Development of Exhaust Speciation Profiles for Commercial Jet Engines.

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SOUTHWEST AIRLINES

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California Air Resources Board

UMR UNIVERSITY OF MISSOURI-ROLLA

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

Center of Excellence for Aerospace Particulate Emissions Reduction Research

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Overview

- Introduction
- The chronology of the project
- The team
- The objectives
- Combustion gases and representativeness of data
- The PM results from dedicated engine studies (physical properties)
- The TOG (UCR) results
- PM composition/HAPS results from dedicated engine studies
- The airport study
- Conclusions recommendations
- The APEX Campaign series
- Impact on the field
- Acknowledgements

Chronology of the JETS APEX2 Project

The primary objective of project JETS APEX2 was to collect and develop exhaust speciation profiles from modern commercial jet engines.

Fall 2004 - CARB initiated discussions with Oakland International Airport (OAK) and Southwest Airlines (SWA) to provide access to in-service commercial B737 aircraft for such measurements.

January 2005 - Discussions took place with the UMRCOE on approach employed in APEX and Delta Atlanta Hartsfield studies and an expanded project was developed based on the original CARB concept, meeting a critical National PM Road Map milestones that followed Project APEX (APEX1 - April 2004) and Project Delta-Atlanta Hartsfield (UNA UNA - September 2004).

Spring 2005 - Project JETS APEX2 emerged as a multi-agency (CARB, NASA, FAA, EPA, UMR, UCR, UCF, AEDC, GE, Boeing, SWA, OAK and ARI) funded study.

August 2005 – Project JETS APEX2 successfully completed.

Objectives

- Produce the first measurements with state-of-art analytical equipment of speciated total organic gases (TOG) and particulate matter (PM) from engines on typical in-use Boeing 737-type commercial aircraft

- Provide data to address critical science questions/issues arising from the 2004 APEX and DELTA ATLANTA HARTSFIELD studies relating to:
  - methodology development,
  - plume modeling,
  - the nature of aircraft generated PM and HAPs emissions and their fate

The Team

- Sponsors: CARB, SWA, OAK, UMRCOE, NASA, FAA, EPA
- Participants: AEDC, ARI, CARB, EPA, NASA (GRC, LaRC), UCF, UCR, UMR
- Observers: GE, Boeing,
- Project Manager: Dr. Phil Whitefield (UMR)

Roles and Responsibilities

Project sponsor: ARB	***Manage contract, coordinate with FAA, airline, airport and principal investigator, verify deliverables are met***
Executive Team	
FAA	Aircraft contracts, operation & fuel costs
SWA	Provide aircraft
OAK	Space & security issues
UMRCOE	Principal Investigator, coordinate tech team members
Technical Team	
UMR	Sampling setup/probes
UMR/ARI	Measure real-time (RT) regulated gases
UMR	Measure RT PM size, number, penetration
UCR	Measure speciated hydrocarbons
UCR	Measure PM mass, EC/OC, metals, ions
ARI	Measure RT PM size/composition, selected gas species
South Coast AQMD	Analyses of light hydrocarbons & metals
Air Toxics Ltd.	Analyses of DNPH samples (upwind and downwind of test location)
Alta Analytical Laboratories	Analysis of dioxin
Boeing/GE	Technical advisors

Fleet:

Southwest currently operates 502 Boeing 737 jets (as of July 20, 2007).

Type	Number	Seats
737-300	194	137
737-500	25	122
737-700	283	137

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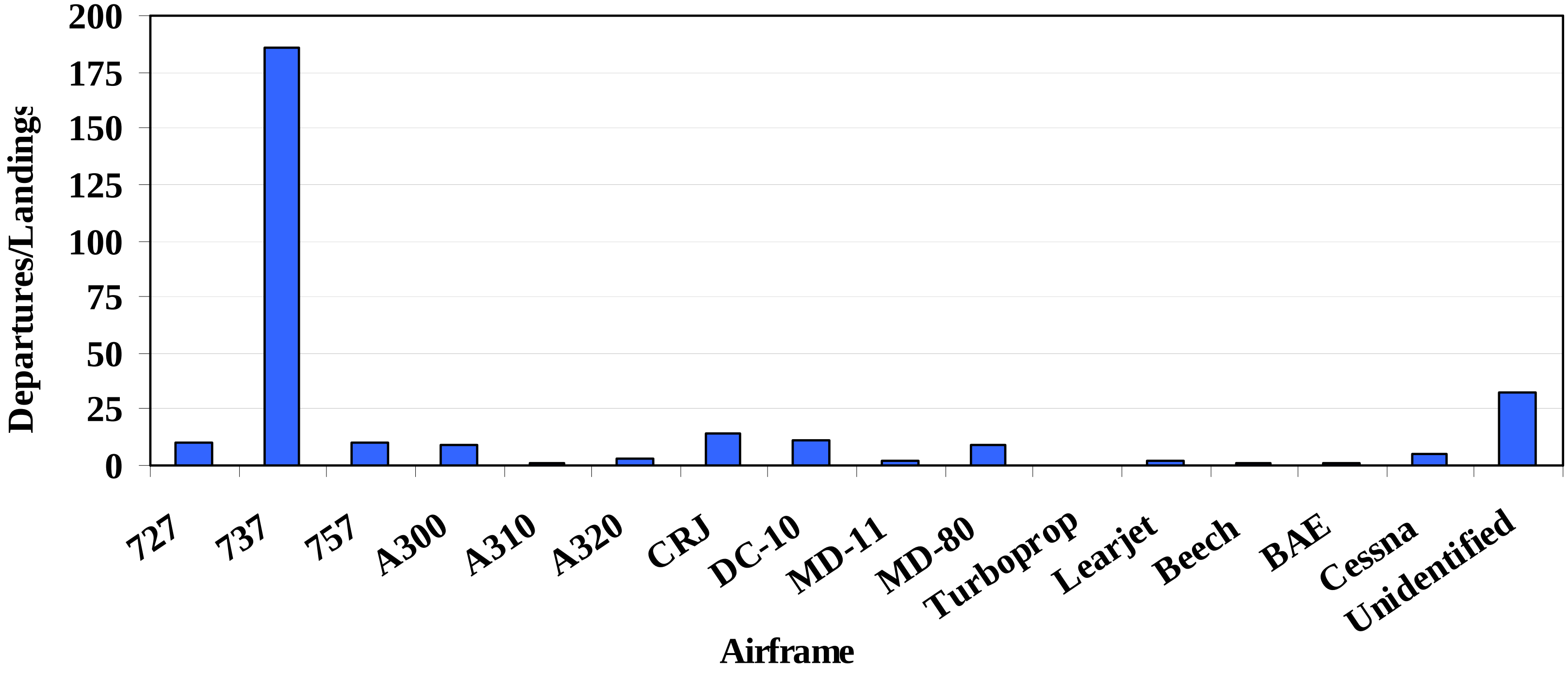
SOUTHWEST AIRLINES

Southwest Airlines' Top Ten Airports: (as of July 20, 2007)

Cities	Daily Departures	Number of Gates	Nonstop Cities Served	Established
Las Vegas	232	21	53	1982
Chicago Midway	227	29	47	1985
Phoenix	205	24	42	1982
Baltimore/Washington	180	26	40	1993
Oakland	148	11	21	1989
Houston Hobby	146	16	29	1971
Dallas (Love Field)	133	14	15	1971
Los Angeles (LAX)	120	11	19	1982
Orlando	116	12	33	1996
San Diego	96	10	16	1982

Distribution of Aircraft Operating Out of OAK on a Typical Day (26 August 2005)



The Boeing 737 Aircraft

- A short to medium range, single aisle, narrow body jet airliner.
- over 7,000 ordered and over 5,000 delivered,
- it is the most ordered and produced commercial passenger jet of all time and has been continuously manufactured by Boeing since 1967.
- The 737 is now so widely used that at any given time, there are over 1,250 airborne worldwide.
- On average, somewhere around the world, a 737 takes off or lands every five seconds.

Boeing 737-300 & 737-700

The -300 was launched in 1981 by USAir and Southwest Airlines, becoming the base model of the 737 Classic series. The 300 series remained in production until 1999 when the last aircraft was delivered to Air New Zealand on December 17, 1999.

The 737-700 was launched by Southwest Airlines in 1993 and entered service in 1998. It replaced the 737-300 in Boeing's lineup, and its direct competitor is the A319. It typically seats 132 passengers in a two class cabin or 149 in all economy configuration.

737's & CFM56 Turbofan Engines

>16000 engines in service operated by 450 customers worldwide

Aircraft	Engine	In-Use
E-3/KE-3/E-6	CFM56-2A	193
KC-135/RC-135	CFM56-2B	1949
DC8-70	CFM56-2C	524
B737-300/-400/-500	CFM56-3	4498
A319/A320	CFM56-5A	1176
A319/A320/A321	CFM56-5B	1981
A340-200/-300	CFM56-5C	1086
B737-600/-700/-800/-900	CFM56-7B	3780

Thrust ranges from 18,500 to 23, 500 lbs.

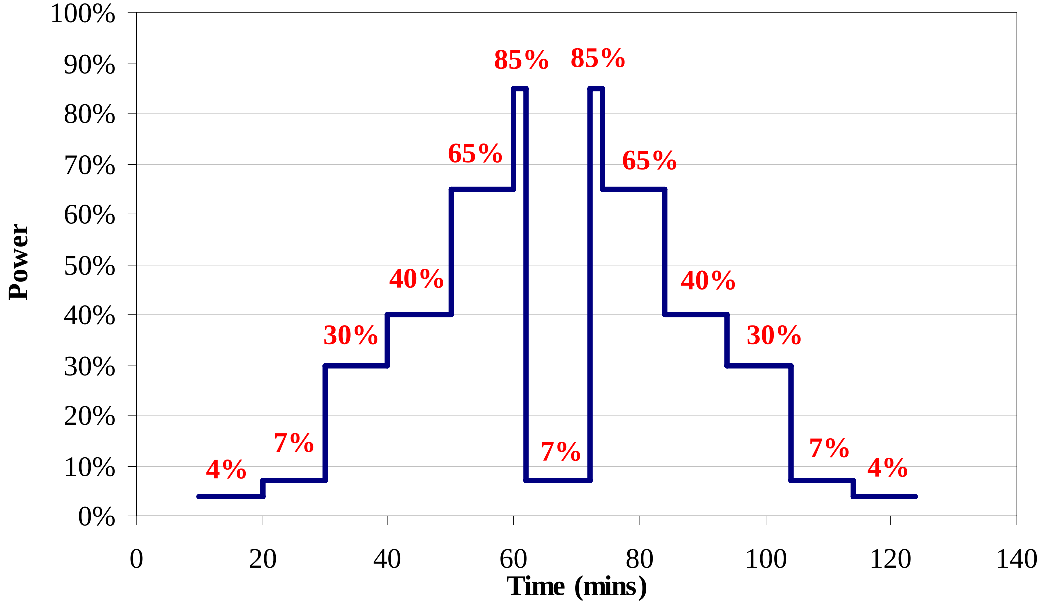
Thrust ranges from 18,500 to 27,300 lbs.

Dedicated Engine Tests - PM Physical Characterization

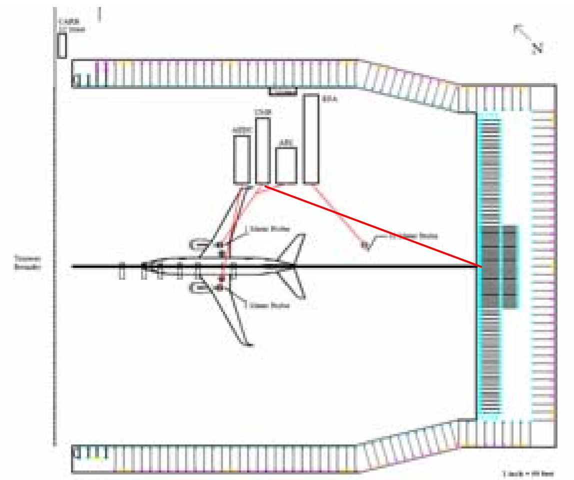
Ground Run-up Enclosure, Oakland International Airport August 23-25, 2005

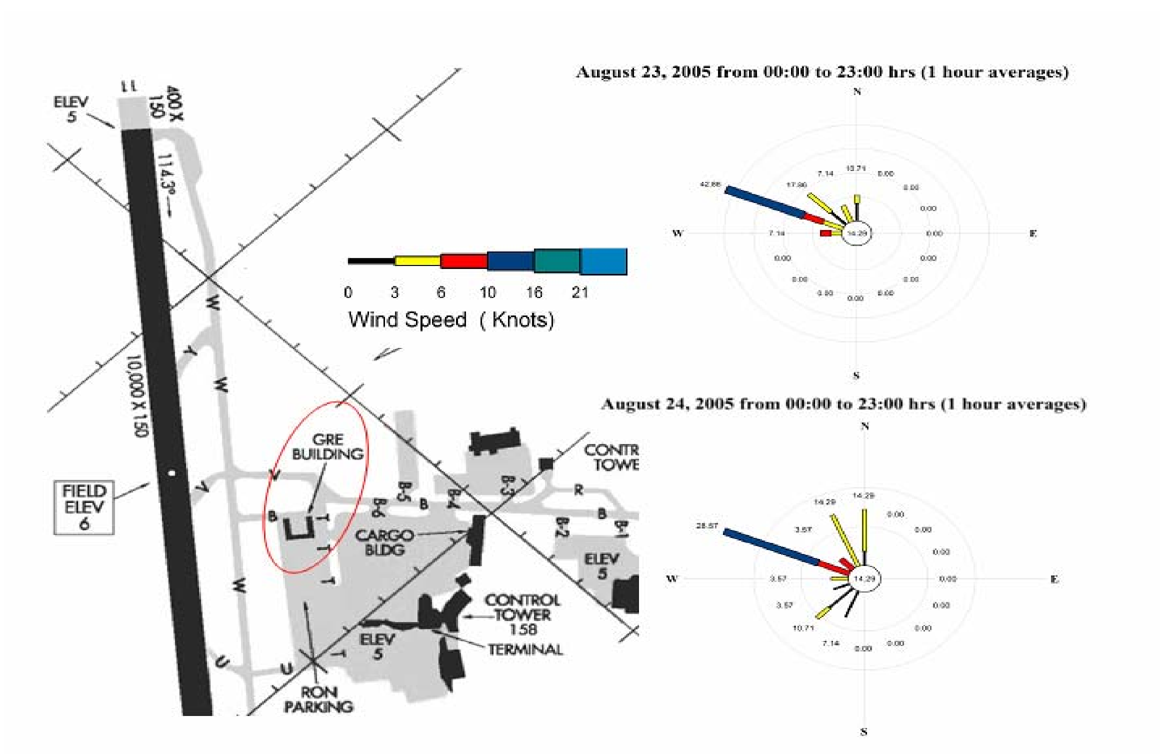
Engine Test Overview

Date	Aircraft Tail No	Airframe	Engine
August 23, 2005	N435WN	B737-700	CFM56-7B22
August 24, 2005	N353SW	B737-300	CFM56-3B1
August 24, 2005	N695SW	B737-300	CFM56-3B1
August 25, 2005	N429WN	B737-700	CFM56-7B22

