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Partners: UMR, MIT, Aerodyne Inc., AEDC, NASA, FAA, and HVL Assoc.

Center of Excellence for Aerospace Particulate Emissions Reduction Research

Summary of APEX Studies and Potential Control Strategies

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Director Missouri S&T COE

Aircraft Emission Control Technology Forum
and Round Table Discussion
AQMD HQ Diamond Bar CA., 13 February 2008

Why Quantify PM Emissions from Commercial Aircraft Operations?

- Continuing growth of commercial air traffic presents a number of environmental concerns as we prepare for the next generation air transportation system.
- Aircraft related PM is one such concern.
- Historically aircraft related PM has not been well characterized.
- Recent research programs in US and Europe have begun to shed light on this issue.

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How to Define PM Species?

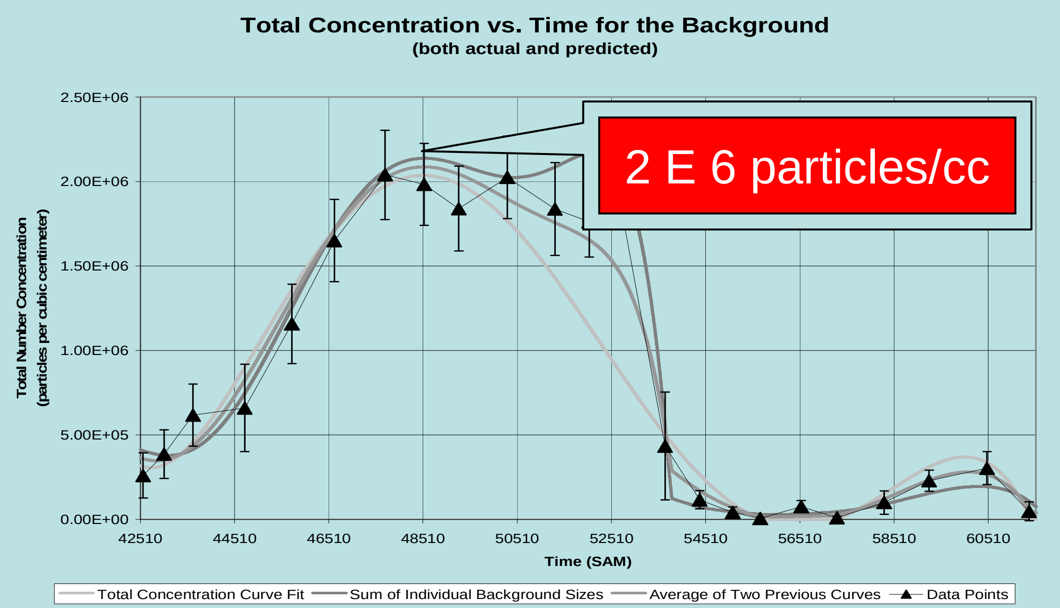
- Non-volatile PM
  - ✓ Soot or black carbon
  - ✓ Dust and crustal matter
  - ✓ Abraded particles

Aircraft Generated

- Volatile PM
  - ✓ Sulfates from fuel sulfur
  - ✓ Organics from lubrication oil
  - ✓ Organics from incomplete fuel combustion
  - ✓ Sprayed liquid particles

Aircraft Engines only one of the major Airport PM Sources

- Turbine Engines
  - ✓ Aircraft
  - ✓ APU
  - ✓ Stationary Power Turbines
- Compression Combustion Engines
  - ✓ Diesel GSE
  - ✓ Trucks
  - Ignition Combustion Engines
    - ✓ Gasoline GSE
    - ✓ Vans
    - ✓ Cars
  - Tire & Brake Wear
  - Open Burning
    - ✓ Training fires
  - Fugitive Dust
    - ✓ Construction activity



Background PM concentration ATL 28 Sept 2004

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How should Aircraft PM Emissions be Quantified?

- Current Regulations set National Ambient Air Quality Standards (NAAQS) with time averaged mass concentrations.
- Engines are certified for smoke emissions

- **National Ambient Air Quality Standards (USA EPA)**
  - **PM_{10}**
    - **150 µg/m3** — **24-hour average**
  - **$PM_{2.5}$**
    - **15 µg/m3** — **annual average**
    - **35 µg/m3** — **24-hour average**
- **ICAO Annex 16 - Aircraft Engine Emissions**
  - **Smoke number engine certification limits**

Current PM Regulations In USA

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How should Aircraft PM Emissions be Quantified?

