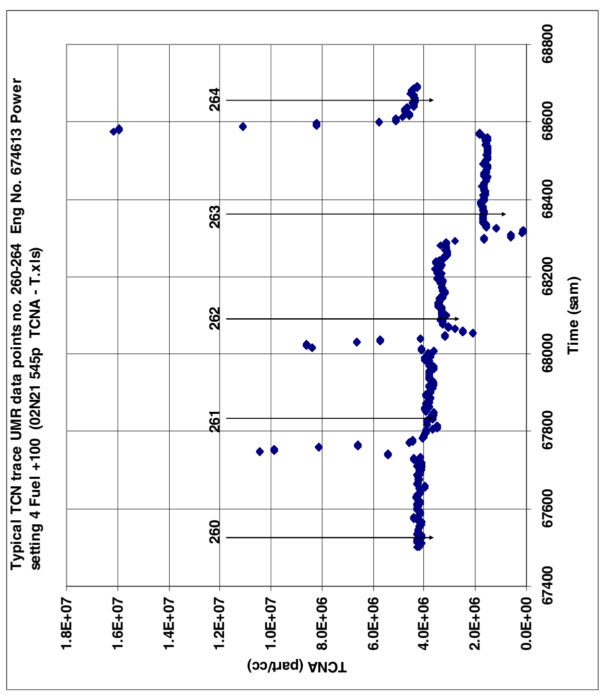
- University of Missouri-Rolla (UMR)
- University of Minnesota
- Air Force Research Laboratory (AFRL)
- NASA Glenn Research Center
- Southwest Research Institute (SwRI)
- United Technologies Research Center (UTRC)
- German Aerospace Center (DLR, Germany)
- Paul Scherrer Institute (PSI, Switzerland).
- Rolls Royce (Derby, UK)

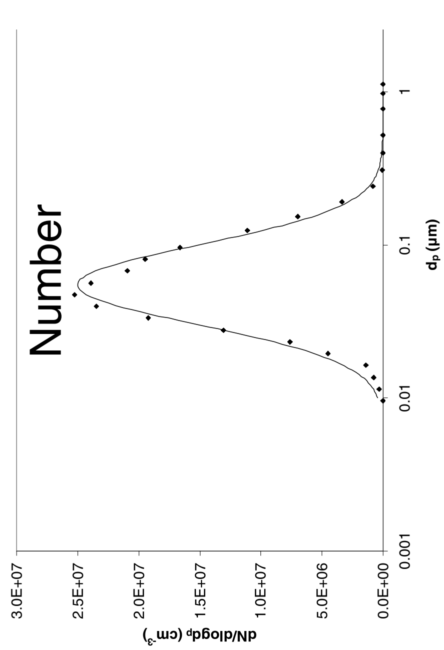
A typical size and number sampling system schematic

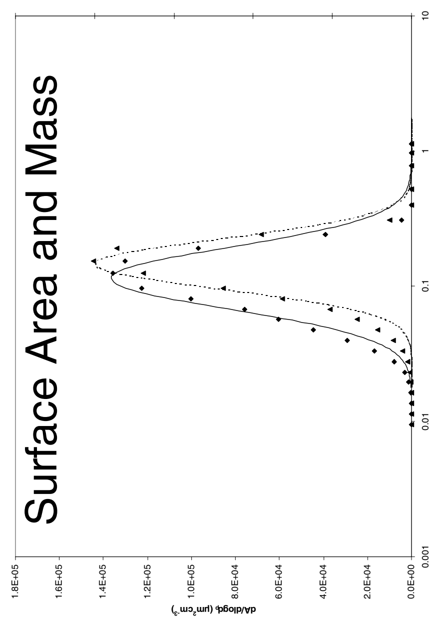


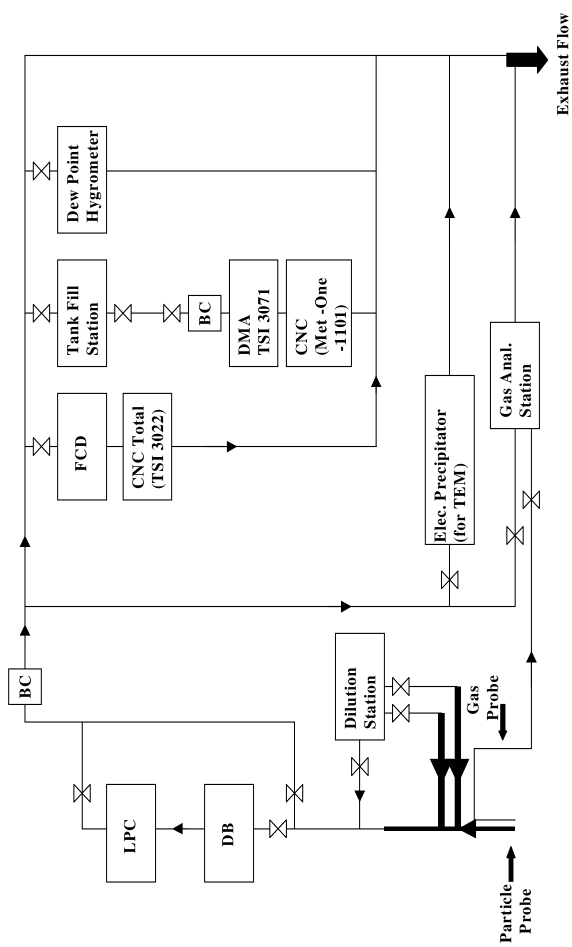

02N21 545p TCNA - T.xls
1.0E+10
1.0E+08
1.0E+06
1.0E+04
1.0E+02
1.0E+00
66500
67000
67500
68000
68500
69000
69500
70000
70500

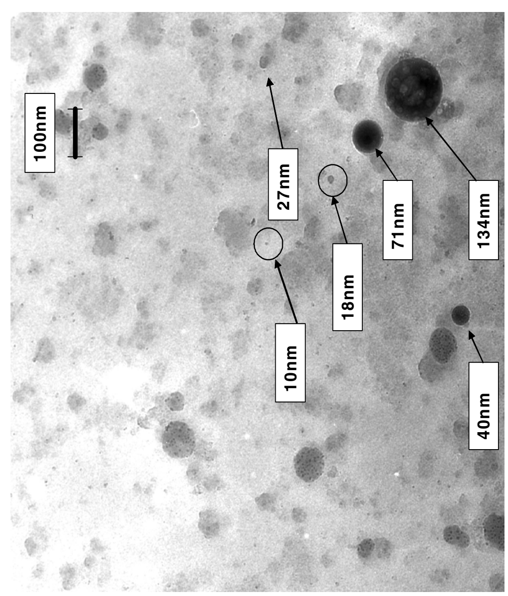

Typical TCN trace UMR data point no. 261 Eng No. 674613 Power setting 4 Fuel +100 (02N21 545p TCNA - T.xls)
<TCN> = (3.8±0.1)E6 (1σ) 102 data pts in 220 secs, sample rate = 0.46 Hz
TCNA (part/cc)
Time (sam)


Typical TCN trace UMR data points no. 260-264 Eng No. 674613 Power setting 4 Fuel +100 (02N21 545p TCNA - T.xls)
260
261
262
263
264
TCNA (part/cc)
Time (sam)


Number
dN/dlogdp (cm-3)
dp (µm)
3.0E+07
2.5E+07
2.0E+07
1.5E+07
1.0E+07
5.0E+06
0.0E+00
0.001
0.01
0.1
1


Surface Area and Mass
dA/dlogdp (µm2cm-3)
dp (µm)


Particle Probe
Gas Probe
LPC
DB
BC
Dilution Station
FCD
CNC Total (TSI 3022)
Tank Fill Station
BC
DMA TSI 3071
CNC (Met -One -1101)
Dew Point Hygrometer
Elec. Precipitator (for TEM)
Gas Anal. Station
Exhaust Flow


100nm
27nm
10nm
18nm
71nm
134nm
40nm

Particle Measurement Methodology

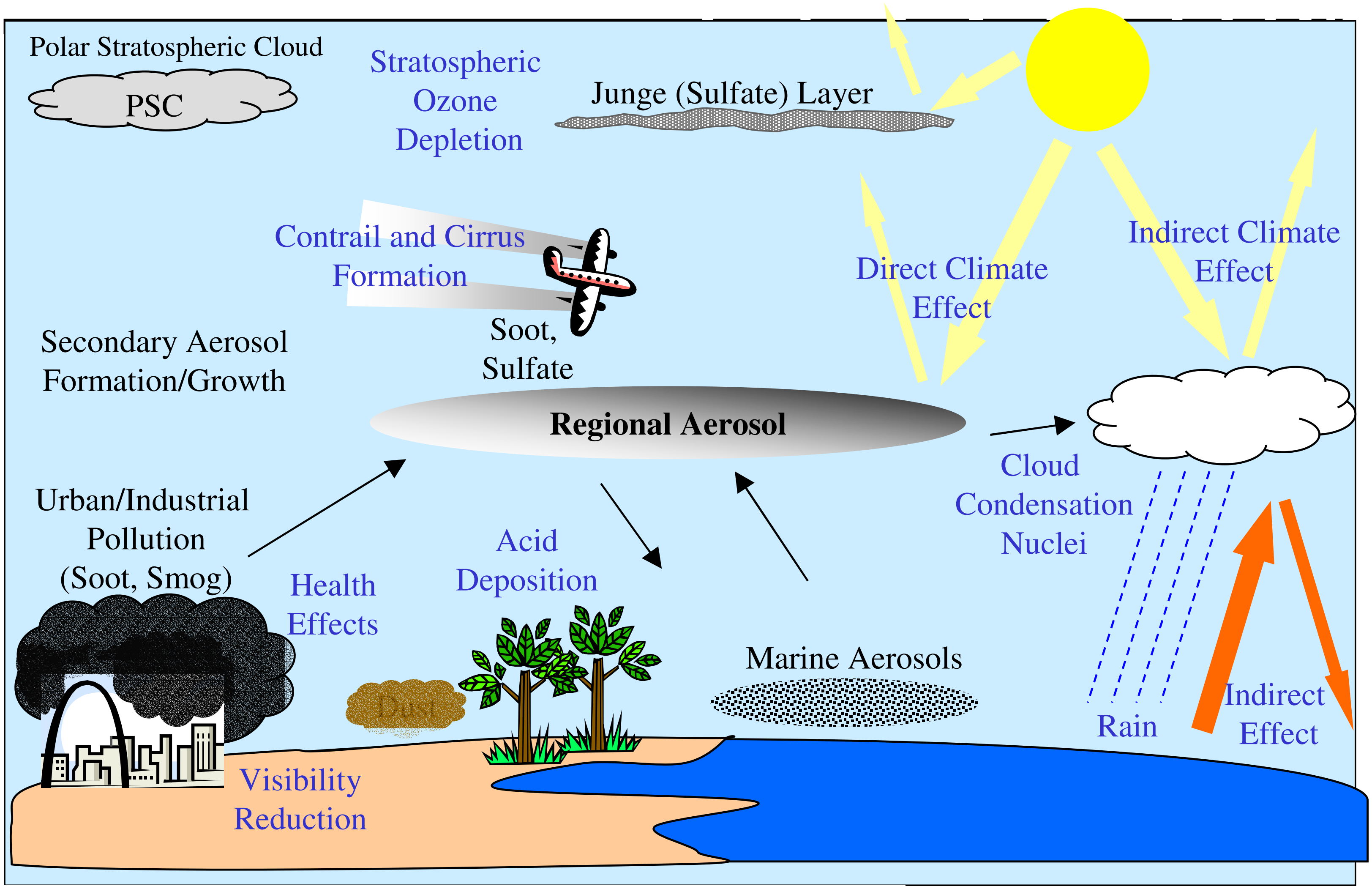
Douglas Worsnop
Aerodyne Research

Aviation Particle Emissions Workshop
West Olmstead, OH

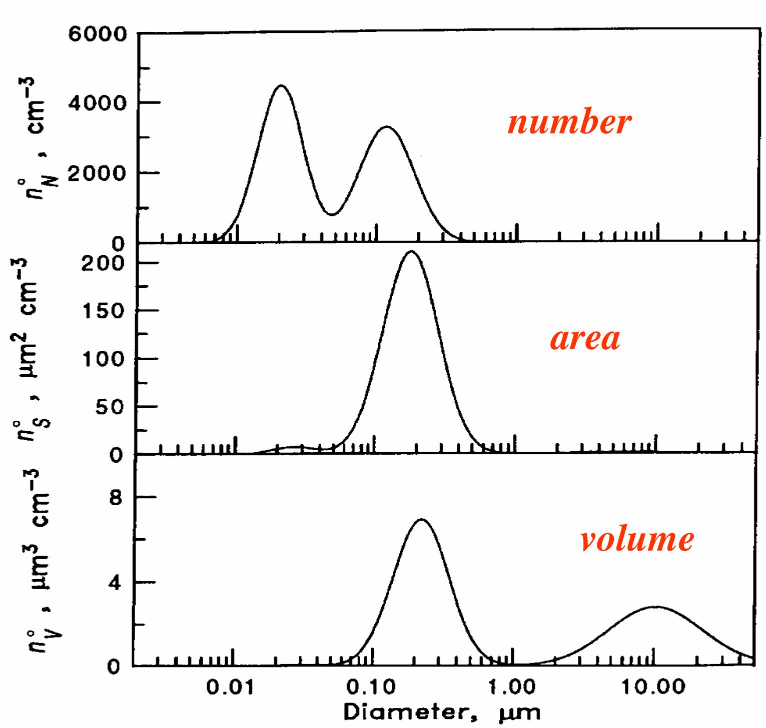
November 18-19, 2003

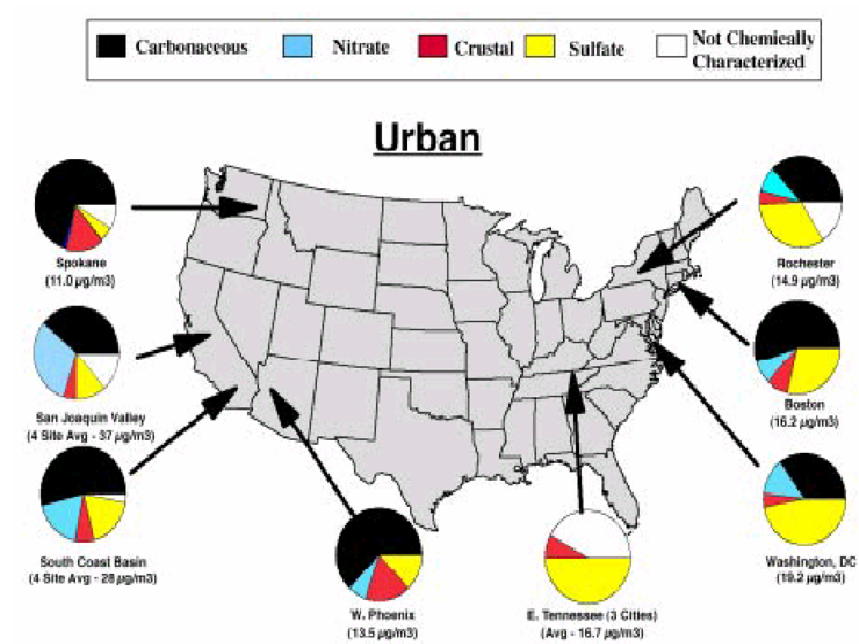
AERODYNE RESEARCH, INC.

Atmospheric Aerosol Sources and Effects



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)

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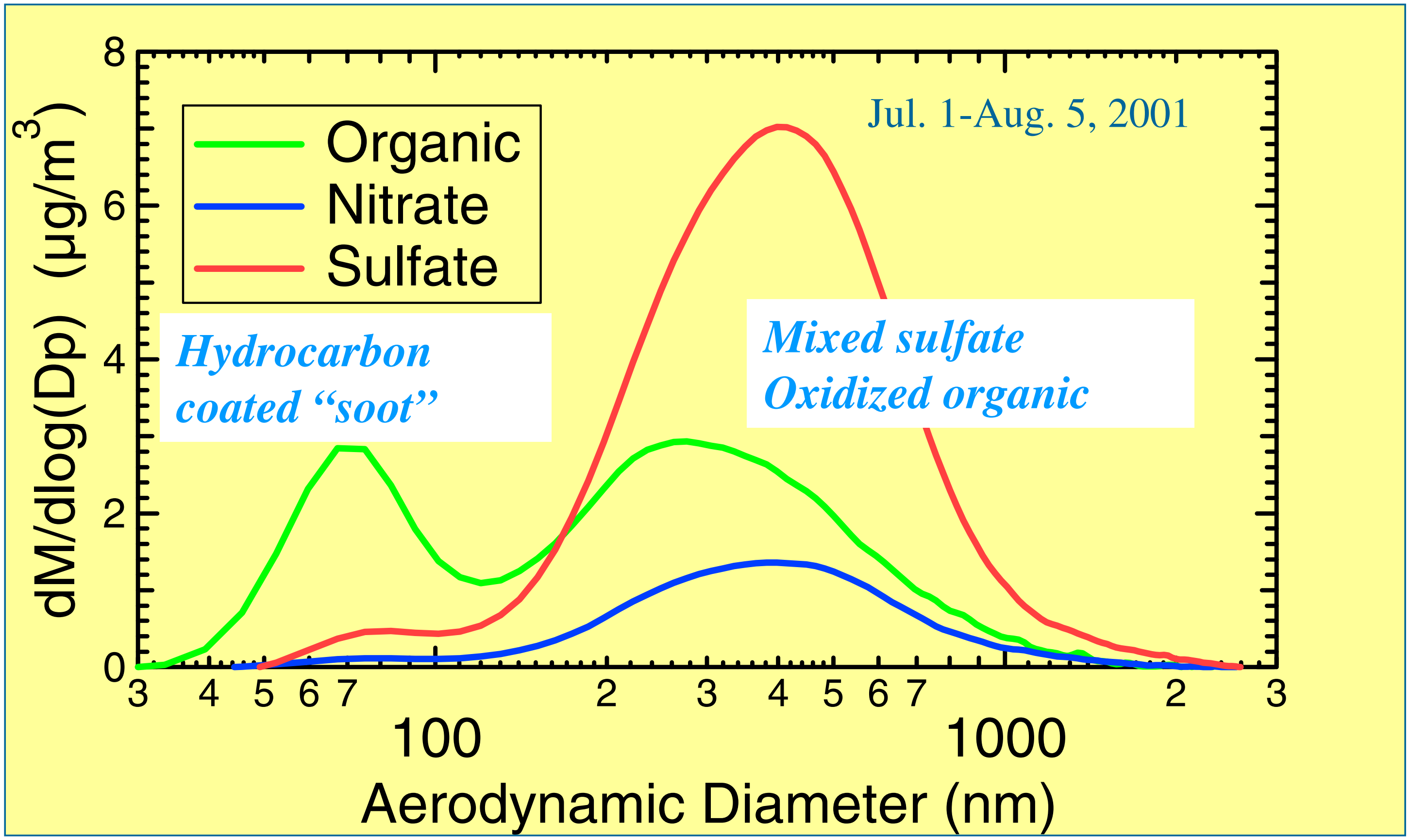
  - **Collected particles:** ***hours***
    - **"complete" chemical analysis (PM2.5, EC/OC, air toxics, limited sizing)**
- **Measurement examples**
  - **Portable Lab ground-based measurements**
  - **EXCAVATE (Langley), JFK, Logan runway experiments** ➠ ***Dryden, LAX?***

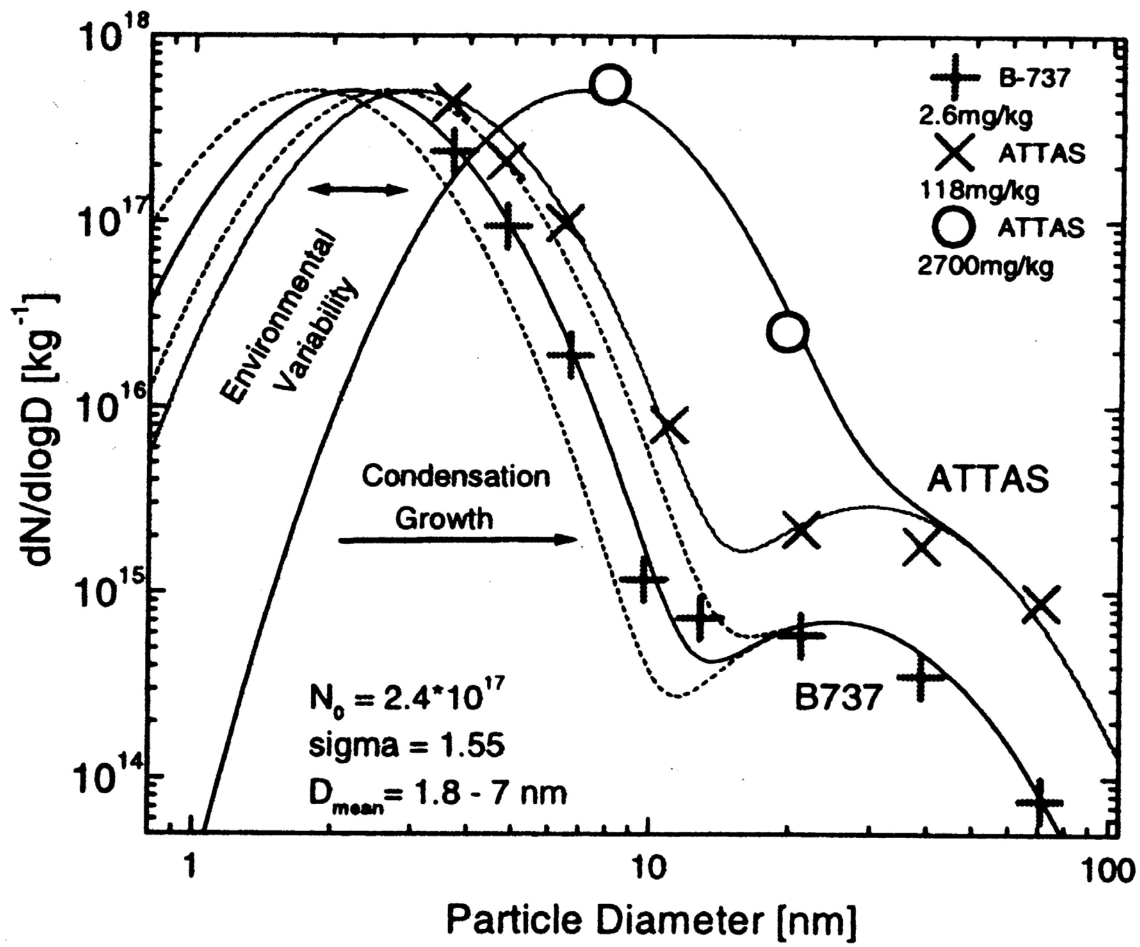
Mass Distribution: Urban Site

New York City (SUNY Albany)



Primary vs Processed Organic Aerosol

Aircraft Particle Size Distribution



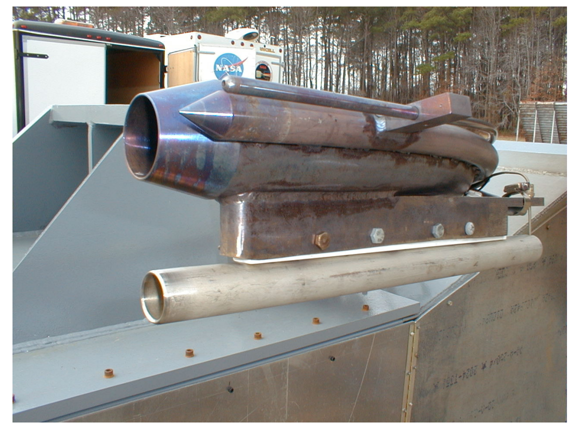
F. Schroeder et al., JGR 105, 19,941-19,954, 2000.

Measurement Challenges

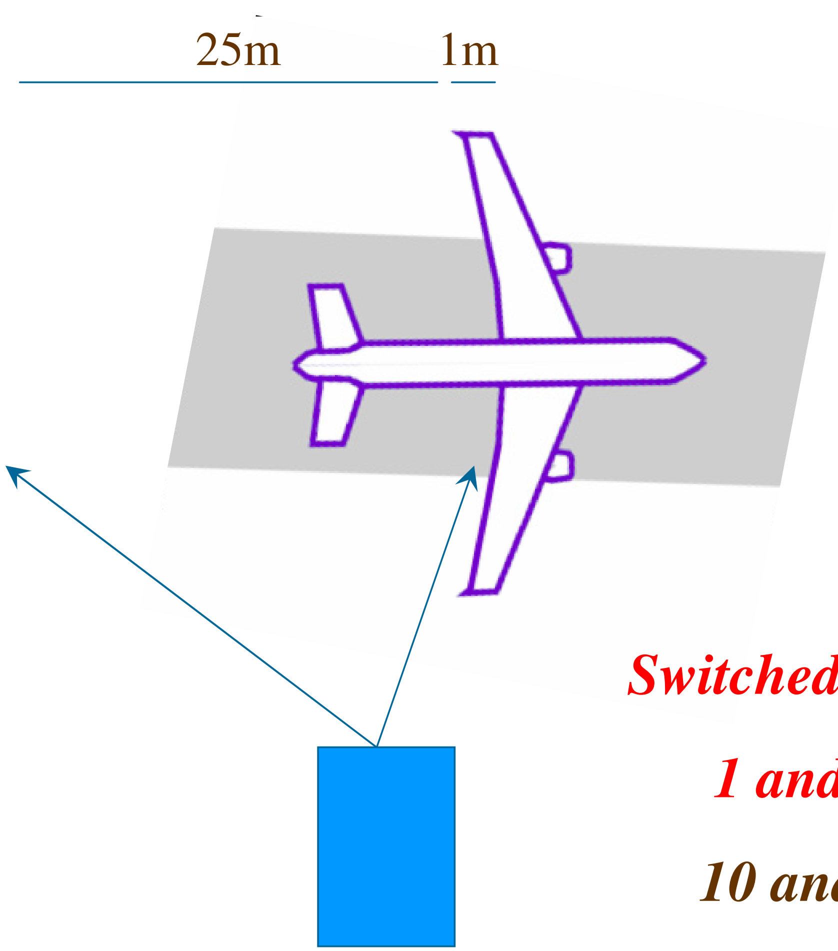
- Real-time Platform for (Gases and) Particles
  - *Sub-micron size and composition*
- Engine Emissions measurement
  - Test cell
  - On-Wing: *Evolution of plume away from engine*
- Airport
  - Downwind of runway
  - Circling of Airport
- *Connect engine exit to local/regional air quality*

Aerosol Chemistry of Commercial Aircraft Emissions NASA EXCAVATE Experiment

EXCAVATE Sampling Probe



EXCAVATE *Evolution of exhaust plume behind plane*

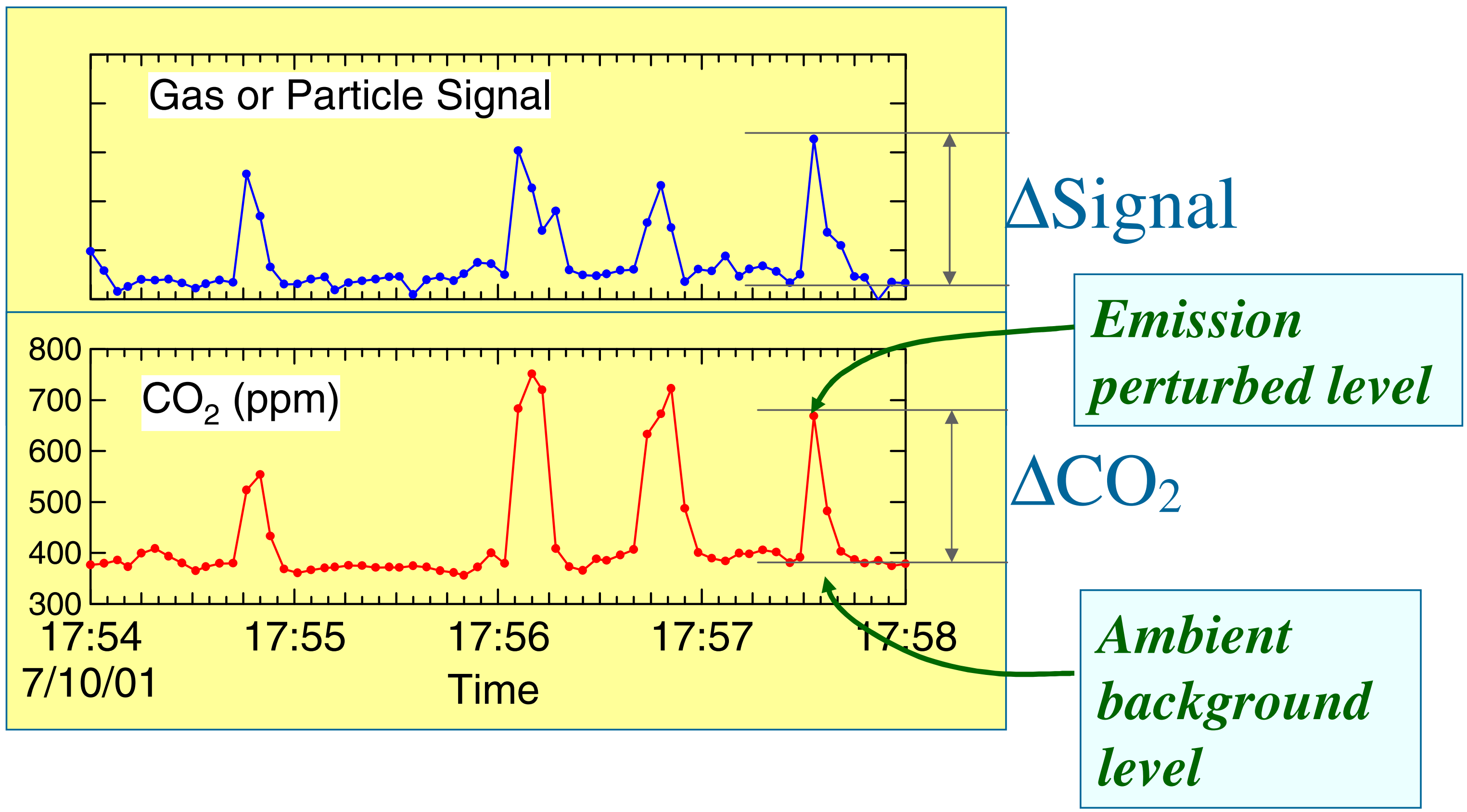


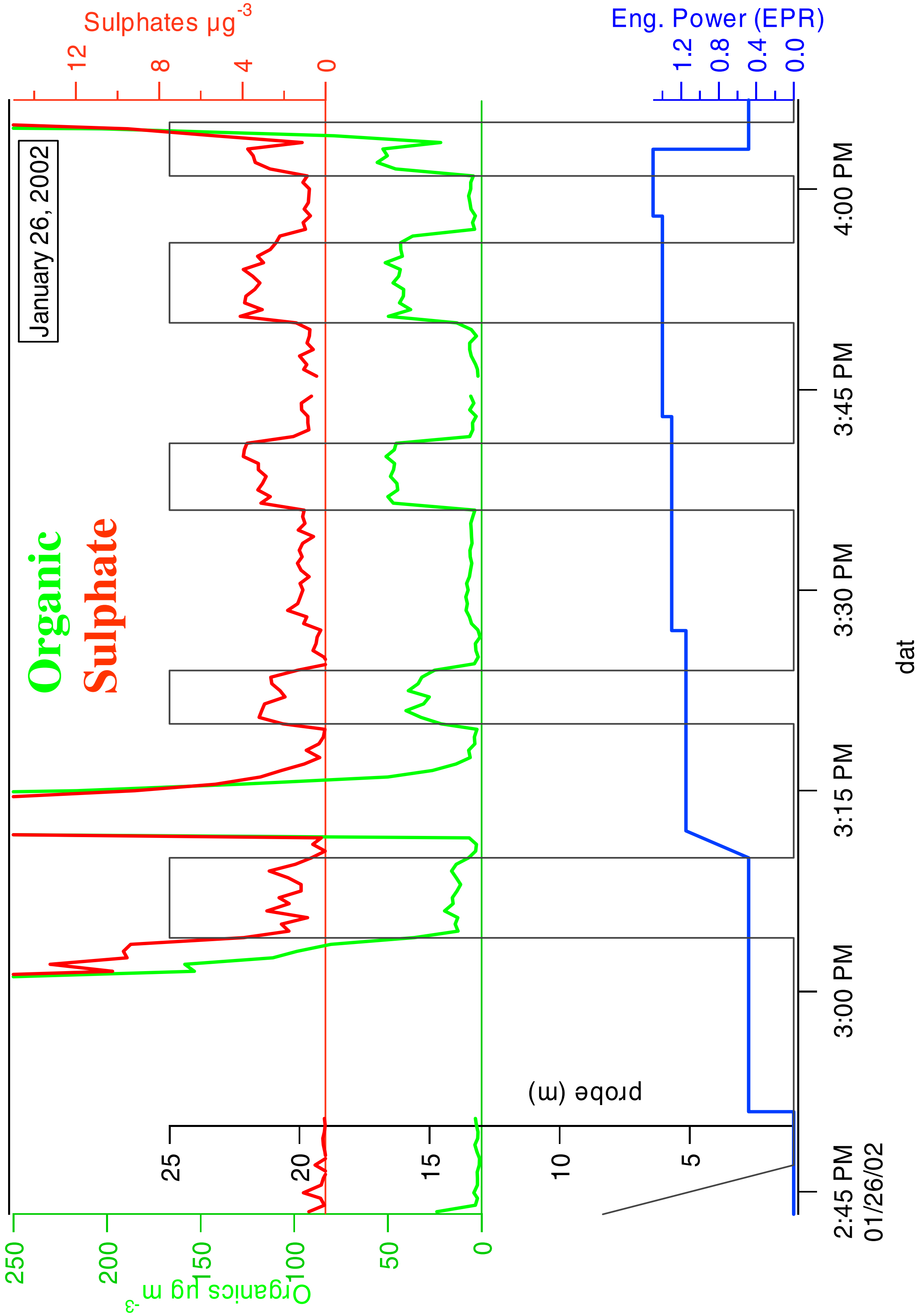
Switched between sampling at

1 and 25 meters

***10 and 35** (with plane forward)*

"*In-plume*" sampling indicated by *above-ambient* CO_2 levels





Sulphates µg-3
12
8
4
0
Eng. Power (EPR)
1.2
0.8
0.4
0.0
January 26, 2002
Organic
Sulphate
probe (m)
25
20
15
10
5
Organics µg m-3
250
200
150
100
50
0
2:45 PM
01/26/02
3:00 PM
3:15 PM
3:30 PM
3:45 PM
4:00 PM
dat

Evolution of Particles: *1 to 25 meters*

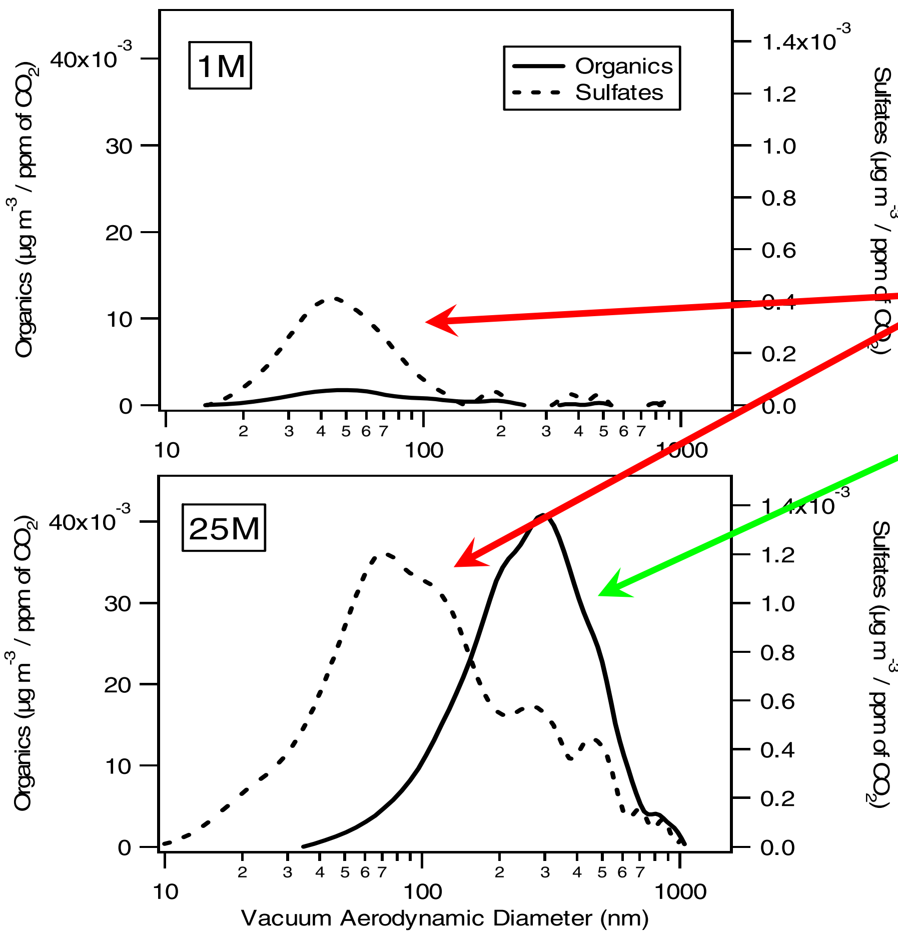


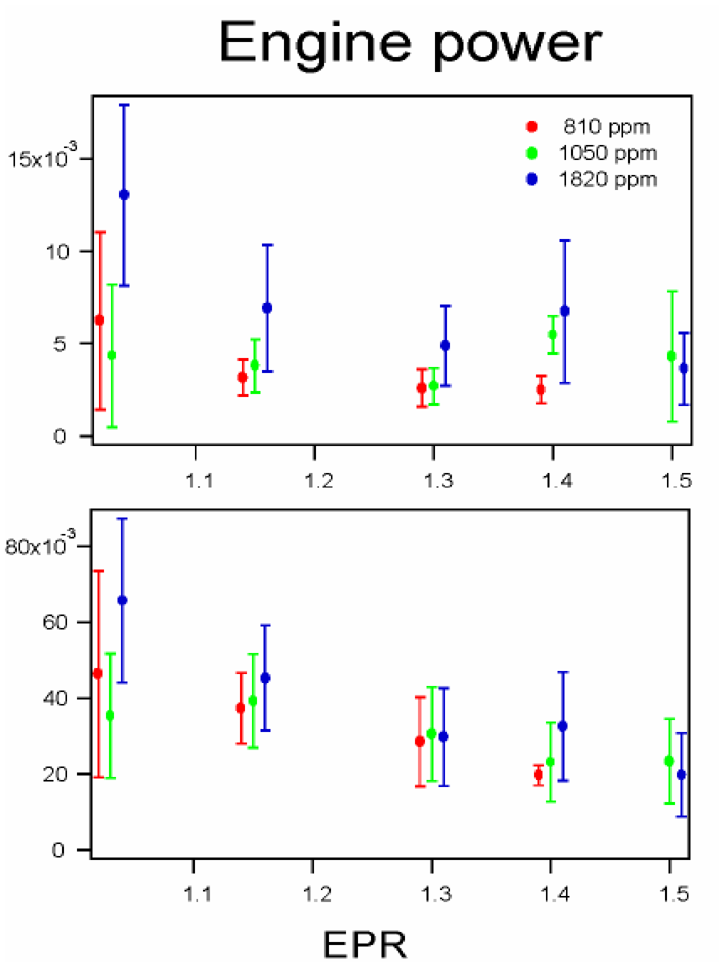
Figure 2: Variation of average aerodynamic diameter of sulfate and organics at 1 and 10 M for engine power of 1.3, 1.4, and 1.5 EPR.