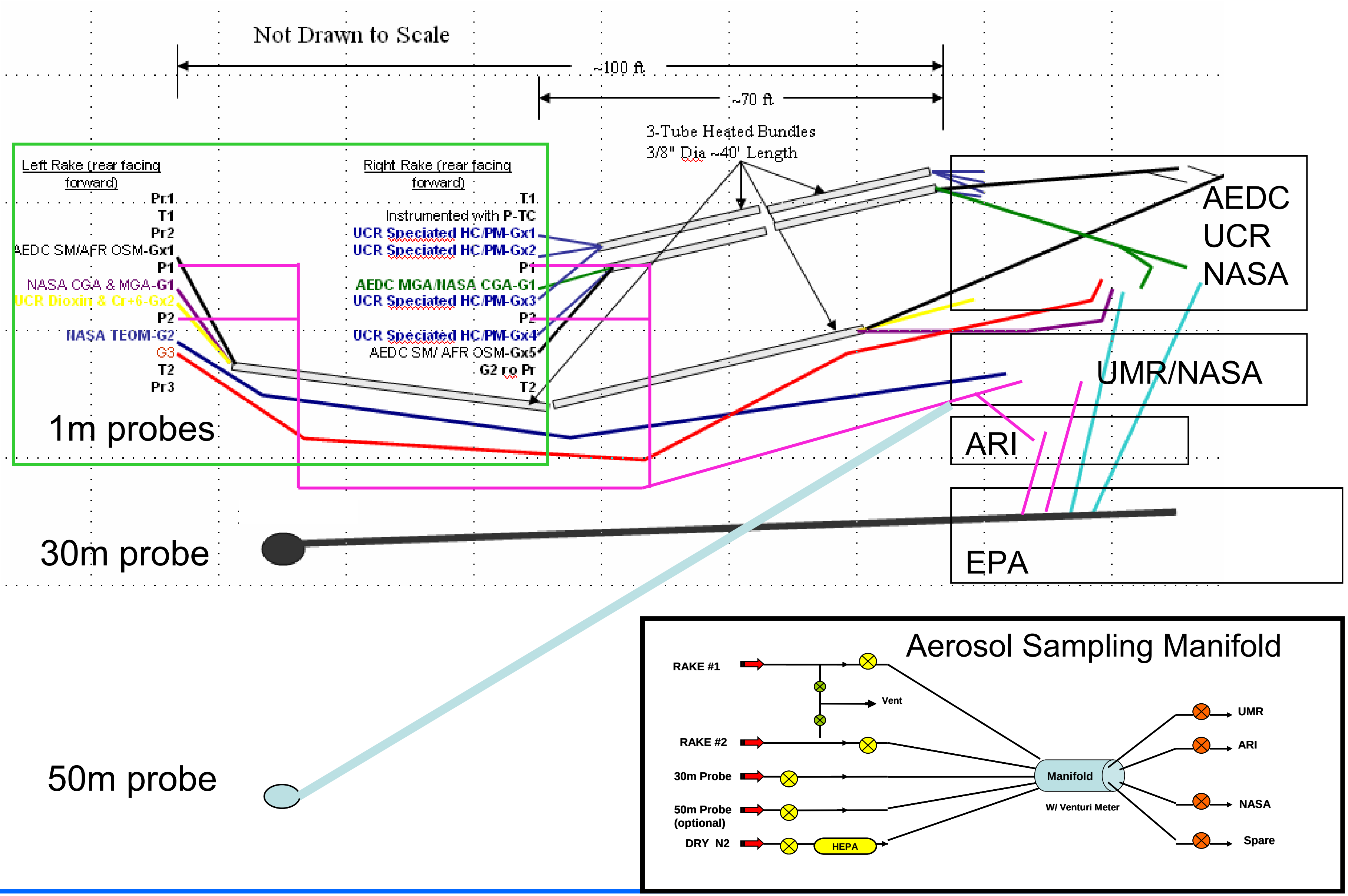


Testing at the GRE

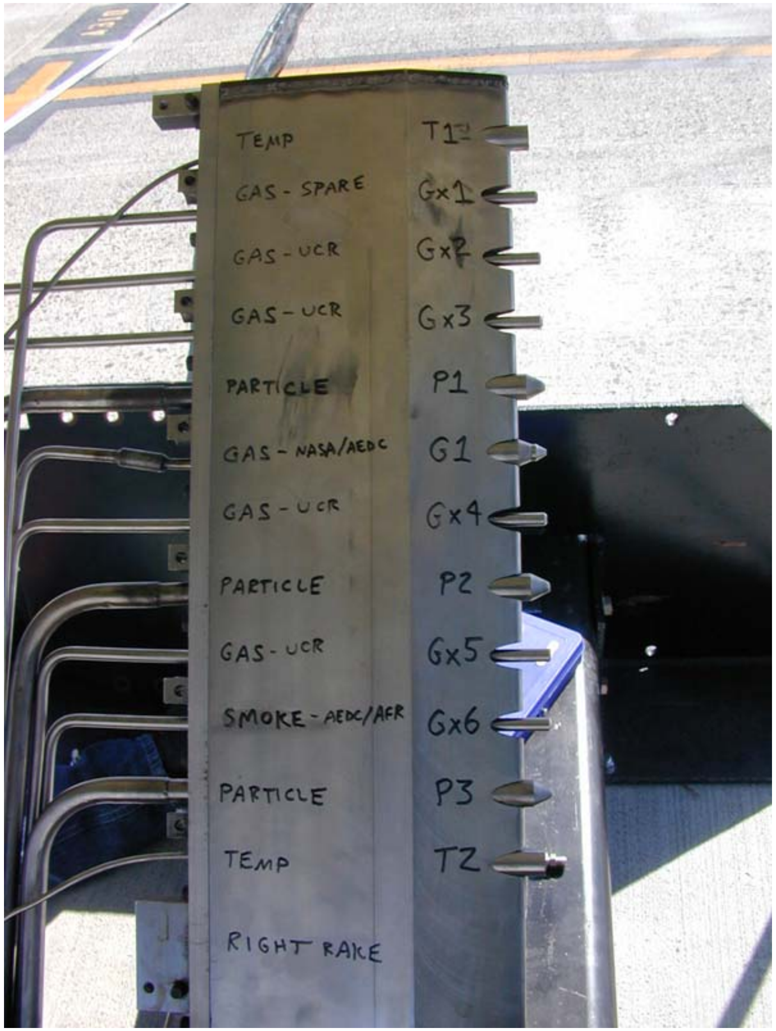




Sampling Distribution Systems for Gases and PM



Sampling Probes



Probe Configuration of the Left and Right Rakes

JETS-APEX2

Aircraft #1 (737-700), #2 & 3 (737-300)

Left Rake (aft looking forward)

Pr1 - Spare

T1 - AEDC

Pr2 –NASA Pressure Transducer

Gx1 - AEDC SM/AFR OSM

P1 - Particle Sampling Group (ganged w/P2)

G1 - NASA CGA & MGA

Gx2 - UCR Dioxin & Cr+6

P2 - Particle Sampling Group (ganged w/P1)

G2 - NASA TEOM

G3 – NASA CGA & MGA

T2 - AEDC

Pr3 - Spare

Right Rake (aft looking forward)

T1 - AEDC

Gx1 - Spare

Gx2 - UCR Speciated HC/PM

Gx3 - UCR Speciated HC/PM

P1 - Particle Sampling Group (ganged w/P2)

G1 - AEDC MGA/NASA CGA

Gx4 - UCR Speciated HC/PM

P2 - Particle Sampling Group (ganged w/P1)

Gx5 - UCR Speciated HC/PM

Gx6 - AEDC SM/ AFR OSM

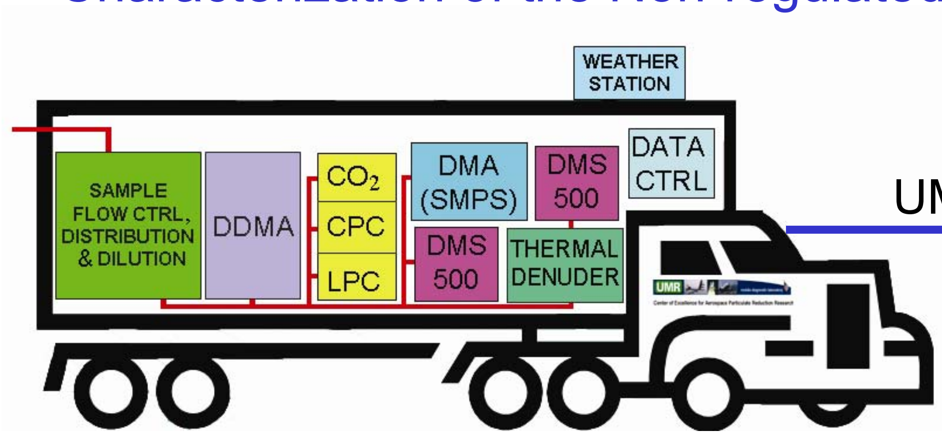
P3 - instrumented with TCs (T1 & T2)– AEDC

T2 - AEDC

G = Gas Probes with 0.062” inlet orifice (incidental water cooling)

Gx = Gas Probes with 0.152” inlet orifice (no water cooling)

Instruments/Media Deployed for the Chemical and Physical Characterization of the Non-regulated Emissions in the Engine Exhaust



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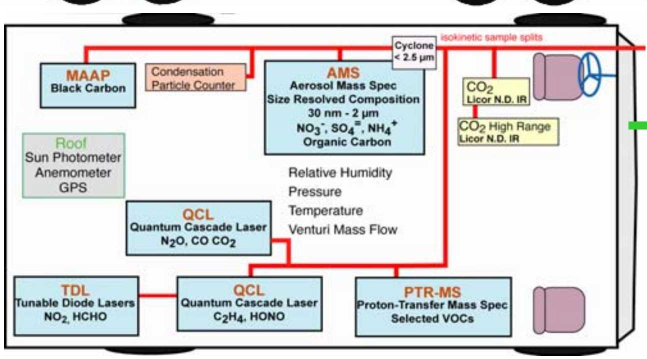
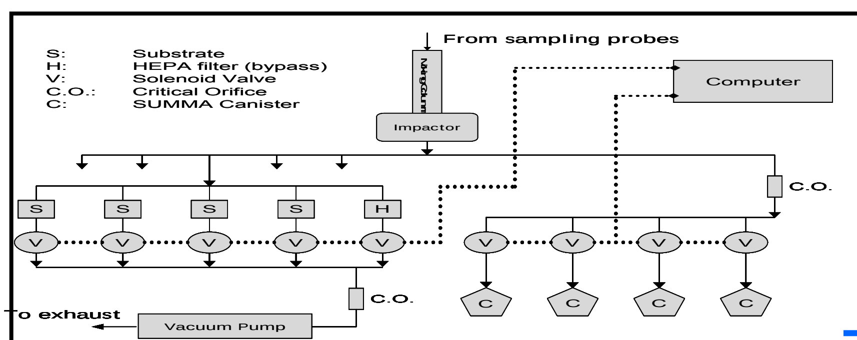
Real-time (RT) PM number & size distribution



ARI

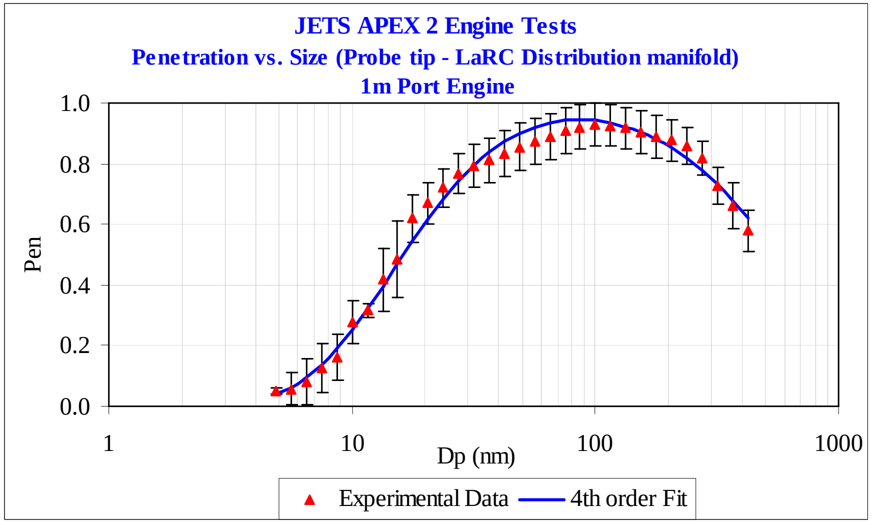
RT PM chemical composition
Up to four species: NO, NO_2, CO, SO_2, &
trace species: HONO, HNO_3, & formaldehyde
in real-time