- PM reduction design strategies in the last 20 years have been so effective that most current/advanced engines in operation today have virtually negligible smoke numbers throughout their operational envelope

- Health impacts are related to several fundamental characteristics of PM not captured by mass concentration or smoke number:

  PM Number

  PM Size

  PM Composition

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First Order Approximation

- **FOA Version 3.0**
  - CAEP developed, accepted, and supported
  - Identified scientific expressions for each driver of aircraft PM emissions…
    - non-volatile, fuel sulfur content, fuel organics

- *INTERIM METHODOLOGY*- FOA will become obsolete once a fully validated & verified database of PM EIs represents the current flying fleet is prepared

Measurements are the gold standard

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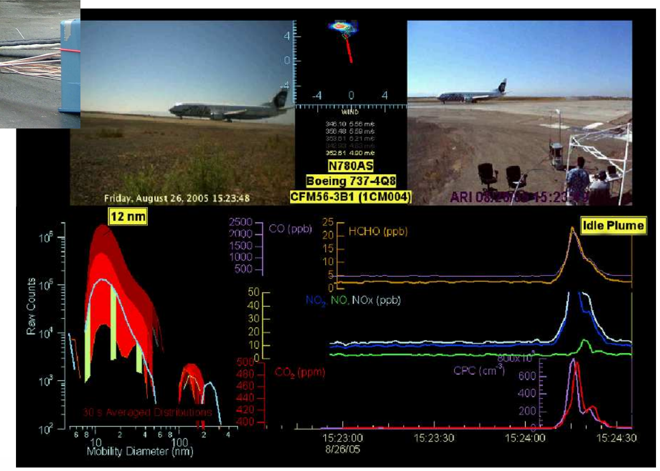
Measurement Campaigns

APEX1
NASA Dryden
April 2004

Delta Atlanta Hartsfield
(UNA-UNA) September 2004



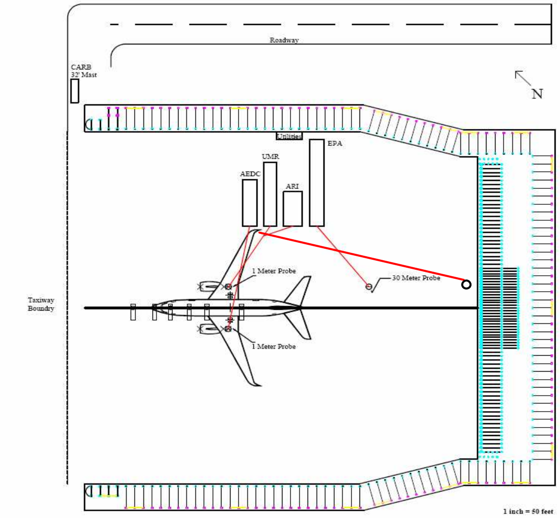
JETS APEX2
August 2005

APEX3 Cleveland
November 2005

APEX Campaigns Strategies

- Emission studies in the near field plume (from 1 to 50m) of stationary commercial transport aircraft:

Mission	Dates	Location	Operator	Airframes	Engines
APEX1	April 2004	NASA Dryden	NASA	DC-8	CFM56-2C1
Delta- Atlanta Hartsfield (UNA-UNA)	September 2004	Atlanta, GA	Delta Airlines	MD-88	JT8D-219
			Delta Airlines	B767-300	CF6-80A2
			Delta Airlines	B767-400ER	CF6-80C2B8F
			Delta Airlines	B757	PW 2037
JETS APEX2	August 2005	Oakland, CA	Southwest Airlines	B737-300 B737-700	CFM56-3B1 CFM56-7B22
APEX3	November 2005	Cleveland, OH	NASA	LearJet 25	CJ610
			Continental Airlines	B737-300	CFM56-3B1
			Continental Express	EMB 145	AE3007A
			FedEx	A300-600	PW 4158
			Continental Airlines	B757-300	RB211-535E-4B



The engines studied represent those that power ~70% of the domestic commercial fleet.

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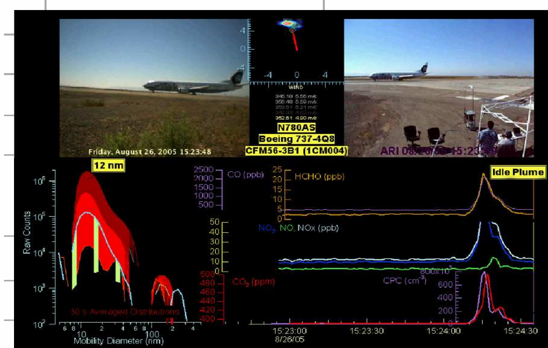
Measurements of the emissions in plumes downwind from aircraft operating under normal LTO (Landing and Take Off) conditions at two large commercial airports.

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



Measurements

- Particle emissions
  - number, size distributions, mass, and composition including number- and mass-based emission indices (EIs).
- Gaseous emissions
  - NOx, CO, and unburned hydrocarbons (UHCs)
  - NO, NO2, SO2,
  - speciated hydrocarbons
    - E.g. formaldehyde, acetaldehyde, benzene, 1,3 butadiene

- The gas phase measurements complement the particle measurements and provide a more specific description of the emissions of aircraft engines than has been available to date.

- The more complete data set will improve estimates of airport contributions to air quality models.