Sulfate

Volatile Organic *primarily oil*

Observed Growth:
condensation of semi-volatile vapors

EXCAVATE Emission Indices (g/kg Fuel)

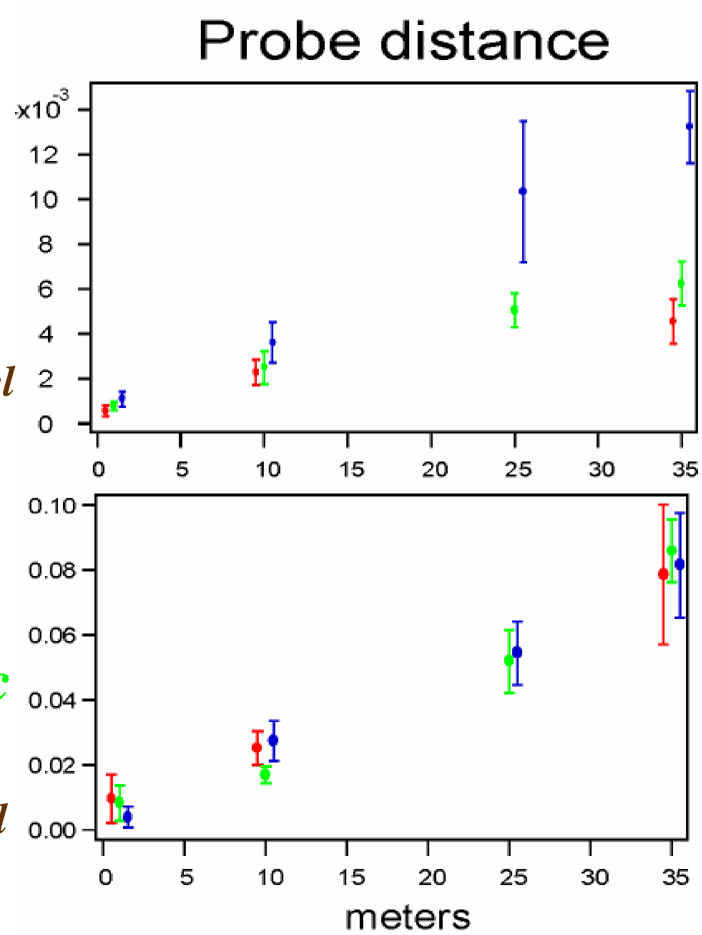


Sulfate

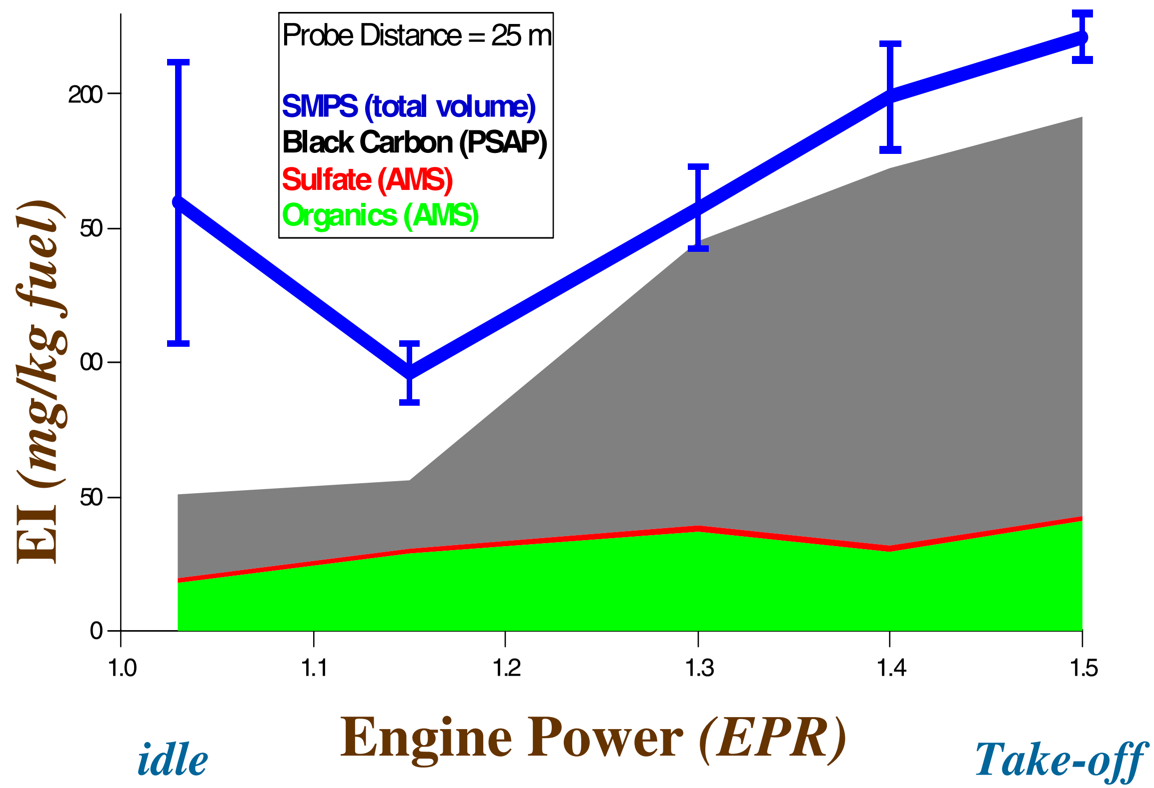
5mg/kg fuel

Volatile Organic

20-60 mg/kg fuel



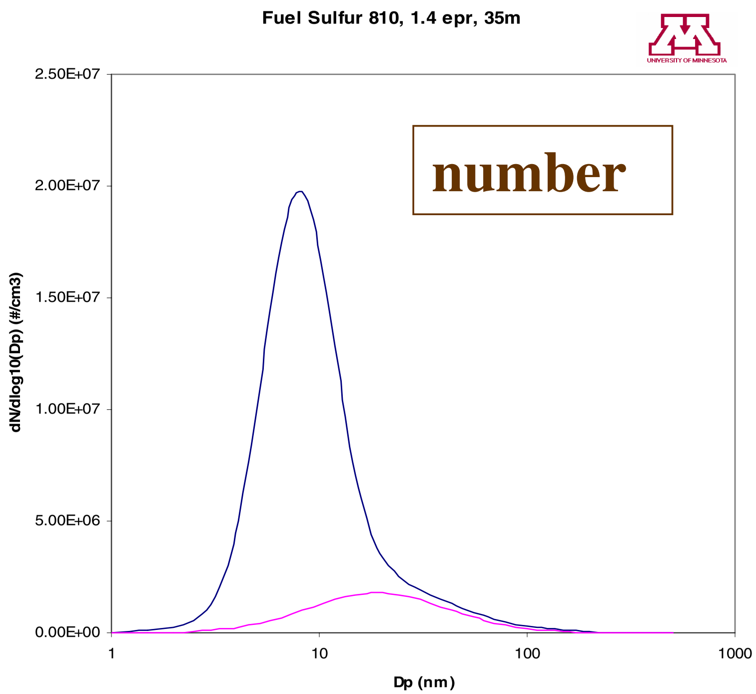
Aerosol Chemistry: *Steady State Operation of B757*

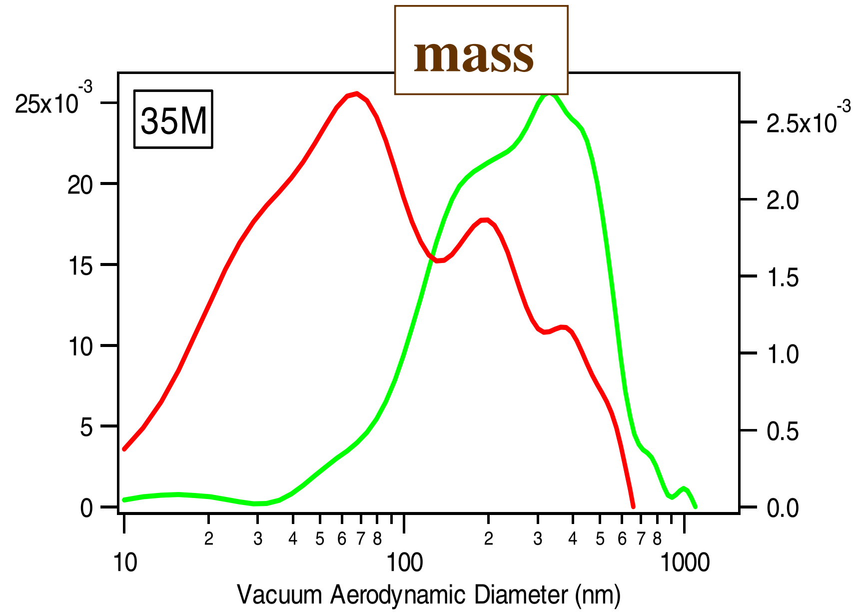


Black carbon dominates at high power

EC/OC higher than diesel at aircraft steady state

Aerosol Number (UMN) and Mass (ARI) at 35 meter behind 757 at 1.4 EPR



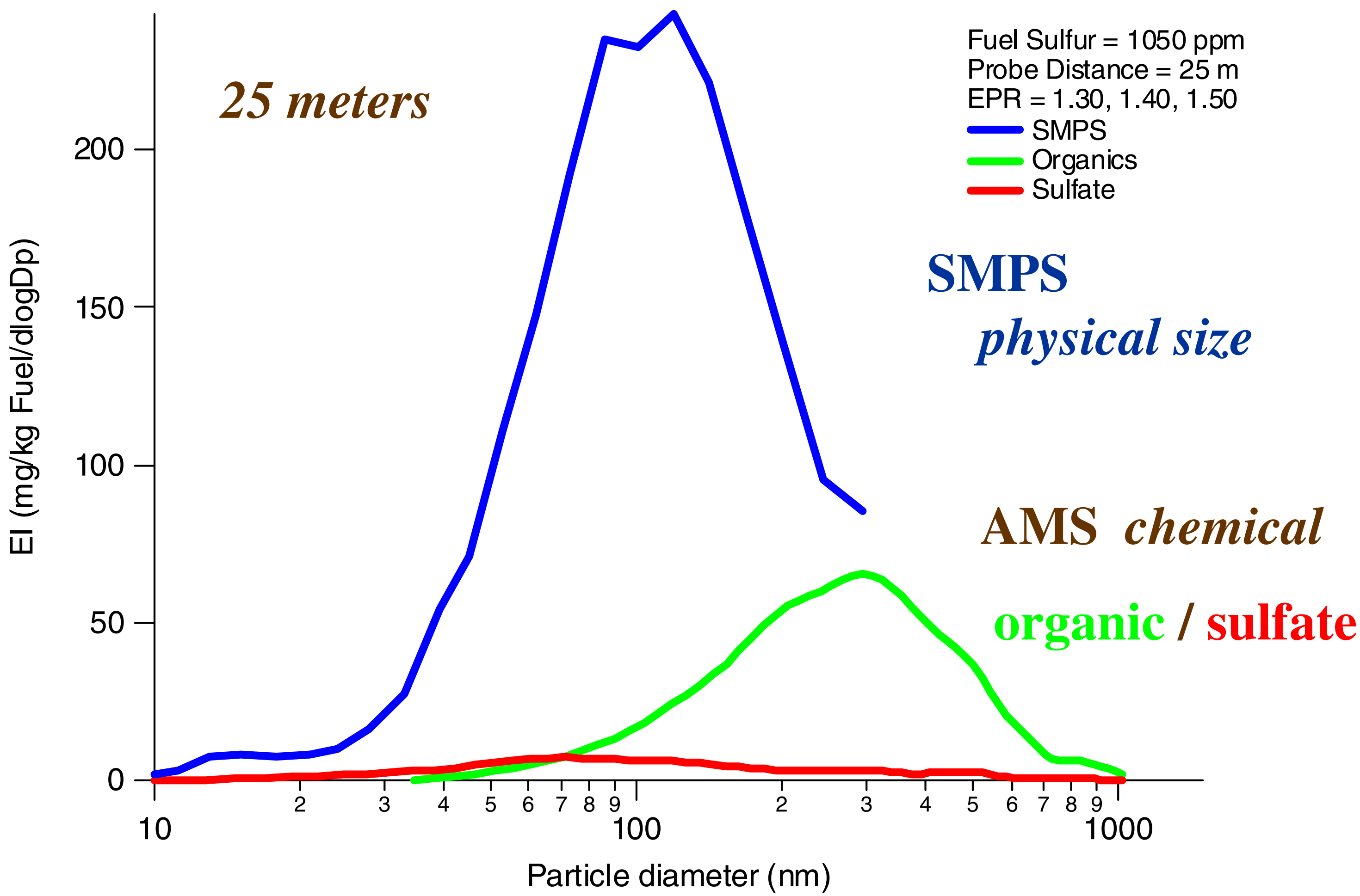


UMN Nano-DMA

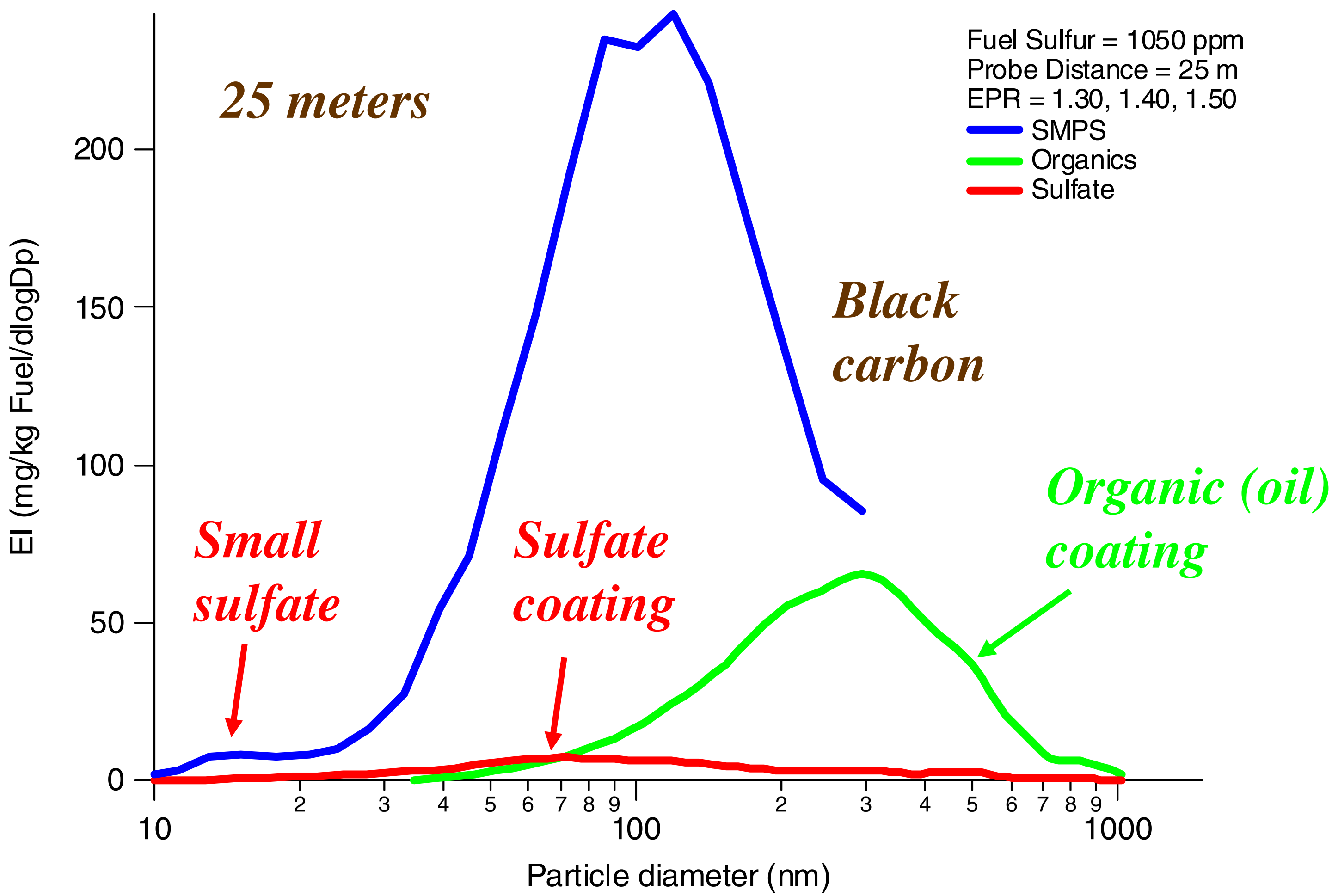
Sulfate *(x10)* Organic C

ARI AMS

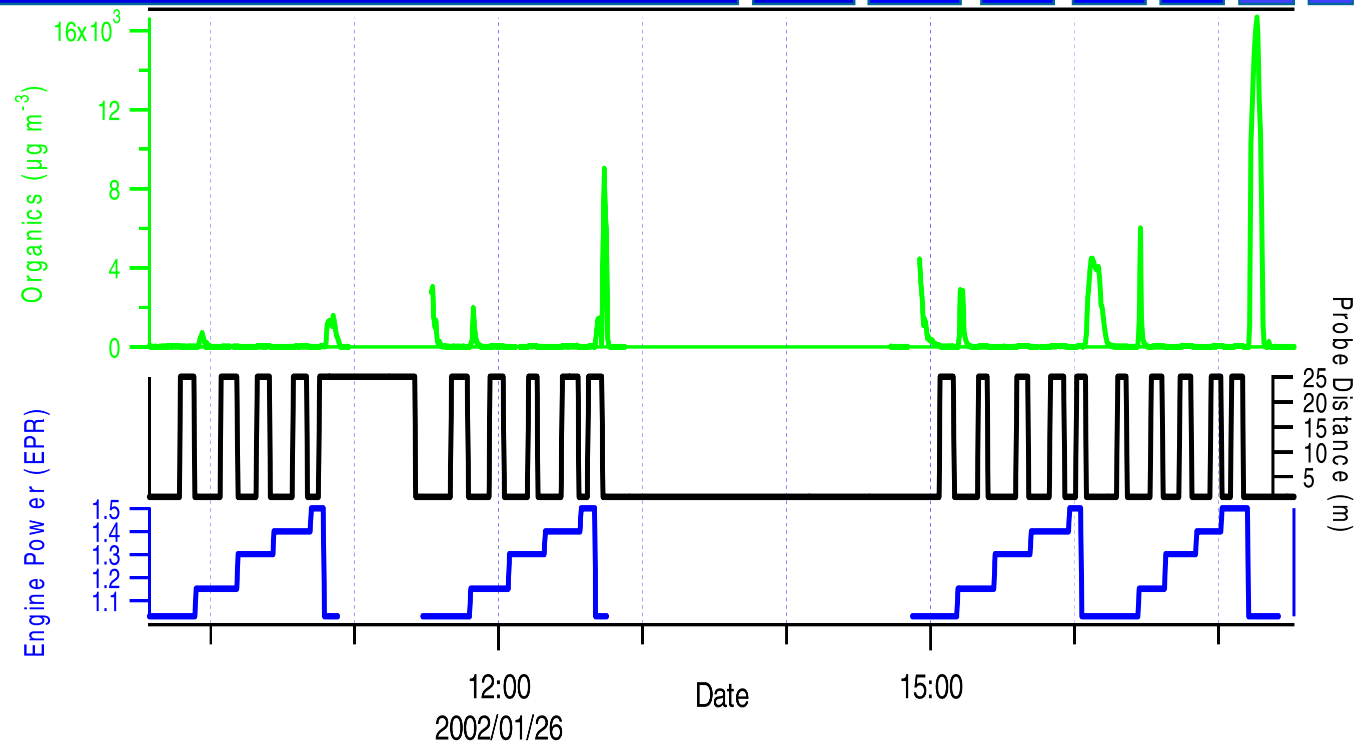
MASS Distributions – B757 at 1.3-1.5 EPR



MASS Distributions – B757 at 1.3-1.5 EPR



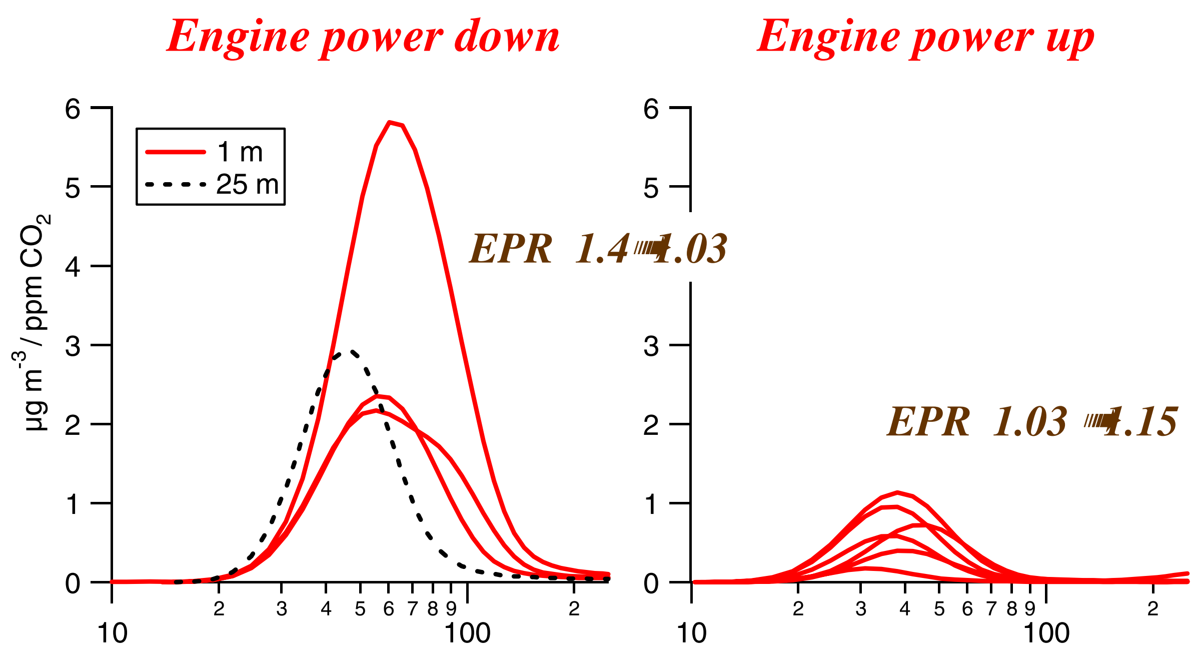
EXCAVATE – Transients



- Transient high mass loadings (~5000 $\mu g\ m^{-3}$) occurred during engine start-up and shut down.
- Mass loadings during steady conditions ranged from 1-30 $\mu g\ m^{-3}$.

Organics size distribution during transient periods

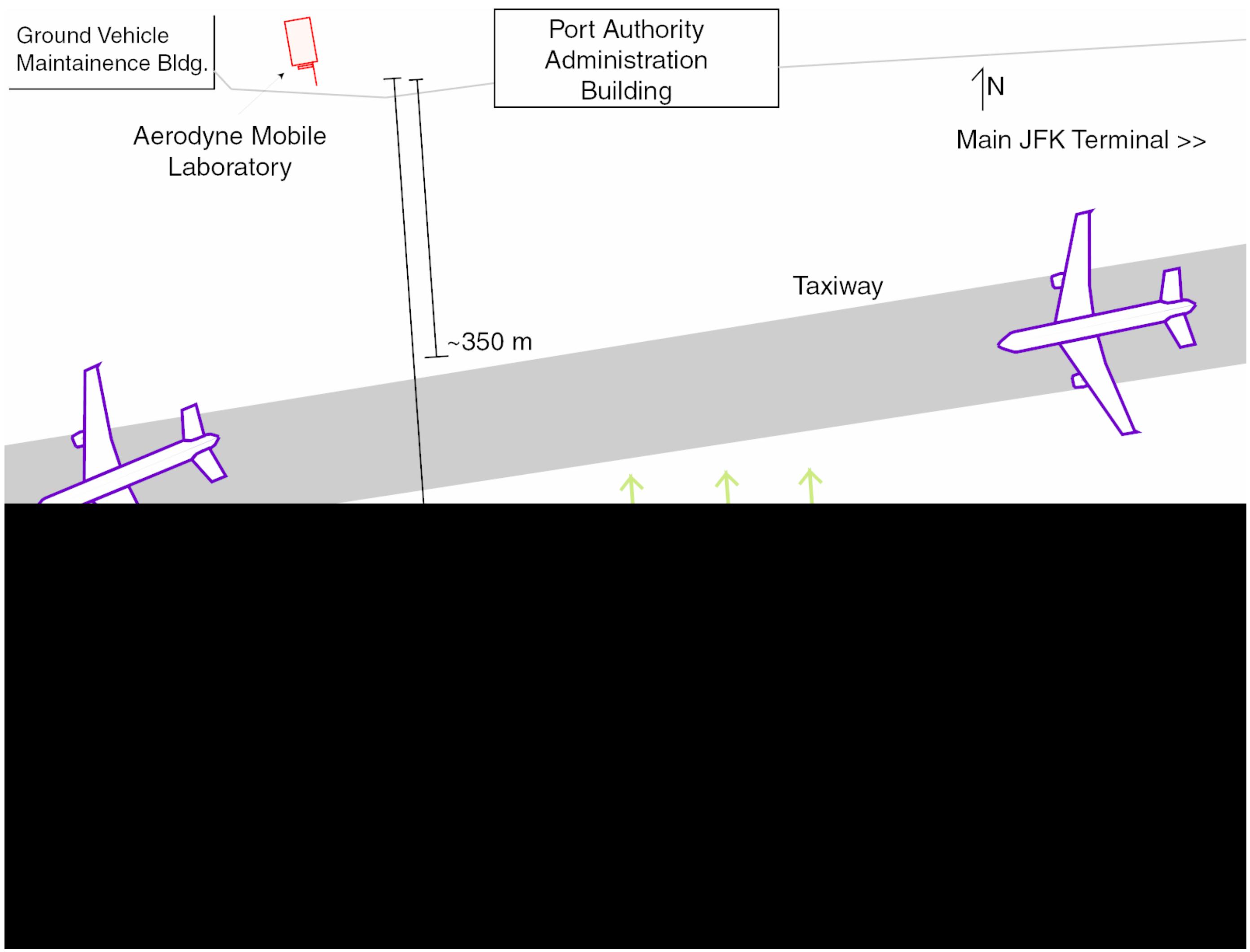
Transient periods



Average vacuum aerodynamic diameter ~ 40-60 nm

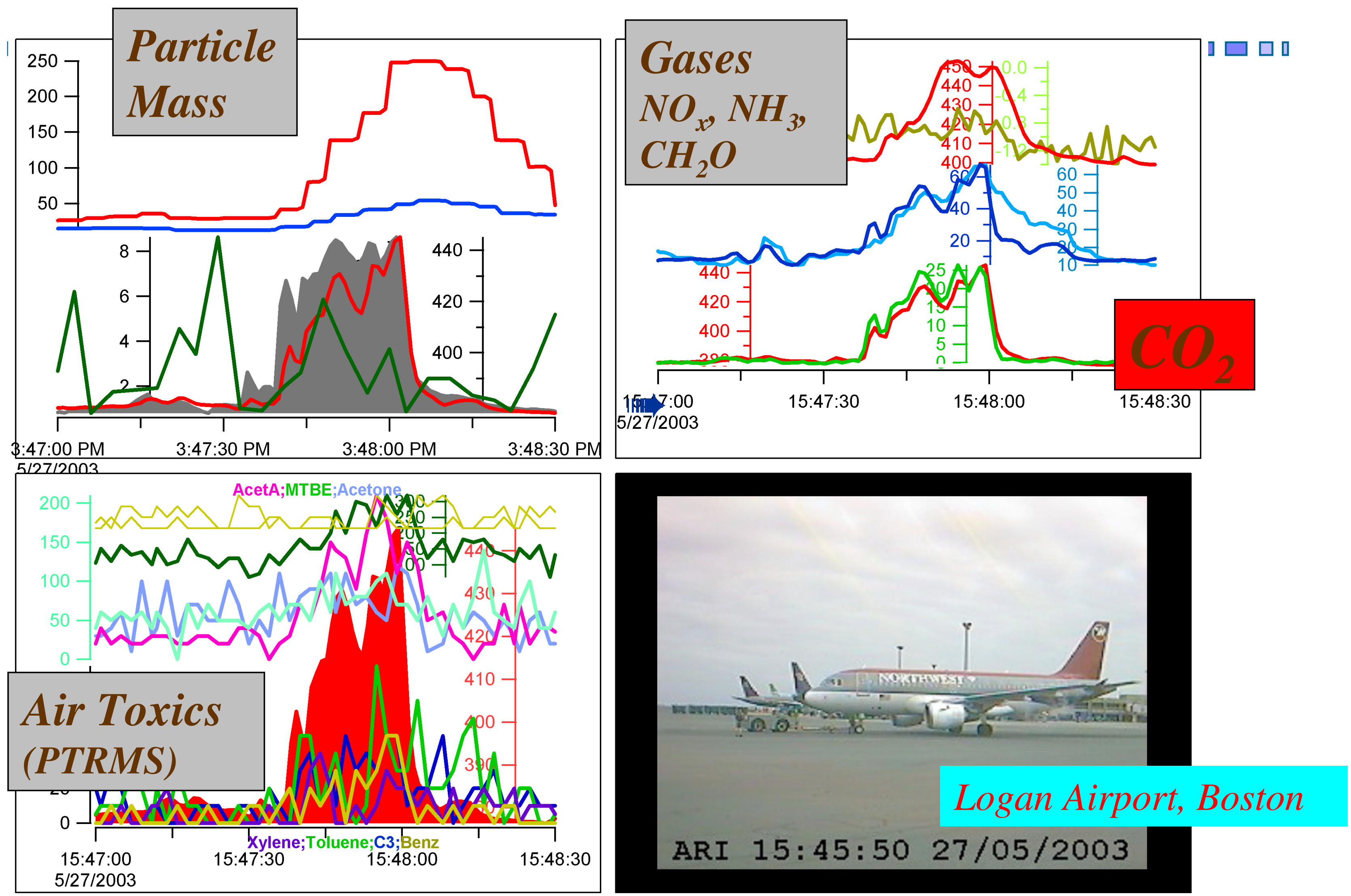
x100 increase in organic (oil/fuel) loading for minutes

ARI Mobile Lab at JFK *Scott Herndon, John Jayne et al*



Simultaneous Gas and Particle Monitoring

Scot Herndon (ARI)



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    - **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:* <10nm *ultrafine:* <100nm *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

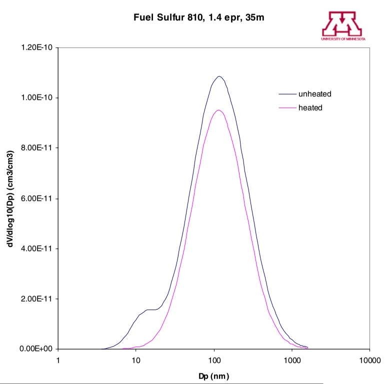
Engine technology   Air Quality

- *Analogy to evolution of both measurement and technology of diesel engines*

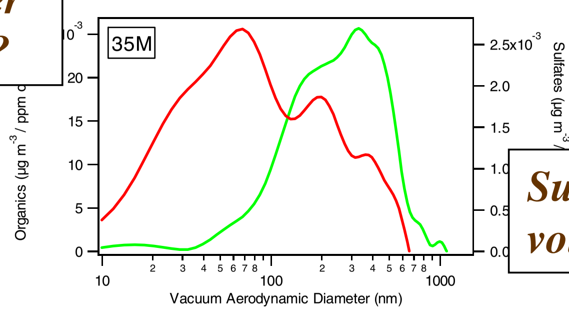
Summary

Airport Measurement of Gas and Sub-Micron Particle Emission

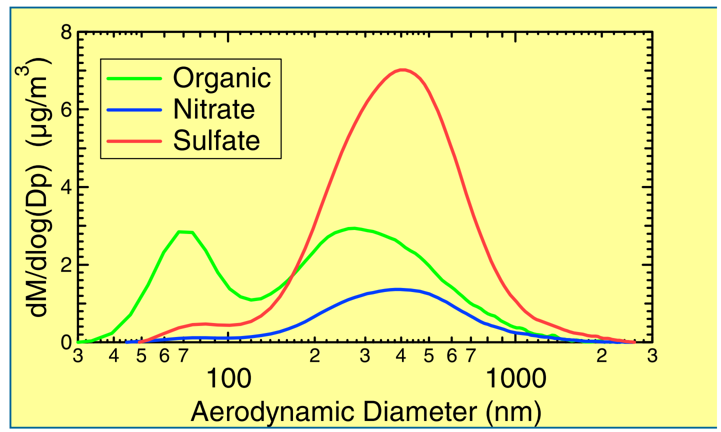
input to local / regional air quality model



Aerosol number nanoparticles ?