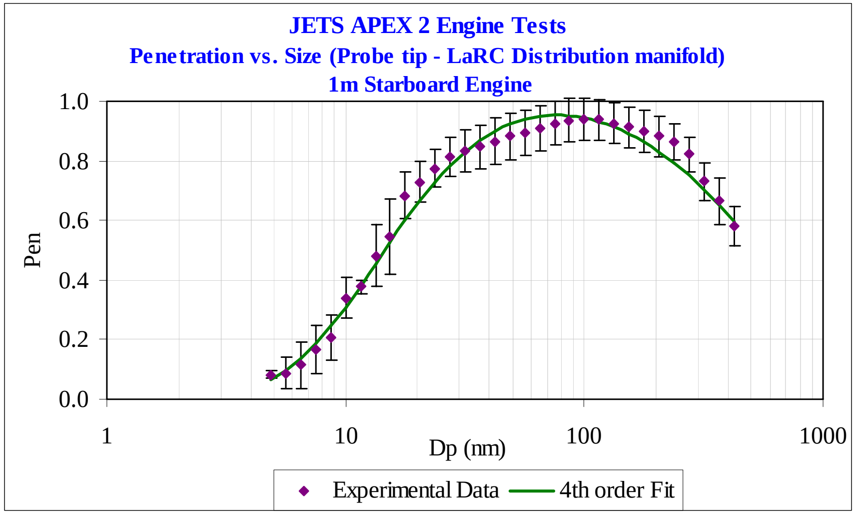


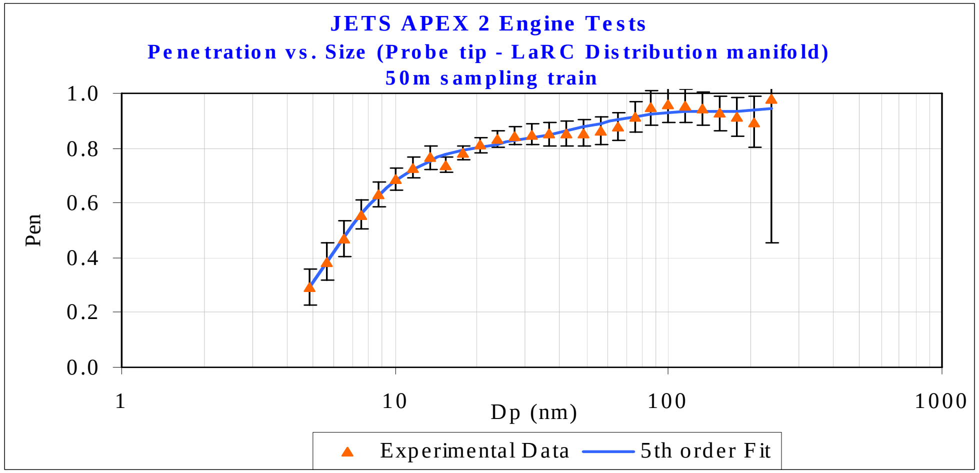
UCR

EC, OC, speciation of PM organics
PM mass, ions, metals, Cr(VI)
C_1-C_8 organic HC speciation
C_4-C_{12} organic speciation
C_{10}-C_{30} organic speciation
Carbonyl analysis

Results of the Line loss calibration experiments



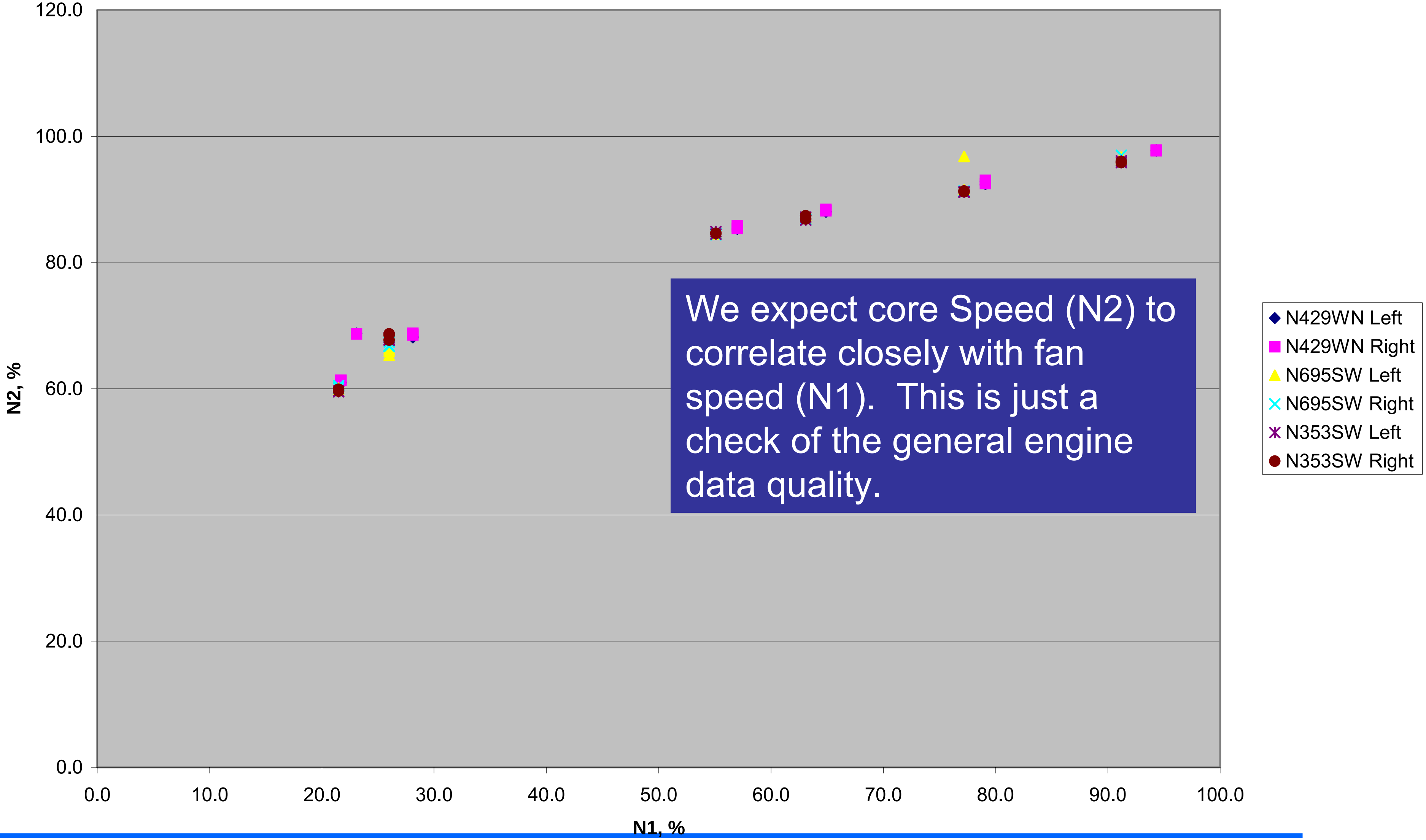




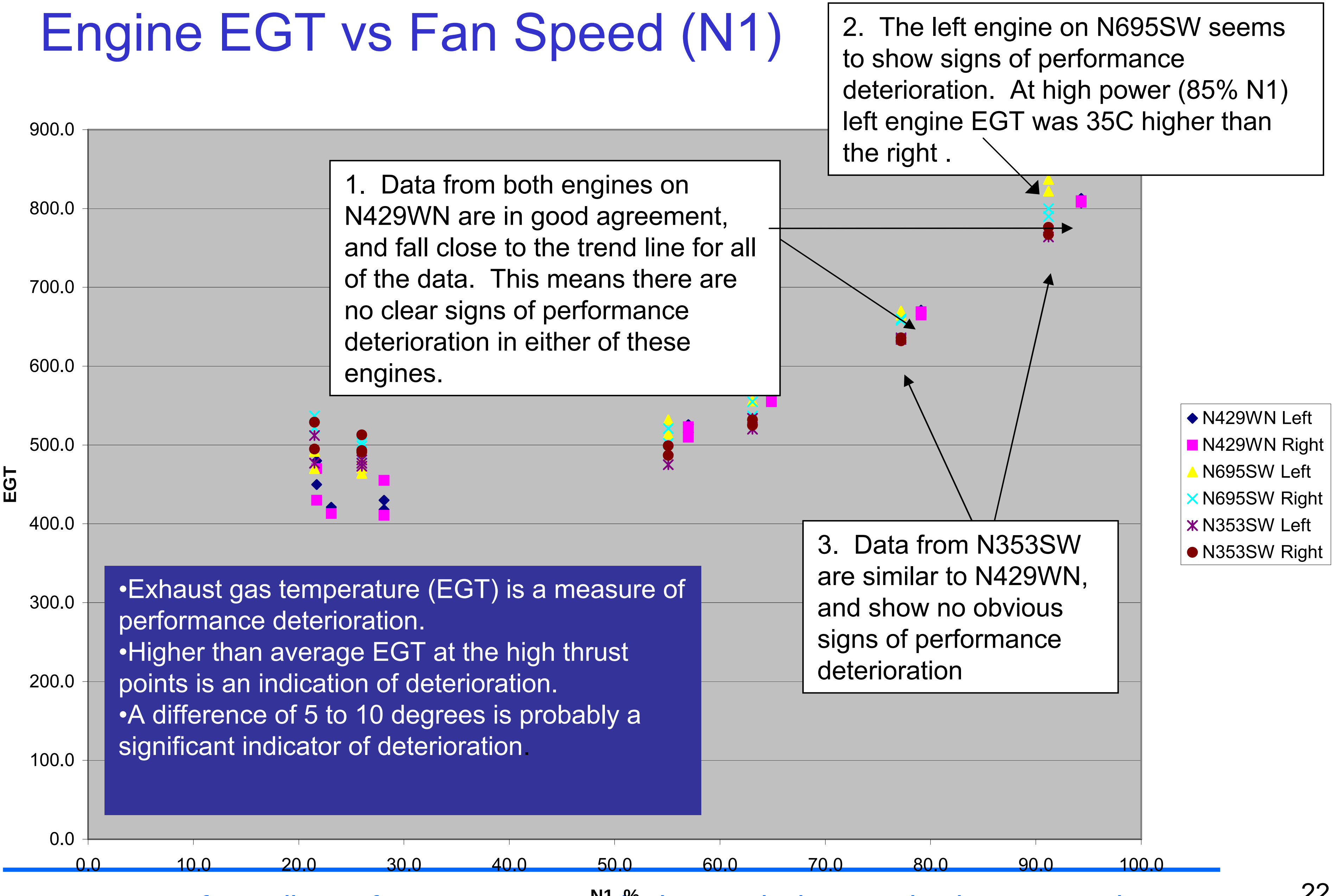
Representative Emissions

- GE analysis of engine performance
- NASA combustion gas analysis with certification data comparison
- Fuels analysis

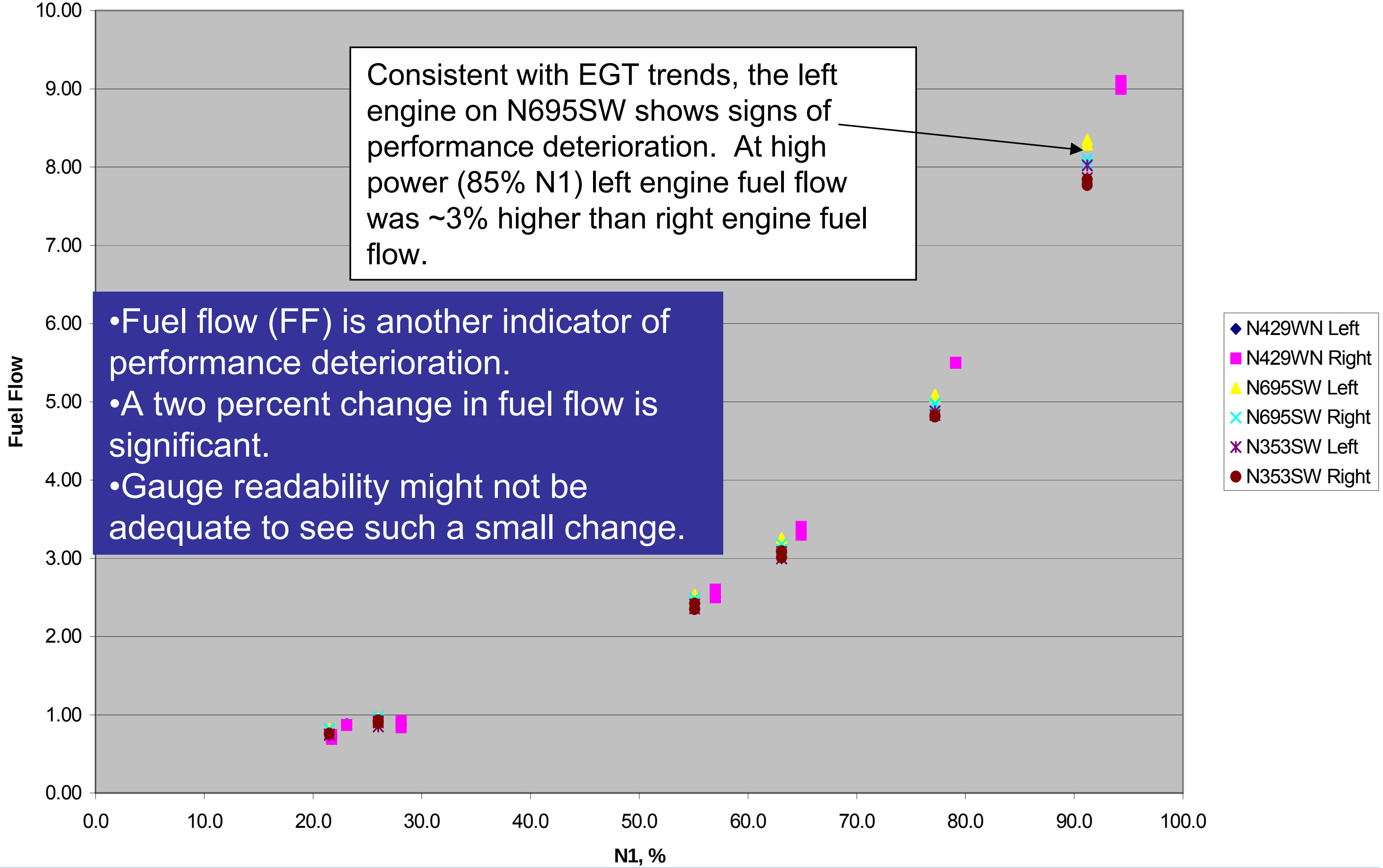
Engine Core Speed (N2) vs Fan Speed (N1)



Engine EGT vs Fan Speed (N1)



Engine Fuel Flow



- Fuel flow (FF) is another indicator of performance deterioration.
- A two percent change in fuel flow is significant.
- Gauge readability might not be adequate to see such a small change.

Summary

Trends in engine core speed, EGT and fuel flow data are generally consistent with expectations.

The only apparent indication of performance deterioration was on the left engine of N695SW.