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Primary Observations and Conclusions

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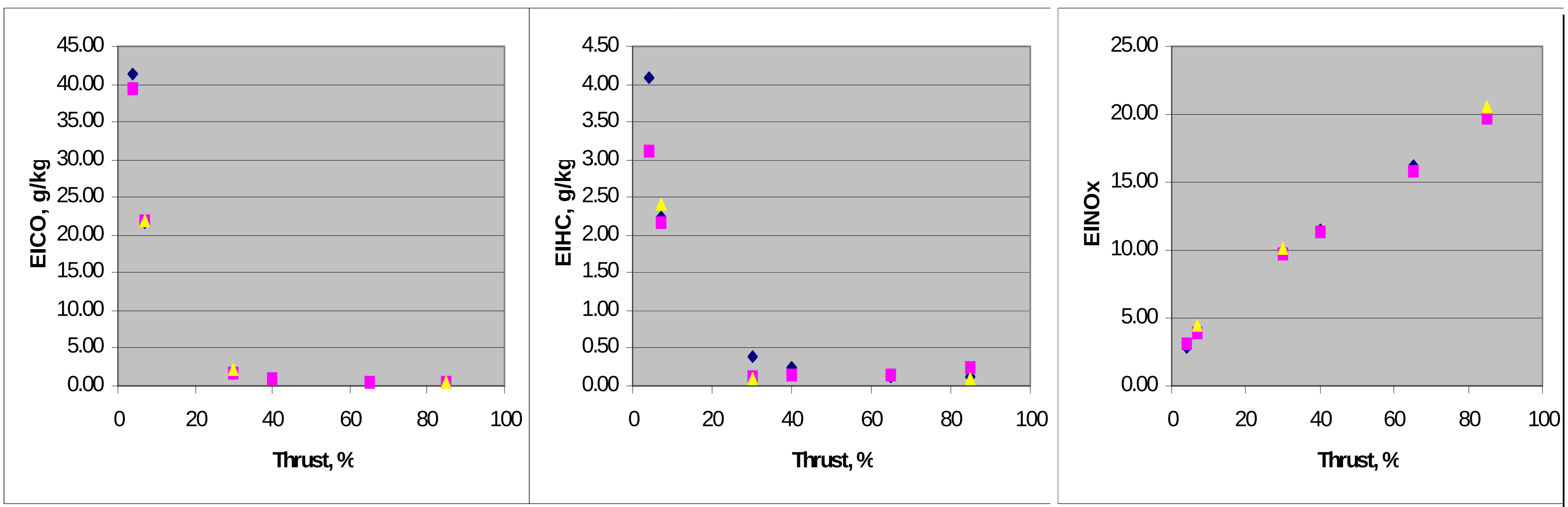
Representative Emissions

- In all cases,
  - the engine combustion gas emissions and engine operating parameters revealed that the engines were operating in a representative manner (through comparison to certification-based emissions measurements).
  - It is reasonable to assume that the PM emissions are also representative and that the results reported should be used with confidence to develop PM emission inventories.



△ ICAO certification data CFM56-7B

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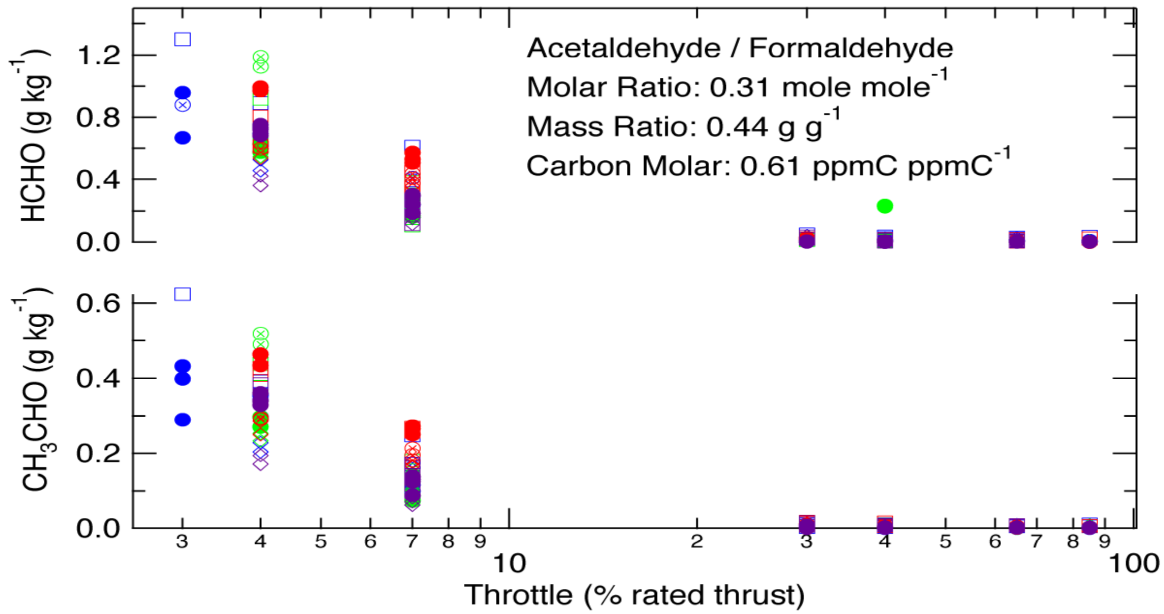
Hydrocarbon Emissions