Sub-micron volatile mass



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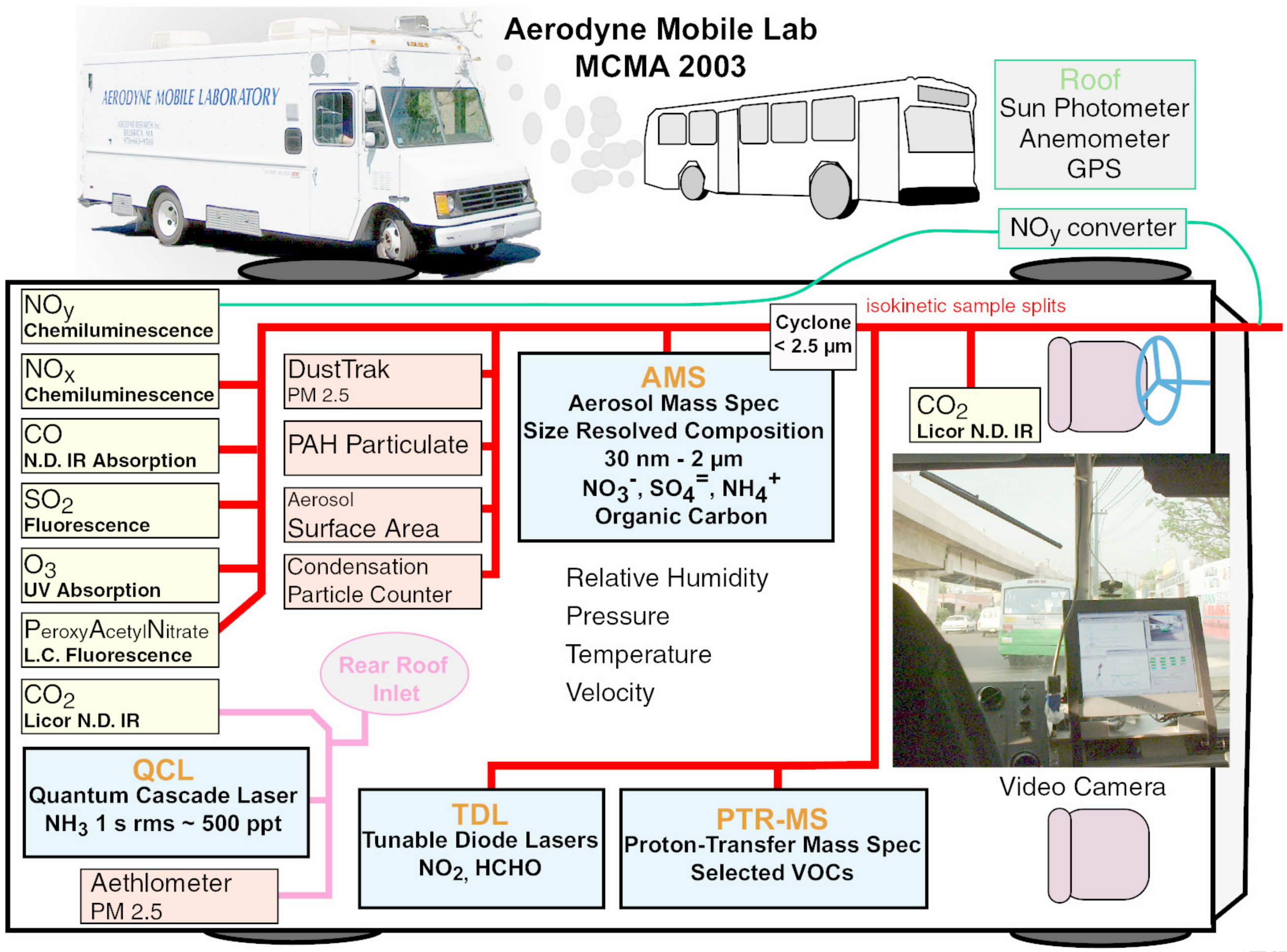
BACKUP

SLIDES

MIT-CAM-ARI
Field Measurement Campaign



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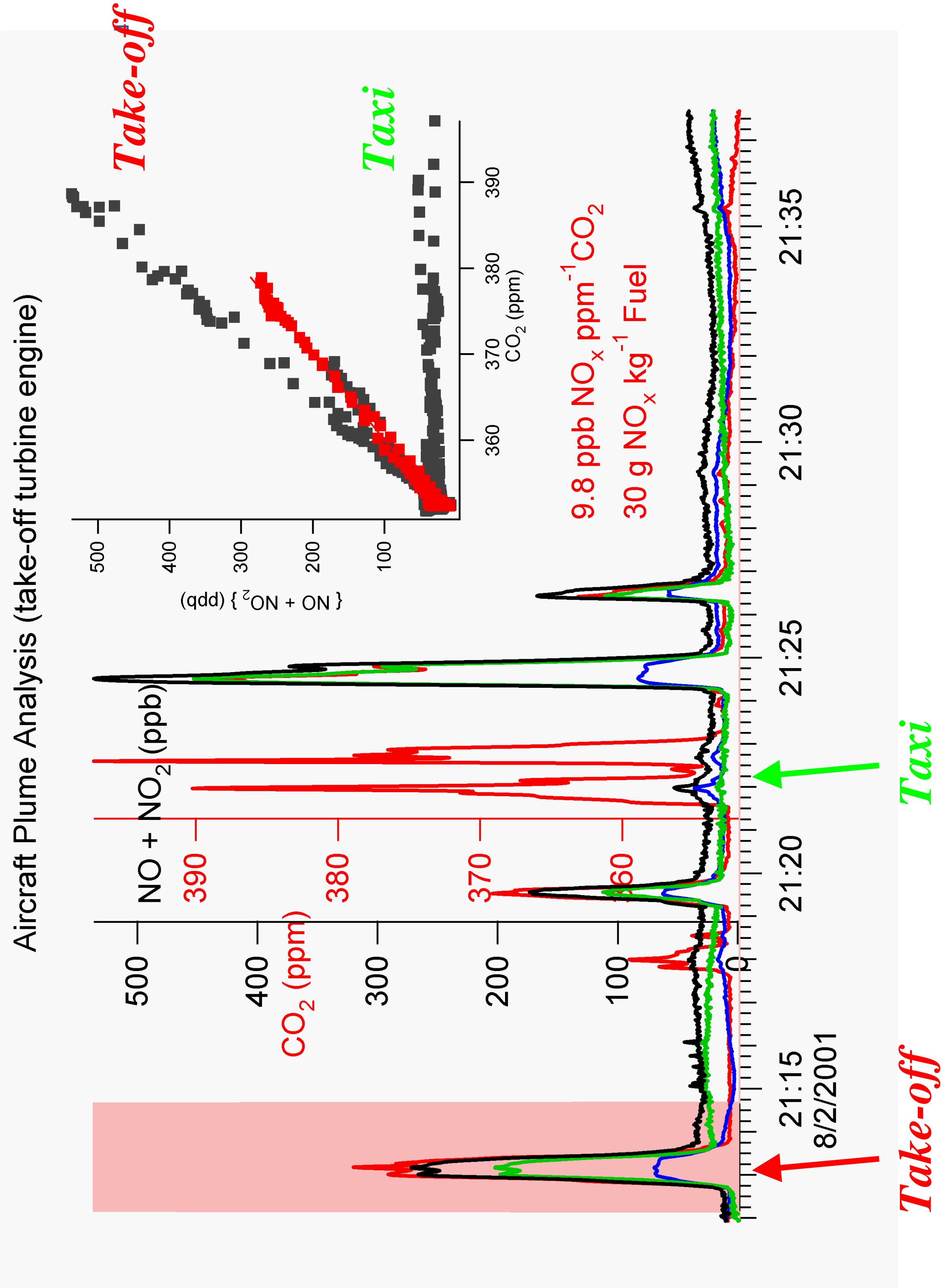
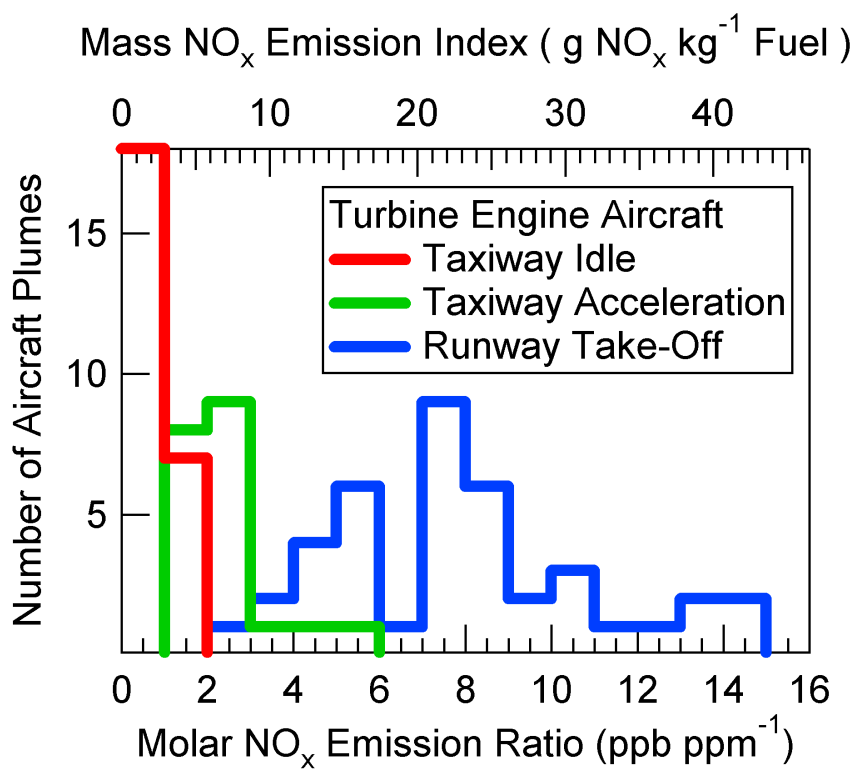


Aircraft Plume Analysis (take-off turbine engine)
NO + NO2 (ppb)
CO2 (ppm)
500
400
300
200
100
0
390
380
370
360
21:15
8/2/2001
21:20
21:25
21:30
21:35
Take-off
Taxi
{ NO + NO2 } (ppb)
CO2 (ppm)
Take-off
Taxi
9.8 ppb NOx ppm-1 CO2
30 g NOx kg-1 Fuel

Preliminary Results: NO_x Emission Ratios by Aircraft State



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

ARI File No. 10017
VGS

Aviation Particle Emissions Workshop
Cleveland, Ohio
November 18-19, 2003

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

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Processes

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

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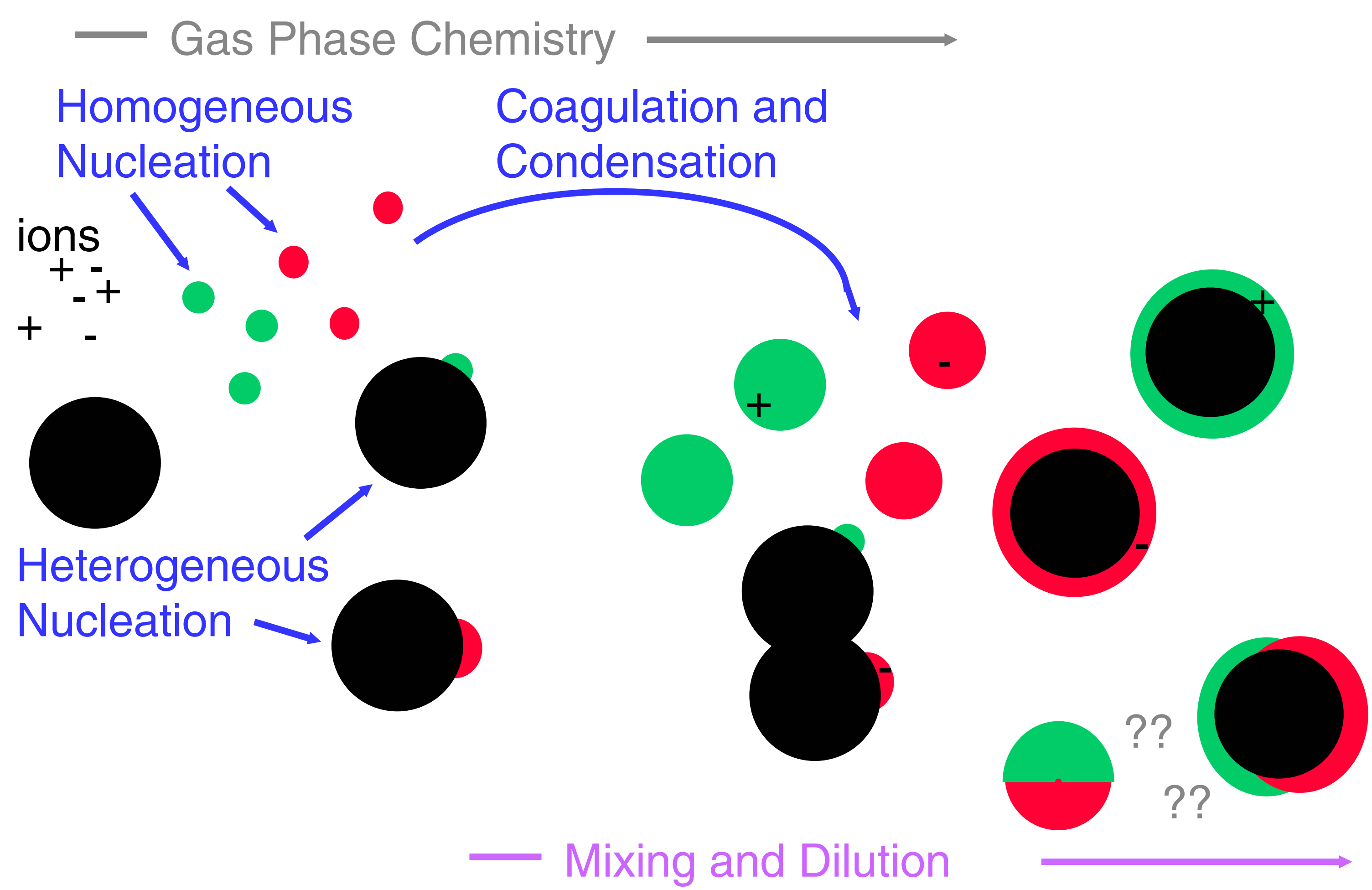
Particle Evolution Stew



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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

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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

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Measured Particle Size Distribution

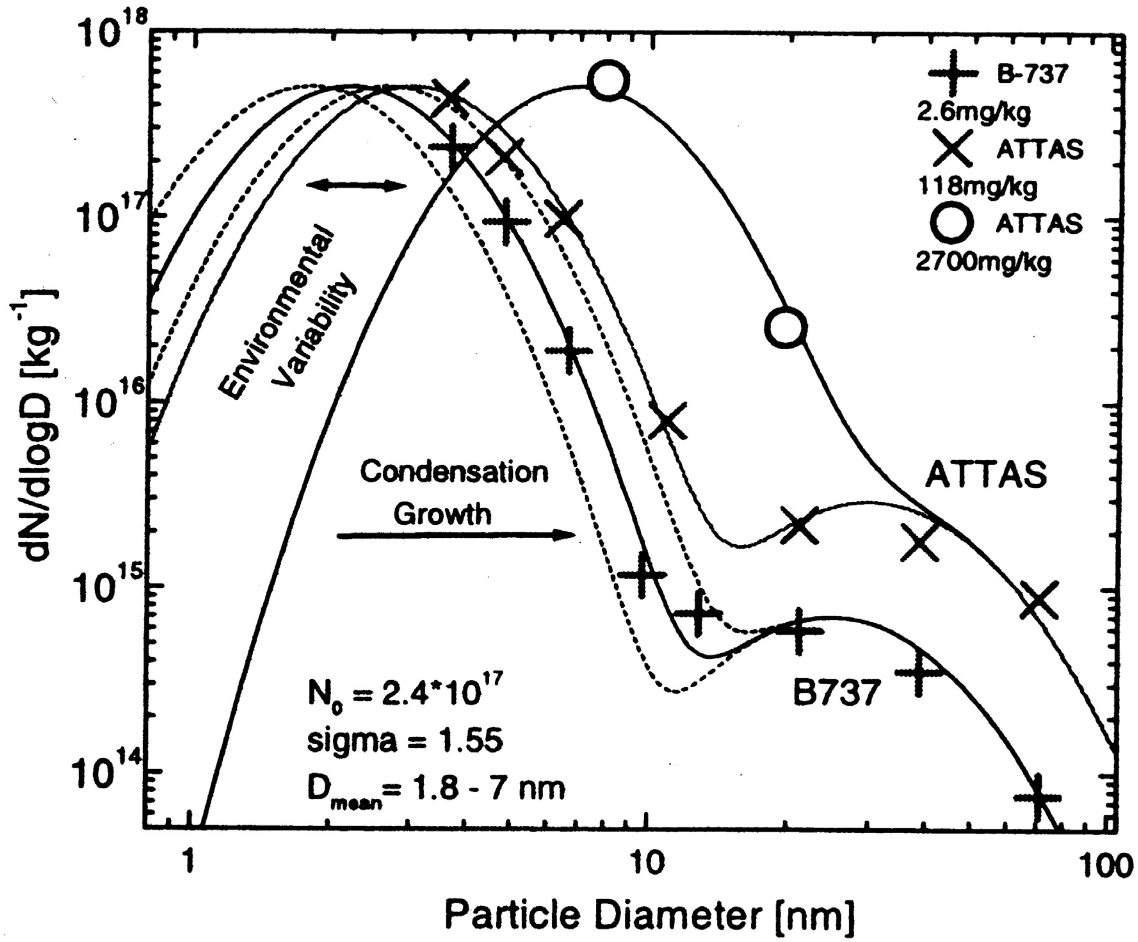

Fig 10. F. Schroeder et al., *JGR 105*, 19,941-19,954, 2000.

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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?)

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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)

Aerodyne Research, Inc.

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

Aerodyne Research, Inc.

Carbonaceous Particulates from Combustors

Med Colket and Dave Liscinsky
United Technologies Research Center

November 18, 2003

NASA Workshop on Aviation Particle Emissions

United Technologies Research Center

Particulate Issues

PM 2.5 is Primary Threat

Combustor (chemical reactions)

Fuel ➠ CO_2, H_2O
PAH, soot (at power)
UHC (idle)
fuel vapor (shut down, start up)

Fuel S ➠ SO, SO_2
Air N2 ➠ NO, NO_x

Turbine (quench)

H_2O, soot
PAH =>condensed particulates
fuel vapor

SO, SO_2
NO => HONO

Near field (quench, nucleation

H_2O
soot
fuel vapor

SO_3 ➠ H_2SO_4
HONO

nuclei

Far field (absorption, condensation

particulates, condensed particulates, aerosols, droplets

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

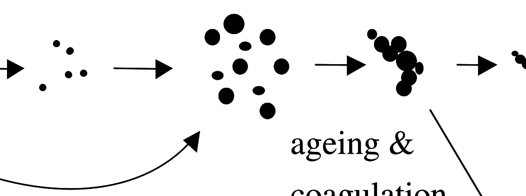
- Uncertainties w.r.t. hydrophobic characteristics of non-volatiles

Soot Formation/Oxidation in Aeroengines

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

Fuel decomposition => soot formation => soot oxidation

$C_{12}H_{23}$ → C_xH_y Alkylated - aromatics, H H_2, C_2H_2 naphthenes → inception: PAH, C_2H_2 → Surface growth & coalescence → ageing & coagulation → oxidation → Oxidation products



spray, vaporization — Gas -phase kinetics

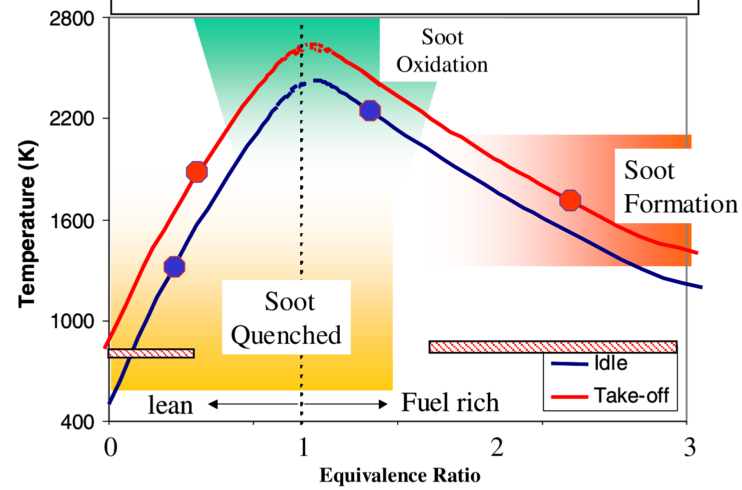
Formation of Soot: $$d(\text{soot mass})/dt = R_{inception} + R_{surface\_gowth} - R_{oxidation}$$

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

Surface Growth: $$R_{surface\_gowth} = k_{growth}\frac{3m}{r}[C_2H_2]$$

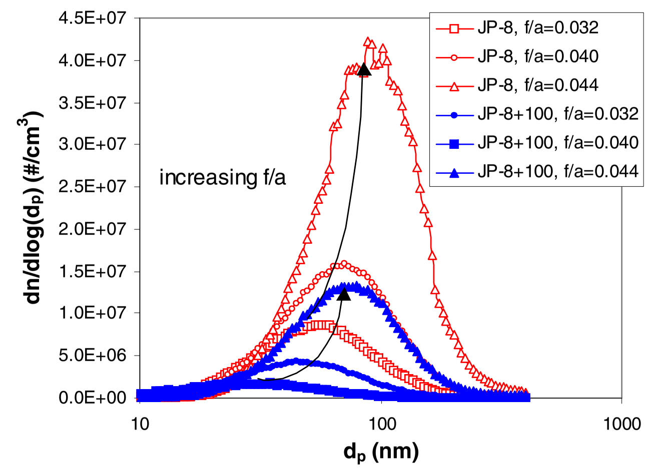
Oxidation: O_2 and OH: $$R_{oxidation} = R_{O2}(NSC) + k_{OH}\frac{3m}{r}[OH]$$

Unoxidized Soot => Visible Smoke Emissions



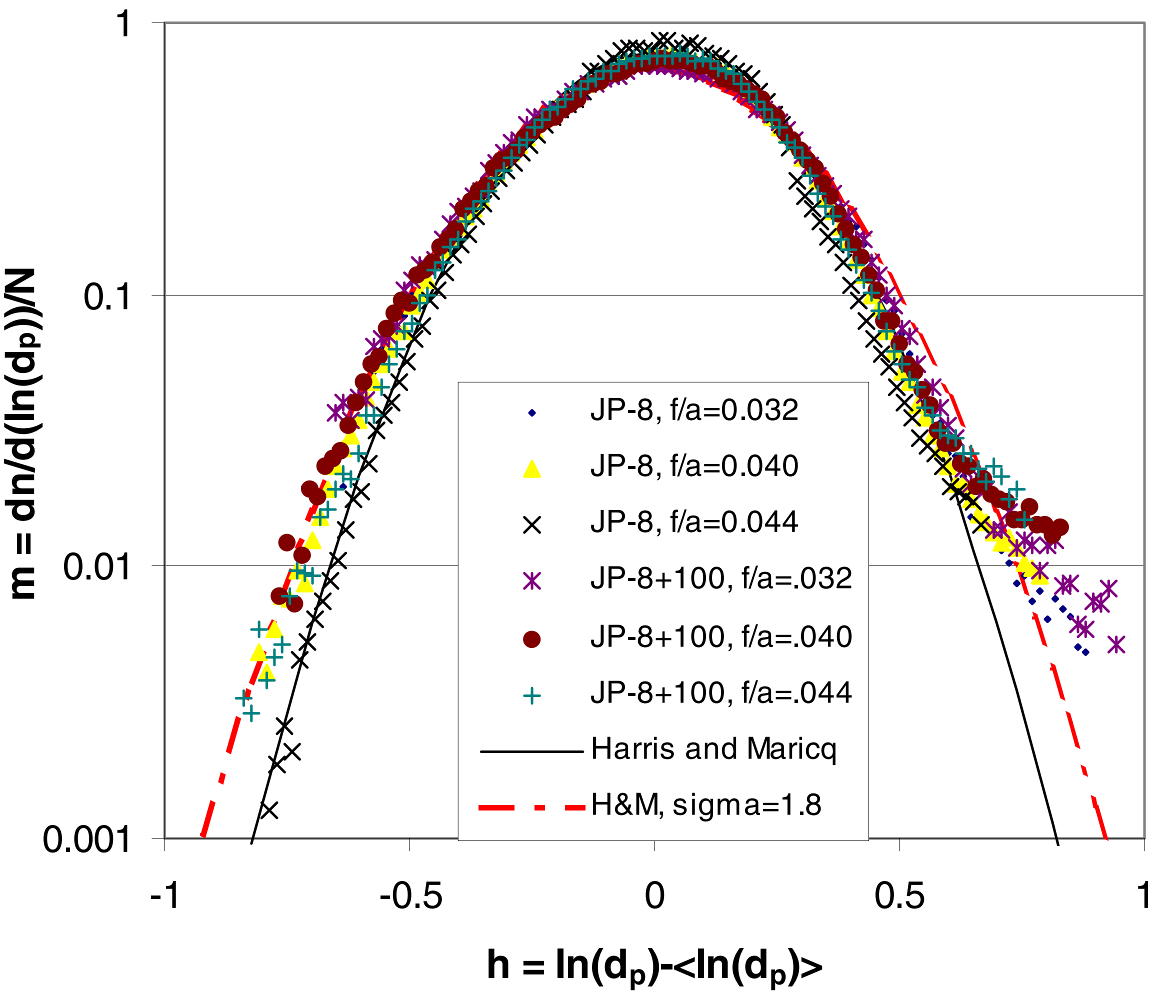
Particle Size Statistics

- Lognormal distributions describe most particle data
  - Polydisperse, size range generally > two orders of magnitude
  - Only carbonaceous material
- Statistical properties
  - Median - nm
  - Mean - nm
  - Concentration
    - $dN/dlogd_p$ (#/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



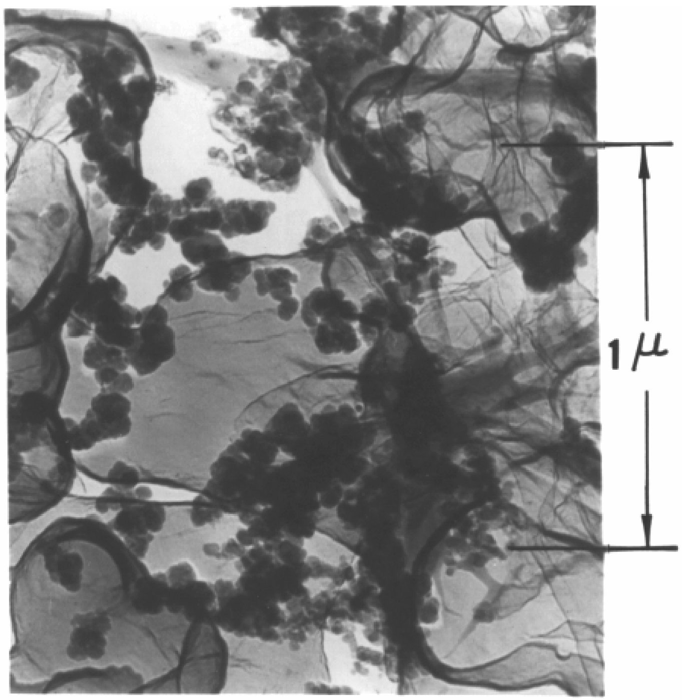
Note that reductions using +100 presented here have not been repeated

Normalized Distributions at 200 psia and 500F Following Harris and Maricq (2003)

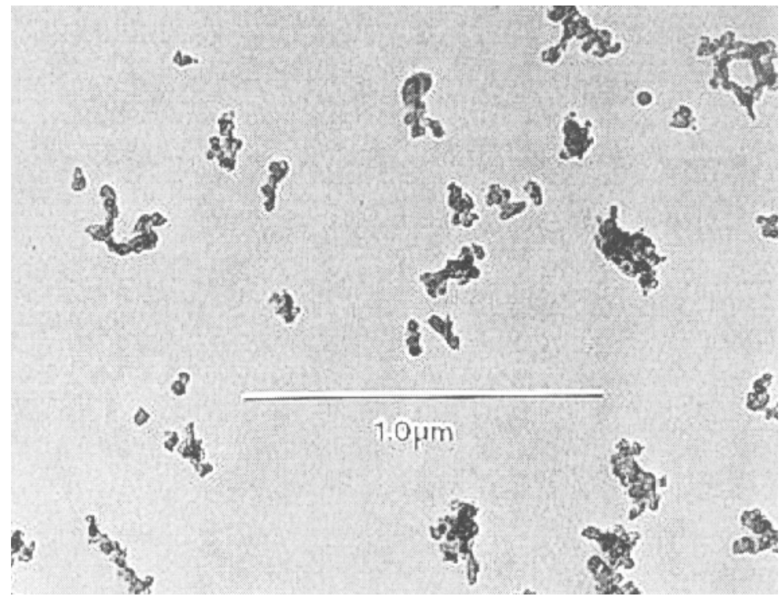


Sizing by Electron Microscopy (TEM) – Old engine technology

Significant agglomeration observed – engine or sampling artifact?



soot collected by impact
on filter paper from an engine
(primary particle diameter ~ 60 nm)
- Elwood, P&W



soot collected by impact on a TEM grid
in SBIF III from behind an F16
(primary particle diameter = ~ 40 nm)
- Brock, Univ. Denver

Aircraft Carbonaceous PM Measurement Challenges

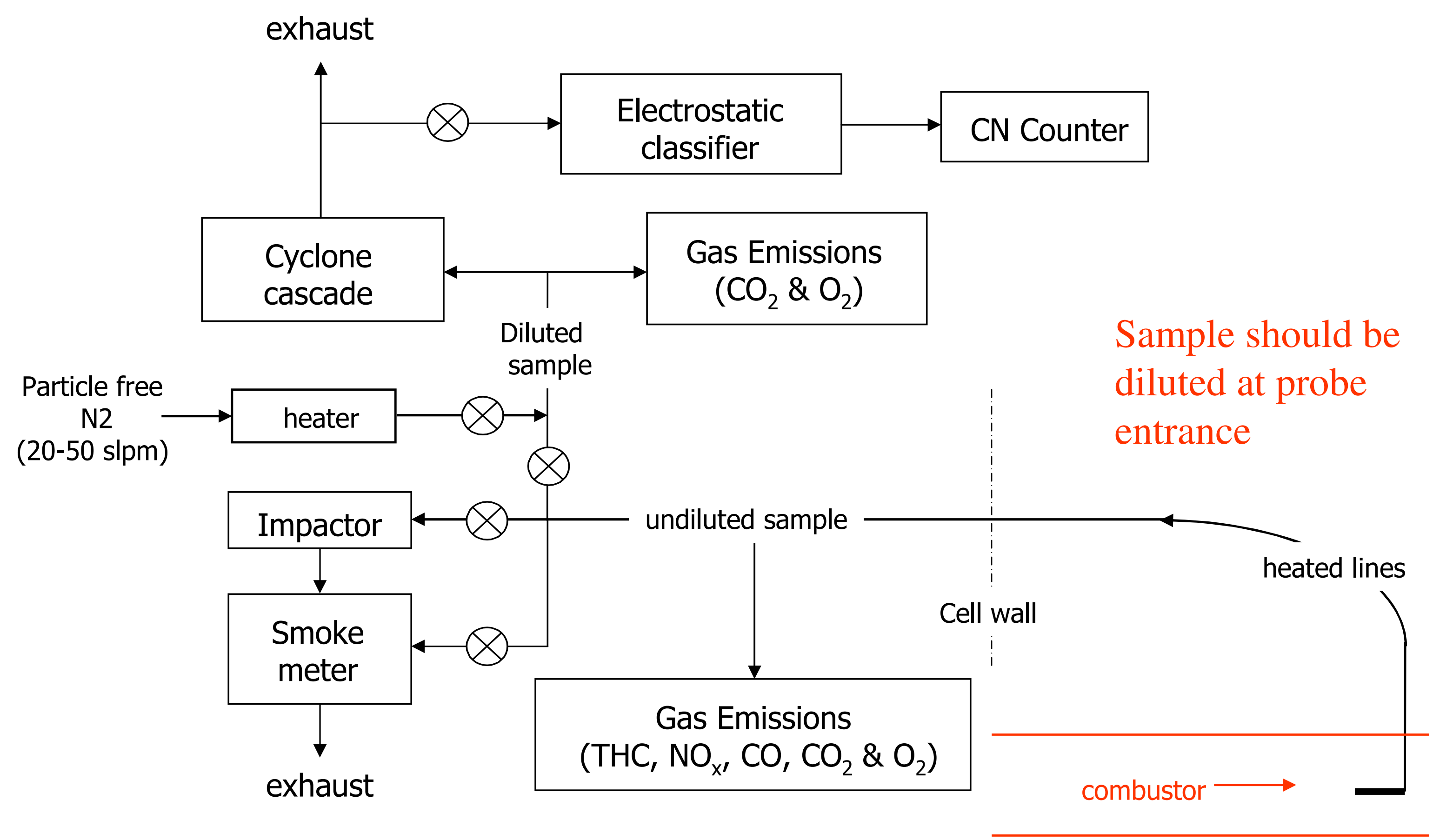
- Needs and Standards
  - No standard methodology or instrumentation established
  - No standard quantification unit established
    - EPA uses mass-based, engine manufacturers likely to use EI
  - Not clear which parameters are of interest to agencies regulating aircraft emissions (e.g., #, mass, or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

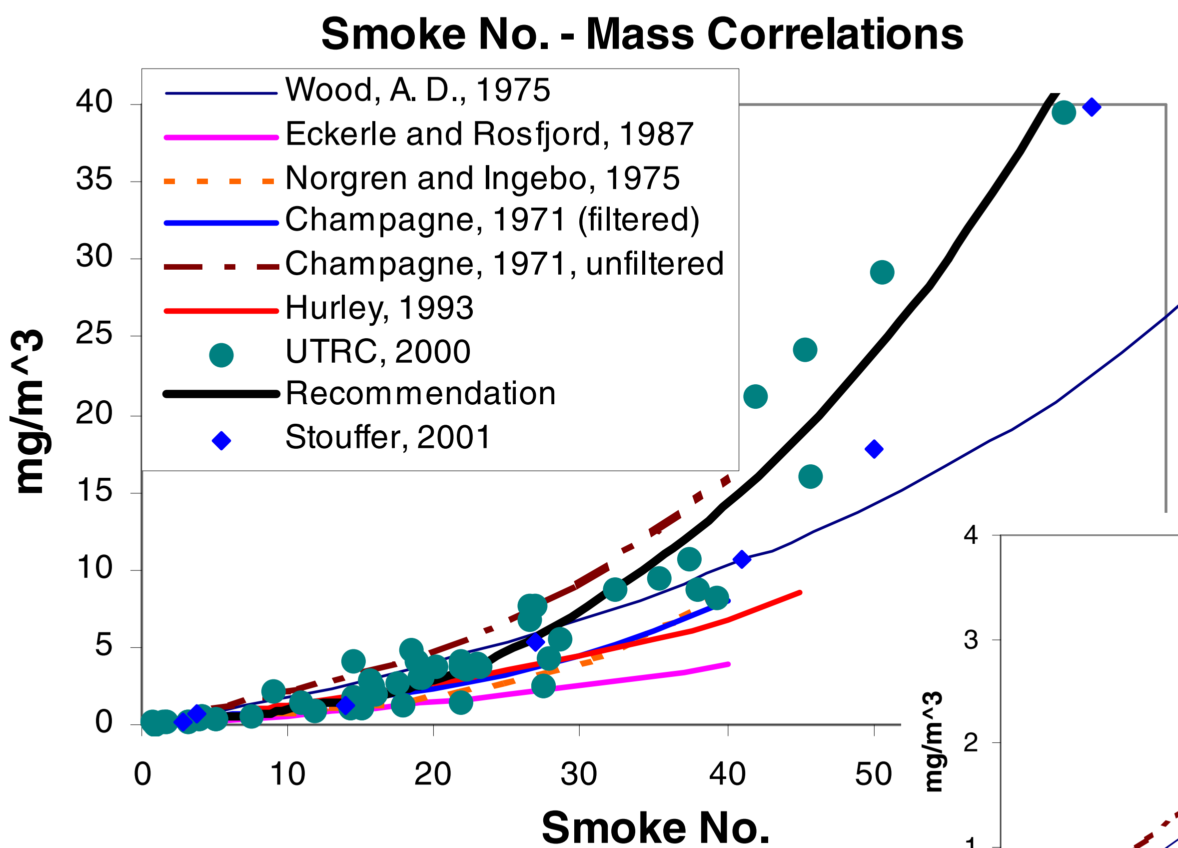
Schematic of Particulate Sampling System

Dilution is used to minimize particle coagulation and condensation

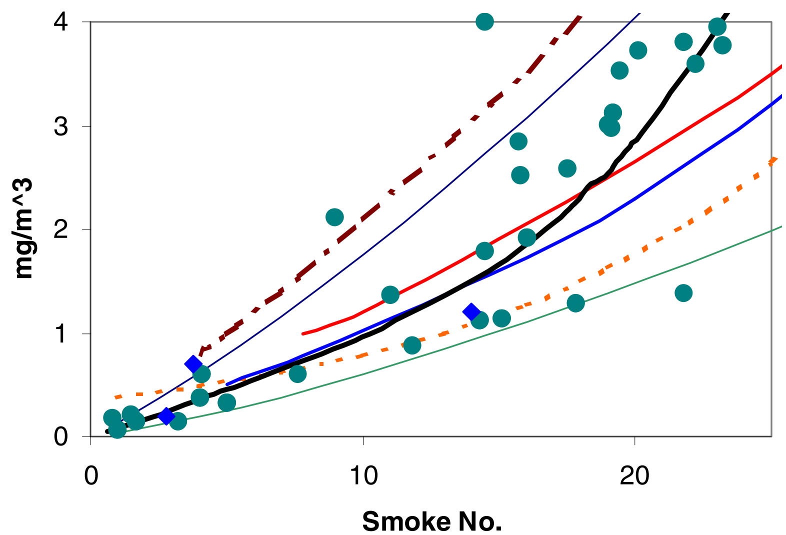


Correlation of Smoke Number

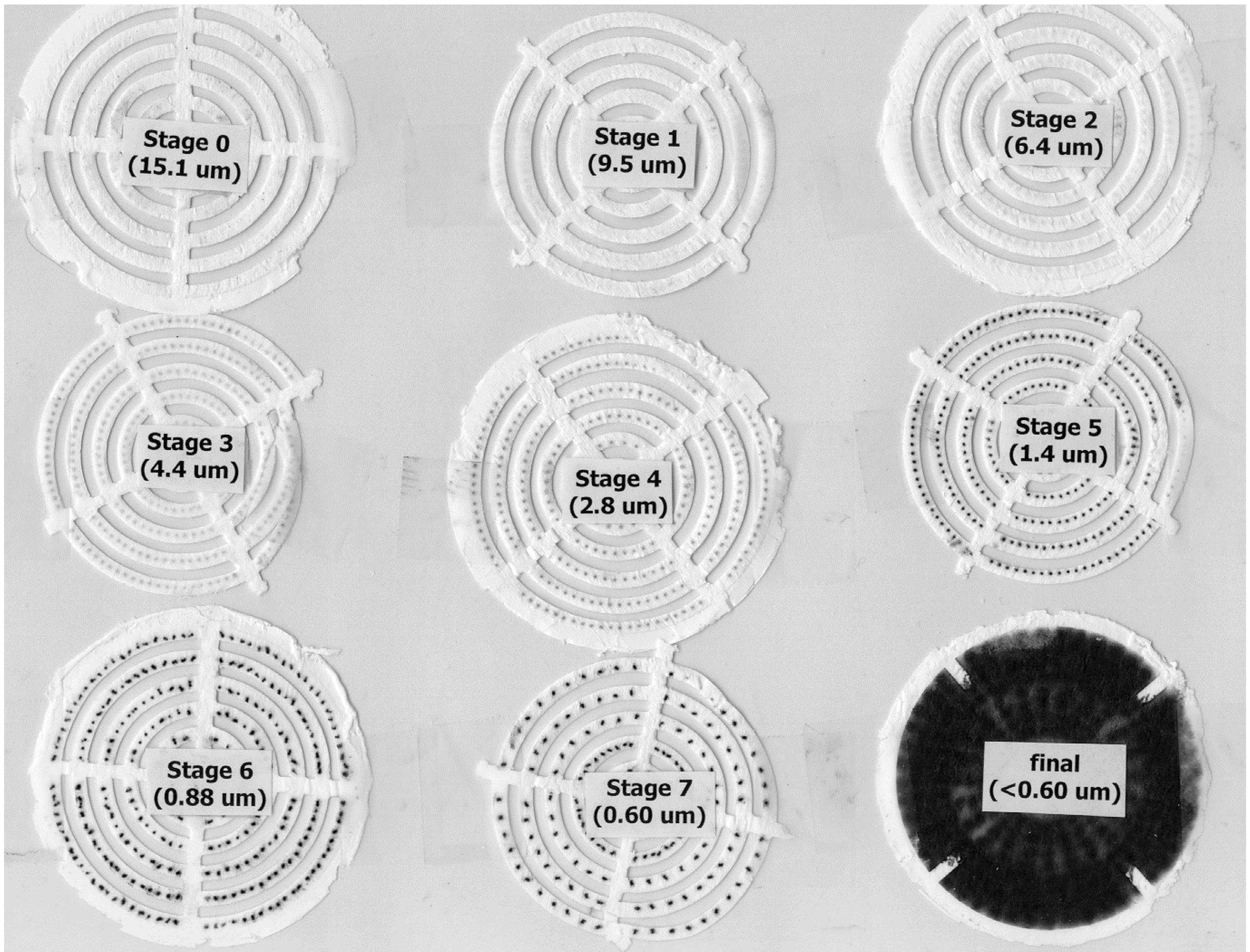
Independent of soot particle size – but ~ factor of two uncertainty