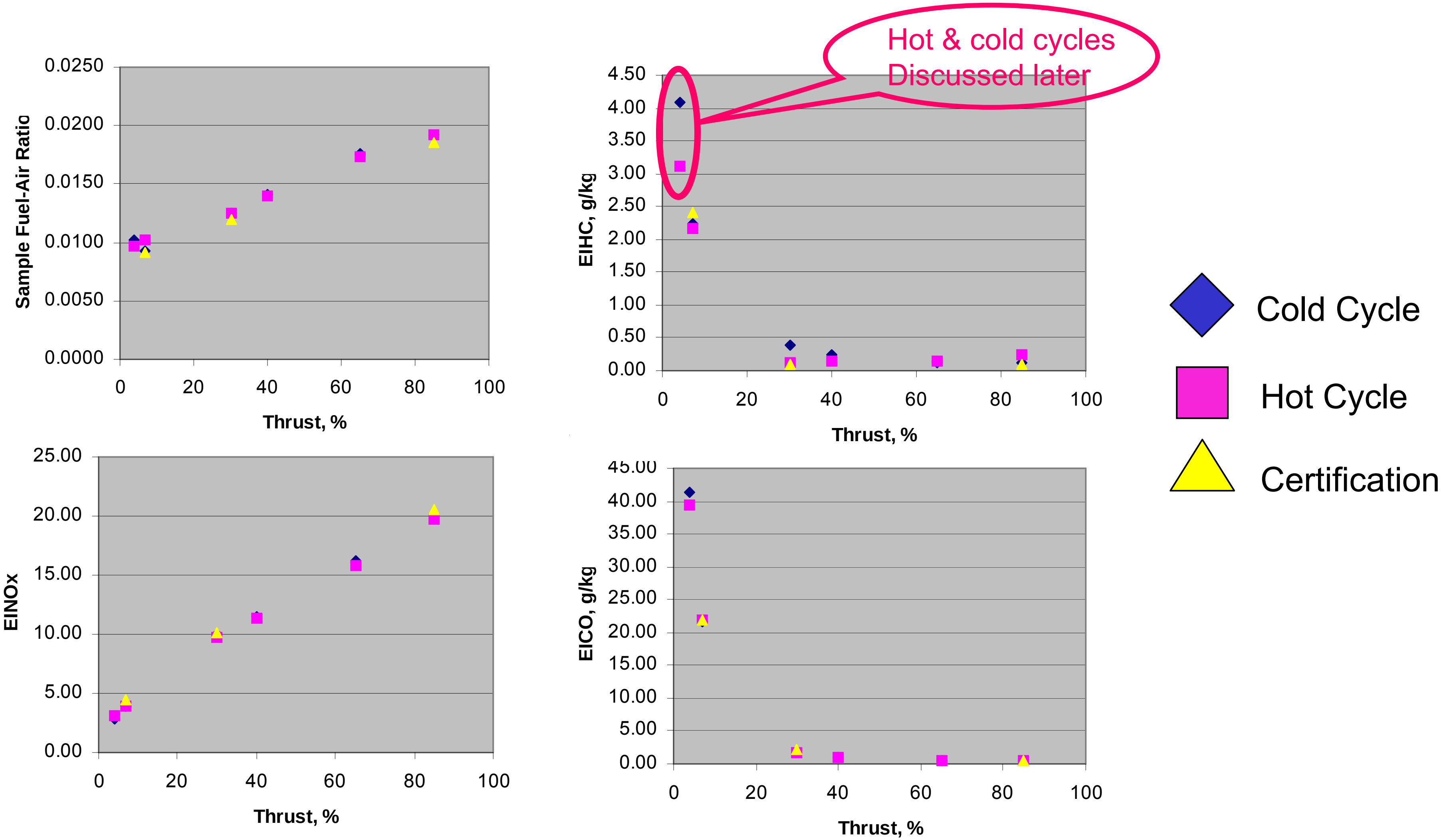
Performance deterioration would tend to increase combustor inlet temperature and fuel-air ratio, which would increase smoke emissions.

JETS APEX2 Engine Performance

Precise characterization of engine performance would require more and/or better quality data and detailed data analysis

- Data are not available for all aircraft
- Ambient temperature/pressure were not provided
- Hand logged steady state engine data accuracy is not always adequate to get significant details (e.g. 1% fuel flow is significant), but we can observe main effects.

Combustion Gas Data



Fuels Analysis
Sulfur and Aromatics

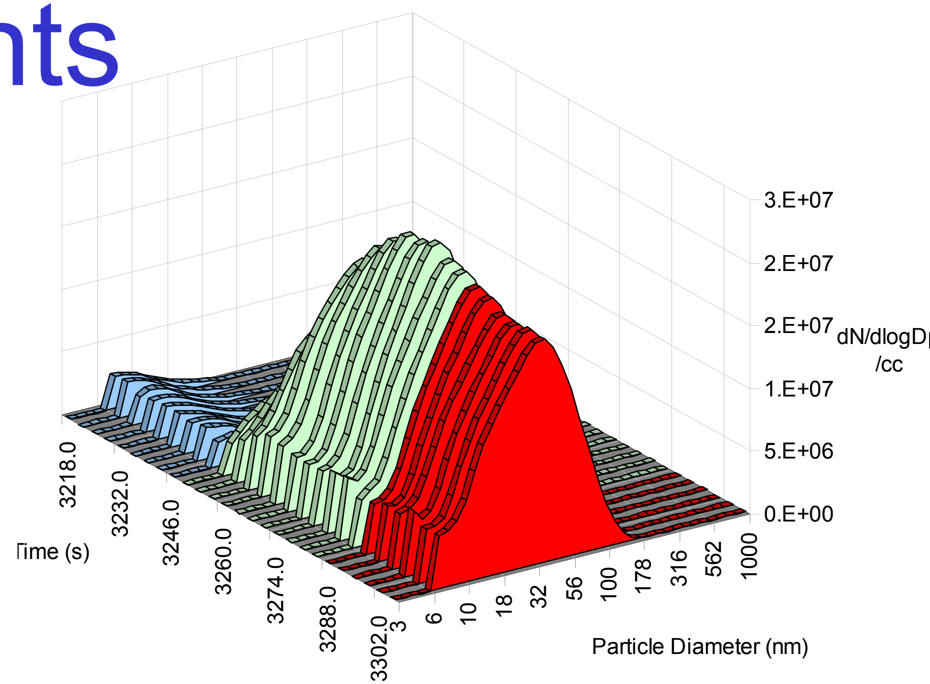
ANALYTICAL METHOD		Fuel Analysis & Methods Evaluation Section (FAME) Monitoring and Laboratory Division, CARB							
		ASTM D5186 SFC/FID			ASTM D86 Automatic			ASTM D5453 Antek	ASTM D4052 Density Mtr
Analysis Date		9/30/05 - 11/2/05			10/25/2005			9/21/2005	
Analyst		JJC / EL			JC / AL			EL	
Sample I.D.		***Total Aromatics (vol %)***	***Total Aromatics (mass%)***	***Polycyclic Aromatics (mass%)***	***T10 (deg C)***	***T50 (deg C)***	***T90 (deg C)***	***Sulfur (ppm)***	***Density (g/mL)***
N3535 SWR		20.5	21.0	1.36	174	206	250	206	0.8206
N3535 SWL		20.3	20.8	1.46	174	207	250	239	0.8198
N429 WNR		20.3	20.7	1.98	173	204	248	412	0.8079
N429 WNL		20.2	20.6	1.92	173	203	248	419	0.8080
N435 WNR		19.6	20.0	0.92	179	205	243	132	0.8252
N435 WNL		19.7	20.0	0.98	179	206	244	125	0.8256
N695 SWR		22.8	23.4	1.99	172	206	252	352	0.8120
N695 SWL		22.6	23.2	1.88	173	206	252	355	0.8217

Carbon-Hydrogen Content

Test	Result	Units	Method	Date	Analyst
Sample Number: 161346-001	**Sample ID:**	**N353SW Jets 2**			**Sample Rcvd:**
Sample Date:	**Description:**				**3/31/2006**
Carbon/Hydrogen Content					
Carbon Content	85.89	WT %	ASTM D-5291	4/9/2006	KC
Hydrogen Content	14.11	WT %	ASTM D-5291	4/9/2006	KC
Sample Number: 161346-002	**Sample ID:**	**N429SW Jets 2**			**Sample Rcvd:**
Sample Date:	**Description:**				**3/31/2006**
Carbon/Hydrogen Content					
Carbon Content	85.29	WT %	ASTM D-5291	4/9/2006	KC
Hydrogen Content	14.71	WT %	ASTM D-5291	4/9/2006	KC
Sample Number: 161346-003	**Sample ID:**	**N435SW Jets 2**			**Sample Rcvd:**
Sample Date:	**Description:**				**3/31/2006**
Carbon/Hydrogen Content					
Carbon Content	85.70	WT %	ASTM D-5291	4/9/2006	KC
Hydrogen Content	14.30	WT %	ASTM D-5291	4/9/2006	KC
Sample Number: 161346-004	**Sample ID:**	**N695SW Jets 2**			**Sample Rcvd:**
Sample Date:	**Description:**				**3/31/2006**
Carbon/Hydrogen Content					
Carbon Content	85.25	WT %	ASTM D-5291	4/9/2006	KC
Hydrogen Content	14.75	WT %	ASTM D-5291	4/9/2006	KC

The fuels used in each aircraft were effectively equivalent.

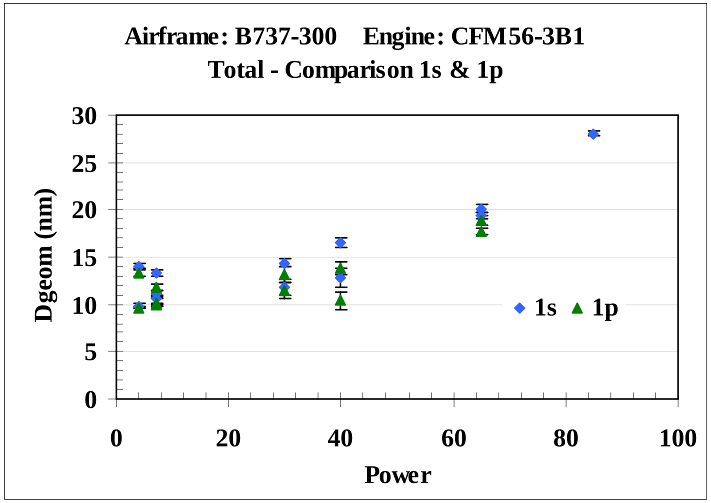
UMR Instruments

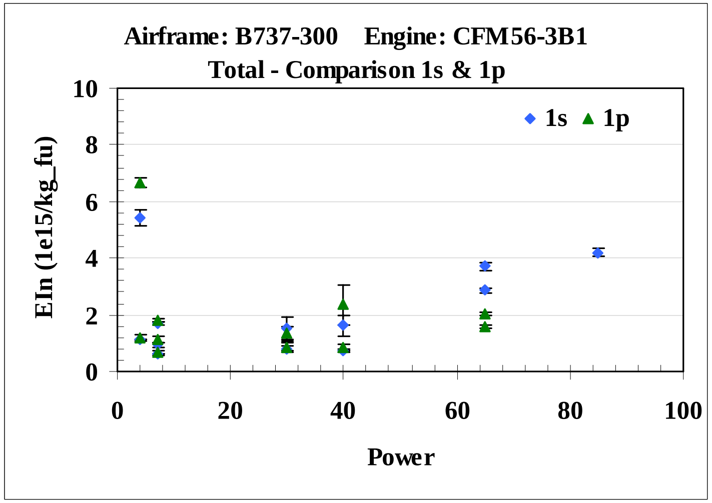


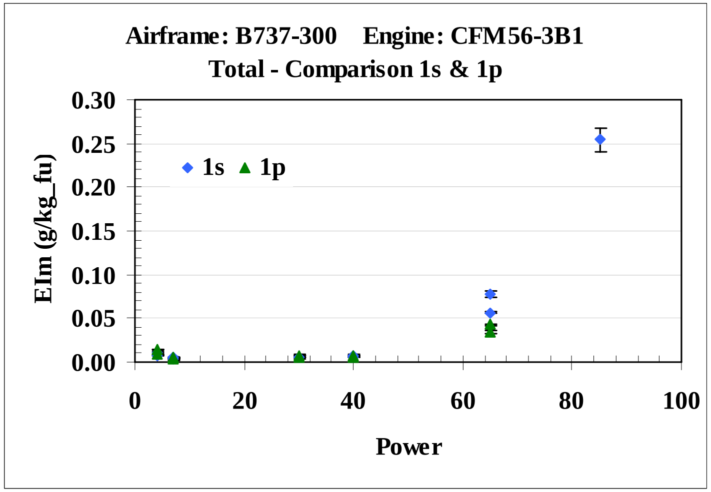
- Instrumentation
  - ✓ Cambustion DMS500 (2)
  - ✓ DMA
  - ✓ TSI CNC
  - ✓ CO_2 detector
  - ✓ Weather station

- Parameters measured (total and non-volatile aerosol)
  - ✓ Dgeom – number based geometric mean diameter
  - ✓ Sigma – geometric standard deviation
  - ✓ Dgeom M – mass (volumetric) based geometric mean diameter
  - ✓ EIn – number based emission index
  - ✓ EIm – mass based emission index

Total aerosol – 1m (s and p)