- Unburned hydrocarbons are emitted as a variety of compounds, including ethylene, formaldehyde, acetaldehyde, and benzene.
- Hydrocarbon emission indices (EI's) are highest at low thrust conditions and each individual EI falls to values below 0.1 g kg-1 at thrusts above 15%.
  - ✓ Hydrocarbon EIs at idle can be 3X to 5X those measured above 15% thrust
- Emissions of the various hydrocarbon species rise and fall with one another, regardless of engine type or thrust setting.
  - ✓ The ratio of one hydrocarbon species to the next remains constant, even when the absolute magnitudes increase by a factor of 10 or more
    - ✓ for older engine technology
    - ✓ operation at low power condition
    - ✓ Operation at low ambient temperature

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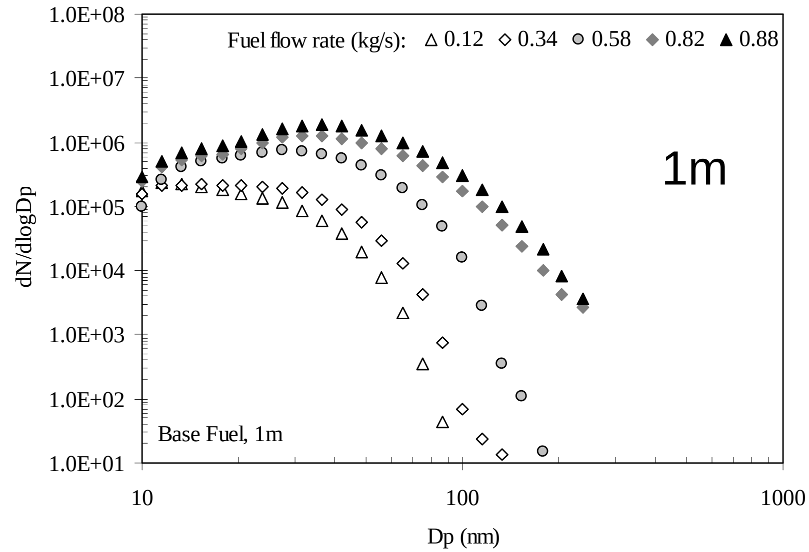
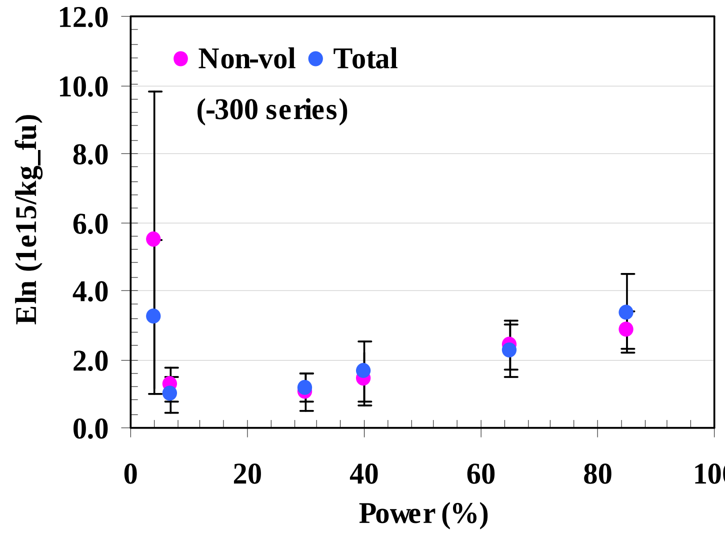
The following trends were observed when emissions were sampled at the exhaust nozzle:

- ✓ black carbon soot (i.e., non-volatile particles) constitutes more than 80% of the mass of PM emissions at all power conditions. At take-off powers, more than 95% of the total PM mass is soot.



- ✓ Conversion of condensable sulfate and organic gaseous emissions to the particle phase is largely suppressed by dilution in sampling probe for samples obtained at the engine exit plane.



Prem Lobo; Donald E. Hagen; Philip D. Whitefield; I
"**Physical Characterization of Aerosol Emission**
Commercial Gas Turbine Engine", *Journal of Pro*
Power (2007), Vol. 23, No. 5, 919-929