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

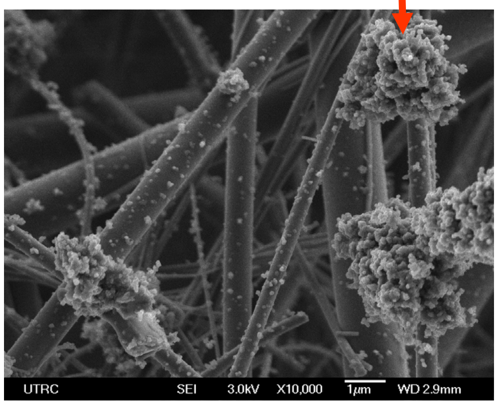


Andersen Impactor Particle Loading for JP-8 at f/a = 0.044, P3 = 200 psia and T3 = 500 F

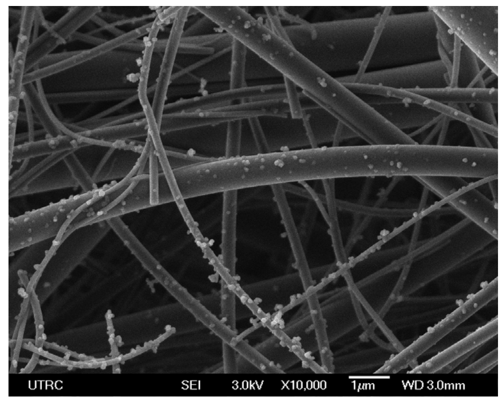
SEM Photomicrographs of Particles using Andersen Impactor

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

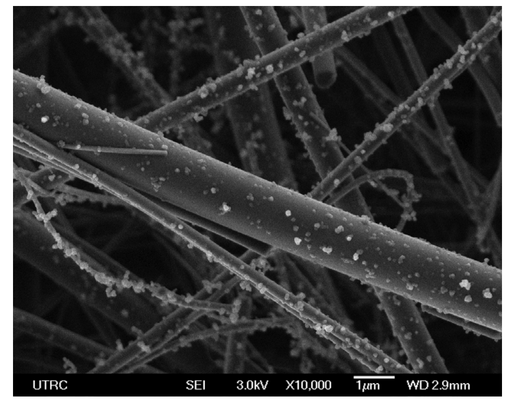
Some rogue particles, but majority are 70-100 nm
- rogues may be sampling line artifacts



Stage 4 (4.4 - 2.8μm)



Stage 7 (0.88 - 0.60μm)



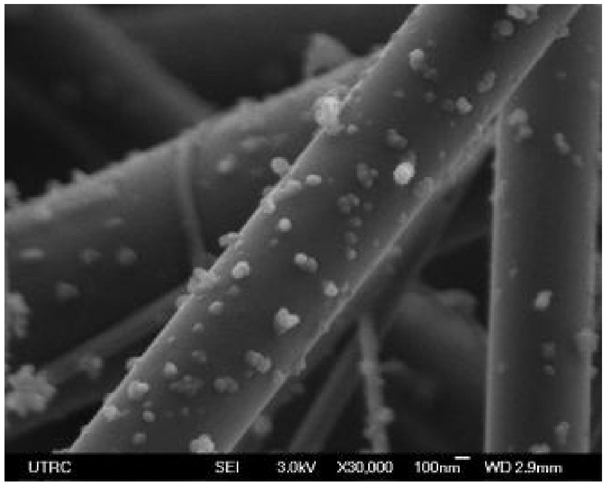
Stage f (< 0.60μm)

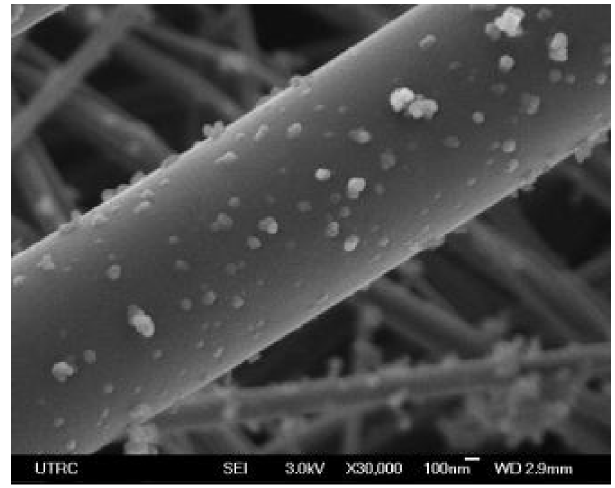
Note large particles were targeted

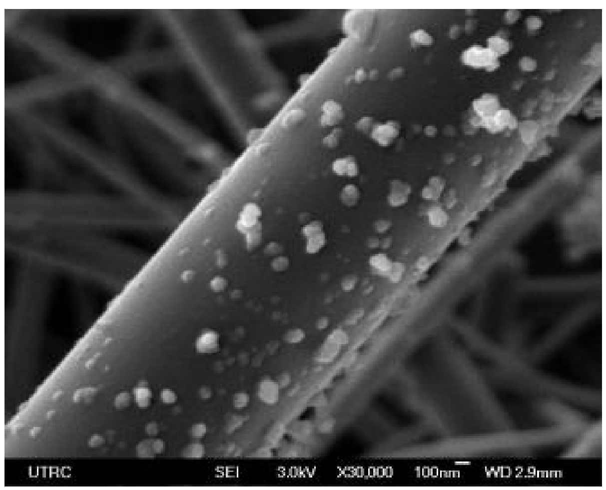
SEM Photomicrographs of Andersen Impactor Filters at 10,000x
(JP-8 at f/a = 0.044, P3 = 200 psia, T3 = 500 F)

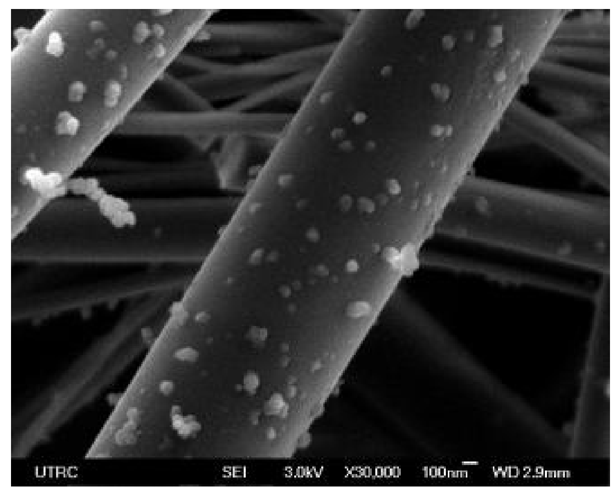
SEM Photomicrographs of Particles using Andersen Impactor

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





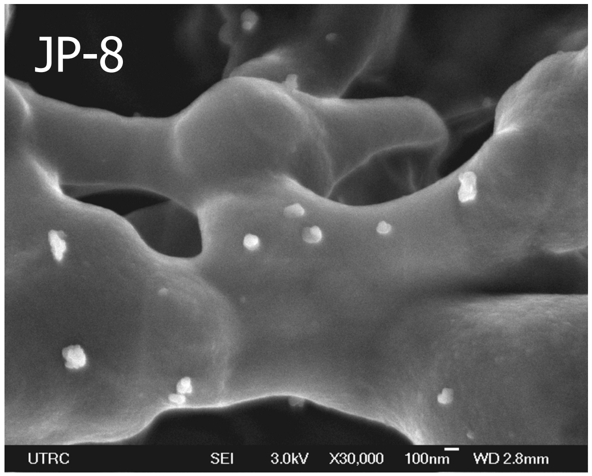


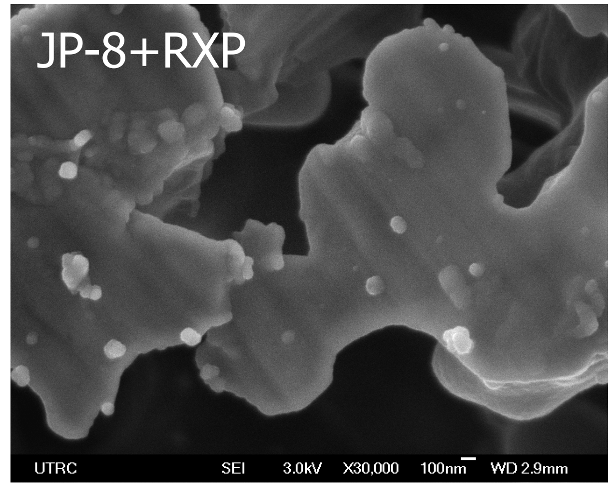


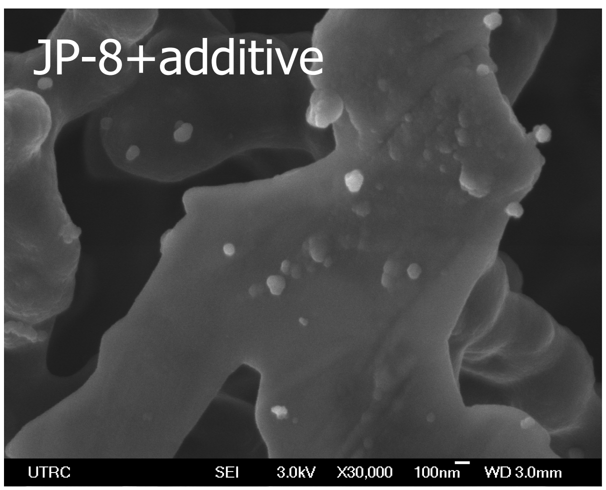
Concerns (unranked)

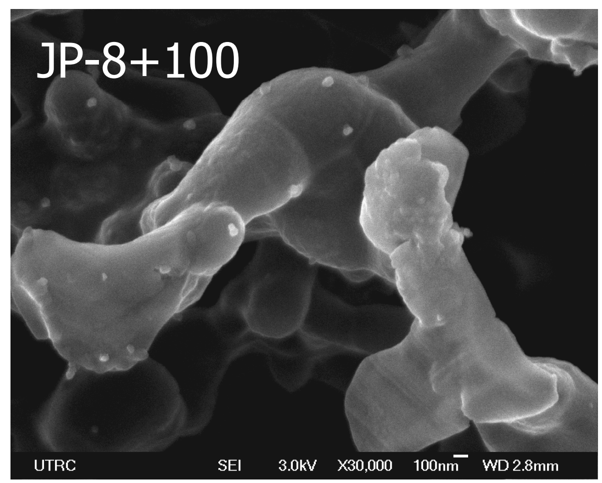
- Role of sulfur/aromatics on non-volatile emissions for advanced engines
- Size range of particles as function of engine operating conditions
- Level of agglomeration
- Hydrophobic vs. hydroscopic character
- Non-volatiles as nucleation site for HC
- Speciation
- Control of emissions via combustor design (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







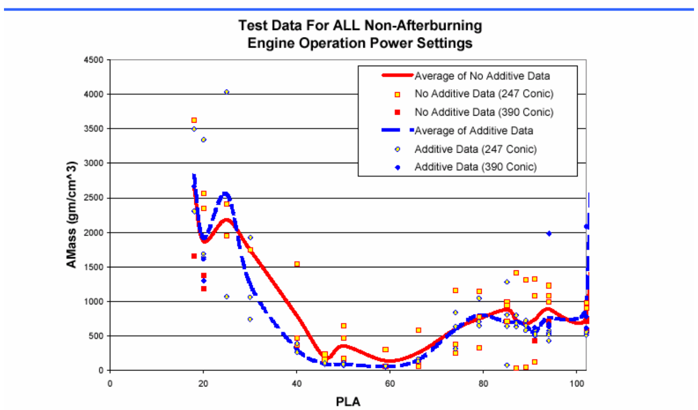


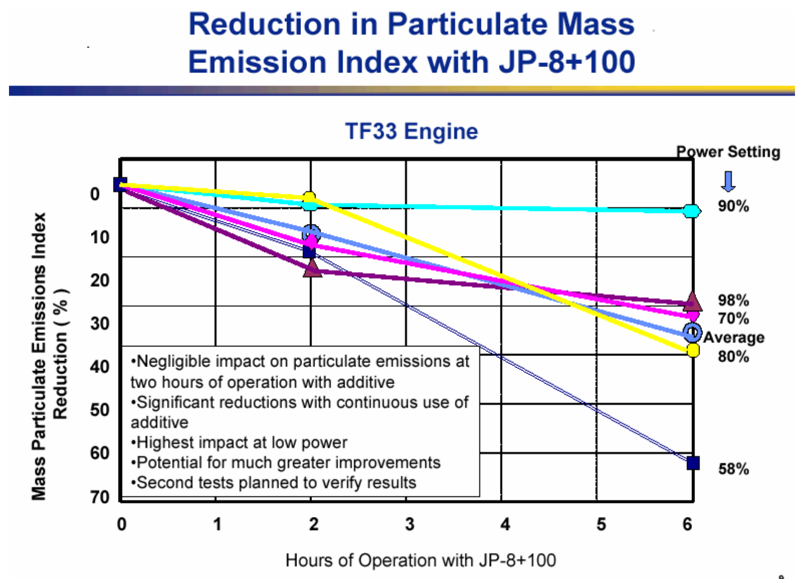
Other Results on JP-8+100

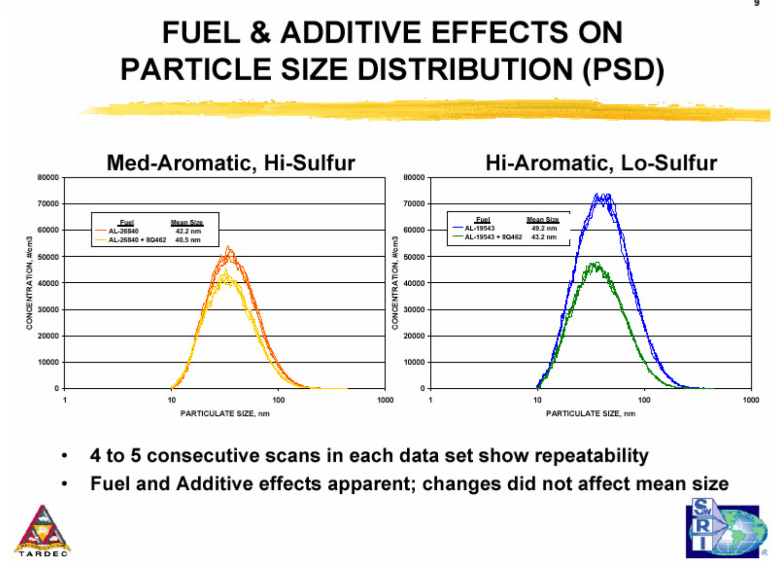
Confusion persists

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

NAVAIR







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

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

Non-standard conditions:

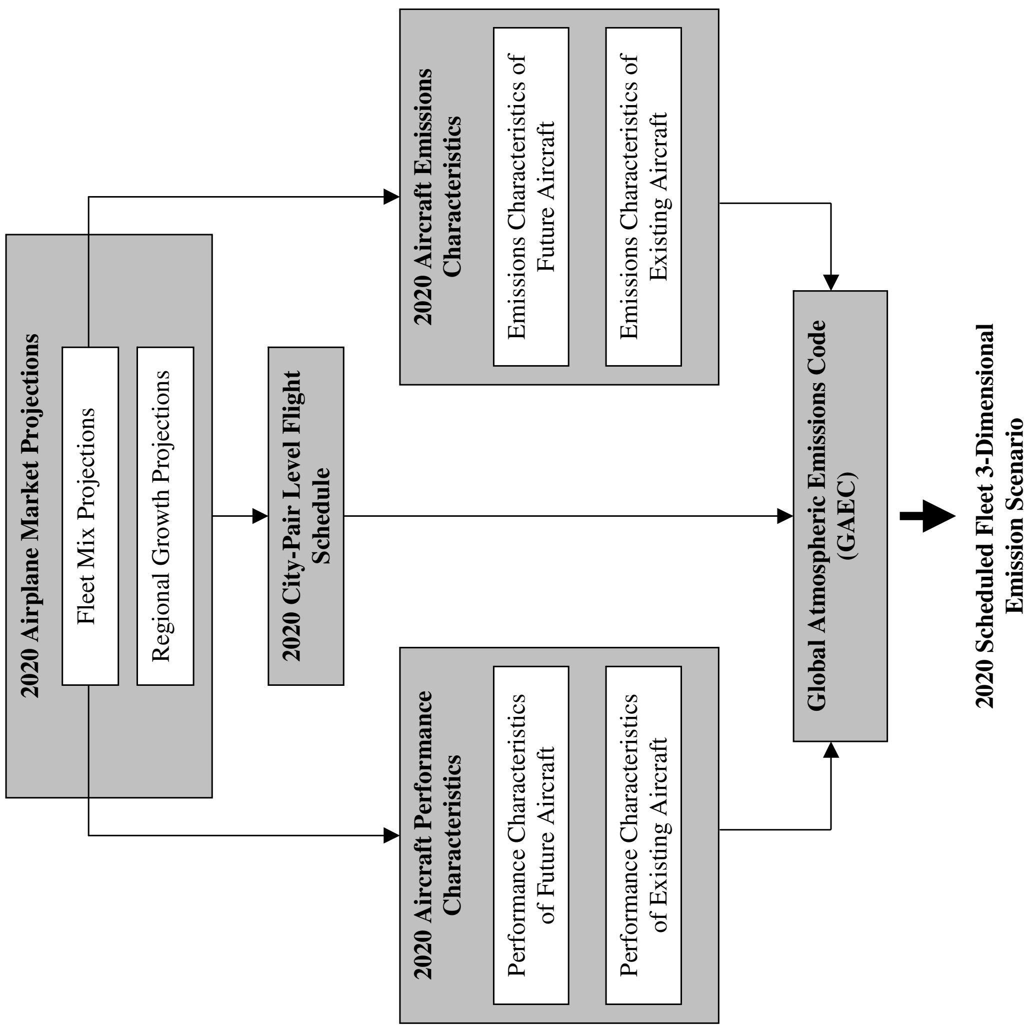
- **Calculated from engine thermodynamical cycle data combustor inlet temperature/pressure (T3/P3) data (Proprietary data)**

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

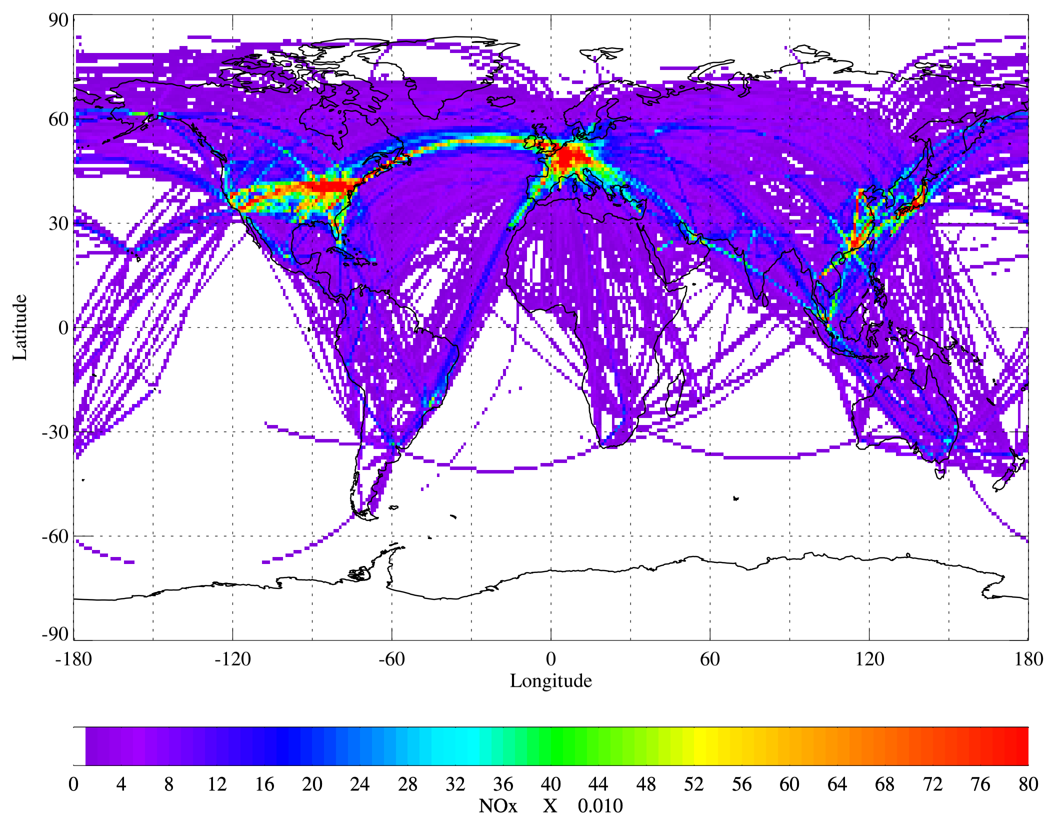
Gas Phase Emission Inventories

- 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 Emissions Characteristics
Emissions Characteristics of Future Aircraft
Emissions Characteristics of Existing Aircraft
2020 Aircraft Performance Characteristics
Performance Characteristics of Future Aircraft
Performance Characteristics of Existing Aircraft
Global Atmospheric Emissions Code (GAEC)
2020 Scheduled Fleet 3-Dimensional Emission Scenario

NOx Emissions at Cruise Altitudes Projected to 2020



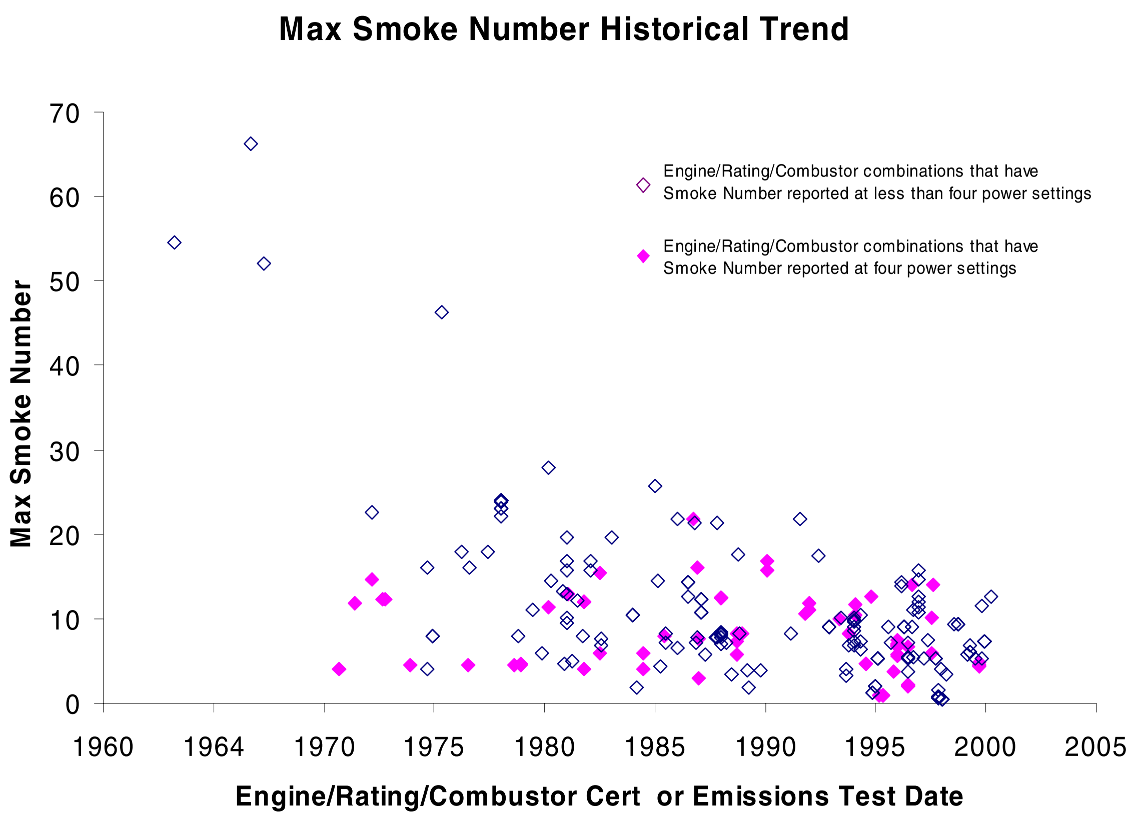
What is Needed for Particulates?

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

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

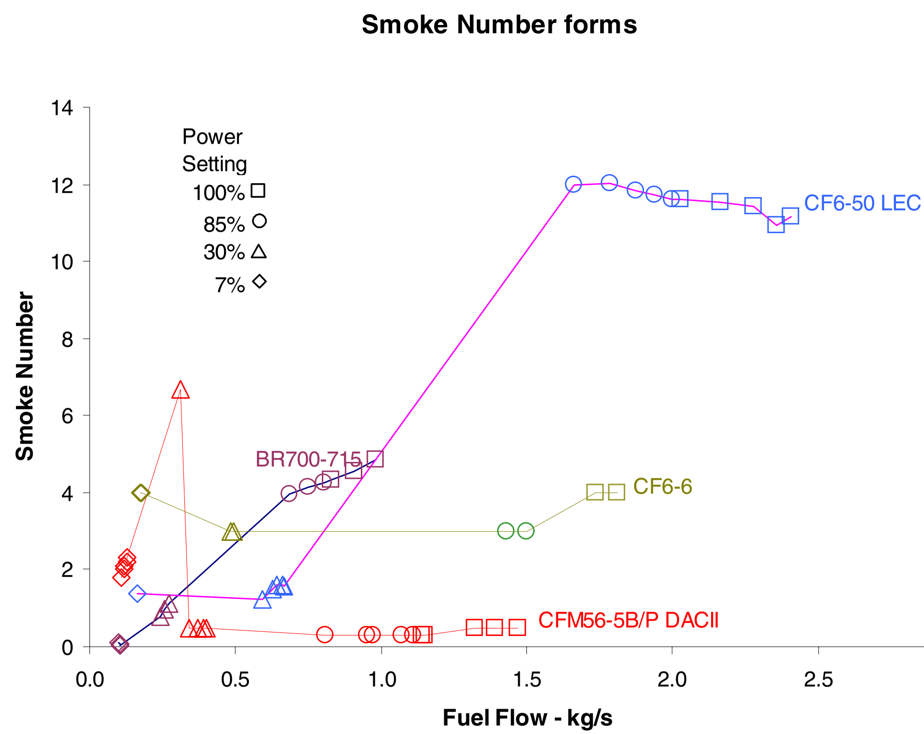
- Where?
  - Airport vicinity (sea level static)?
  - Regional?
  - Global (cruise conditions)?

Smoke number has decreased with time



- Smoke number measurements reported in ICAO databank for all certificated engines
  - For many engines, only peak smoke number is reported

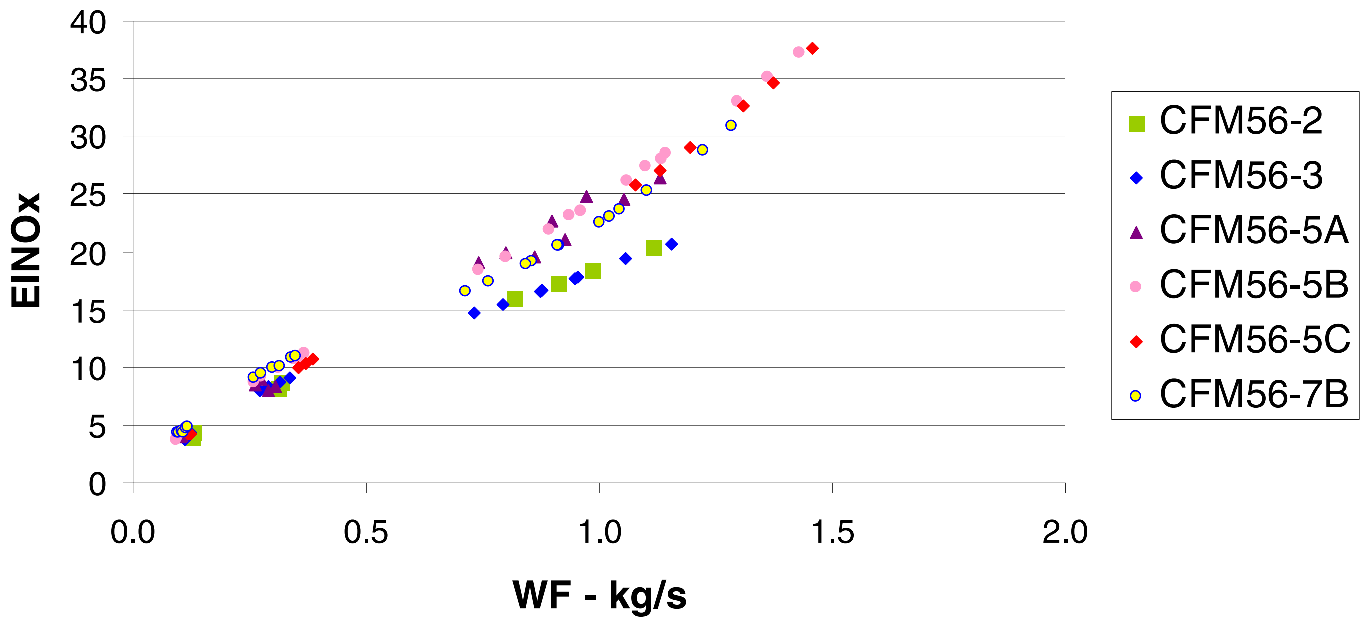
Can smoke number characteristics of different engines have similar functional forms?



Analysis by Doug DuBois

How well does the NOX data collapse for the different variants of the CFM56?

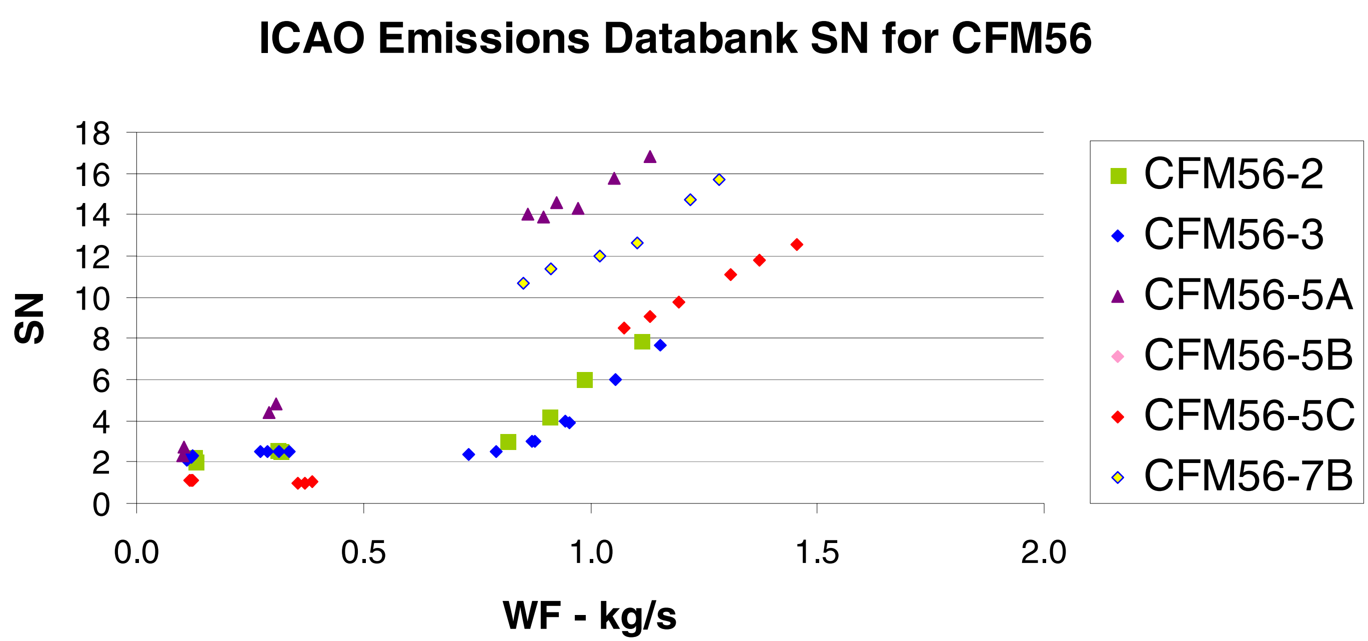
ICAO Emissions Databank NOx for CFM56



- Considering only single annular combustors

Analysis by Doug DuBois

Does the Smoke Number data collapse for the different variants of the CFM56?



- 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 SO_2

Sulfate Aerosol Inventories (cont.)

- Sensitive to engine operating conditions and design
  - $SO_2 \rightarrow SO_3$ 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

U.S. Department of Transportation
Research and Special Programs 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, heating, bending and diameter of the tubing.
- 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).

Development of FOA

<u>Objective</u>: 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.

Measurement Studies/Test Venues

- Dryden Measurements.
  - Spring 2004.
  - 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.

DISCUSSION

Effects of Particles from Airports on Air Quality: Issues and Uncertainties

Don Wuebbles

Department of Atmospheric Sciences
University of Illinois, Urbana, IL

November, 2003

Particle emissions from Airports

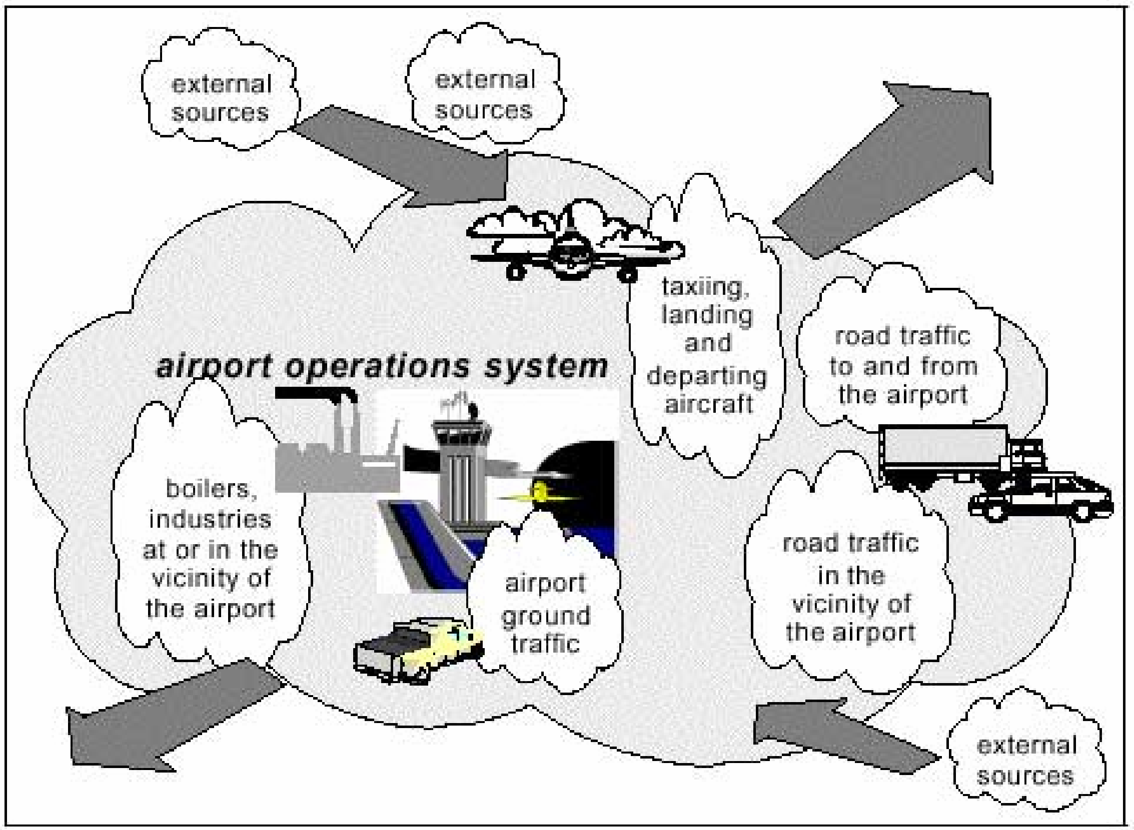


Figure 5 Overview of air pollution sources affecting an airport operations system.