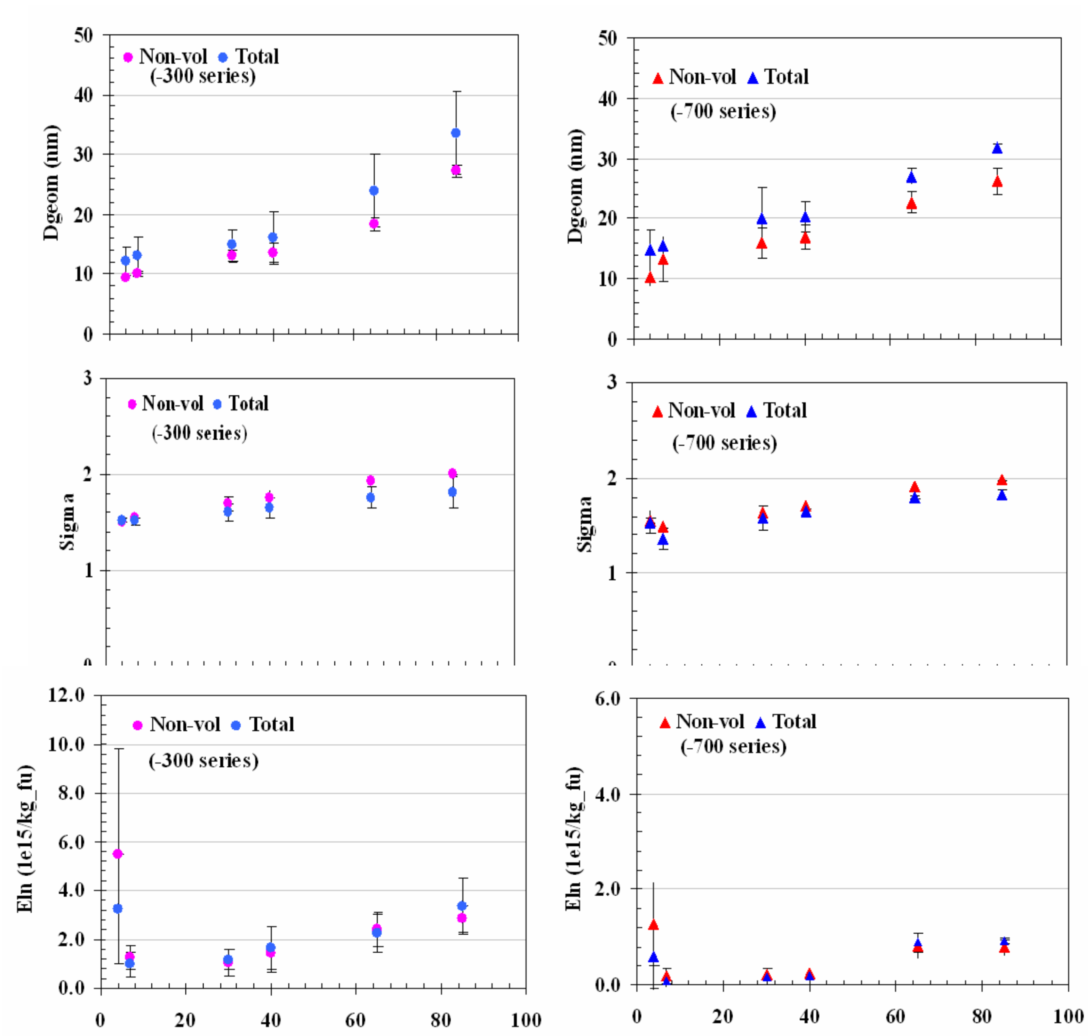






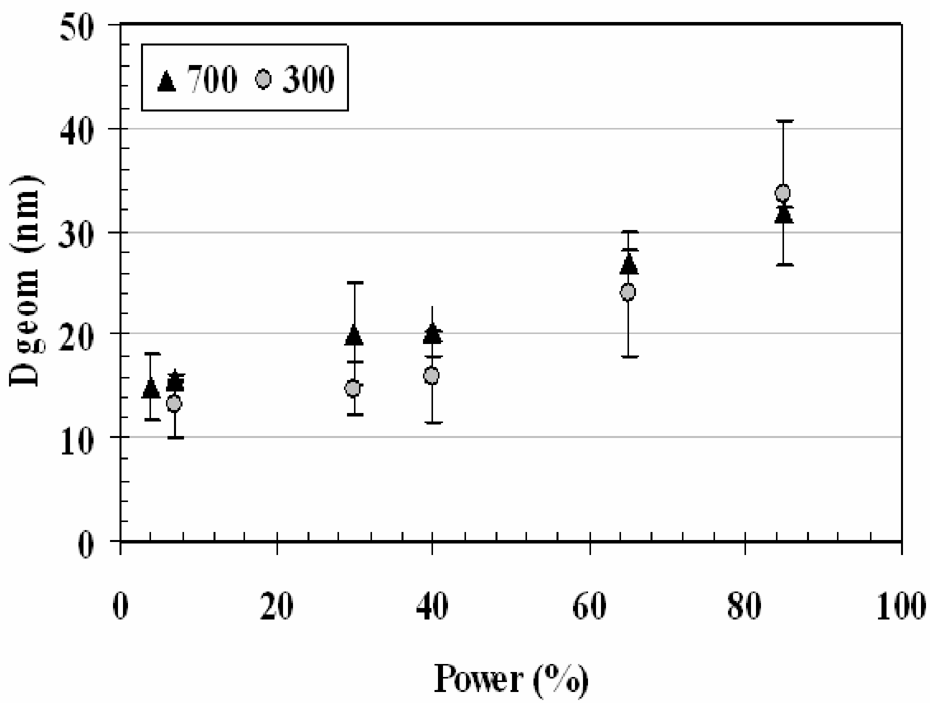
First time two engines sampled simultaneously with "equivalent" sampling systems.

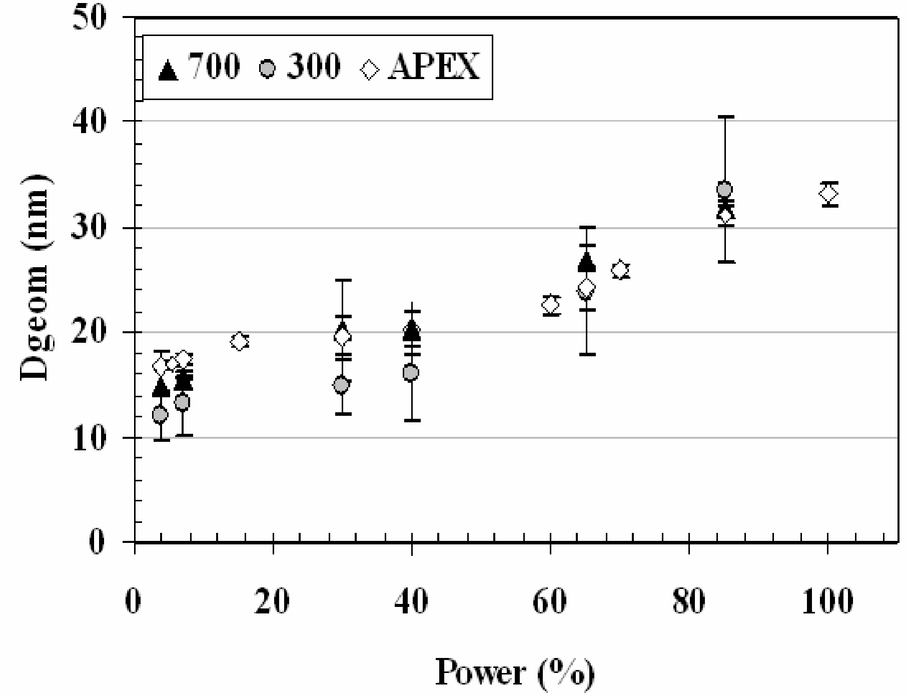
Comparison of total and non-volatile data at 1m



The good agreement between the total and non-volatile data at 1m confirms there is no gas to particle conversion occurring in sampling lines.

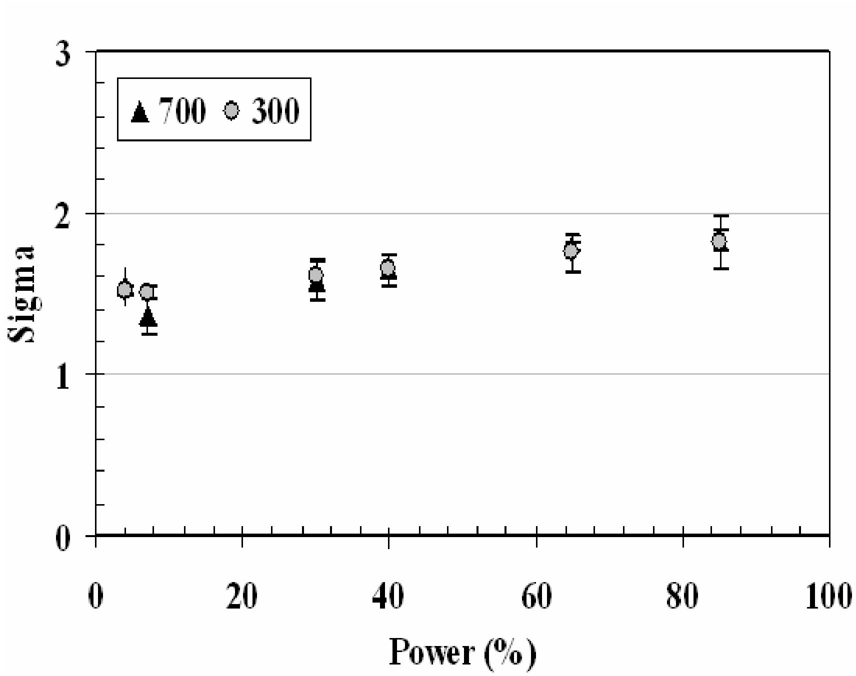
Number based Geometric Mean Diameter (Dgeom) at 1m.

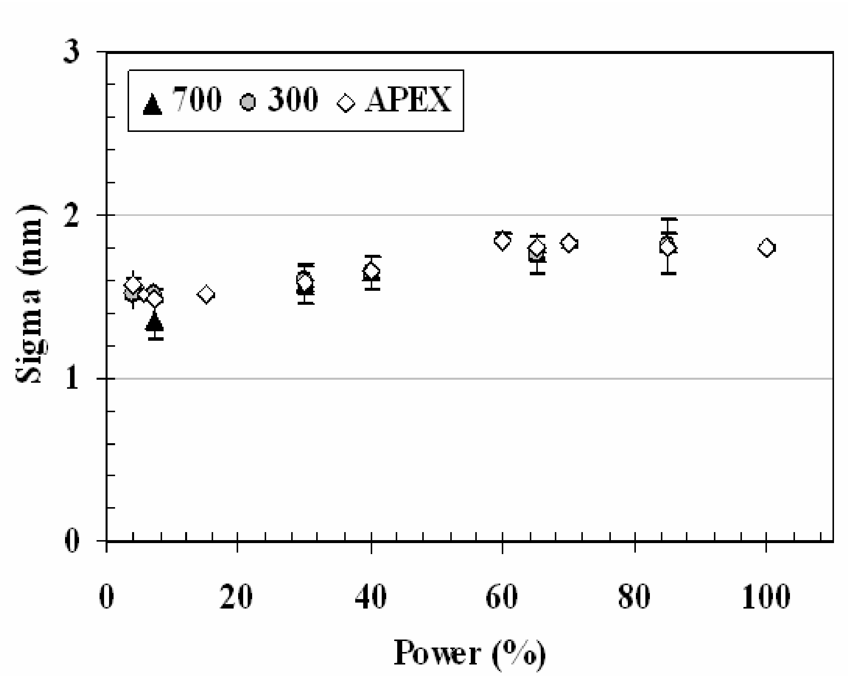




- Both 700 and 300 engine types demonstrate an increase in Dgeom with power.
- No statistically significant difference between engine technologies is discernable since for all data points the error bars overlap.
- CFM56-2C1 engine studied in APEX1 exhibits similar trends.

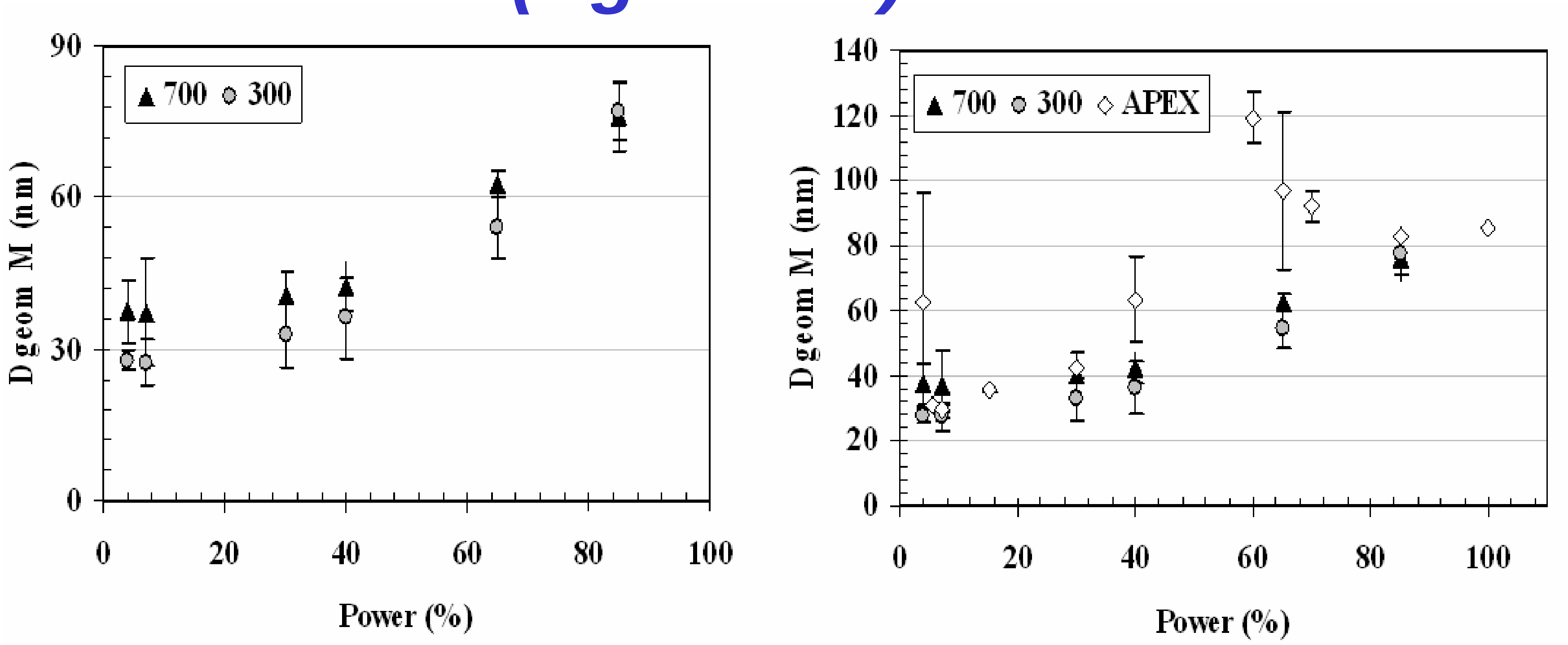
Geometric Standard Deviation (Sigma) at 1m





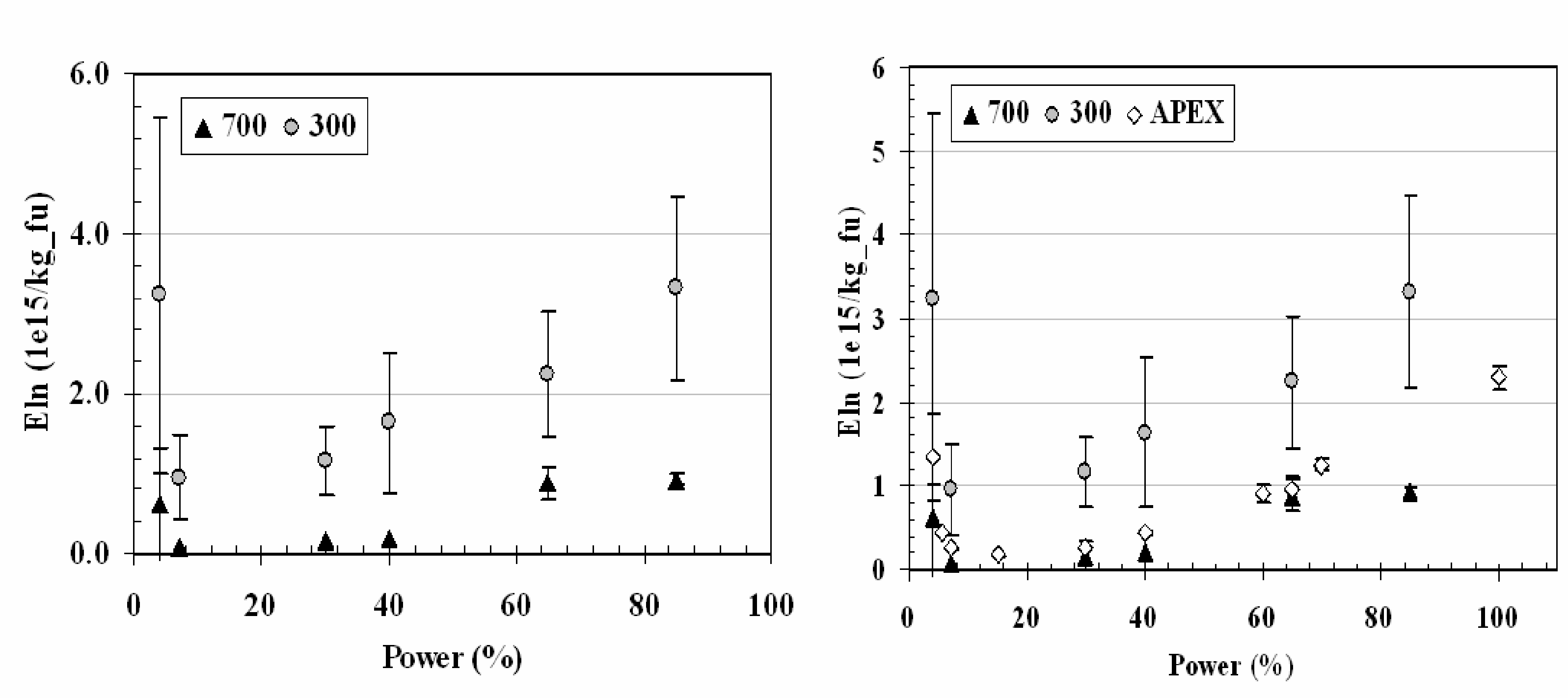
- Both engine types demonstrate a weak positive trend with power.
- No statistically significant difference between engine technologies is discernable.
- CFM56-2C1 engine studied in APEX1 exhibits a similar trend.