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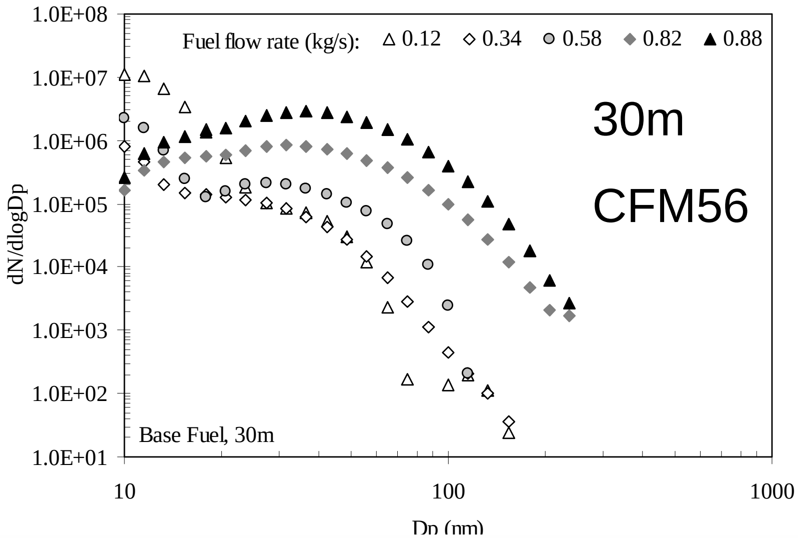
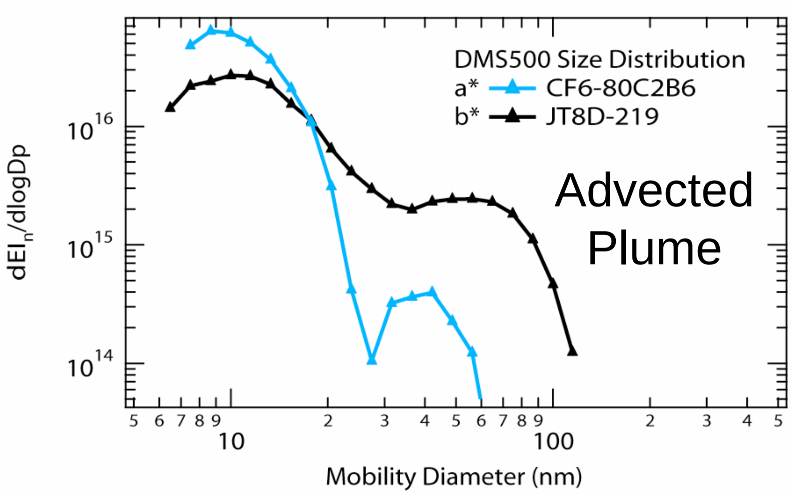
The following trends were observed when emissions were sampled in the plume (> 50m from the exhaust nozzle):

- the number-based PM emissions are dominated by volatile particles that form as the plume expands and cools
  - these volatile particles are mostly composed of sulfates and organics
  - The mass of particles in the plume does not change significantly as the plume travels downwind but the number of particles increases by at least an order of magnitude indicating that these newly formed particles do not contribute significantly to the total PM mass in the plume.





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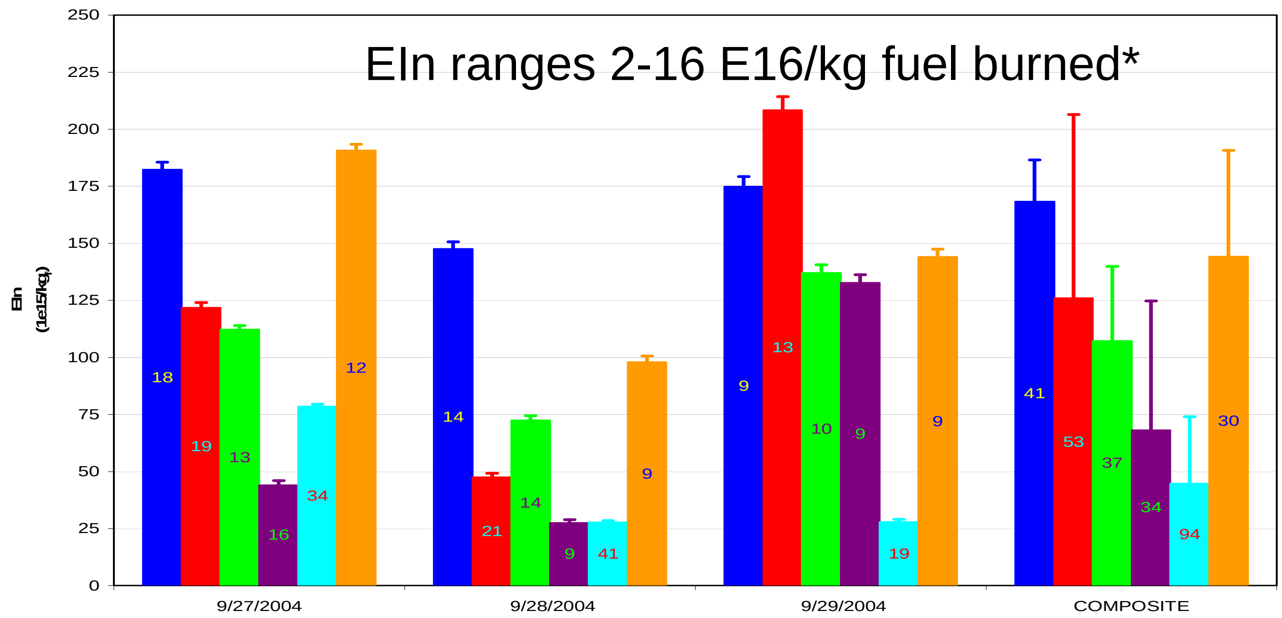