Conflicting Messages in the Media

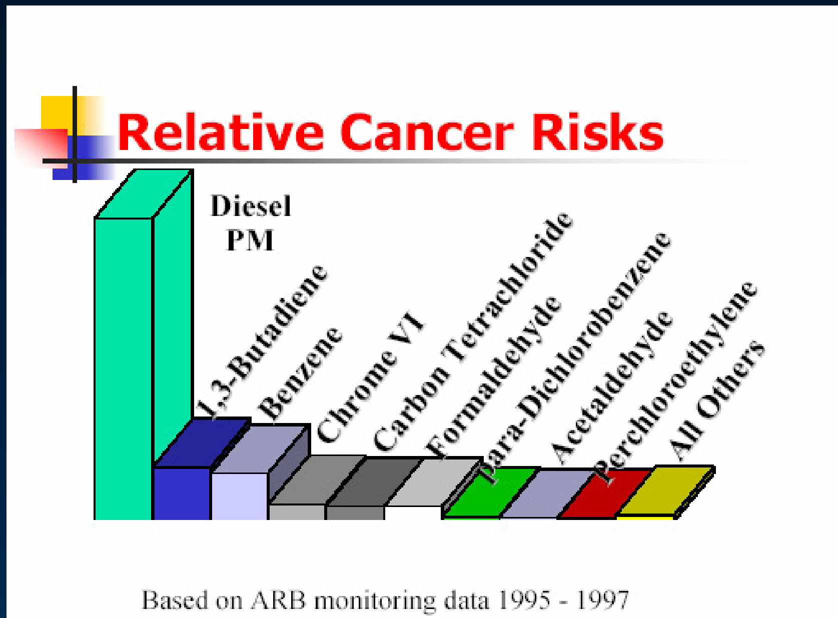
(CHICAGO) December 19, 1999 – The City of Chicago today released two air quality studies that show that O'Hare International Airport has a minimal impact on air quality in the area around the airport, compared to other sources such as motor vehicle traffic and industrial operations. Further, the studies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

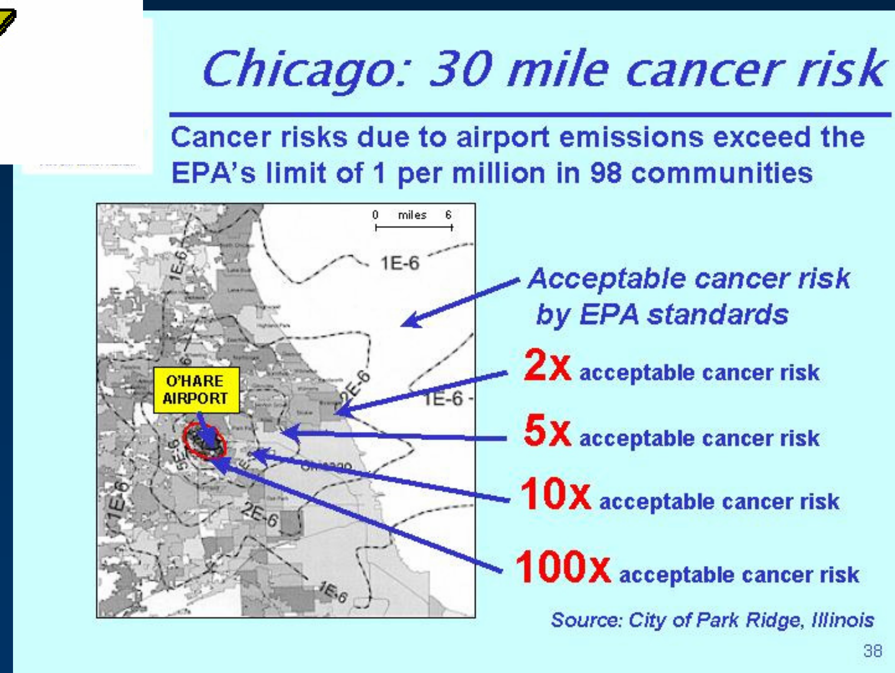
O'HARE RANKS AS MAJOR POLLUTER: "LIKE HAVING A POWER PLANT AS A NEIGHBOR"
NRDC (1996)

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

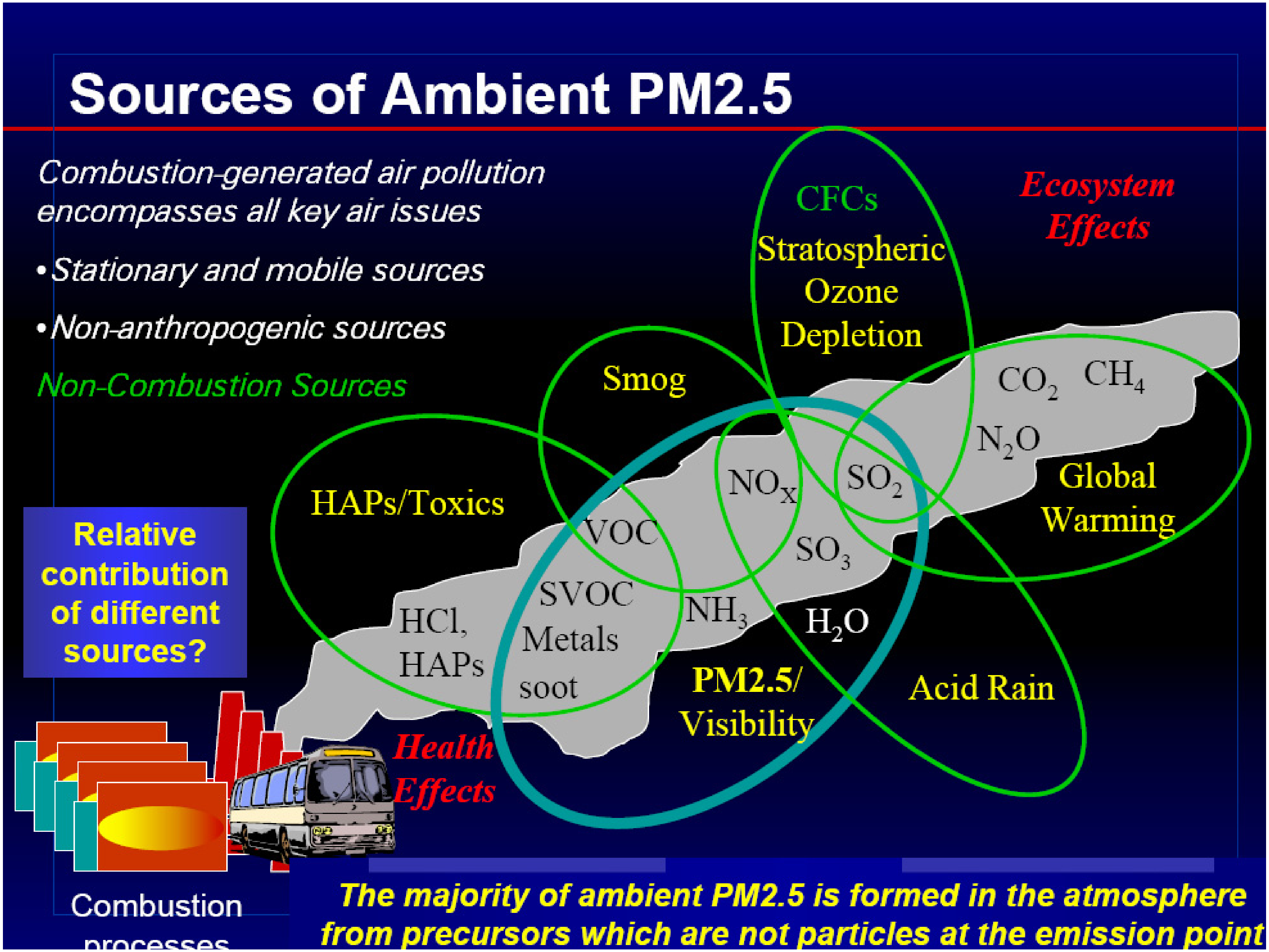
- Existing controls on aircraft particle emissions based on smoke number
  - Dominated by largest soot particles collected onto a filter
  - Sampling particles smaller than 300 nm too inefficient
    - Most soot particles being emitted from current engines much smaller than this

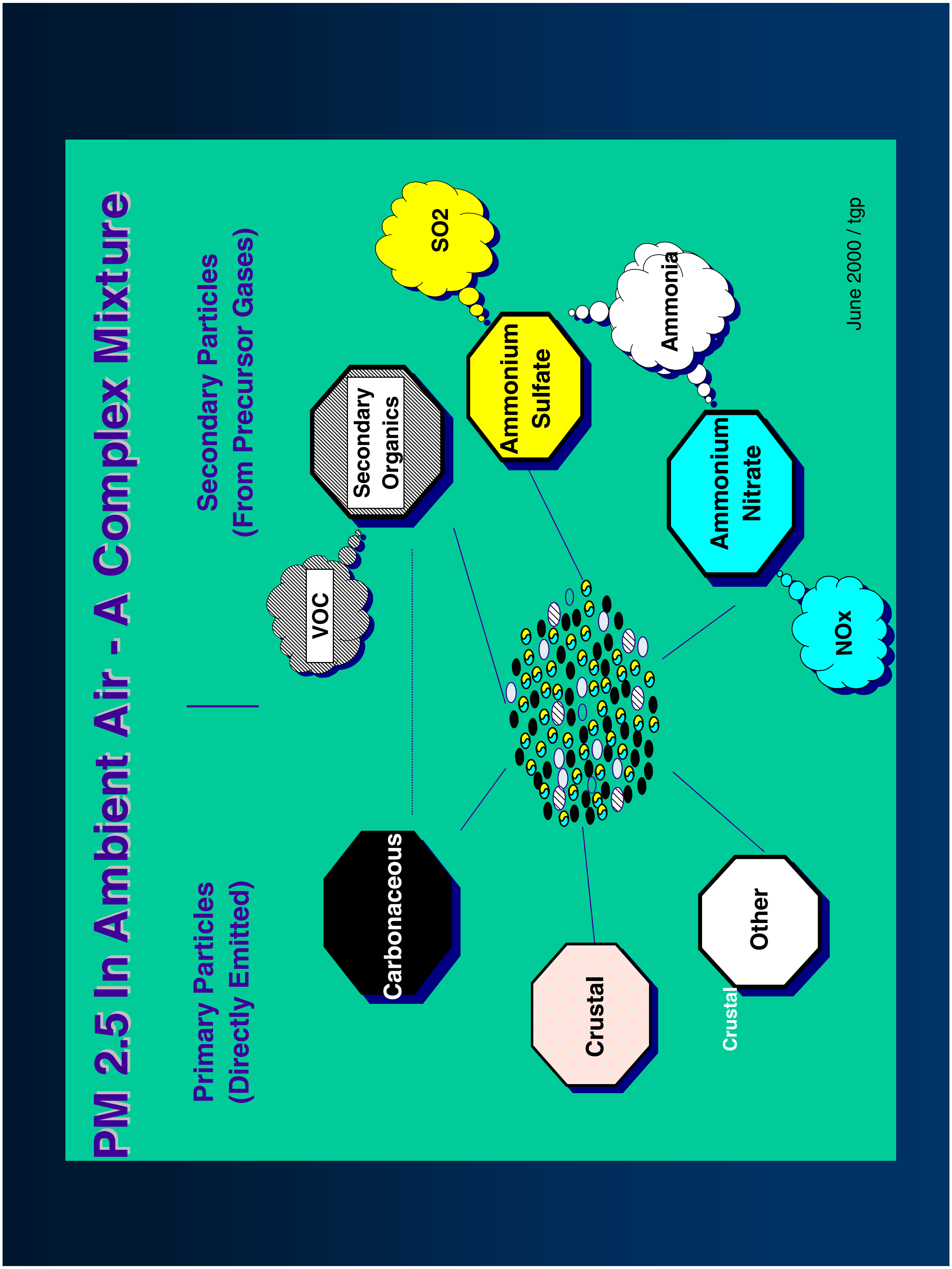

Relative Cancer Risks
Diesel PM
1,3-Butadiene
Benzene
Chrome VI
Carbon Tetrachloride
Formaldehyde
Para-Dichlorobenzene
Acetaldehyde
Perchloroethylene
All Others
Based on ARB monitoring data 1995 - 1997


Chicago: 30 mile cancer risk
Cancer risks due to airport emissions exceed the EPA's limit of 1 per million in 98 communities
0 miles 6
1E-6
2E-6
O'HARE AIRPORT
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
38

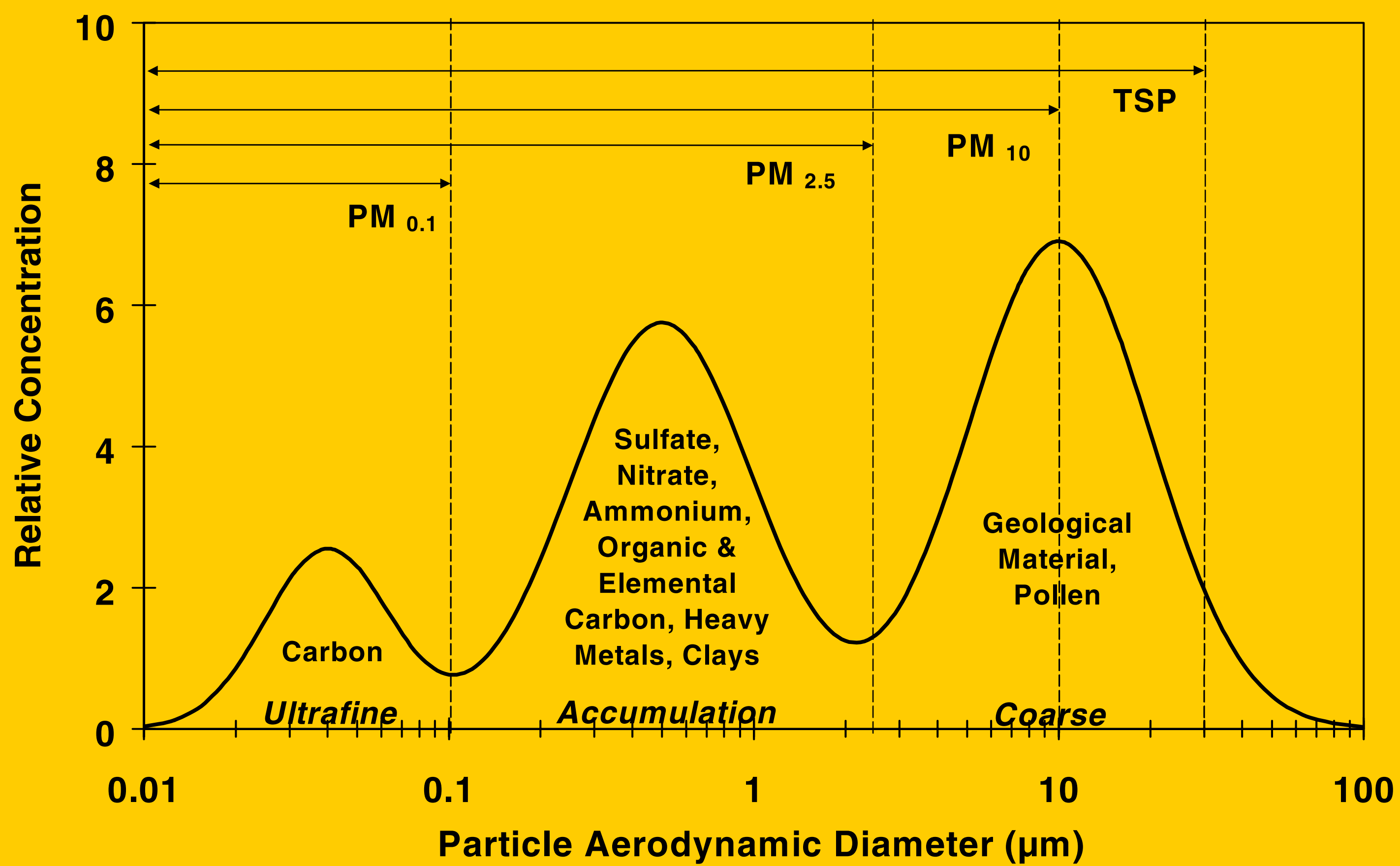
U.S. Particle Standards

Particle Size	Level	Averaging Time	Requirements
$PM_{2.5}$	15 µg/m^3	Annual	3-year arithmetic average, spatial averaging
$PM_{2.5}$	65 µg/m^3	24-hour	3-year average of 98th percentile at each monitor
PM_{10}	50 µg/m^3	Annual	3-year arithmetic average – no spatial averaging
PM_{10}	150 µg/m^3	24-hour	3-year average of 99th percentile at each monitor


Sources of Ambient PM2.5
Combustion-generated air pollution encompasses all key air issues
• Stationary and mobile sources
• Non-anthropogenic sources
Non-Combustion Sources
Relative contribution of different sources?
Combustion processes
CFCs
Stratospheric Ozone Depletion
Ecosystem Effects
Smog
HAPs/Toxics
CO_2 CH_4
N_2O
Global Warming
NO_X
SO_2
SO_3
VOC
SVOC
Metals
soot
HCl, HAPs
NH_3
H_2O
PM2.5/ Visibility
Acid Rain
Health Effects
The majority of ambient PM2.5 is formed in the atmosphere from precursors which are not particles at the emission point


PM 2.5 In Ambient Air - A Complex Mixture
Primary Particles
(Directly Emitted)
Secondary Particles
(From Precursor Gases)
Carbonaceous
Crustal
Other
Crustal
VOC
Secondary
Organics
Ammonium
Sulfate
SO2
Ammonia
Ammonium
Nitrate
NOx
June 2000 / tgp

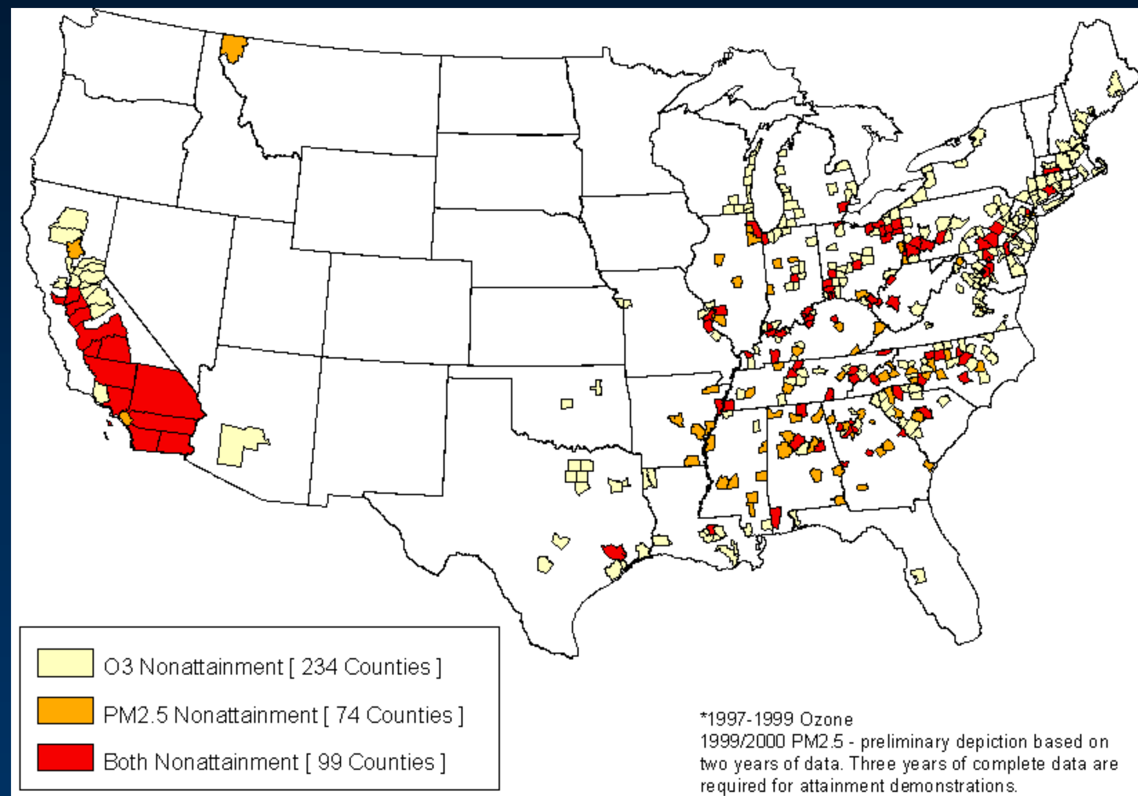
Ambient Particle Size Distribution



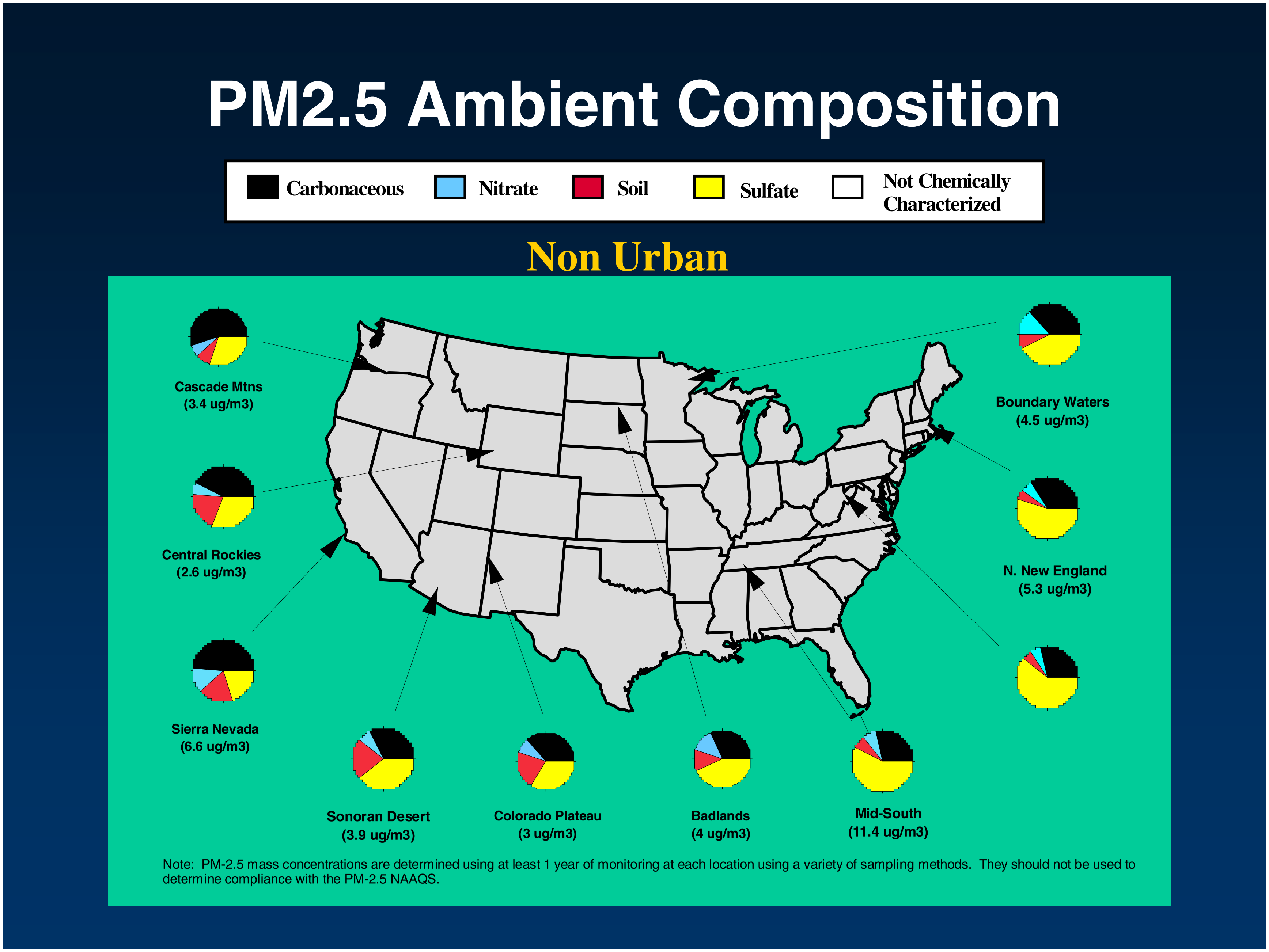
Watson et al., 1998

$PM_{2.5}$ 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/m3 (the annual fine particle standard)



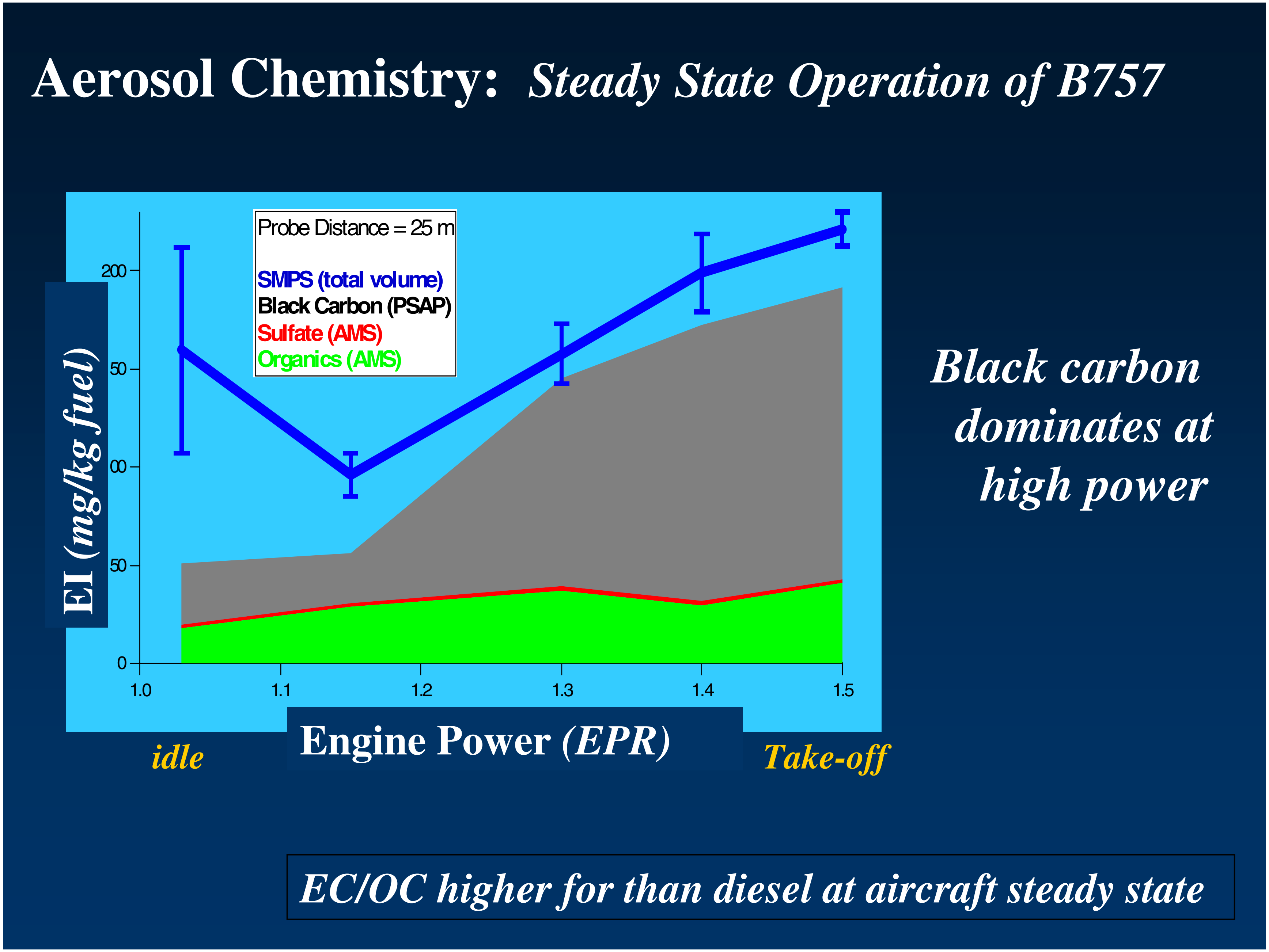
*1997-1999 ozone
1999/2000 PM2.5--preliminary depiction base on two years of data. Three years are required for attainment demonstrations.



PM2.5 Ambient Composition
Carbonaceous
Nitrate
Soil
Sulfate
Not Chemically Characterized
Non Urban
Cascade Mtns (3.4 ug/m3)
Central Rockies (2.6 ug/m3)
Sierra Nevada (6.6 ug/m3)
Sonoran Desert (3.9 ug/m3)
Colorado Plateau (3 ug/m3)
Badlands (4 ug/m3)
Mid-South (11.4 ug/m3)
Boundary Waters (4.5 ug/m3)
N. New England (5.3 ug/m3)
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.

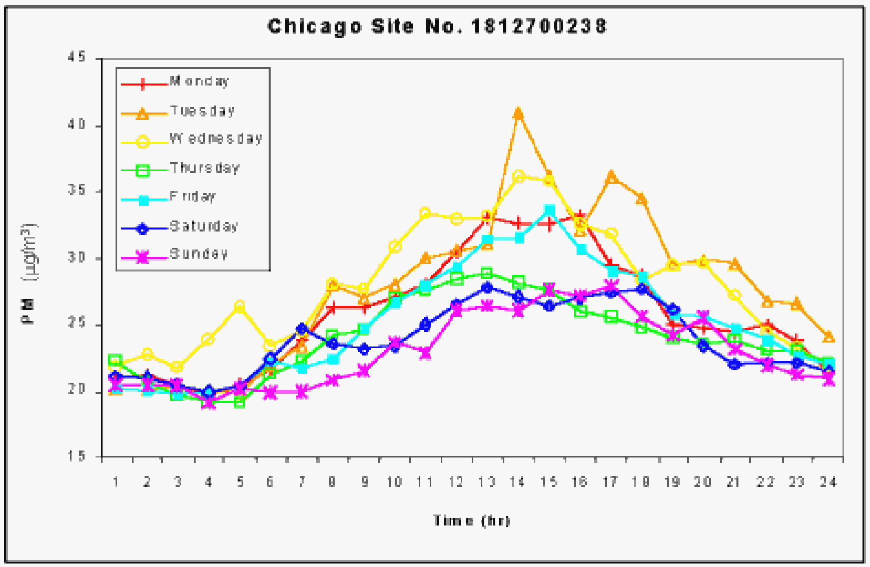
PM2.5 from Aircraft

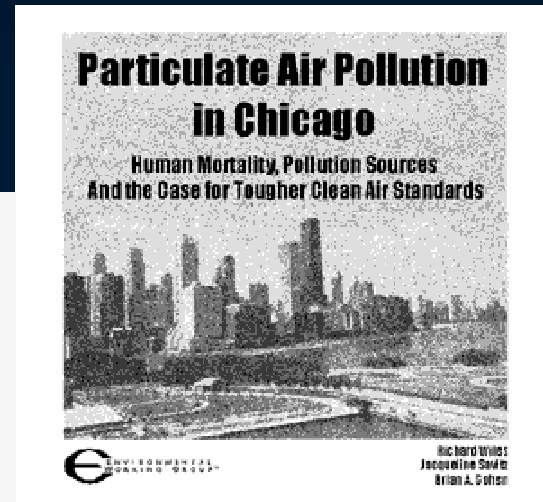
- Modern aircraft produce PM with aerodynamic diameters less than 2.5 µm.
- PM emissions are affected by fuel flow, engine design, operating conditions, altitude, fuel composition, etc.
- PM is composed of both volatile and non-volatile components. The non-volatile components are more prevalent.
- Coagulation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

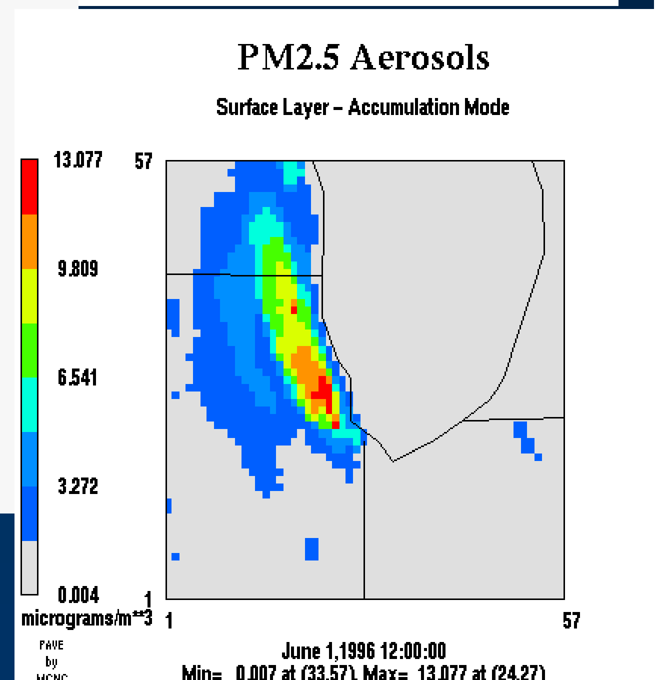

Aerosol Chemistry: Steady State Operation of B757
Probe Distance = 25 m
SMPS (total volume)
Black Carbon (PSAP)
Sulfate (AMS)
Organics (AMS)
EI (mg/kg fuel)
0
50
00
50
200
1.0
1.1
1.2
1.3
1.4
1.5
Engine Power (EPR)
idle
Take-off
Black carbon dominates at high power
EC/OC higher for than diesel at aircraft steady state

PM from O'Hare Airport?

PM_{10} at Chicago, IL; 1995 - 1999







Estimated Airport Growth

1990-2010

Table 2-3. Estimated commercial jet aircraft activity growth, 1990 – 2010.

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

EPA420-R-99-013
April 1999

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

$$C = \frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\}$$

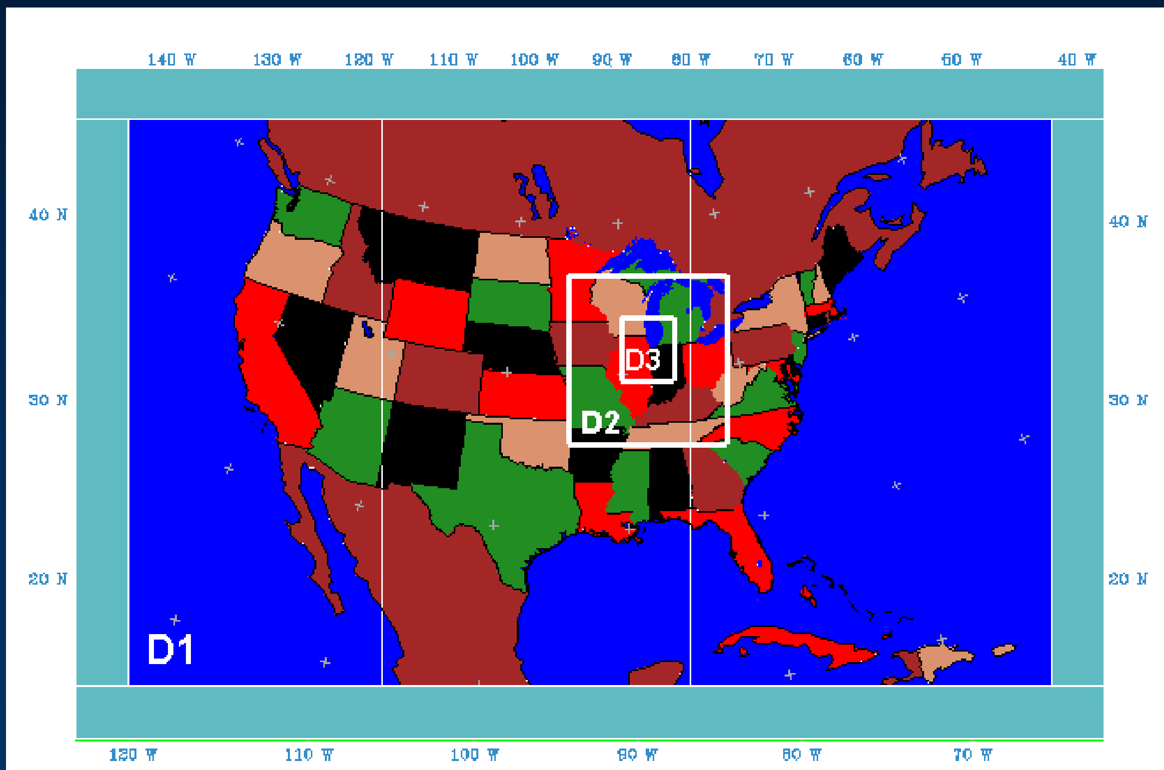
Typical Gaussian Equation

  - EPA AERMOD dispersion model

Disadvantages of Gaussian Plume Models

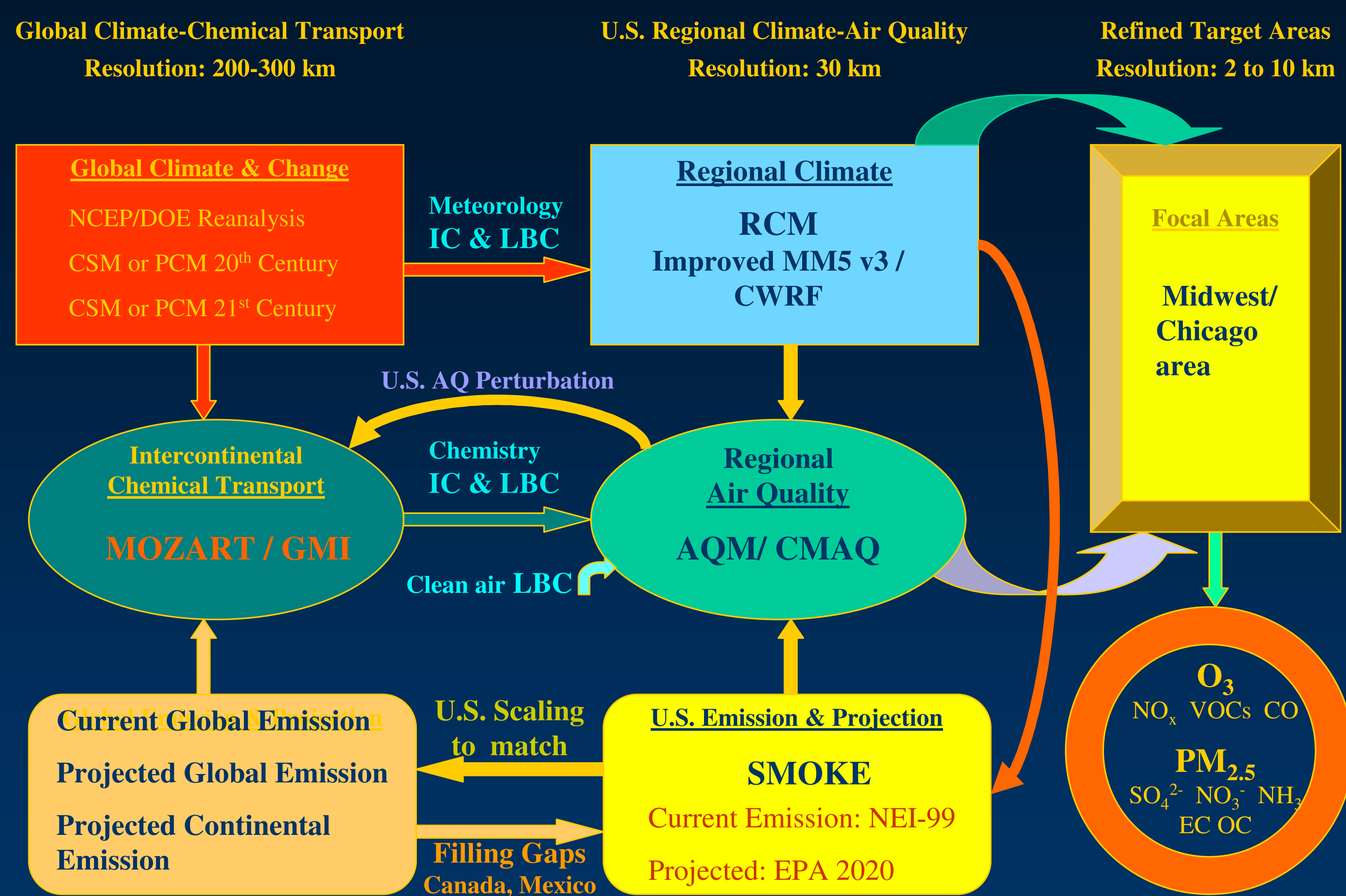
- Inaccurate in regions with complex terrain
- Inaccurate in rapidly changing conditions
- Inaccurate in calm conditions or low wind speeds
- Generally have trouble treating dry and wet deposition accurately
- Generally have insufficient treatments of chemical, physical and microphysical processes

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.