Mass based Geometric Mean Diameter (Dgeom M) at 1m.



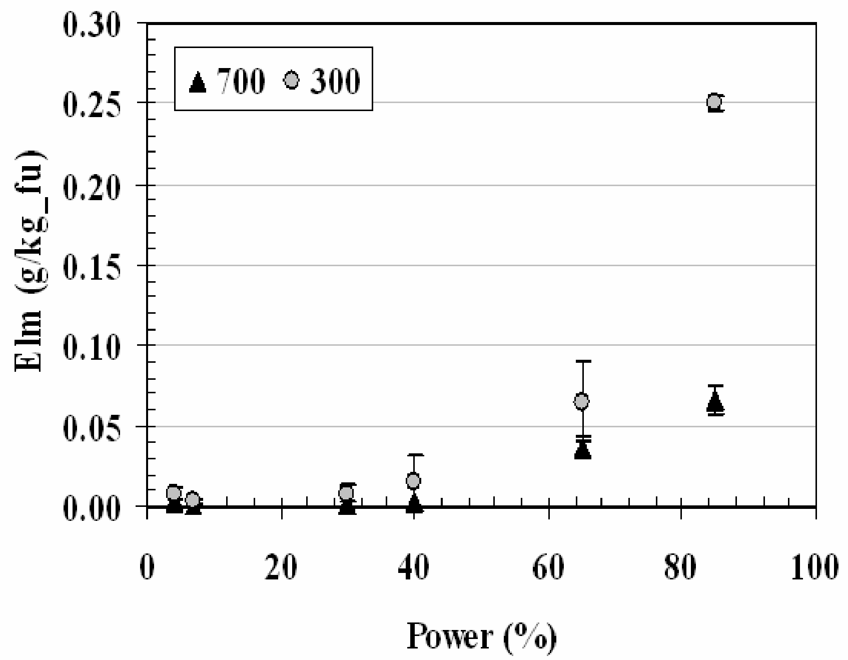
- Both engine types demonstrate an increase with power.
- No statistically significant difference between engine technologies is discernable.
- This is not the case when comparison is made to the even older technology engine (CFM56-2C1) data from APEX1.
- On average, the DgeomM value for the CFM56-2C1 engine exceeds that for the engine studied in JETS APEX2 by ~60%.

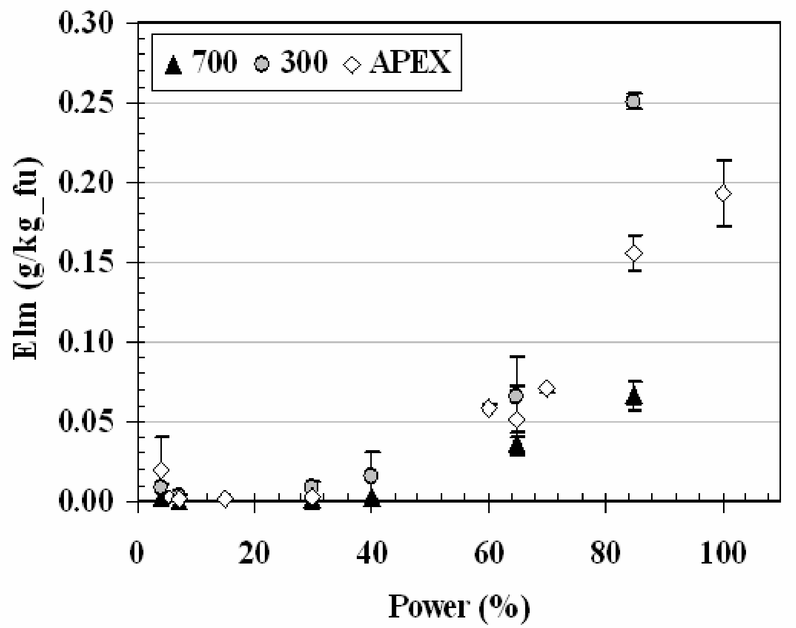
Number based Emission Index (EIn) at 1m



- Both engine types demonstrate a minimum ~ 20% power.
- The new technology engines (700) produce fewer particles per kilogram of fuel burned. This difference is large and statistically significant. Averaged across all powers, this difference represents a (79 ± 12) % reduction in number-based emissions normalized to fuel flow.
- EIn for the APEX1 engine falls between those of the -300 and -700 series and the differences between all engines are statistically significant at higher powers.

Mass based Emission Index (EIm) at 1m

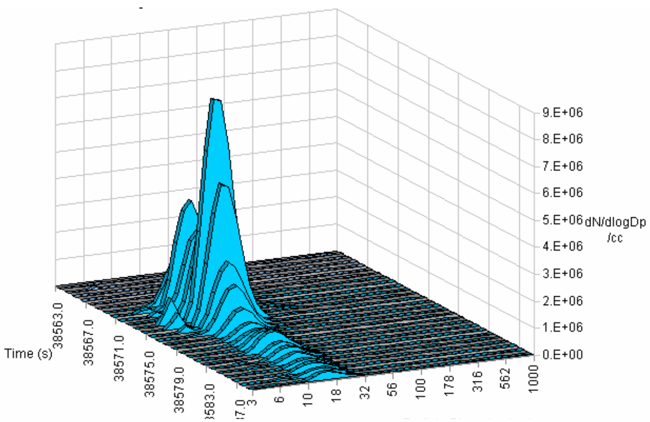


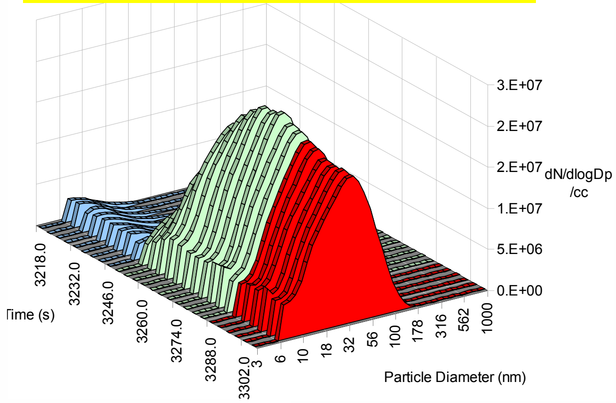


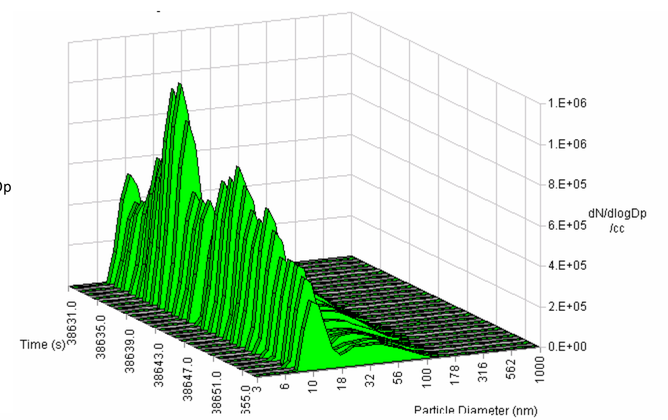
- Mass-based emission index exhibited a trend to increase with power.
- The trend is stronger for the older engine technology (-300 series).
- There is a large and statistically significant difference at high power representing a 72% reduction in mass-based emissions normalized for fuel flow at 85% power.
- CFM56-2C1 engine studied in APEX1 exhibited a similar trend to the -300 series.

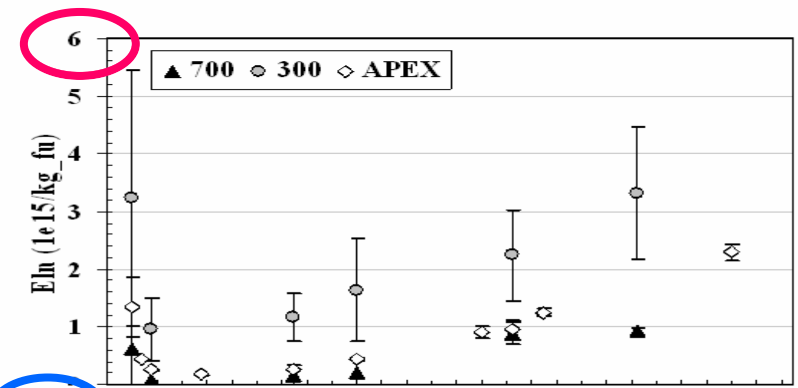
7% Taxi 50m | Spool Up 7-85% 1m | 85% Take Off 50m