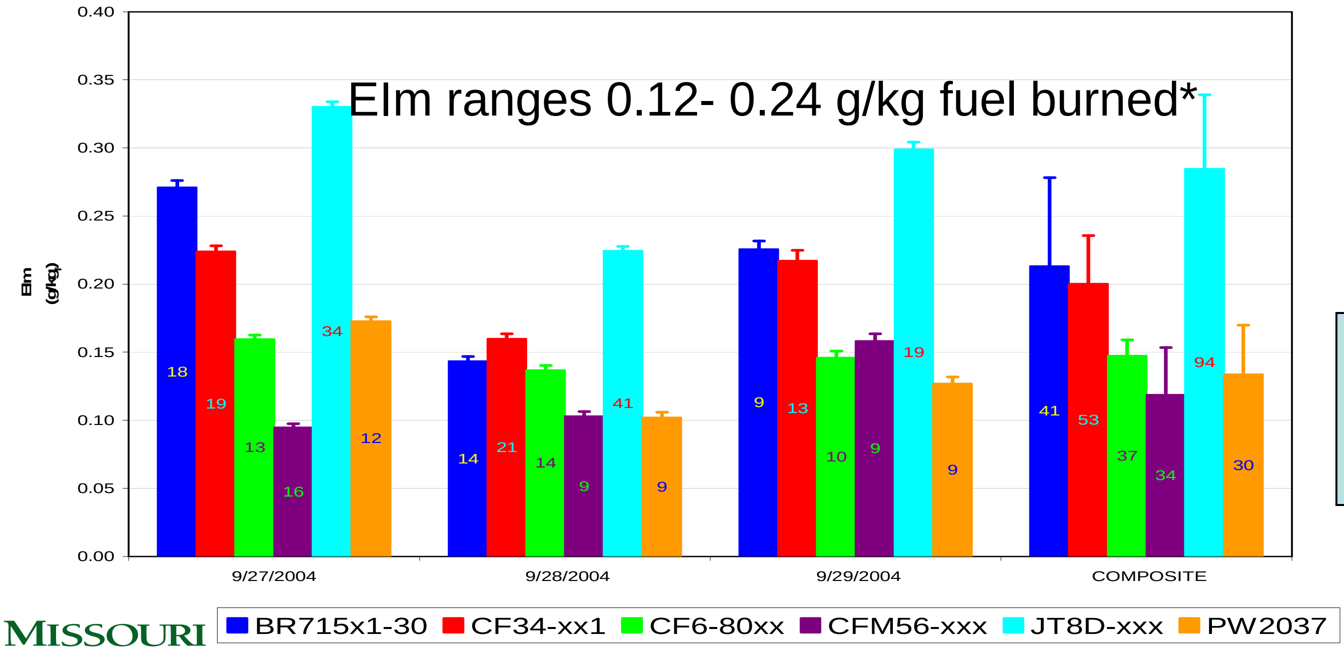

Delta Atlanta Hartsfield Study

- From the advected plume data, on any given day the engine-engine variability within a given class is less than 5% for mass- and number-based emission indices.

- From the advected plume data, the day to day variability for a given engine class ranged from 10-30 % for mass- and 10-80% for number-based emission indices.

- Changes in ambient atmospheric conditions are likely to impact PM emissions. A larger impact would be expected on particle number than on particle mass as was observed in the advected plume data.

IPCC Rpt (pg 74 -75)
Soot in plume
EIm ~ (0.01- 0.2)g/Kg fuel
EIn ~ (0.3-50.0)E15/Kg fuel

*for all engine types studied

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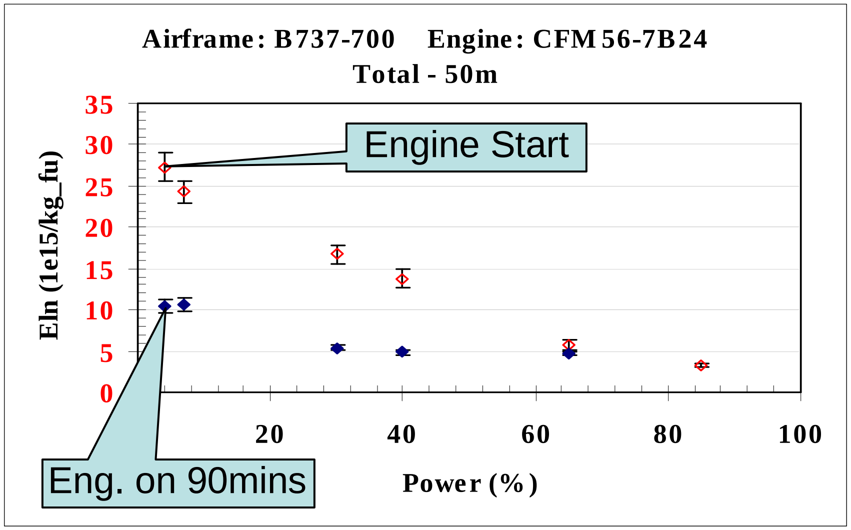
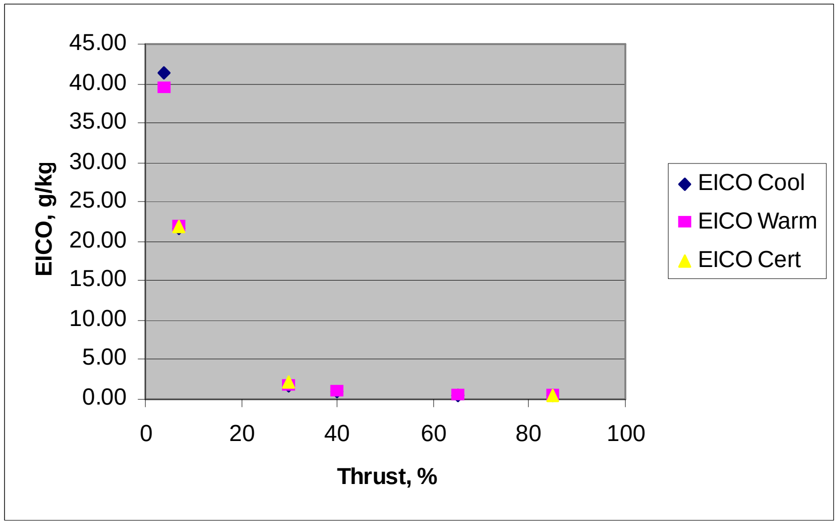
Engine Warm-up Conditions