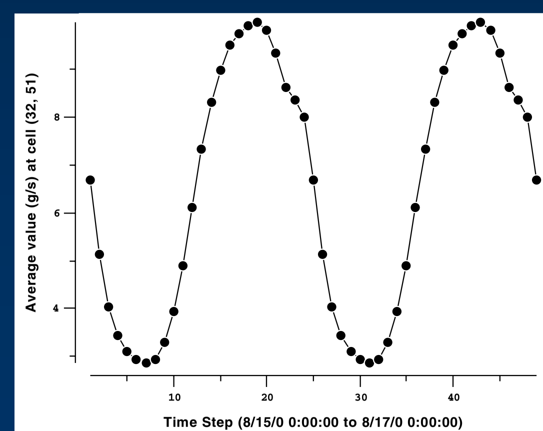
Hartsfield's Emissions in Current Inventory

Daily emissions (tons/day)						
SO_2	VOC	CO	NH_3	NOx	PM_{10}	$PM_{2.5}$
1.30	2.78	14.26	0	13.45	1.37	0.95

Composition of $PM_{2.5}$ emissions (%)			
EC	OC	SO_4	NO_3
65.87	29.21	4.60	0.32

T Odman et al. (2003)

Diurnal Profile of emissions



GIT: Preliminary Assessment of Hartsfield's Impact

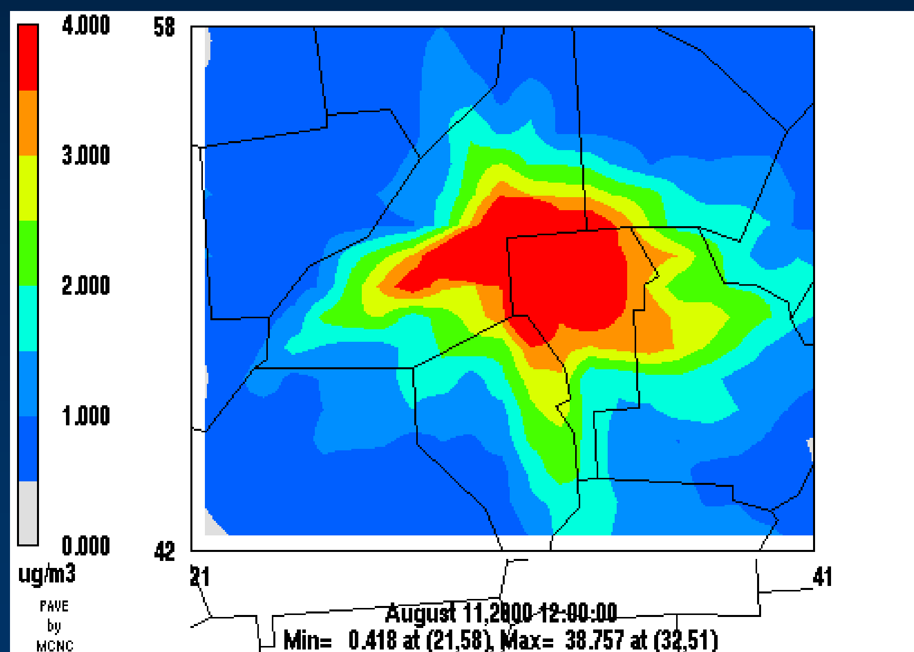
- The impact of Hartsfield's emissions during the August 11-20, 2000 period was assessed using the "brute-force" approach

- 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

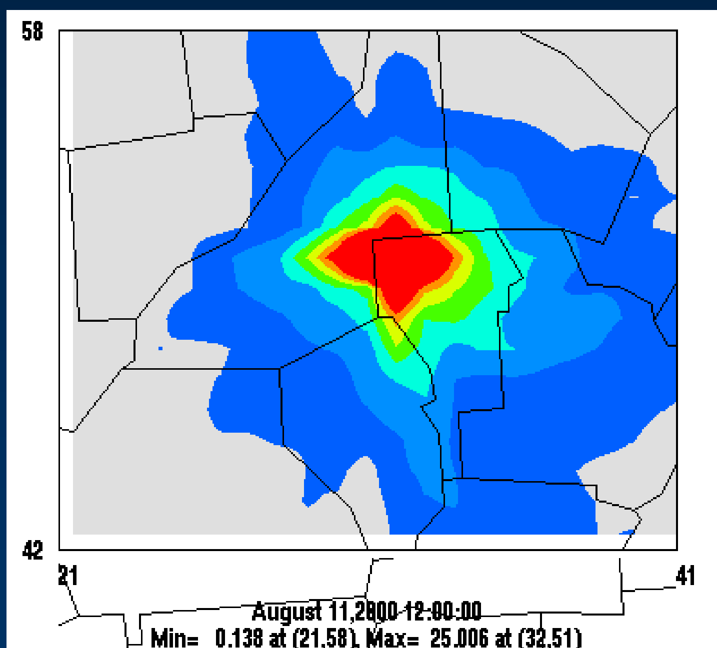


T Odman et al. (2003)

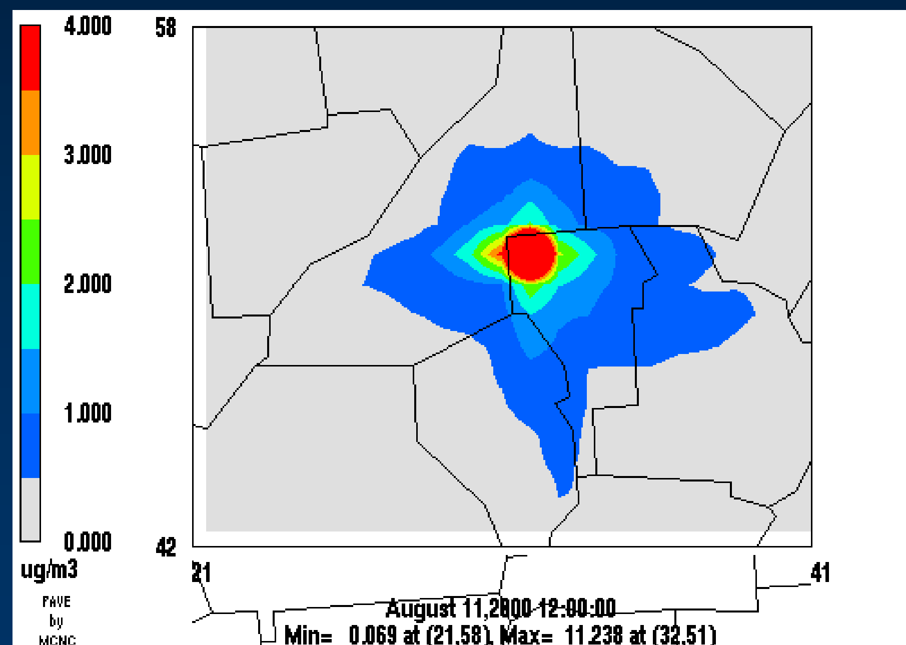
GIT: Composition of $PM_{2.5}$ Impact

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

Elem. Carbon



Organic Carbon

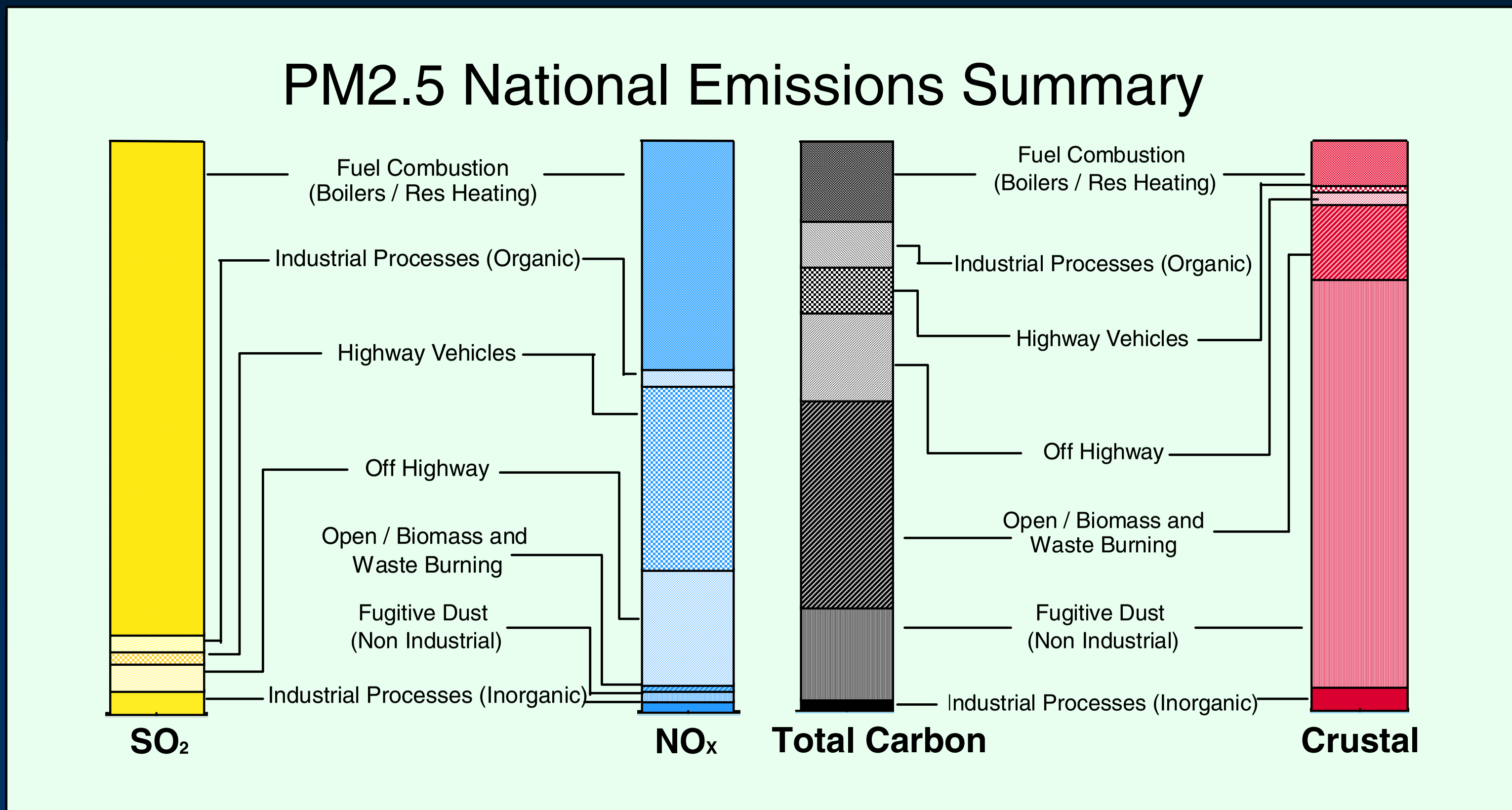


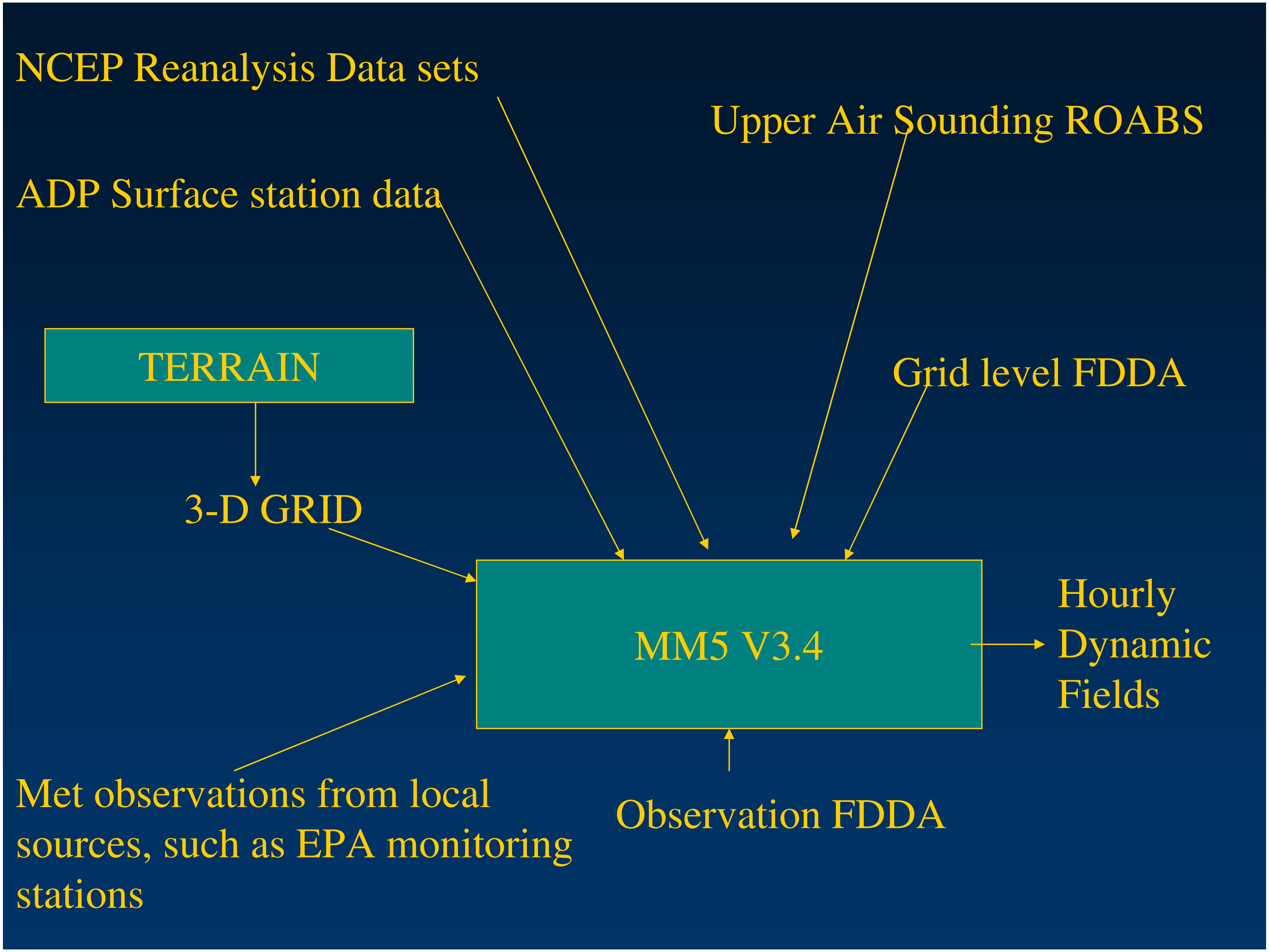
T Odman et al. (2003)

Summary

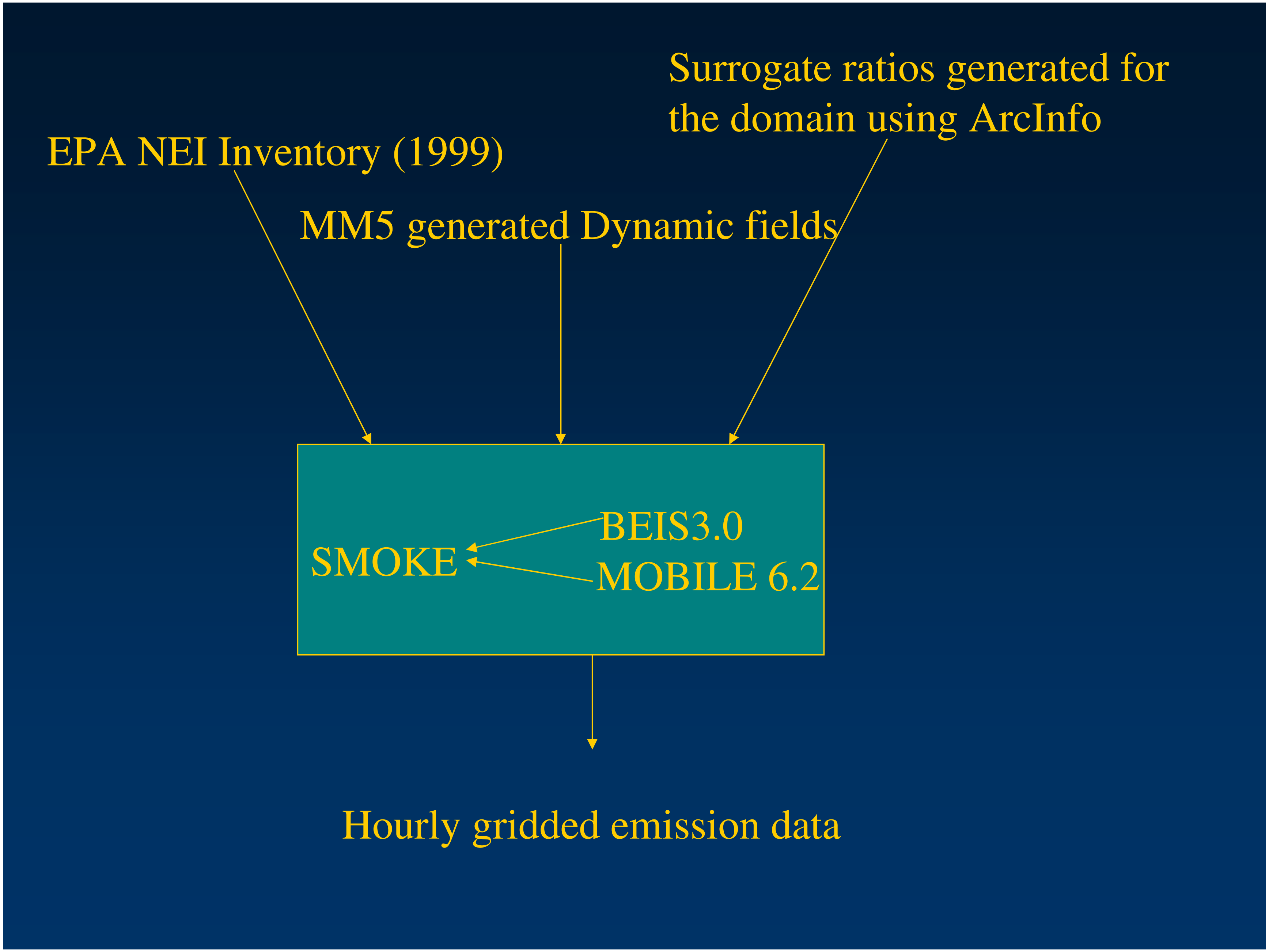
- Modeling studies underway to investigate the impact of aircraft emissions from Chicago O'Hare and Atlanta Hartsfield airports on regional air quality, especially $PM_{2.5}$.
- Preliminary analysis shows significant impact of Hartsfield on EC and OC in Atlanta metro counties
- Dispersion models (like 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

Sources of PM2.5

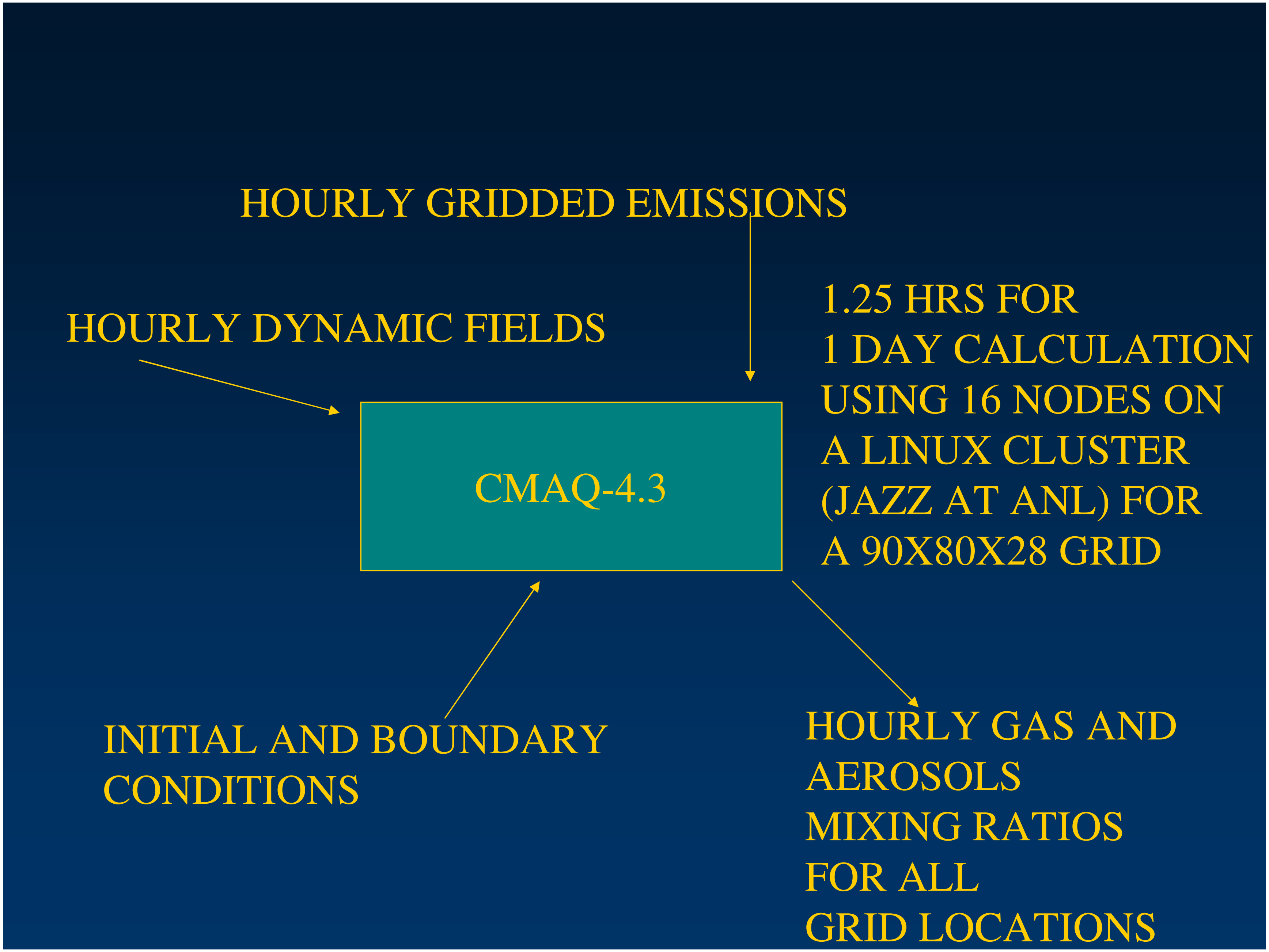


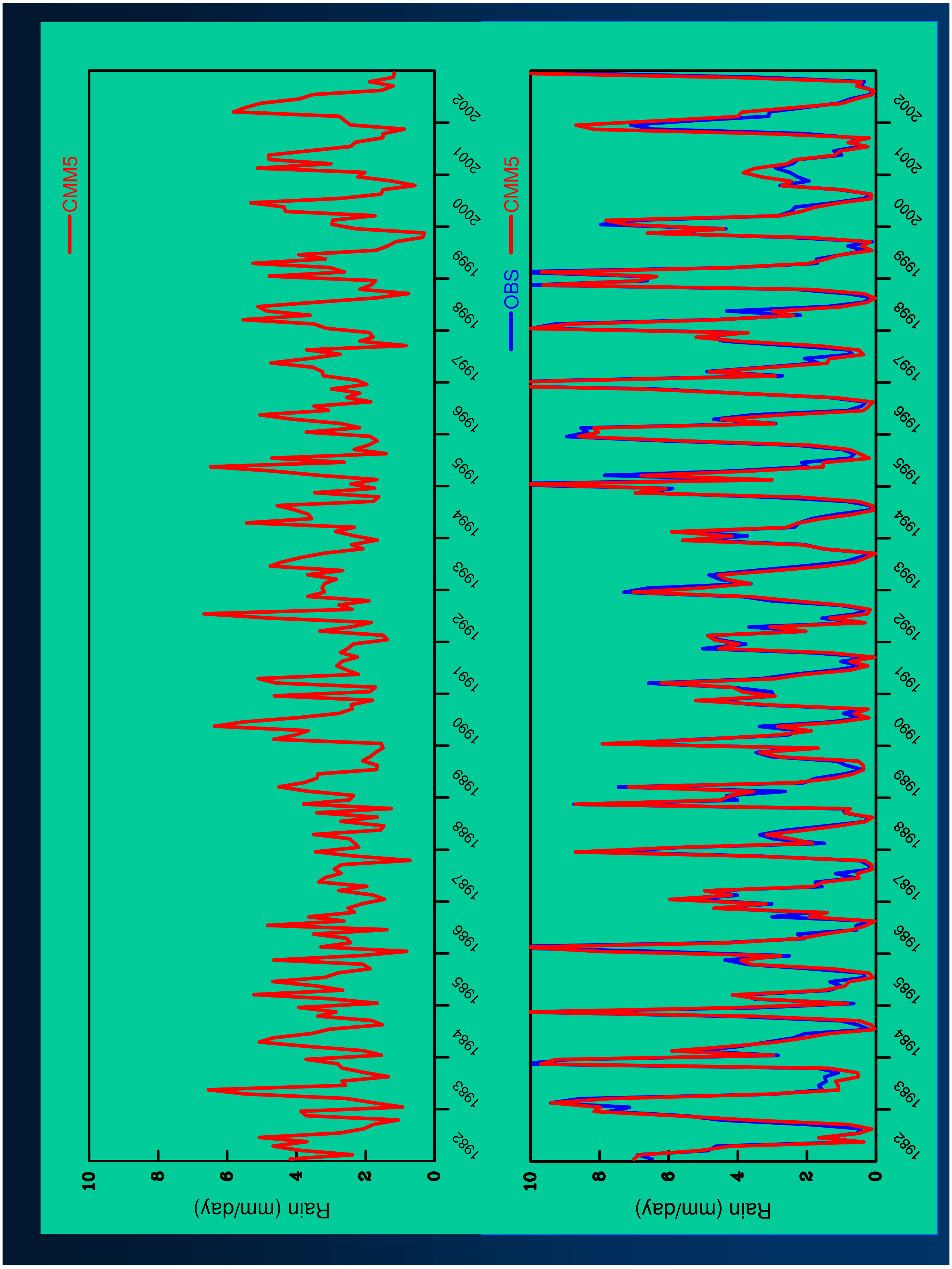


NCEP Reanalysis Data sets
Upper Air Sounding ROABS
ADP Surface station data
TERRAIN
Grid level FDDA
3-D GRID
MM5 V3.4
Hourly
Dynamic
Fields
Met observations from local sources, such as EPA monitoring stations
Observation FDDA



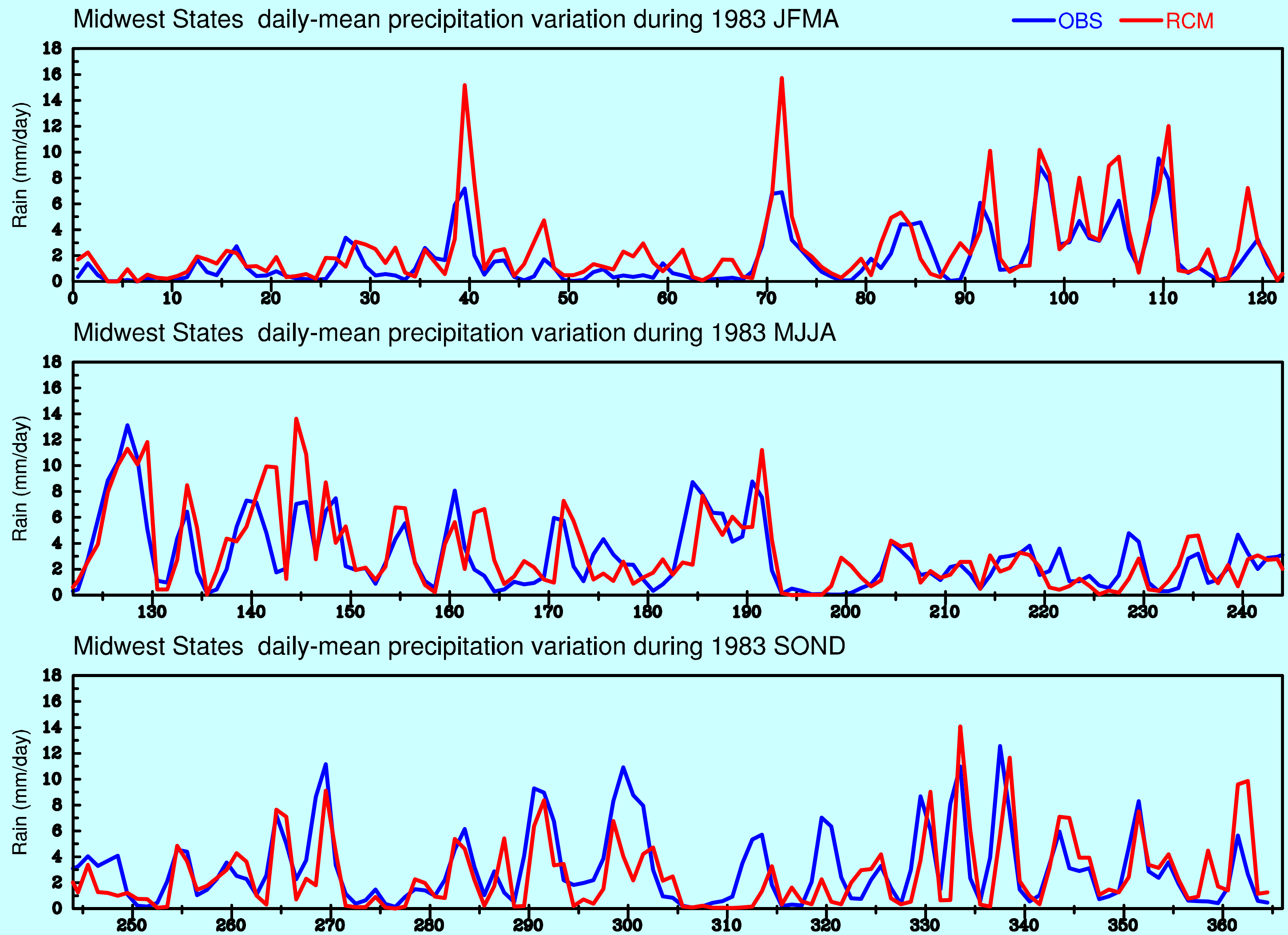
EPA NEI Inventory (1999)
MM5 generated Dynamic fields
Surrogate ratios generated for
the domain using ArcInfo
SMOKE
BEIS3.0
MOBILE 6.2
Hourly gridded emission data


HOURLY GRIDDED EMISSIONS
HOURLY DYNAMIC FIELDS
1.25 HRS FOR
1 DAY CALCULATION
USING 16 NODES ON
A LINUX CLUSTER
(JAZZ AT ANL) FOR
A 90X80X28 GRID
CMAQ-4.3
INITIAL AND BOUNDARY
CONDITIONS
HOURLY GAS AND
AEROSOLS
MIXING RATIOS
FOR ALL
GRID LOCATIONS

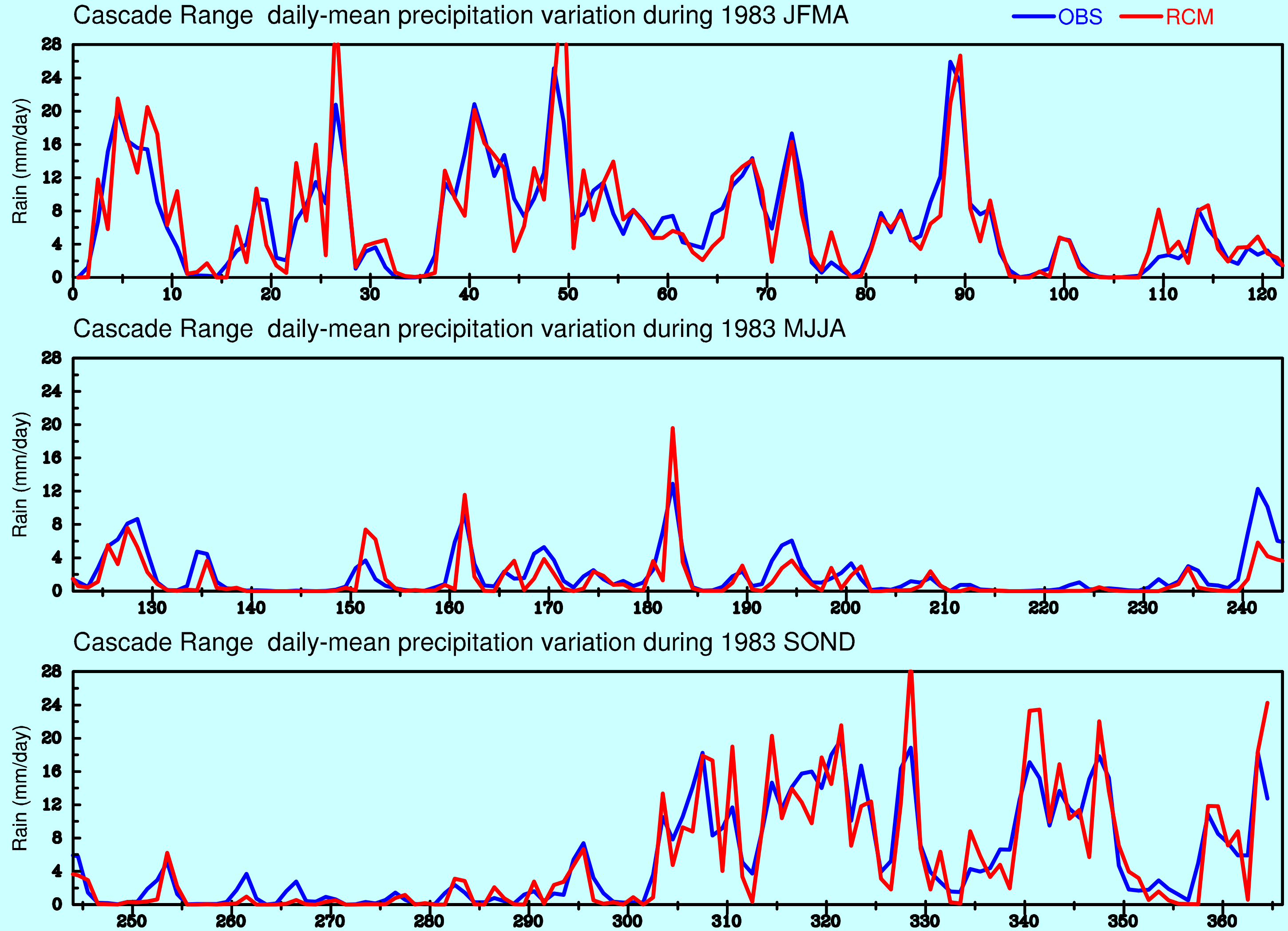


CMM5
Rain (mm/day)
OBS
CMM5
Rain (mm/day)

CMM5 Skill: Daily Fluctuations



CMM5 Skill: Daily Fluctuations



Local Air Quality: Connecting the Dots

NASA's 2003
Aircraft Particle Emissions Workshop

North Olmsted , Ohio

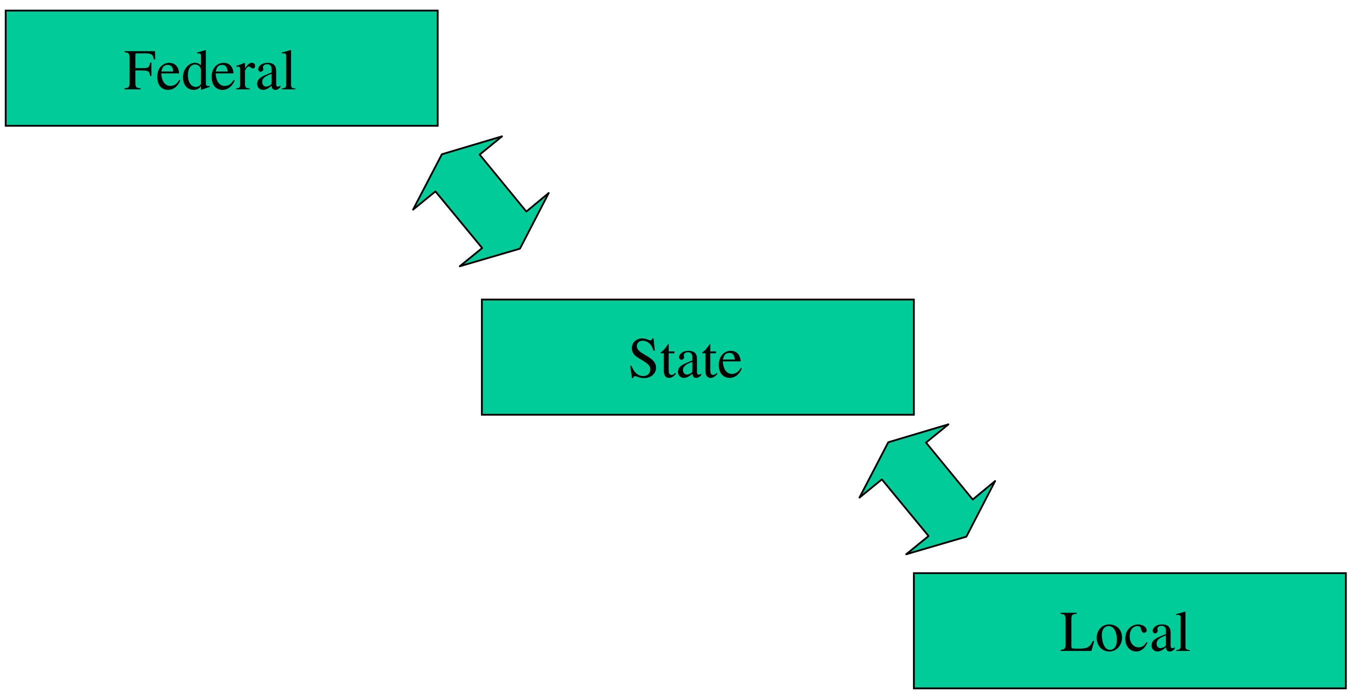
November 18 & 19, 2003

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*

Air Pollutant	California Standard	Federal Primary Standard
	Concentration Averaging Time	Concentration Averaging Time
Ozone	0.09 ppm, 1-hr. avg. >	0.12 ppm, 1-hr avg.>
		0.08 ppm, 8-hr avg.>
Carbon Monoxide	9.0 ppm, 8-hr avg. >	9 ppm, 8-hr avg.>
	20 ppm, 1-hr avg. >	35 ppm, 1-hr avg.>
Nitrogen Dioxide	0.25 ppm, 1-hr. avg. >	0.053 ppm, ann. avg.>
Sulfur Dioxide	0.04 ppm, 24-hr avg.>	0.03 ppm, ann. avg.>
	0.25 ppm, 1-hr. avg. >	0.14 ppm, 24-hr avg.>
Suspended Particulate Matter (PM_{10})**	30 µg/m^3, ann. geometric mean >	50 µg/m^3, ann. arithmetic mean >
	50 µg/m^3, 24-hr average>	150µg/m^3, 24-hr avg.>
Suspended Particulate Matter ($PM_{2.5}$)**		15 µg/m^3, ann. arithmetic mean >
		65 µg/m^3, 24-hr avg.>
Sulfates	25 µg/m^3, 24-hr avg. $\geq$	
Lead	1.5 µg/m^3, 30-day avg. $\geq$	1.5 µg/m^3, calendar quarter>
Visibility-Reducing Particles	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)	

•*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?