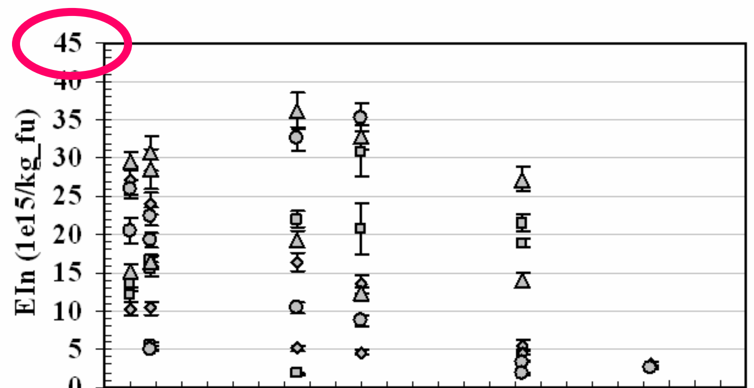
B737-300, CFM56-3B1

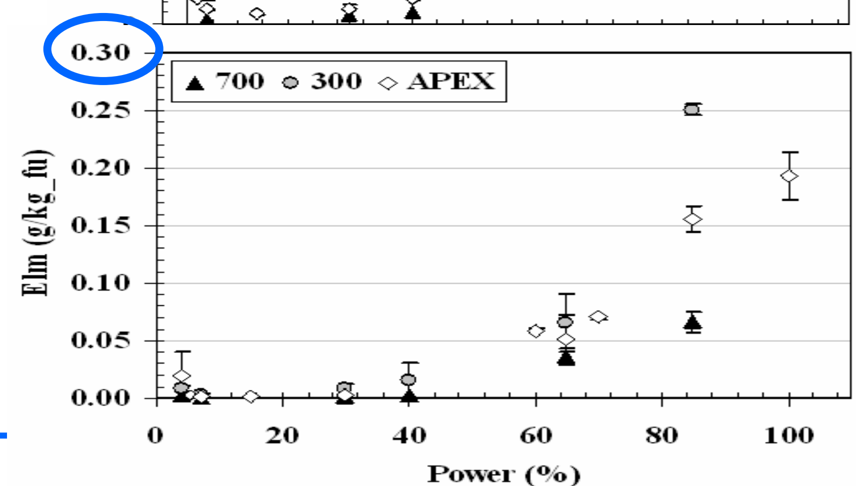


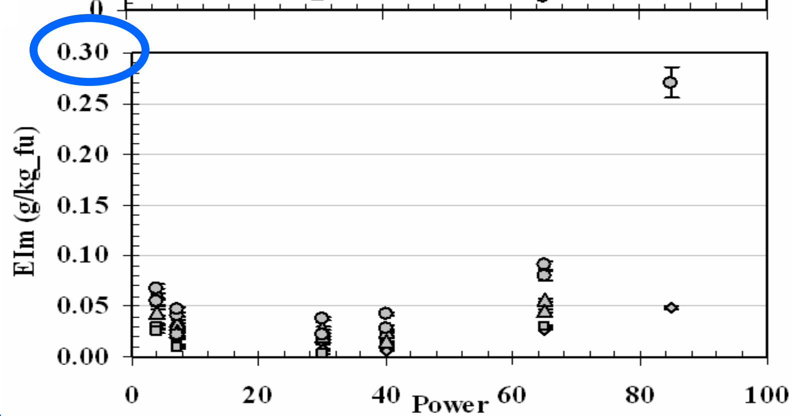






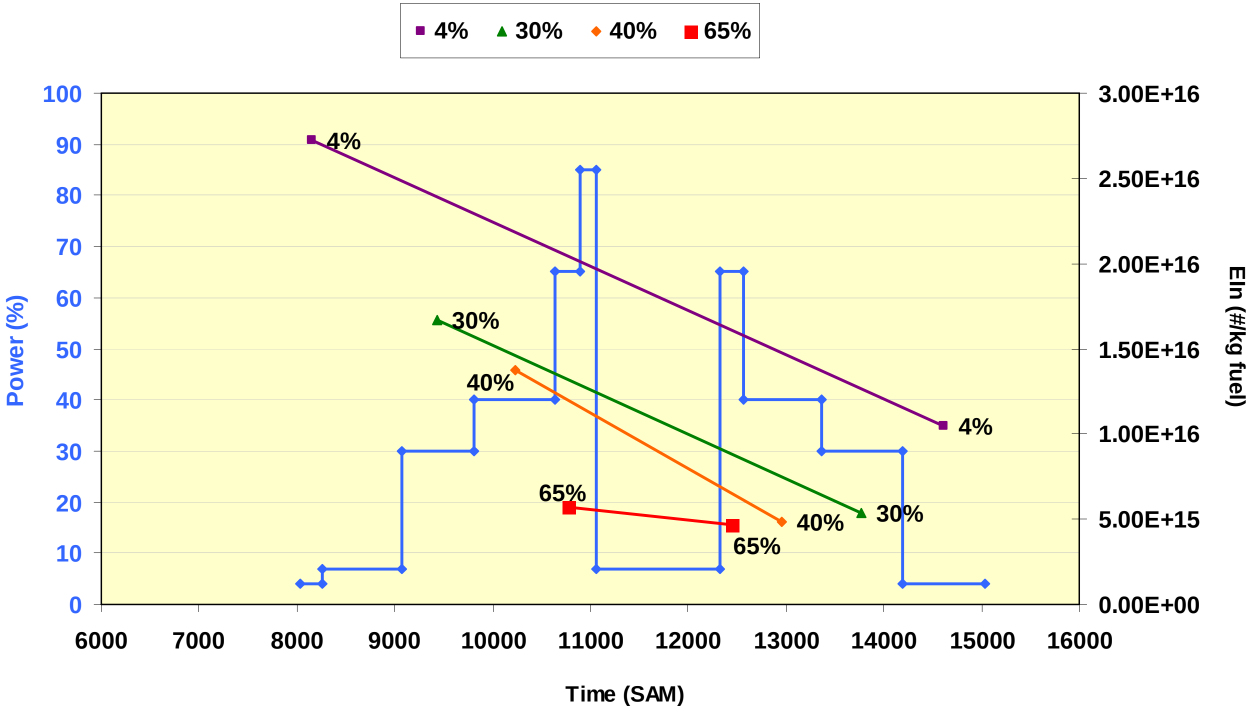






Engine Warm Up Effect

N435WN 737-700 CFM 56-7B22



Emissions taken at the same engine operating power (4%), were separated in engine on-time by a period of ~100 minutes.

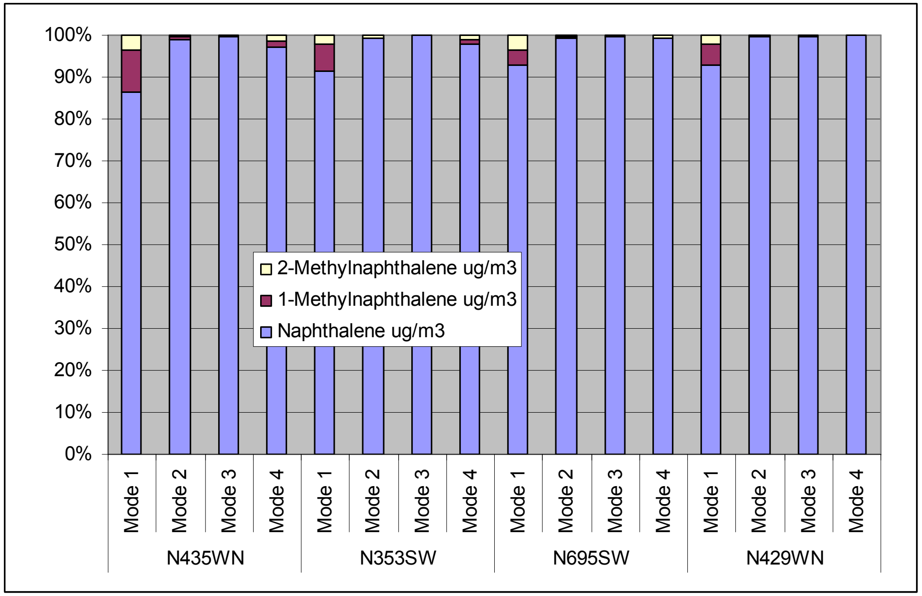
The difference in EIn at 4% represents a 63% reduction in number-based emissions normalized to fuel flow.

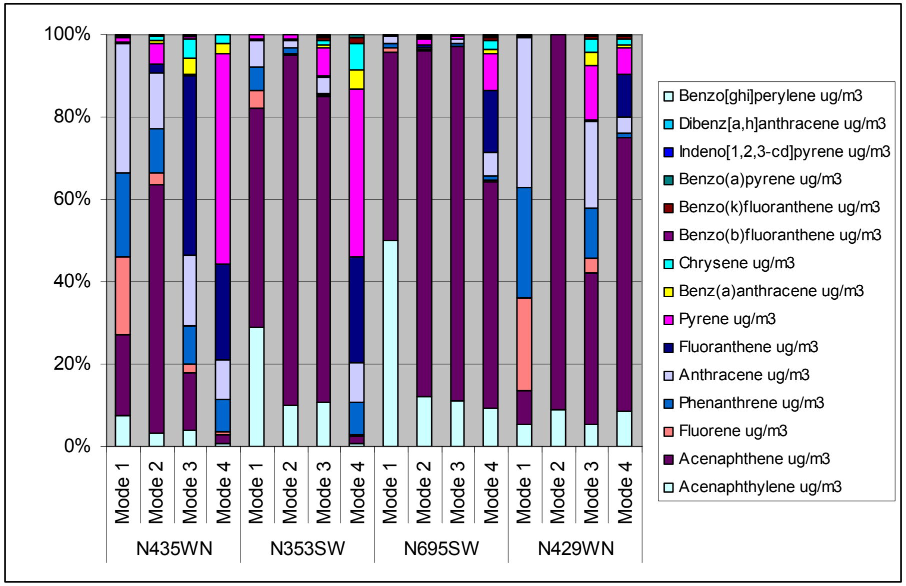
Dedicated Engine Tests

Filter Sampled TOG Studies by UCR

UCR Measurements

- Measurement of TOG, PM mass, metals and ion concentrations were conducted on the exhaust products collected on filter membranes by the University of California - Riverside Center for Environmental Research and Technology.
- The analytical methods employed are considered standard methods for such measurements and are described in detail in the methodology sections of the report.
- After the field campaign was completed, analysis of the DNPH cartridges and SUMMA canisters revealed anomalous CO2 concentrations which were attributed to a leak in a sub-system of the sampler.
- Also, C4-C12 hydrocarbon values based on the concentrations measured from the Thermal Desorption Tubes (TDS) were much lower than expected from APEX and other research.
- Since this leak introduced an unquantifiable dilution in these sub-systems, the emission factors for the light hydrocarbons and carbonyls could not be calculated.





The Naphthalenic PAHs

- The relative distributions of the substituted naphthalenes to non-substituted naphthalenes for the idle modes are in general agreement with the work from Spicer et al.1992, 1994.

- There was a sharp decrease in the relative contribution of substituted naphthalenes at the higher load points.

- Trends in the non-naphthalenic compounds:
  - ➢acenaphthylene, present significantly only in the idle mode
  - ➢fluoranthene decreasing with increasing power.

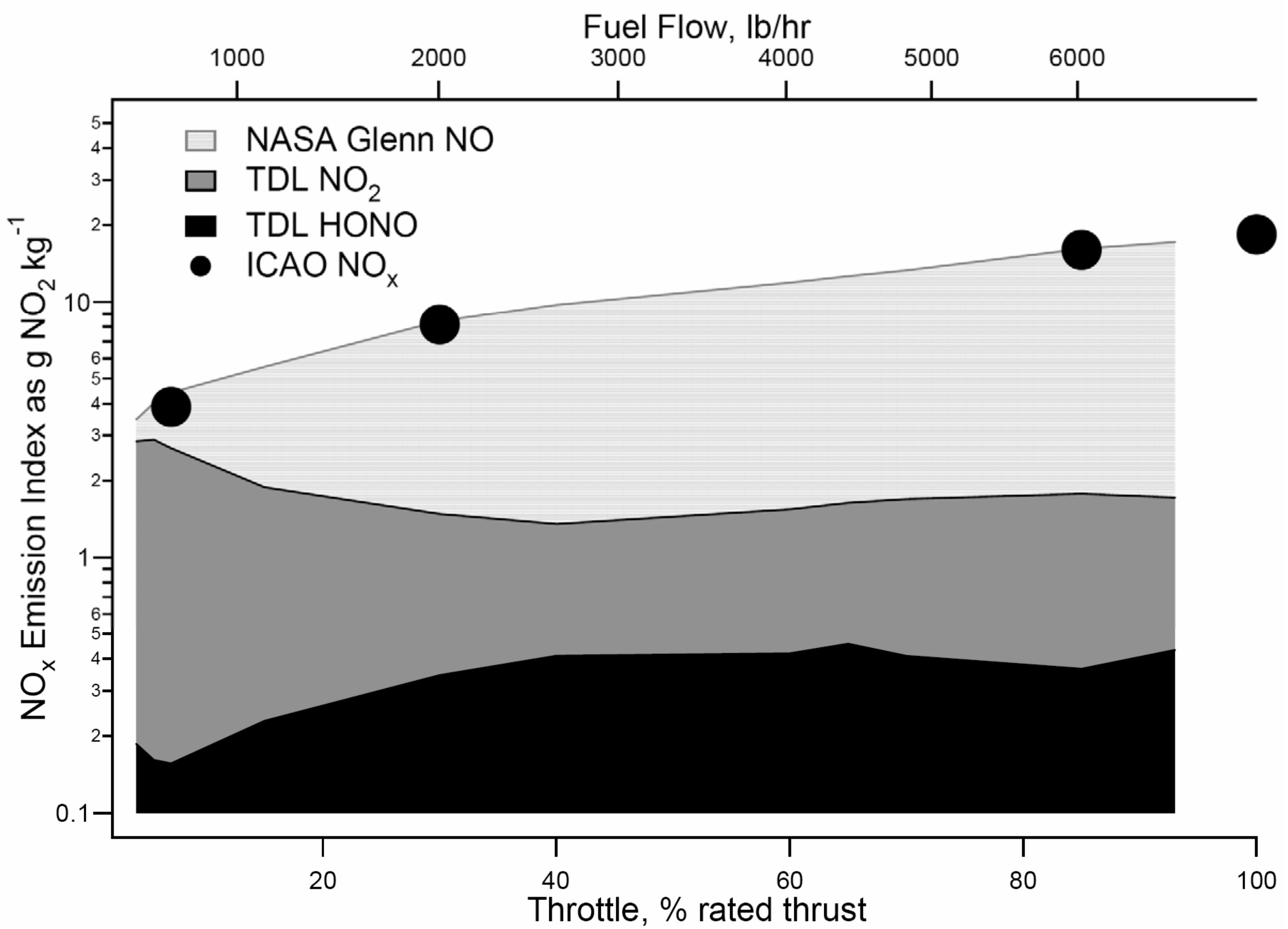
Summary of UCR qualitative Results

- **Organic gases and aerosol chemical speciation**
- With respect to Chromium (VI), results were not significantly different to ambient concentrations.
- The variability in the metal distributions was much greater between engines than between engine loads.
- The mass of the ions collected on the Teflo filter were so low that only sulfate ions were above the detection limits of the instrument. In the case of the sulfate, the extracted ions (<1 ppm in water) were very close to the lower detection limit of the instrument.
- Due to a leak in a sub-system of the sampler emission factor calculations could not be performed since any dilution taking place in these filter media were no longer quantifiable.
- Only the mass concentration of species was measured.
- The major three contributors to the carbonyl emissions are formaldehyde, acetaldehyde, and acetone.
- Formaldehyde and acetaldehyde are most dominant carbonyl species in the aircraft exhaust emissions.
- .

Dedicated Engine Tests

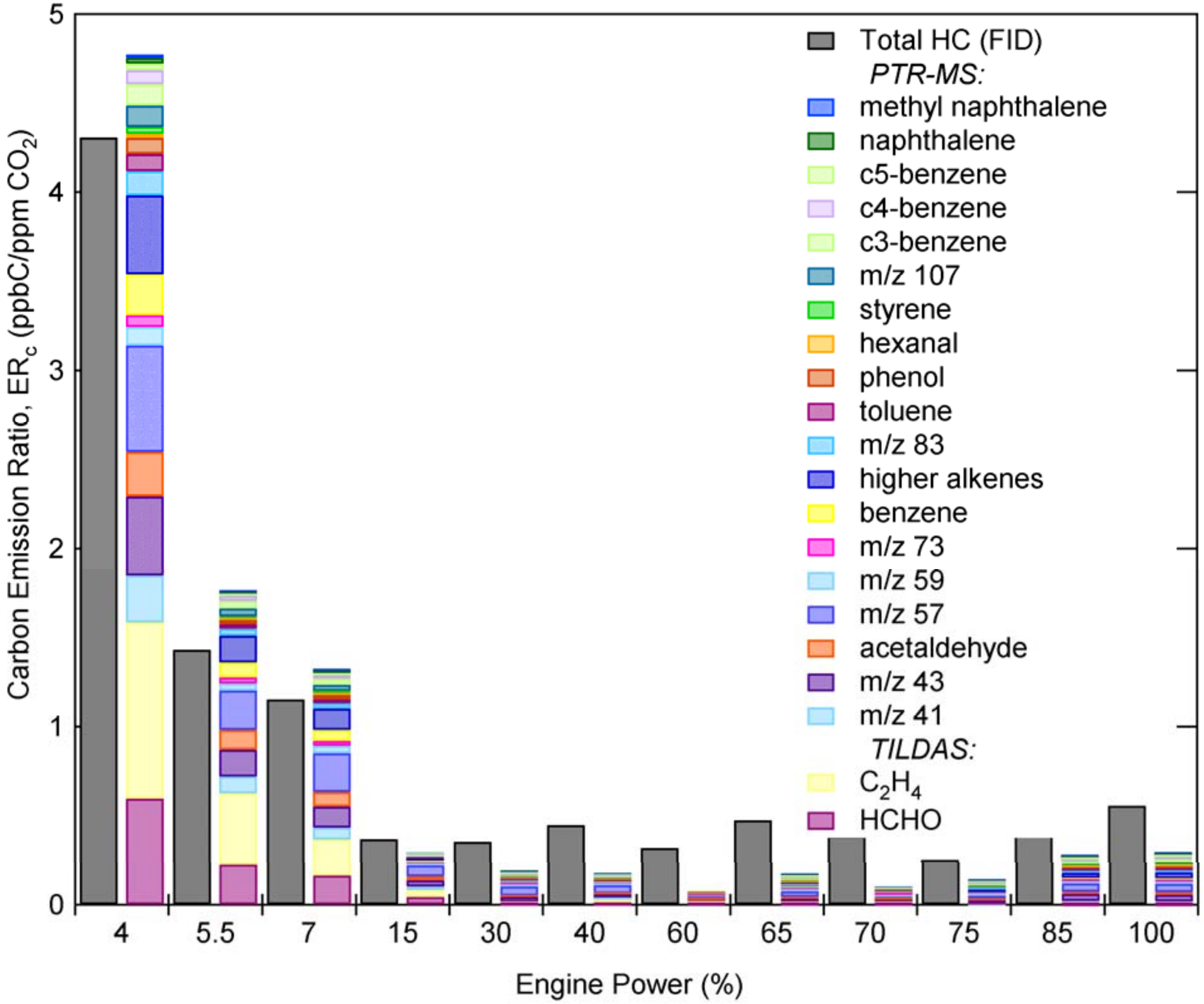
Combustion Gases, HAPS and PM composition