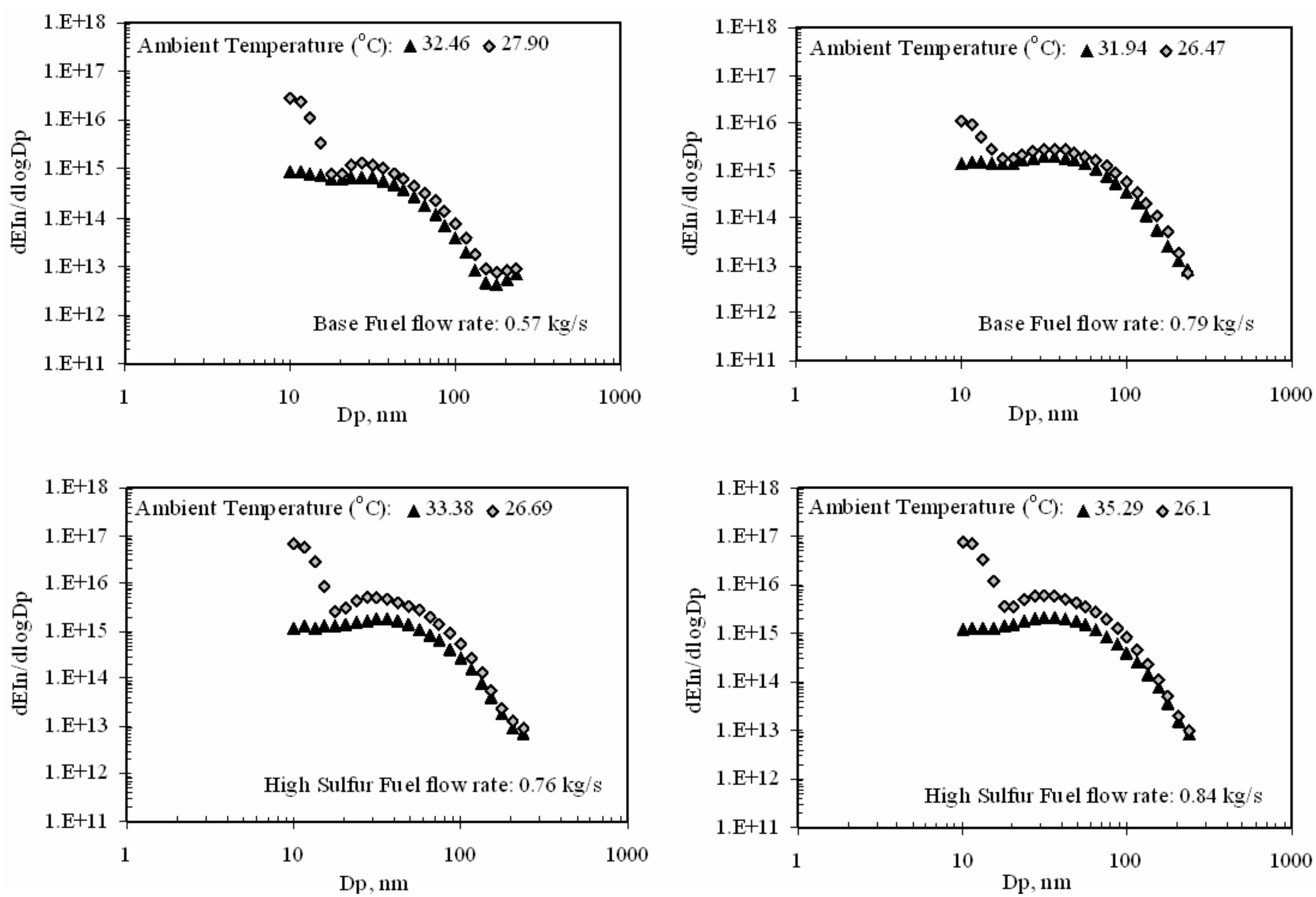




- Engine-on-time (warm up) impacts the absolute values of PM parameters and will need to be taken into account for credible inventory development.

- This effect is not observed for the combustion gases monitored for certification.