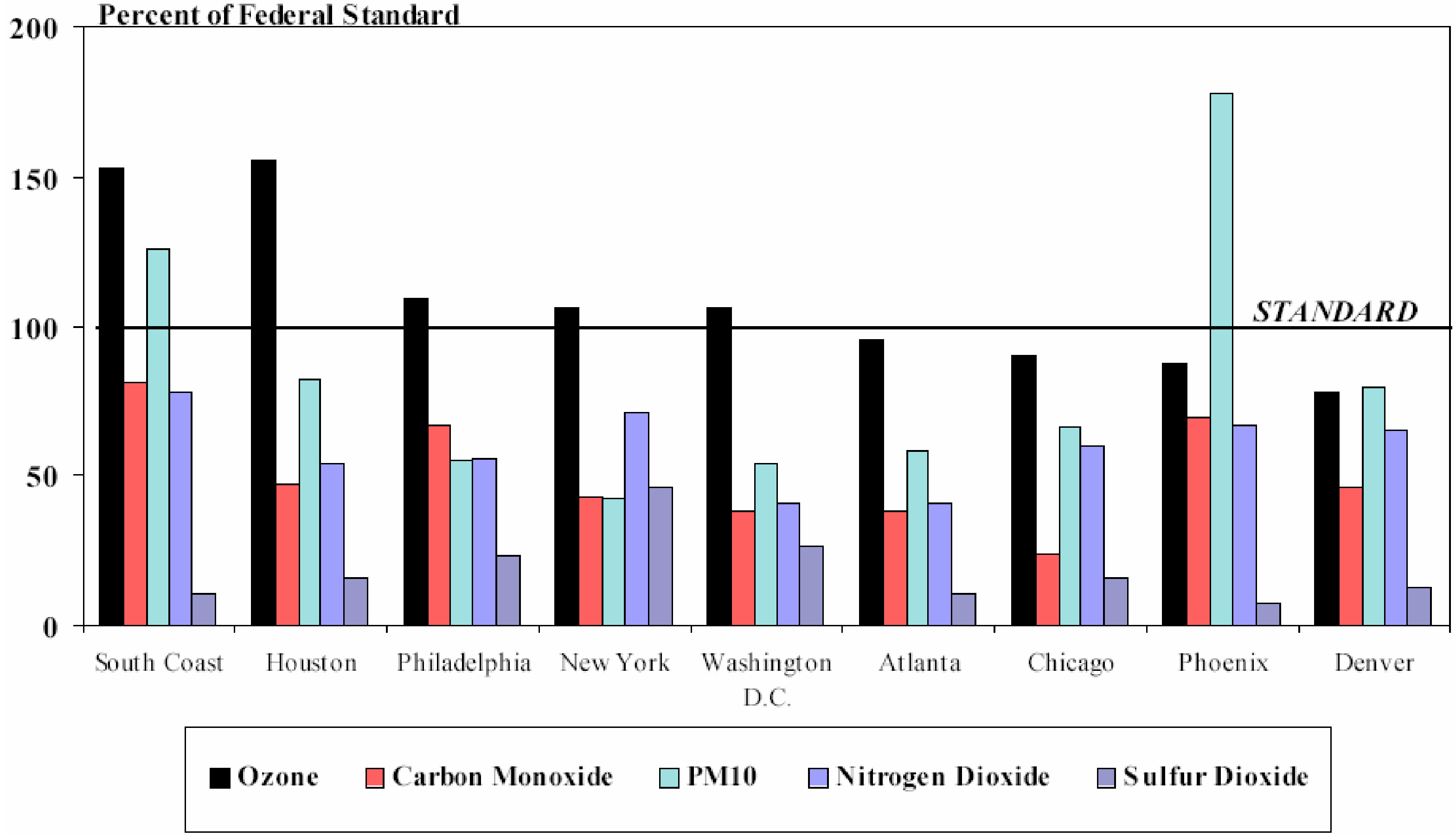
- A Federal agency is required to determine if their action “conforms” to the applicable SIP, by ensuring that the action does not:
  - Cause or contribute to new violations of any NAAQS,
  - Increase the frequency or severity of existing violations of any NAAQS,
  - Delay the timely attainment of any 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.
- Reference: Air Quality Procedures For Civilian Airports & Air Force Bases, FAA-AEE-97-03, AL/EQ-TR-1996-0017 (April 1997)

South Coast Air Quality Management District 2003 Air Quality Management Plan

- SCAQMD has jurisdiction over an area of approximately 10,743 square miles where 15 million people live.
- Governing Board adopted the 2003 Air Quality Management Plan (AQMP) on August 1, 2003.
- 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.

University of California at Riverside

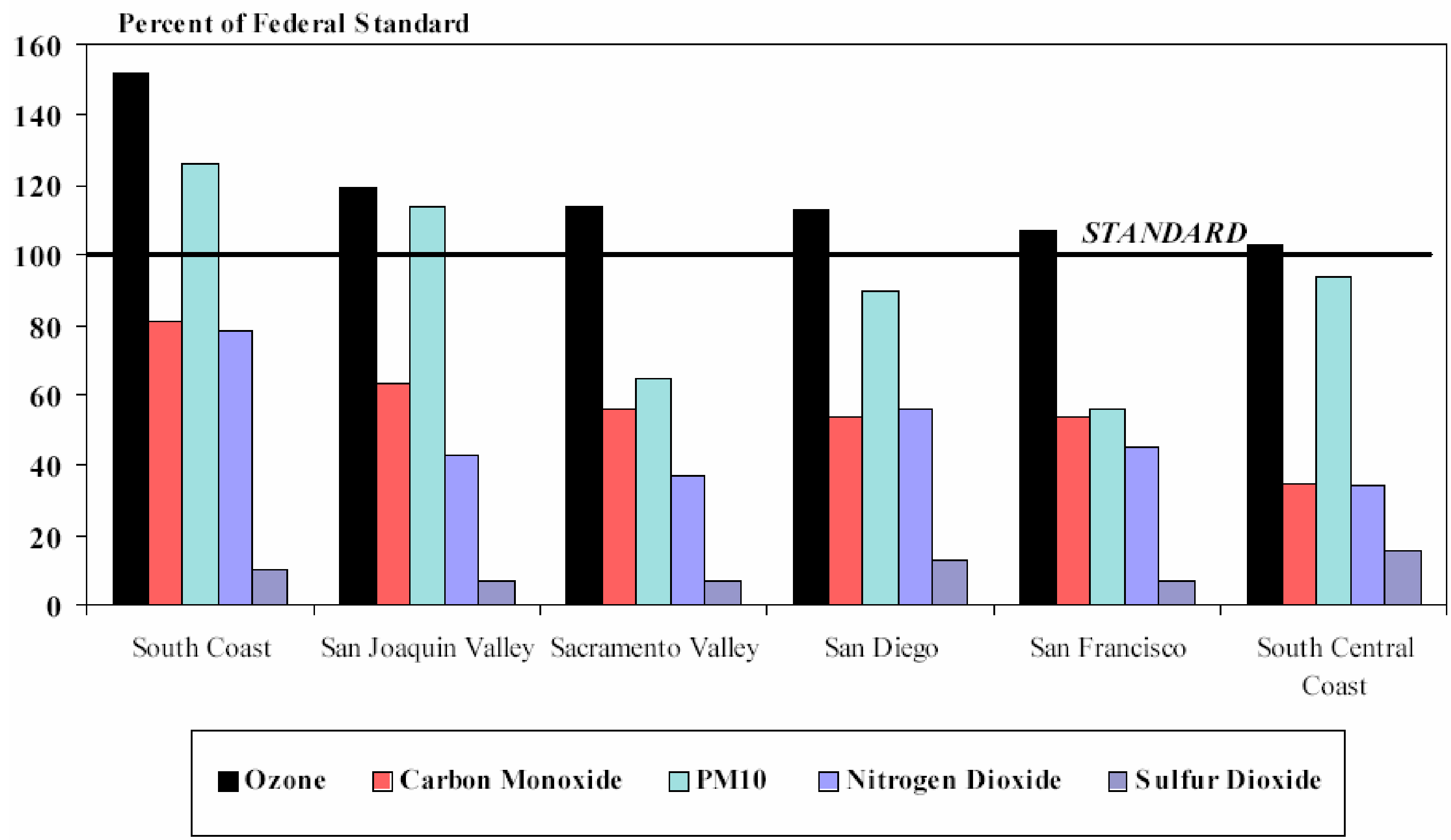
South Coast Air Basin Compared to Major U.S. Metropolitan Areas



Center for Environmental Research and Technology

University of California at Riverside

South Coast Air Basin Compared to Other Air Basins in California



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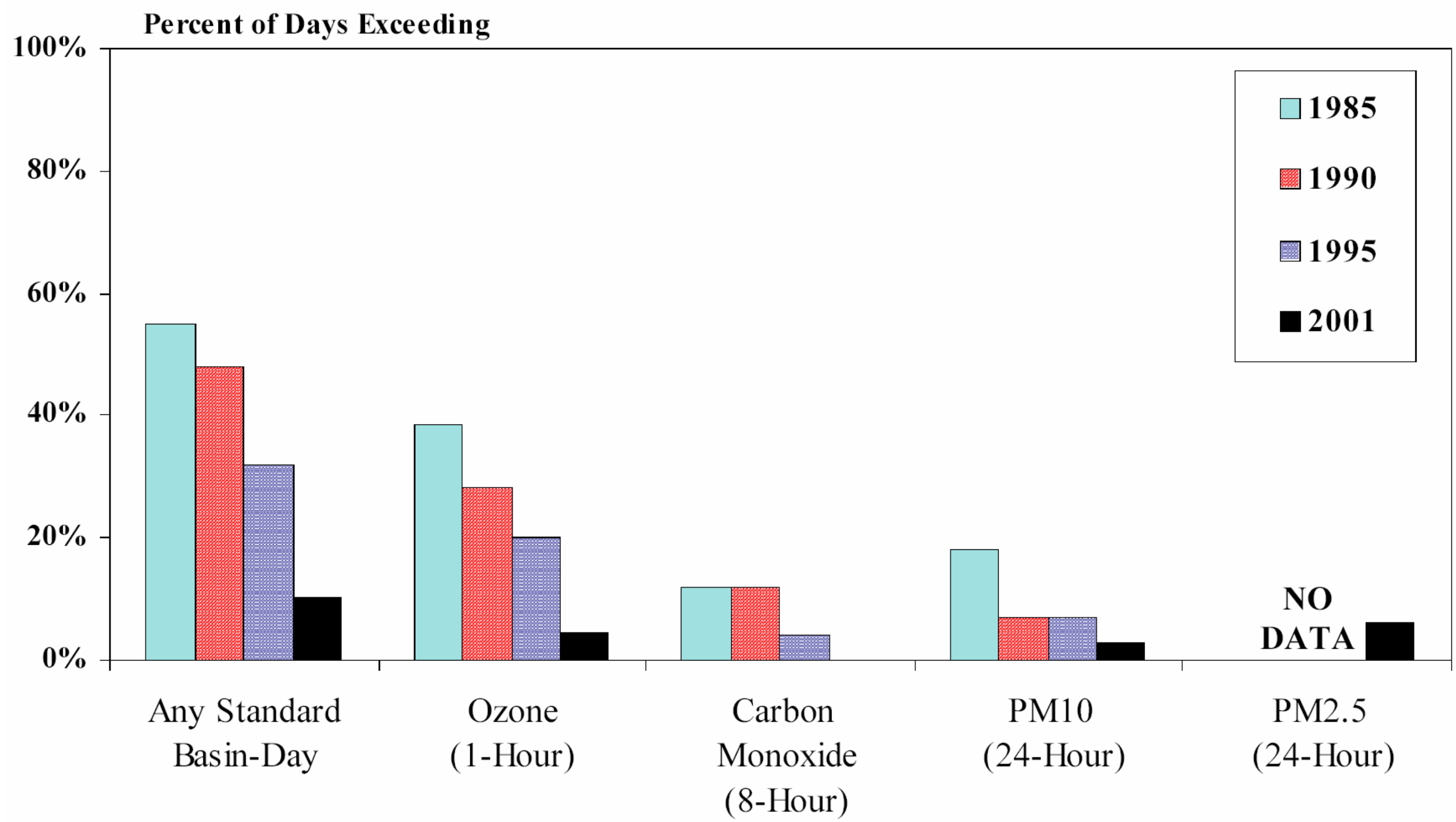
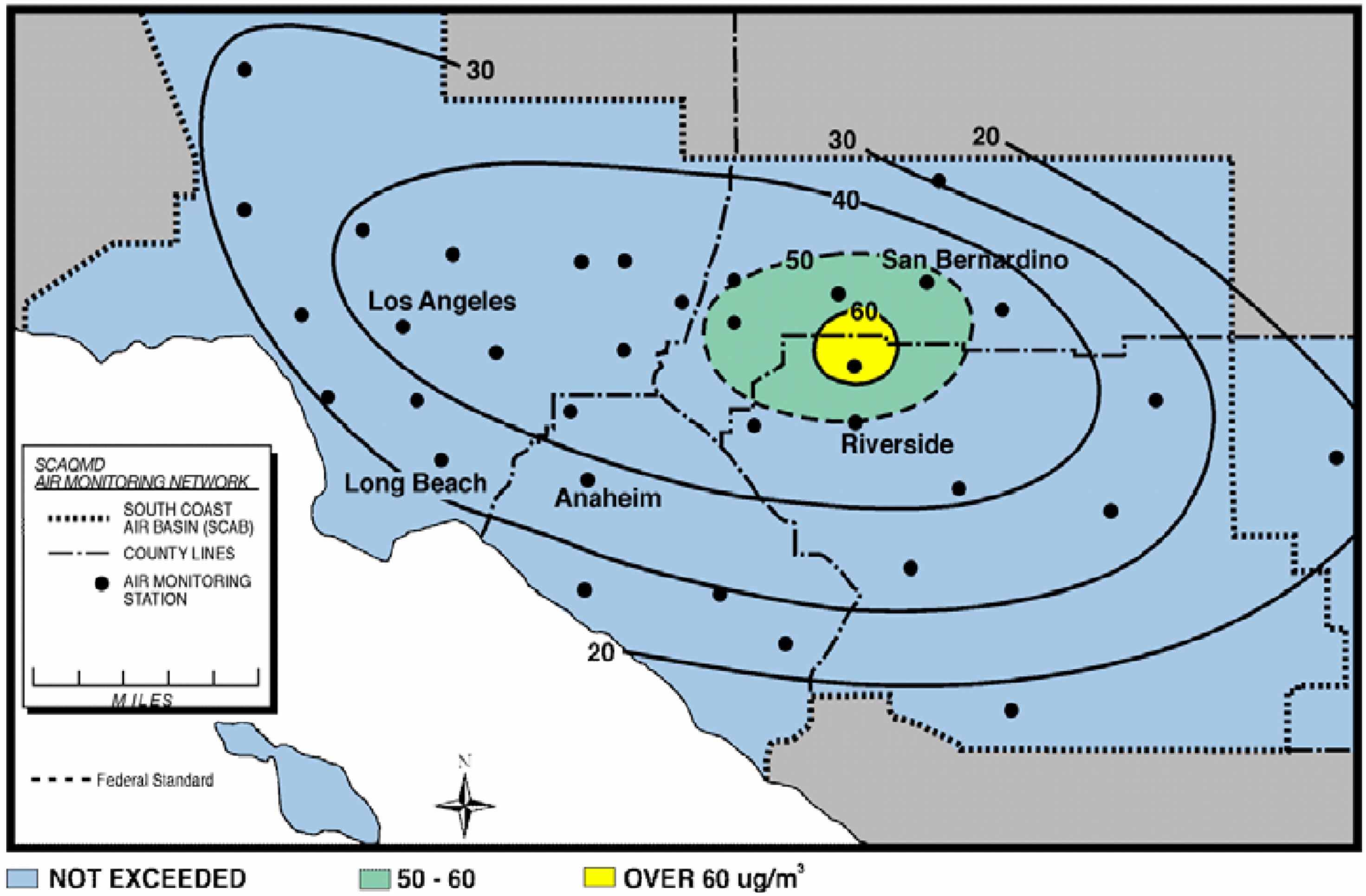
Percent of Days Exceeding Federal Standards at Most Affected Locations



Annual Average PM_{10} Concentration for 2001



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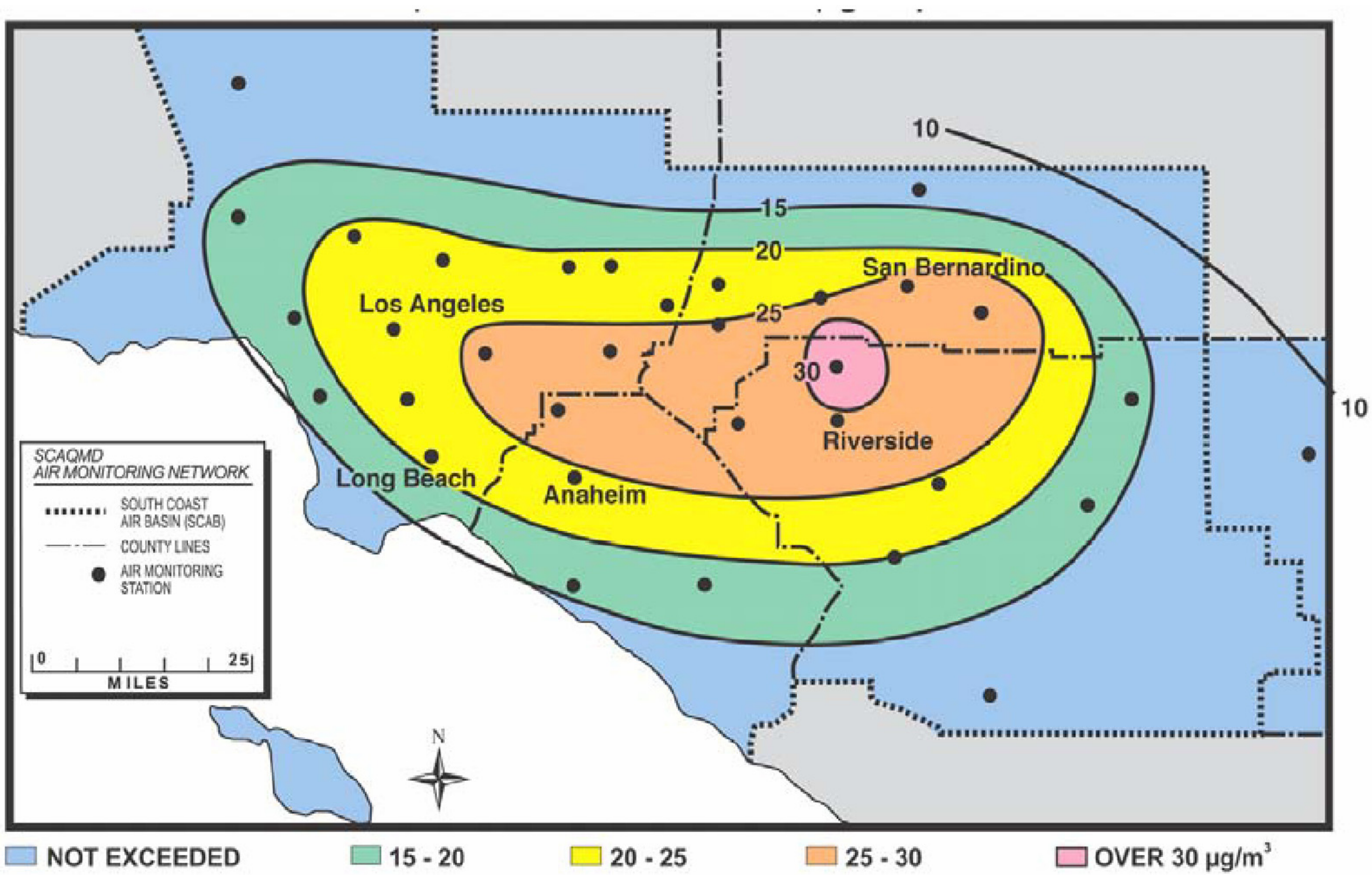
Annual Average $PM_{2.5}$ Concentration for 2001



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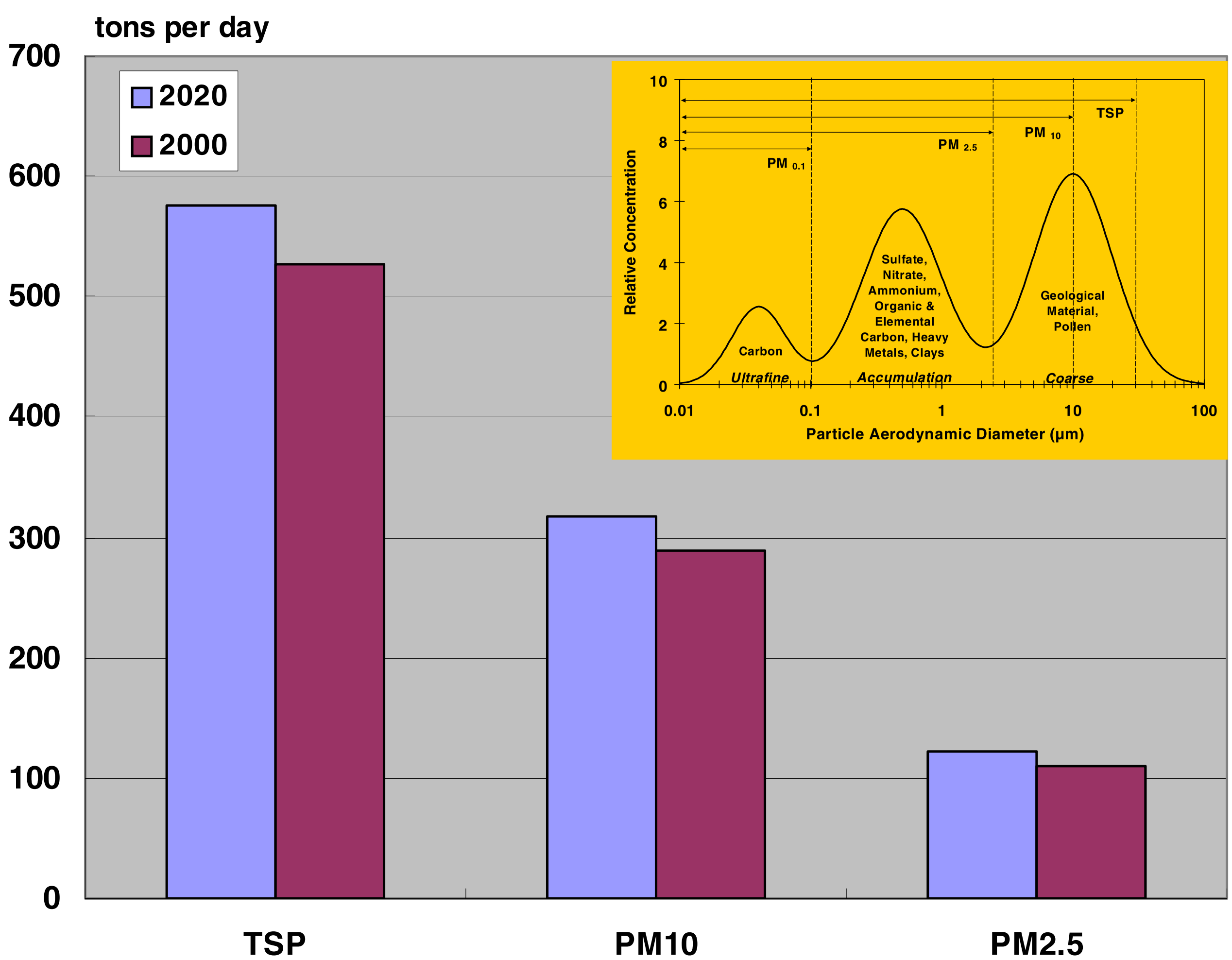
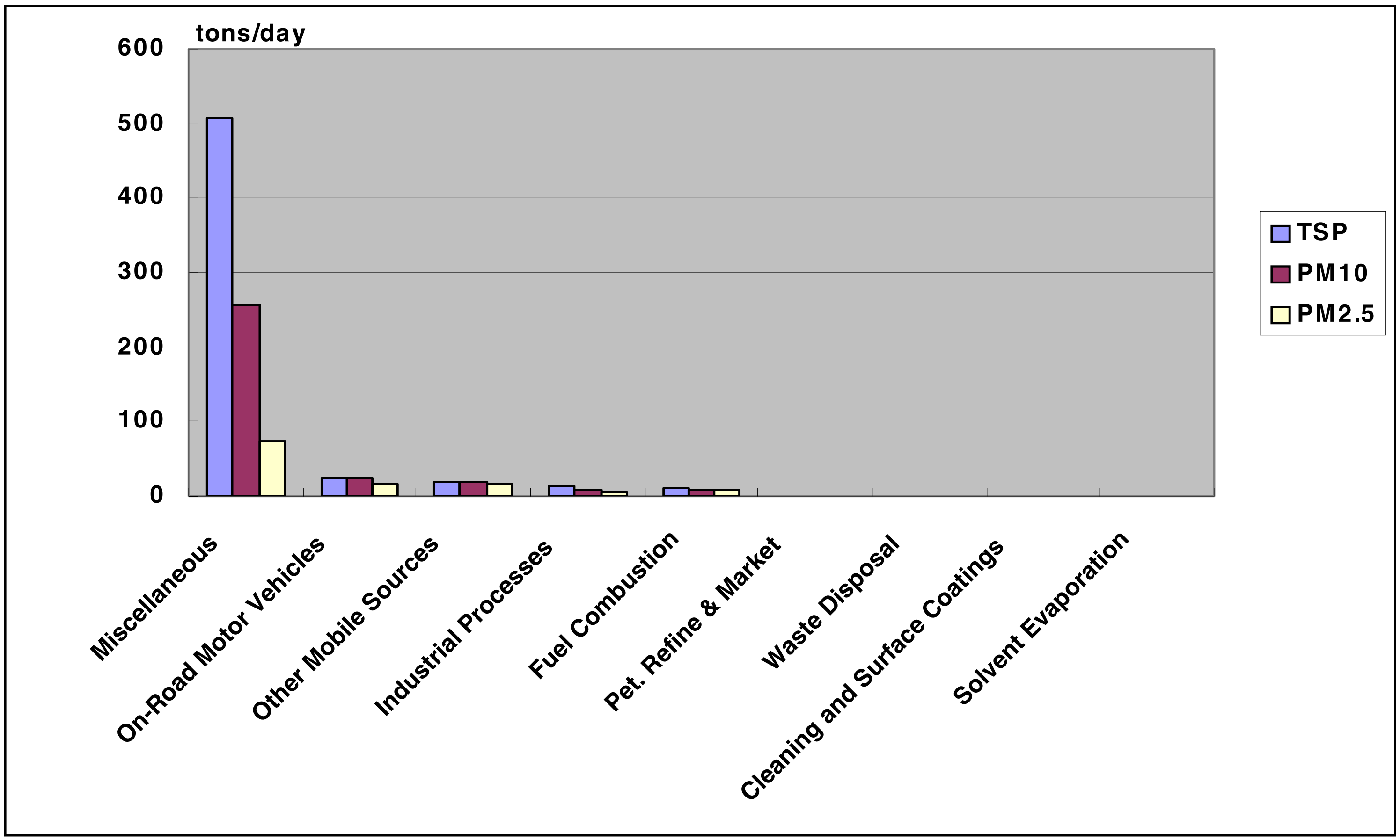
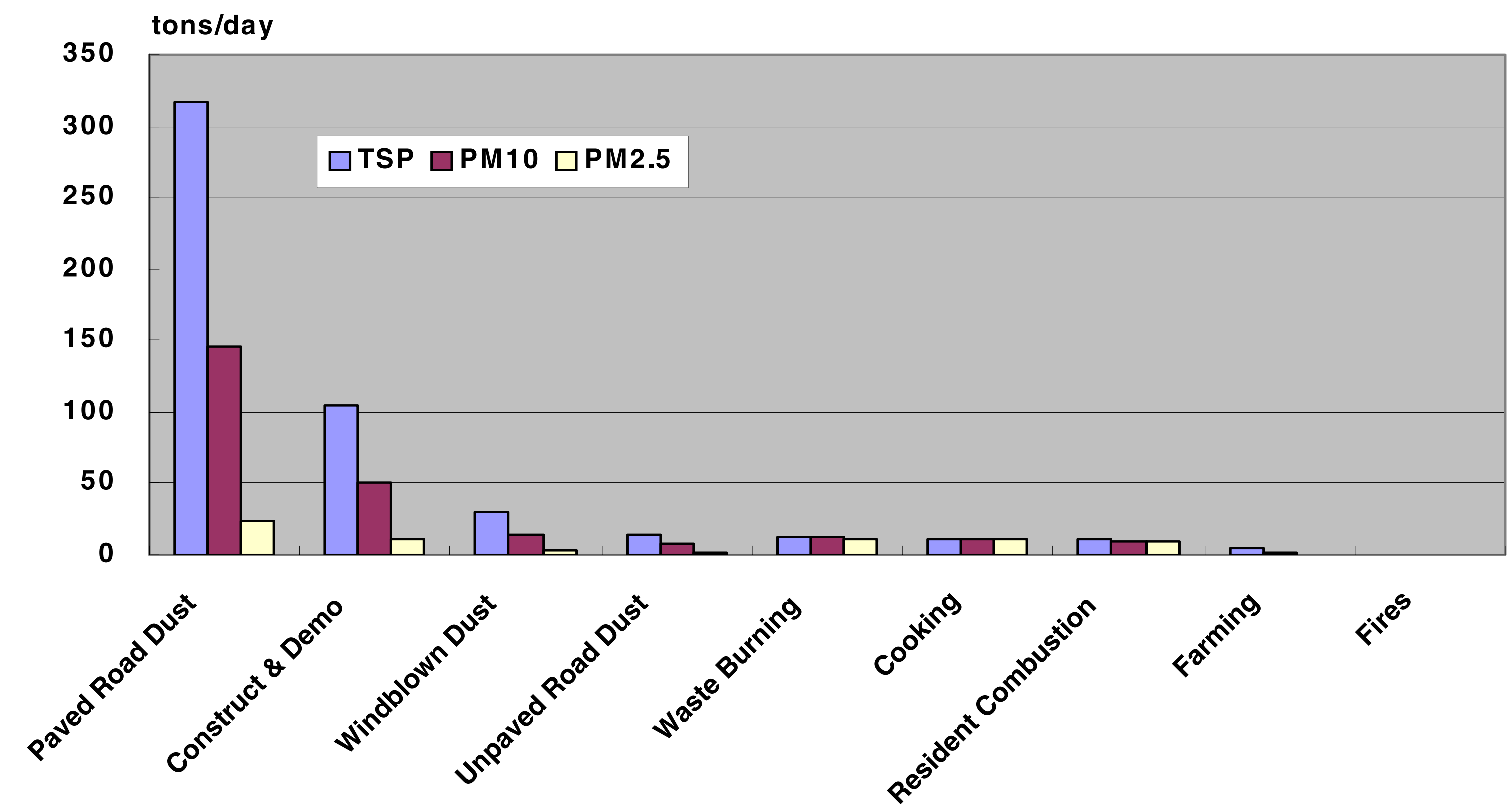
Annual Average PM Emissions