Atmospheric Conditions



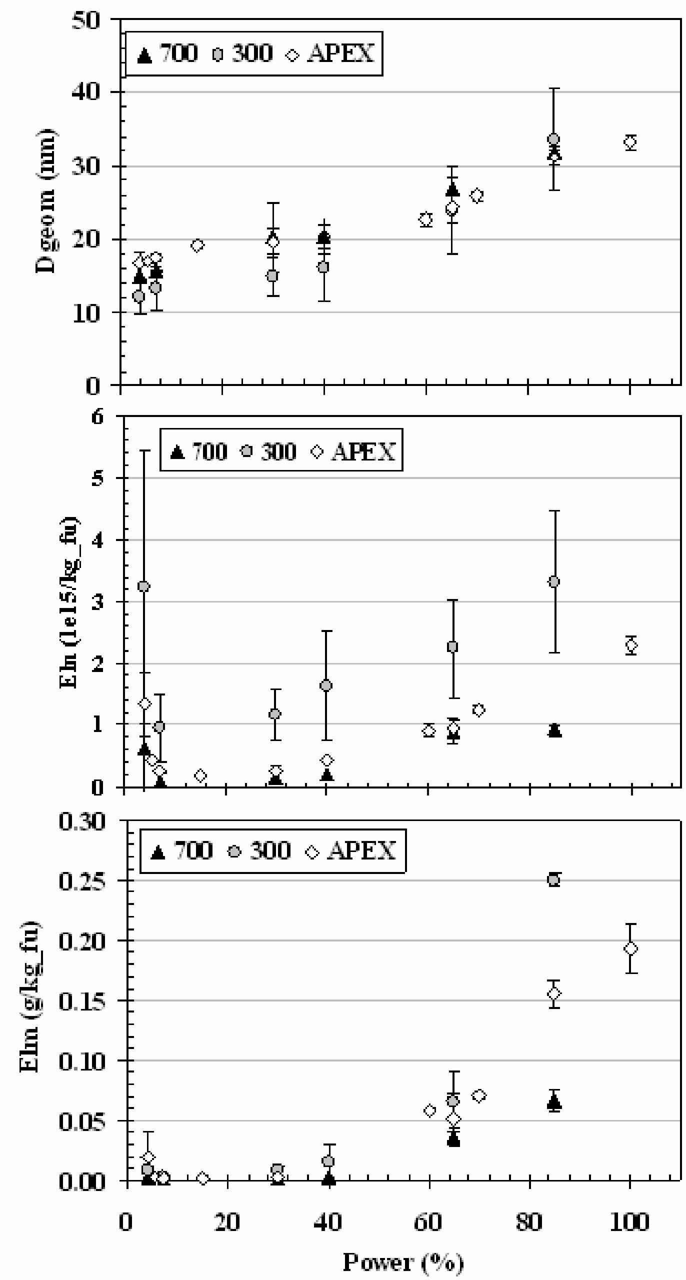
New mode appears at lower temp with mean dia ~10-12nm
EIn increases by 10X

Temperature change 79°F to 95°F

Little or no change in rel. humidity (desert!)

Engine to Engine Variation

- ✓ The absolute PM parameters for each engine type (i.e CFM56, CF6, RB211 etc.) were unique and could vary significantly with sub-type e.g. CFM56-2C1, -3B. -7B (EIm ratio 3B:7B is 4:1)
- ✓ Credible inventories based on nozzle emissions will require engine specific data like that measured in these studies.
- ✓ Statistically significant engine-to-engine PM emissions variation within a given sub-type could not be resolved because of the high variance between the small set of engine sub-types sampled.



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Knowledge Gaps

- The engine specific nature of these PM emissions indicates that additional studies will be needed to adequately characterize important engine types as yet to be examined i.e. the 50,000– 100,000 lb thrust engines employed by such aircraft as the B747, B757, B767, B777, B787, A300, A310, A330, A340, A350 and A380

- These results indicate that a mass-based inventory alone will not capture the significant volatile PM production observed in the plume.

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APEX Reports/Publications Status

- **APEX1**
  - **NASA Report**
    - Wey et al. "Aircraft Particle Emissions eXperiment (APEX)", NASA/TM-2006-214382, ARL-TR-3903, Cleveland, OH, September 2006
  - **Special edition of Journal Propulsion and Power**
    - Journal of Propulsion and Power (2007), Vol. 23, No. 5

- **Delta Atlanta Hartsfield**
  - **PARTNER Report** http://web.mit.edu/aeroastro/partner/reports/index.html
  - **Environmental Science and Technology**
    - Scott C. Herndon, John T. Jayne, Prem Lobo, Tim Onasch, Gregg Fleming, Donald E. Hagen, Philip D. Whitefield, and Richard C. Miake-Lye, "Commercial Aircraft Engine Emissions Characterization of in-Use Aircraft at Hartsfield-Jackson Atlanta International Airport", accepted for publication in *Environmental Science and Technology* (2008)

- **JETS APEX2**
  - **CARB Report** http://www.arb.ca.gov/research/abstracts/04-344.htm

- **APEX 3 Raw Data** http://particles.grc.nasa.gov

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Potential Control Strategies

- APEX studies aimed at gathering credible data for accurate emission inventories.
- Data indicates source apportionment feasible.
- A focus on operations at idle and taxi could seriously impact/reduce aircraft PM and HAP emissions.

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Acknowledgements

- The APEX Studies research teams
- FAA, NASA, EPA, DOD, CARB
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