Annual Average PM Emissions by Source Category in 2020



Annual Average PM Emissions for Miscellaneous Category in 2020



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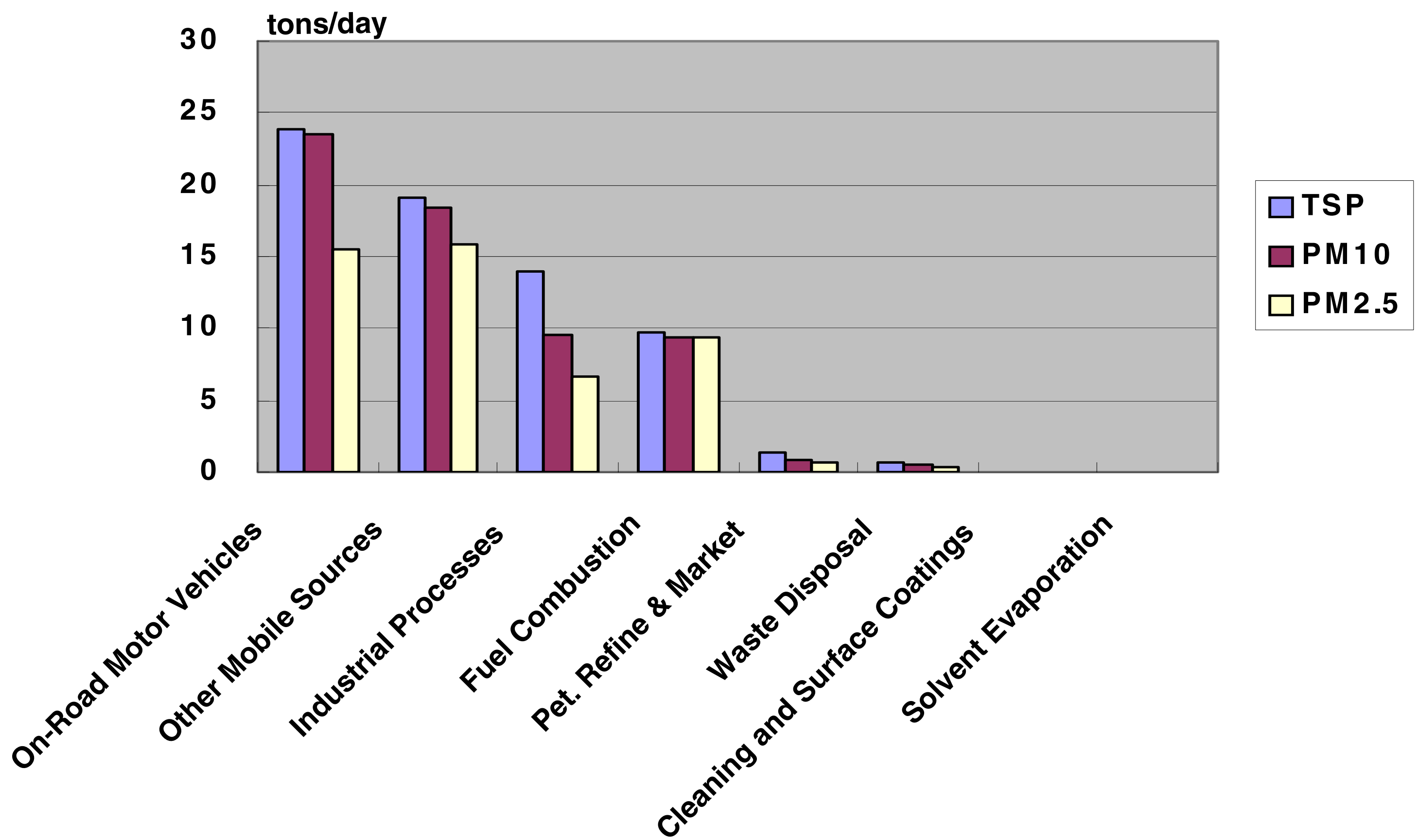
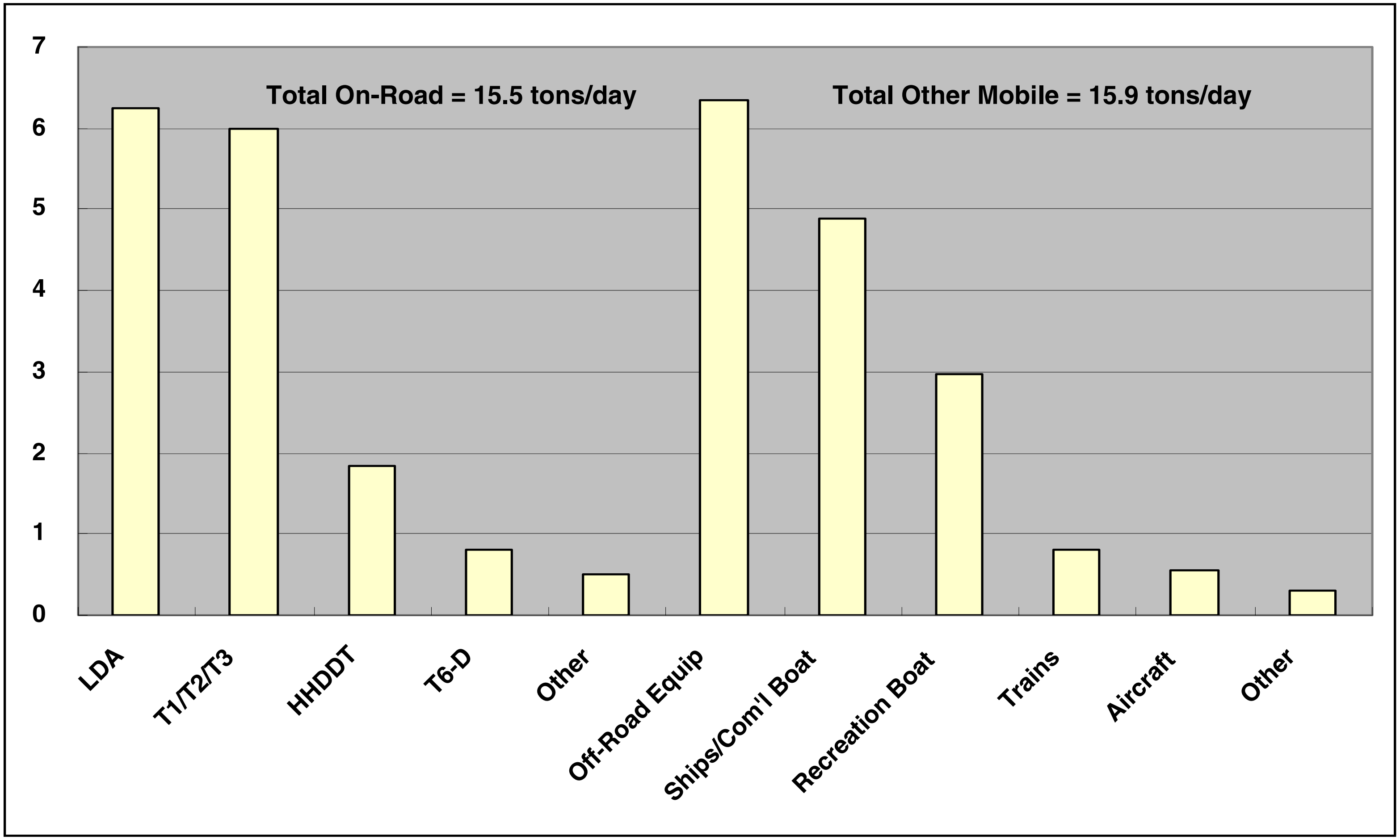
Annual Average PM Emissions in 2020 Without Miscellaneous Source Category



Center for Environmental Research and Technology

Annual Average $PM_{2.5}$ Emissions in 2020 Without Miscellaneous Source Category



- What issues are fuzzy or unknown?
- Looking beyond current requirements

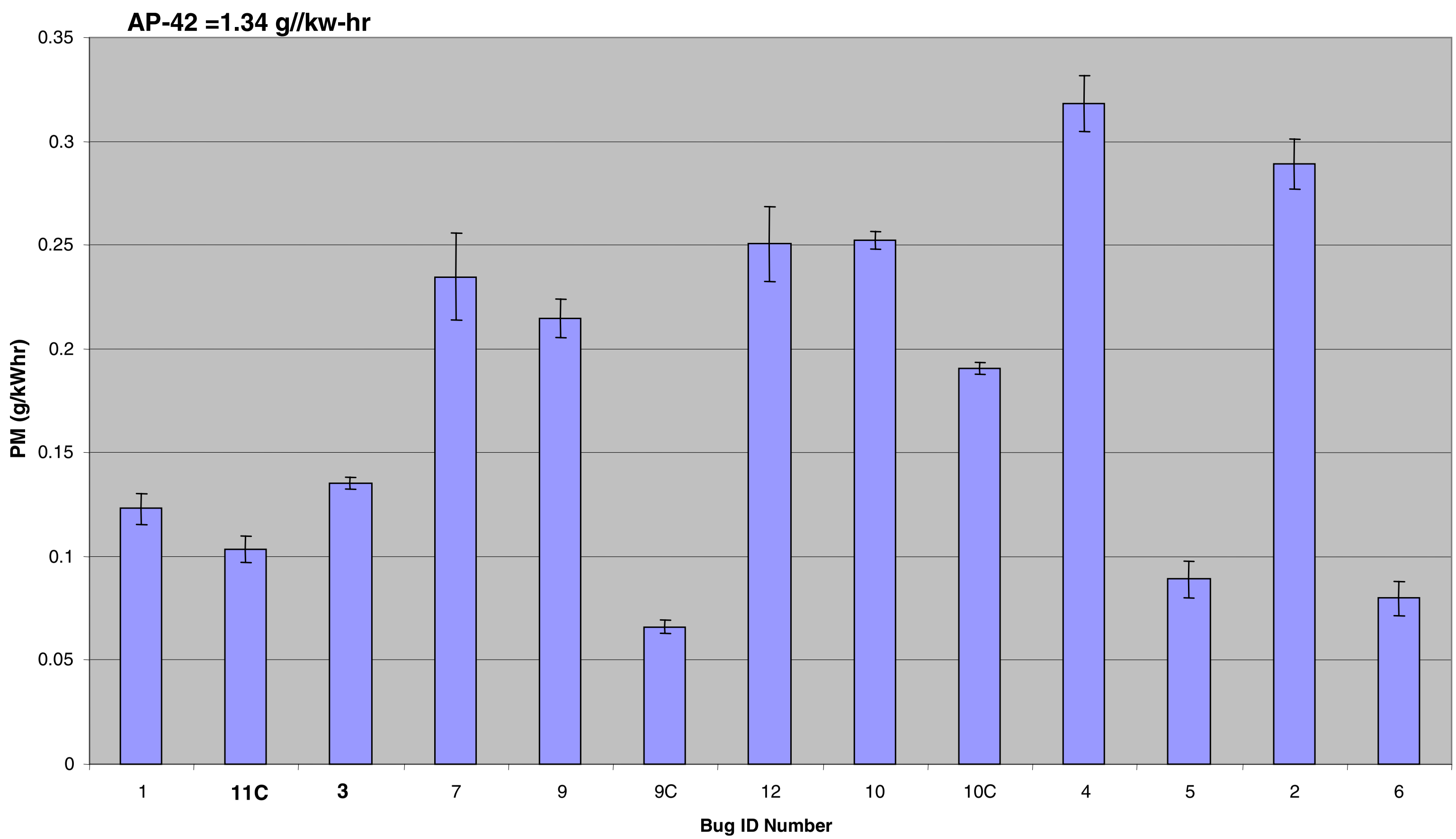
SCAQMD: "Uncertainties Associated with the 2003 Air Quality Management Plan"

- Demographic and Growth Projections
- Input Elements to Air Quality Models
  - Ambient Air Quality Monitoring Data
  - Meteorological Measurements
  - Emissions Inventory
- Air Quality Models

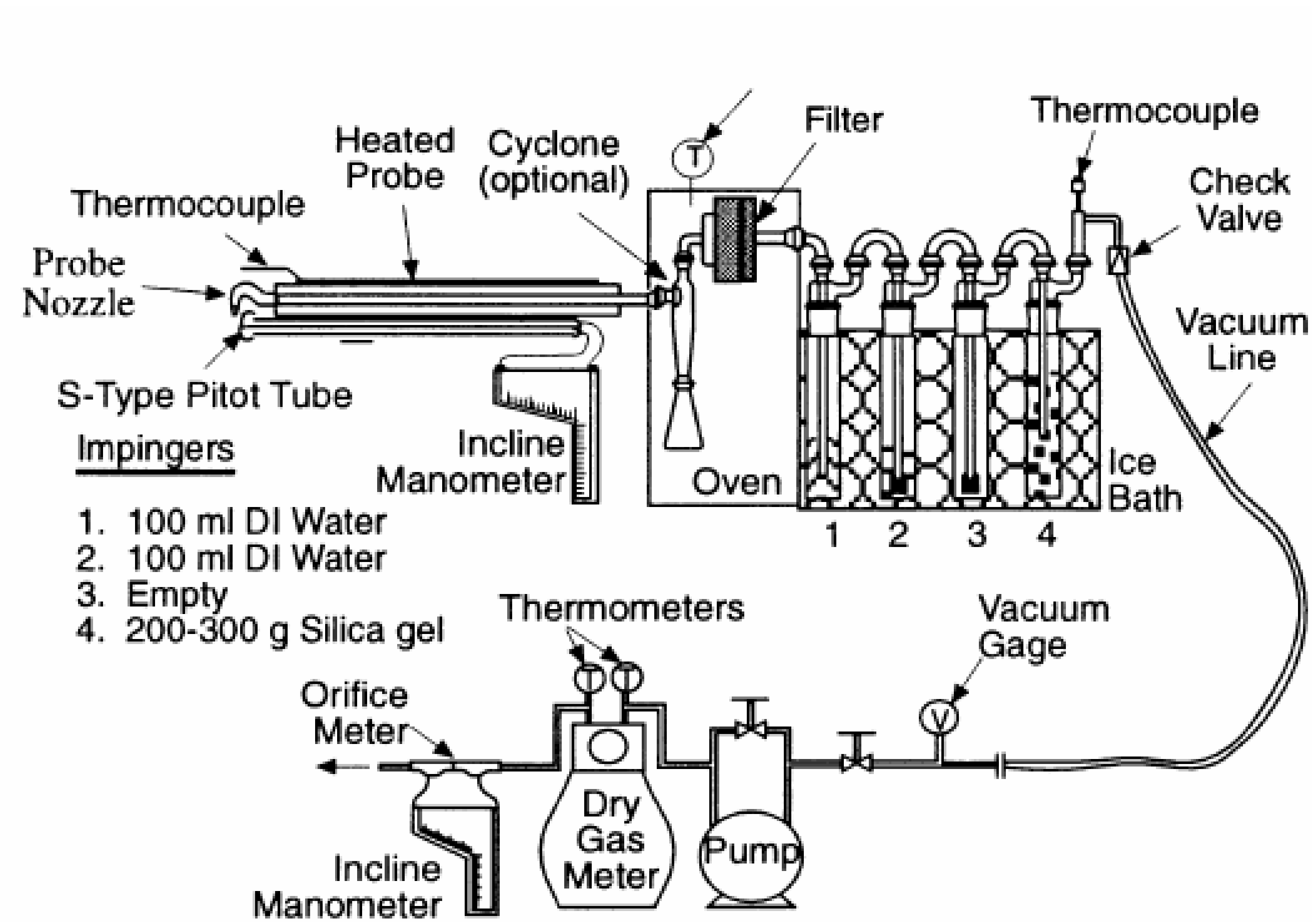
EPA's AP-42 Emission Factors - Small Diesel Engines

	SMALL DIESEL (< 600 hp)			
Pollutant	Emission Factor (lb/hp-hr) (power output)	Emission Factor (g/kW-hr) (power output)	Emission Factor (lb/MMBtu) (fuel input)	Emission Factor Rating
NOx	0.031	18.85	4.41	D
CO	6.68E-03	4.06	0.95	D
SOx	2.05E-03	1.25	0.29	D
PM_{10}	2.20E-03	1.34	0.31	D
CO_2	1.15	699.20	164	B
Aldehydes	4.63E-04	0.28	0.07	D
TOC		0.00		
Exhaust	2.47E-03	1.50	0.35	D
Evaporative	0.00	0.00	0.00	E
Crankcase	4.41E-05	0.03	0.01	E
Refueling	0.00	0.00	0.00	E

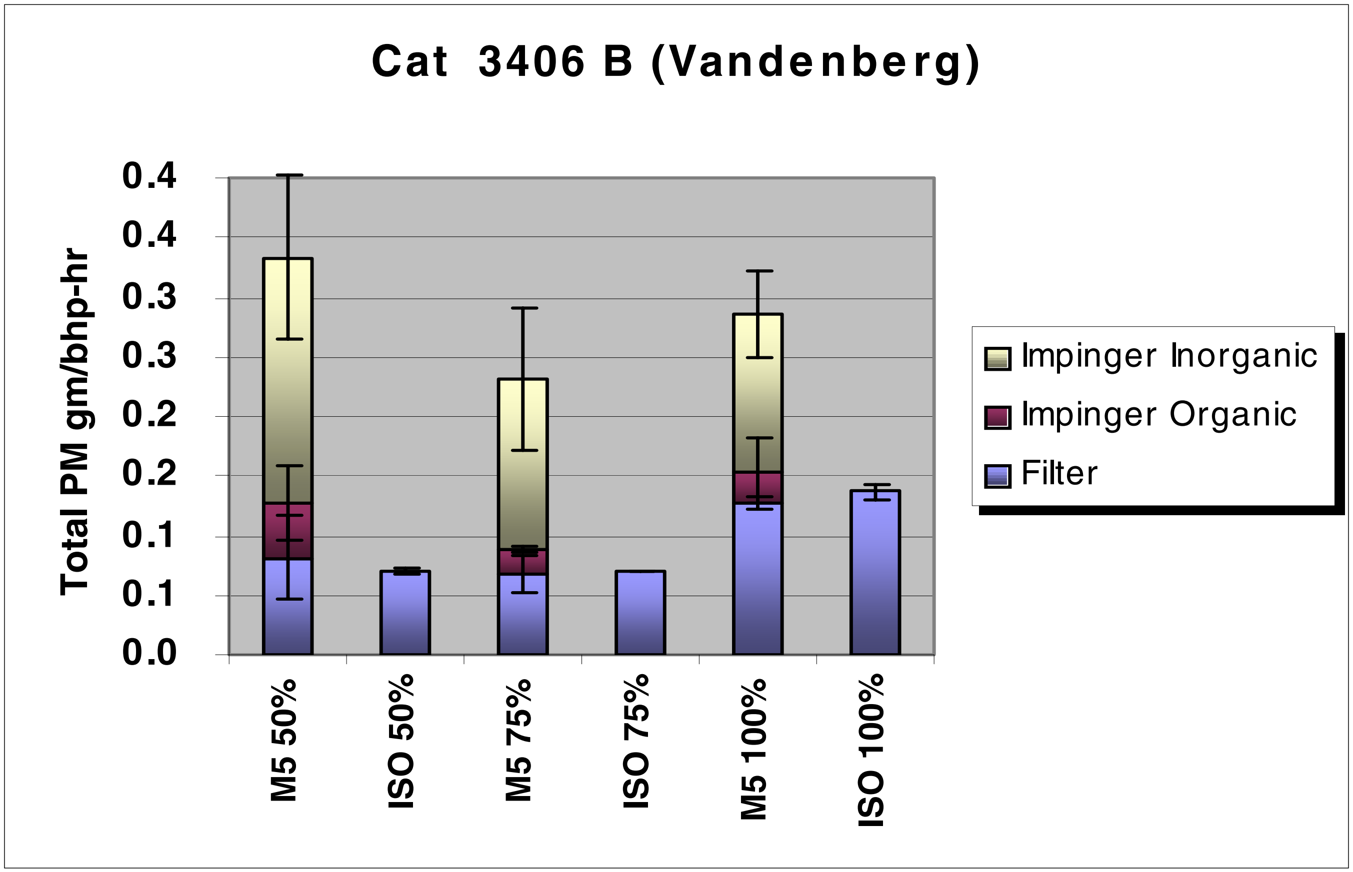
Issue: Measured $PM_{2.5}$ Emission Factors are much less than AP-42 (gen sets)



Issue: How to Measure $PM_{2.5}$



Issue: Mass of $PM_{2.5}$ Differs with Test Method



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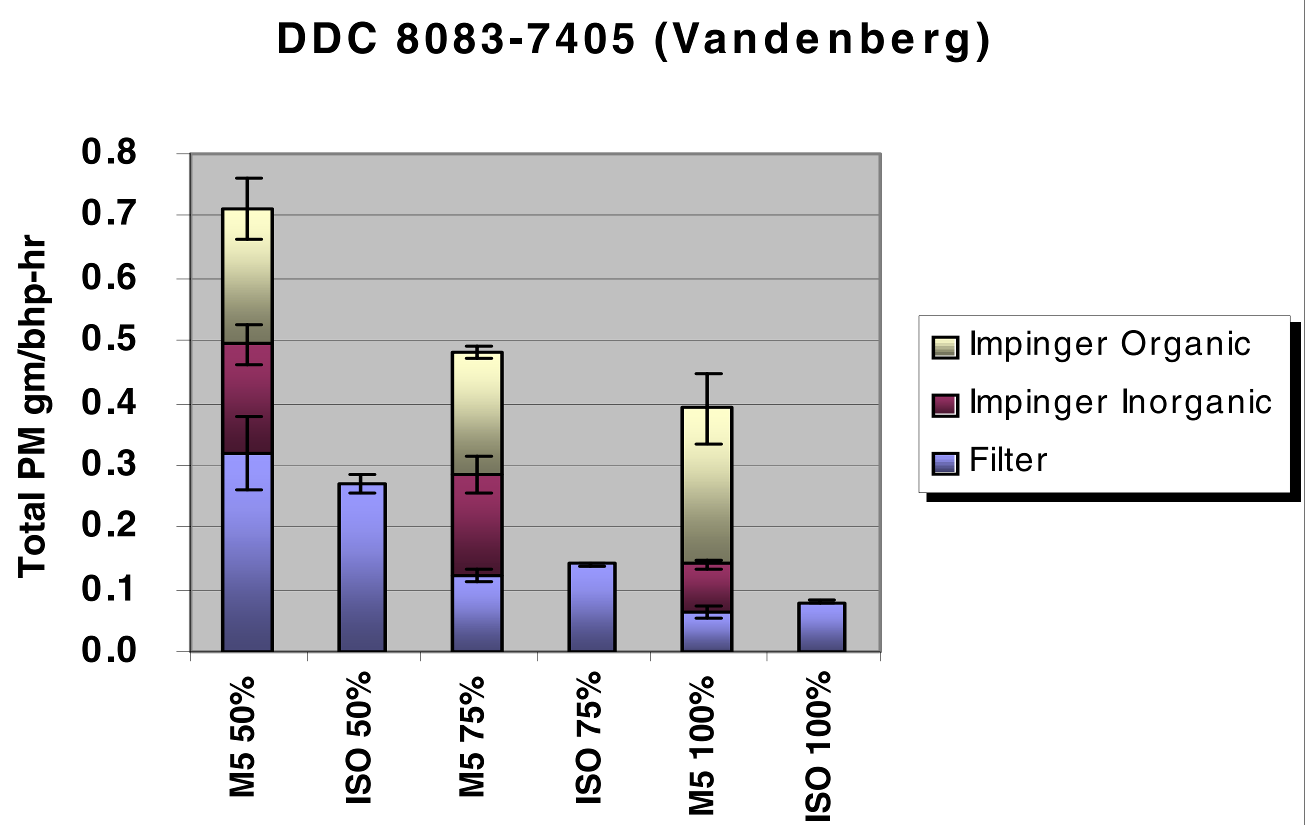


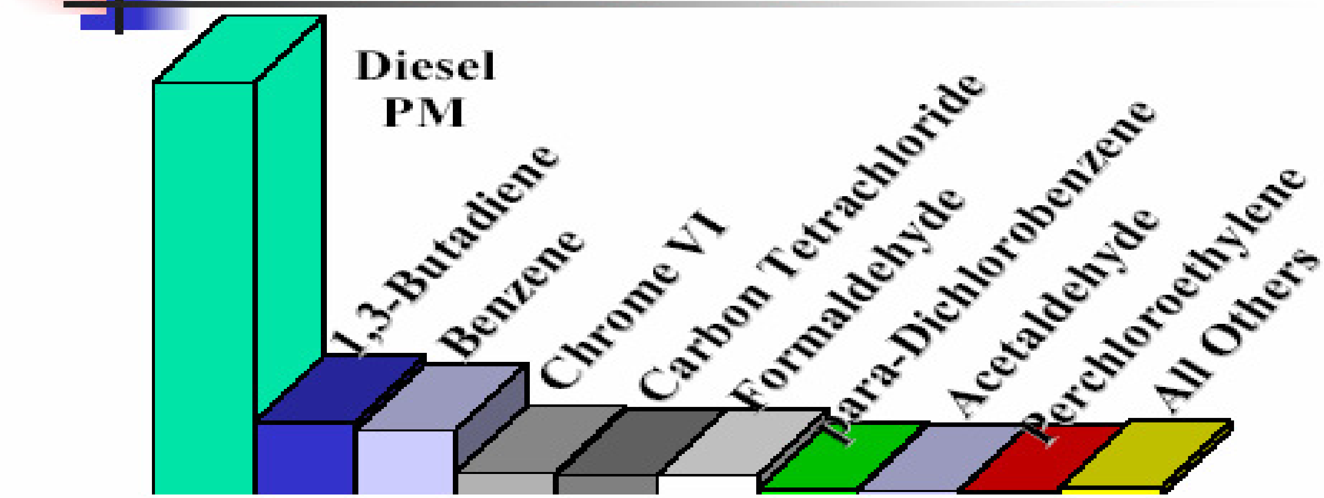
Issues: How do you measure low PM emissions and what do filters really measure?*

- 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 ≅ 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 < 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



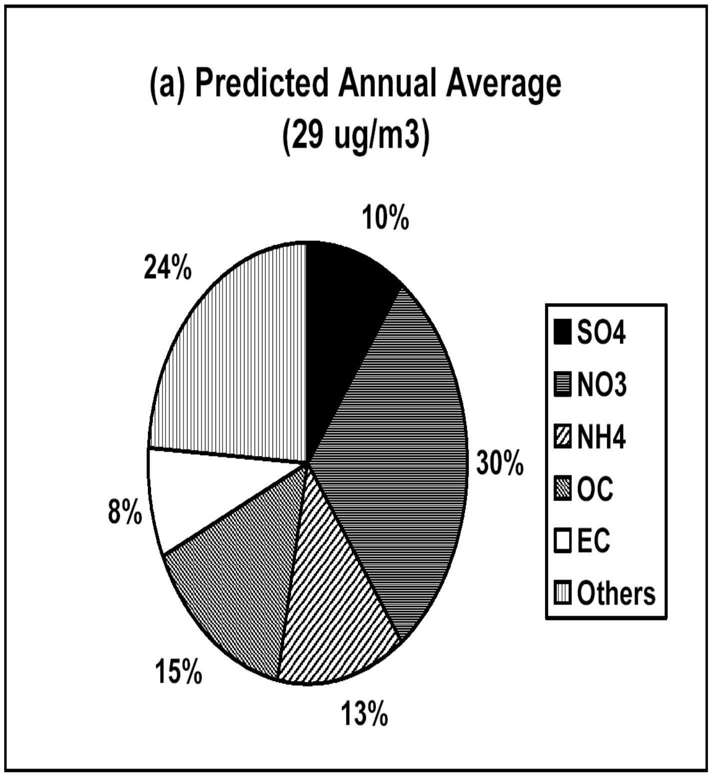
Based on ARB monitoring data 1995 - 1997

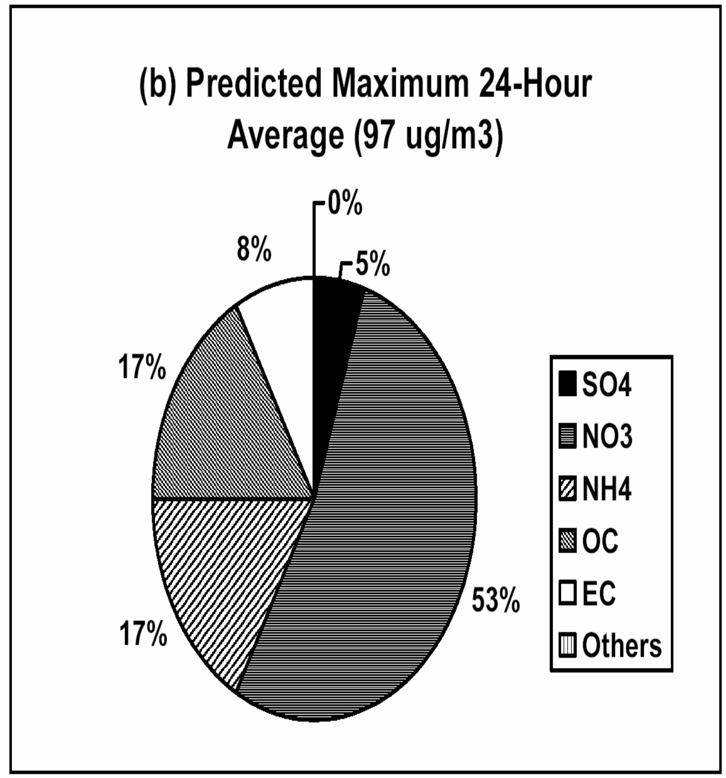
Issue: Data from U.S. EPA National Toxics Inventory (Ranked in Order)

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

Reference: FAA's Document Select Resources Materials and Annotated Bibliography on the Topic of Hazardous Air Pollutants (HAPs) Associated with Aircraft, Airports and Aviation, July 1, 2003

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





New controls likely for NO_3, NH_4, OC and EC

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?

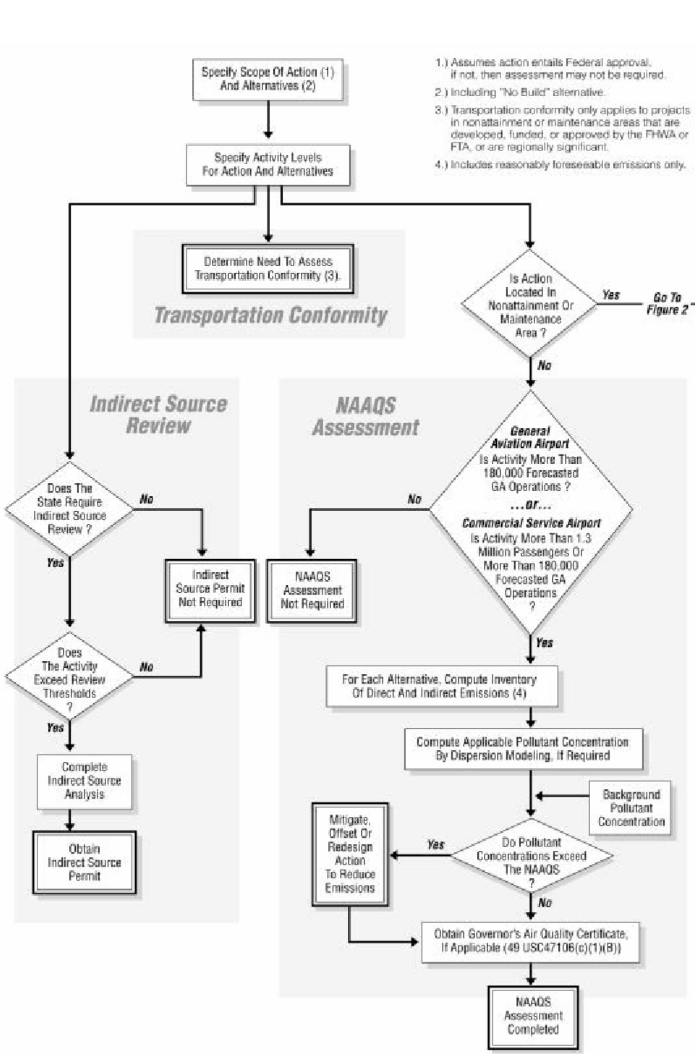


Figure 1. Air Quality Assessment Process for Airports and Air Bases - Part 1

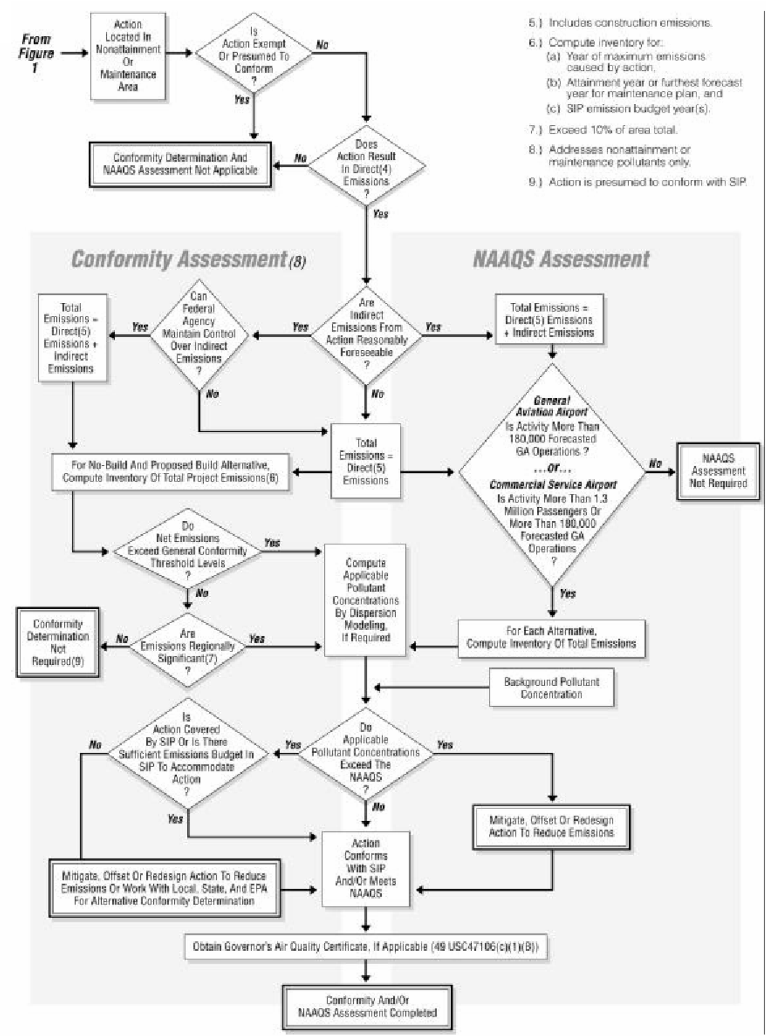


Figure 2. Air Quality Assessment Process for Airports and Air Bases - Part 2

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 CO_2 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 know 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.

Measurement Methodology Report (continued)
(APEW Meeting Cleveland 18-19 Nov 03)

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

-- size and chemical evolution in the plume behind the engine.

Sampling issues more complex at exit plane than in plume.

Methodologies 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, engine to engine… fleet variability's.
Leads to uncertainty ranges needed for modeling (dispersion, LAQ…)

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.

Session 3:
Particle Modeling—Current Understanding and Issues

R.C. Miake-Lye
M. Colket

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

<u>Needs for airport inventories</u>:

- 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.

<u>Additional needs for global inventories</u>:

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

<u>Other</u>:

- 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

Last Name	First Name	Affililation	Email Address
Anderson	Bruce	NASA LaRC	Bruce.E.Anderson@nasa.gov
Baughcum	Steven	Boeing Company	Steven.L.Baughcum@boeing.com
Bhargava	Anuj	Pratt & Whitney	anuj.bhargava@pw.utc.com
Blevins	Linda	Sandia Labs	lgblevi@sandia.gov
Christie	David	Honeywell	David.Christie@Honeywell.com
Colket	Med	United Tech. Research Center	colketmb@utrc.utc.com
Corporan	Edwin	WPAFB	edwin.corporan@wpafb.af.mil
Culler	Stephen	NASA GRC	stephen.h.culler@nasa.gov
Dodds	Will	GE Aircraft Engines	willard.dodds@ae.ge.com
Draper	Julie	FAA	julie.draper@faa.gov
Fleming	Gregg	U.S. DOT/Volpe Center	fleming@volpe.dot.gov
Hagen	Donald	University of Missouri-Rolla	hagen@umr.edu
Hawkins	Betty	Air Transport Association	bhawkins@airlines.org
Helgeson	Norman	U.S. Navy	norman.helgeson@navy.mil
Howard	Robert	AEDC	robert.howard@arnold.af.mil
Jayne	John	Aerodyne Research Inc.	jayne@aerodyne.com
Kinsey	John	Nat. Risk	kinsey.john@epa.gov
Kretchmer	Penny	ASC/ENVV (Anteon)	penny.kretchmer@wpafb.af.mil
Kundu	Krishna	NASA GRC	Krishna.Kundu@nasa.gov
Lee	Chi-Ming	NASA GRC	chi-ming.lee-1@nasa.gov
Lilenfeld	Harvey	Harvey Lilenfeld Associates	hlil@umr.edu
Liu	Nan-Suey	NASA GRC	nan-suey.liu-1@nasa.gov
Manning	Bryan	EPA	manning.bryan@epa.gov
Massey	Sara	Airports Council International-N.A.	smassey@aci-na.org
Meyers	Clayton	NASA Glenn (Did not attend)	clayton.l.meyers@nasa.gov
Miake-Lye	Rick	Aerodyne Research Inc.	rick@aerodyne.com
Miller	Wayne	University of California	wayne.miller@ucr.edu
Moses	Clifford	Southwest Research Institute	cmoses@swri.edu
Penko	Paul	NASA Glenn Research Center	paul.penko@grc.nasa.gov
Redhead	Ian	Airports Council International-N.A.	iredhead@aci-na.org
Rivera	Monica	NASA GRC	Monica.D.Rivera@grc.nasa.gov
Rohde	John	NASA GRC	John.Rohde@grc.nasa.gov
Russell	Ted	Georgia Tech	trussell@ce.gatech.edu
Sanders	Terry	NASA GRC	Terry.Sanders@nasa.gov
Scruggs	Shannon	Delta Air Lines	shannon.scruggs@delta.com
Sepulveda	Domingo	Pratt & Whitney	domingo.sepulveda@pw.utc.com
Strange	Richard	Pratt & Whitney	richard.strange@pw.utc.com
Voorhees	William	US Navy - NAVAIR	william.voorhees@navy.mil
Wayson	Roger	UCF/U.S. DOT/Volpe Center	wayson@pegasus.cc.ucf.edu
Wey	Thomas	Taitech, Inc.	thomas.wey@grc.nasa.gov
Wey	Changlie	QSS	changlie.wey@grc.nasa.gov
Whitefield	Philip	UMR	pwhite@umr.edu
Worsmop	Doug	Aerodyne Research Inc.	worsnop@aerodyne.com
Wuebbles	Don	University of Illinois	wuebbles@atmos.uiuc.edu
Zaccardi	Vincent	AEDC	vince.zaccardi@arnold.af.mil

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13. ABSTRACT ***(Maximum 200 words)***
The Aviation Particle Emissions Workshop was held on November 18–19, 2003, in Cleveland, Ohio. It was sponsored by the National Aeronautic 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.

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