Composition of NO_y: (note log scale)



APEX results: Wormhoudt et al., JPP 2007

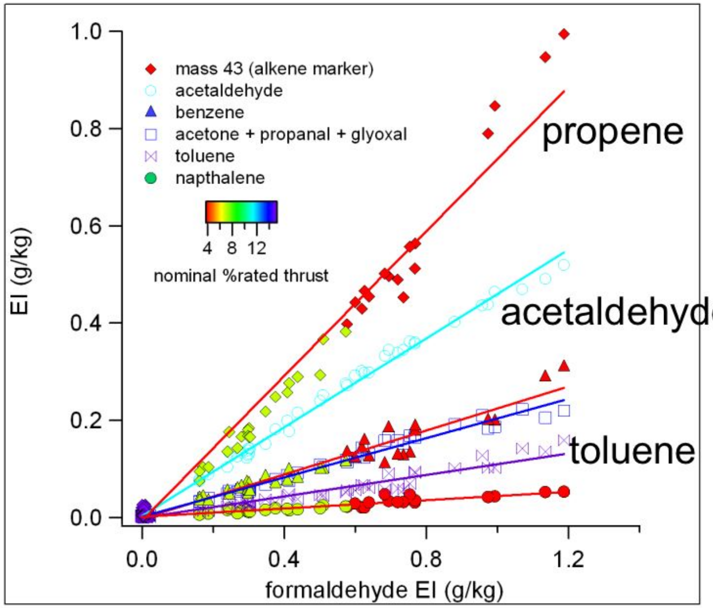
Composition of hydrocarbon emissions



APEX results: Yelvington et al., JPP 2007

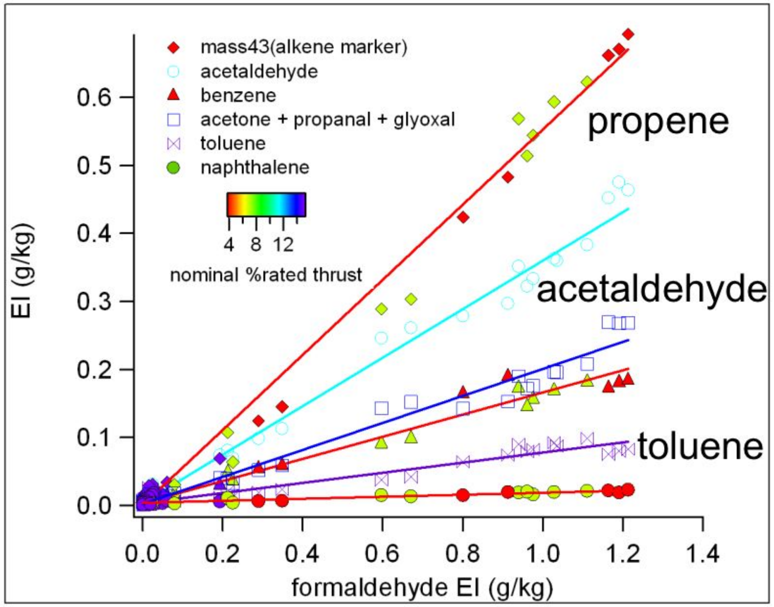
Compound Emissions Scaling – variety of compounds

APEX 2



Includes 4 B737s.

APEX 3



Includes 1-B737, 2-B757, 1-A300.

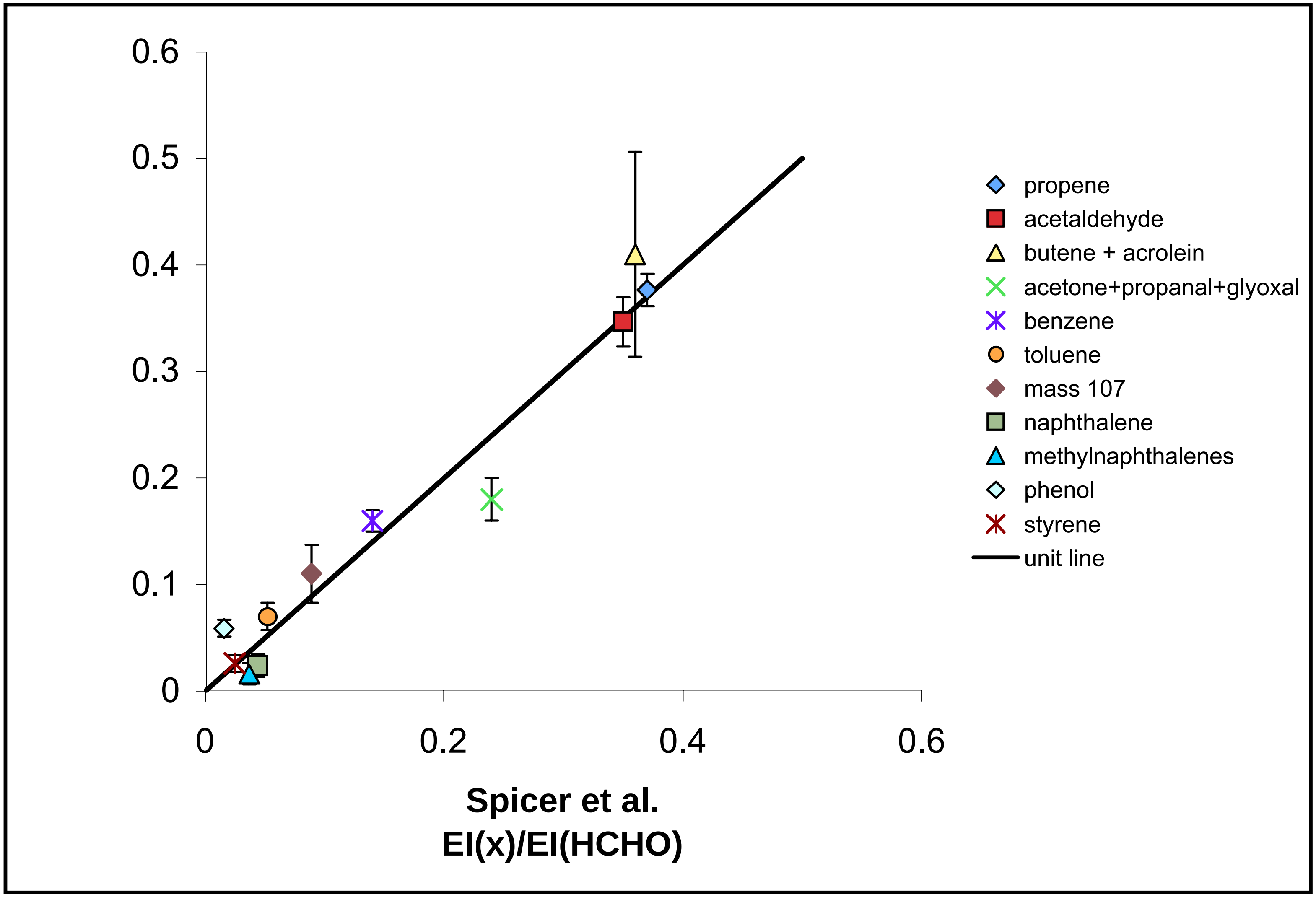
NMHC ERs for CFM56-3 Spicer et al.

Compound	ER (mmole/mole)	Compound	ER (mmole/mole)	Compound	ER (mmole/mole)
Ethylene	0.77	acetone	0.0089	1-nonene	0.0027
formaldehyde	0.572	C5-ene	0.0072	Propane	0.0025
Acetylene	0.211	2-methylpentane	0.0066	1-CH_3-naphthalene	0.0024
Propene	0.151	benzaldehyde	0.0062	Hexanal	0.0023
acetaldeyde	0.135	1-heptene	0.0061	C5-cyclohexane	0.0023
Acrolein	0.061	naphthalene	0.0059	Ethylbenzene	0.0023
1-butene	0.044	C5-ene	0.0055	C4-benzene	0.0023
Glyoxal	0.044	cis-2-butene	0.0052	o-xylene	0.0022
1,3-butadiene	0.044	styrene	0.0041	2-CH_3-naphthalene	0.0020
Benzene	0.03	n-undecane	0.0040	C5-benzene	0.0020
methylglyoxal	0.029	n-pentane	0.0038	1-decene	0.0018
Ethane	0.024	n-dodecane	0.0038	C13-alkane	0.0014
butanal/croton aldehyde	0.019	m,p-xylene	0.0037	C14-alkane	0.0013
Propanal	0.017	2-methyl-2-butene	0.0037	n-heptane	0.0009
1-pentene	0.015	1-octene	0.0034	n-octane	0.0008
1-hexene	0.012	n-decane	0.0031	n-nonane	0.0007
Toluene	0.0097	phenol	0.0029	C12-C18 alkanes	0.0045

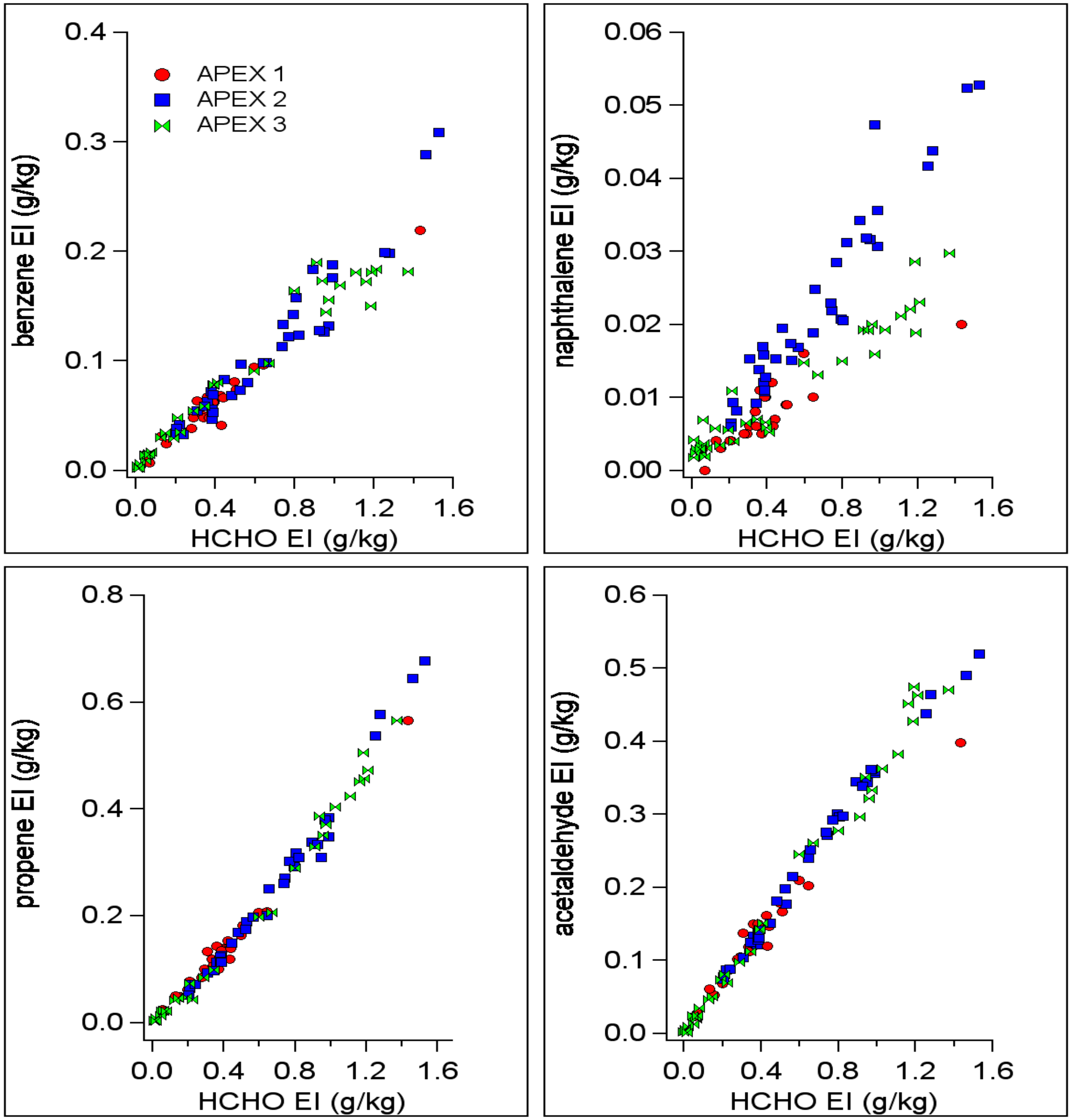
EI_x/EI_{HCHO} for 4-15% rated thrust

Compound	APEX 1 EI_x/EI_{HCHO}	APEX 2 EI_x/EI_{HCHO}	APEX 3 EI_x/EI_{HCHO}	Spicer et al. EI_x/EI_{HCHO}
Methanol	0.18	0.14	0.12	--
Propene	0.36	0.39	0.38	0.37
Acetaldehyde	0.32	0.36	0.36	0.35
butene + acrolein	0.30	0.45	0.48	0.36
acetone + propanal + glyoxal	0.18	0.16	0.20	0.24
Benzene	0.15	0.17	0.16	0.14
Toluene	0.056	0.082	0.073	0.052
mass 107	0.088	0.138	0.103	0.089
mass 121	0.074	0.119	0.085	--
mass 135	0.035	0.074	0.051	--
mass 149	0.014	0.038	0.027	--
Naphthalene	0.018	0.034	0.020	0.044
methylnaphthalenes	0.009	0.023	0.016	0.037
dimethylnaphthalenes	0.0026	0.011	0.0083	--
Phenol	0.063	0.064	0.050	0.016
Styrene	0.020	0.035	0.023	0.025
acetic acid	0.16	0.057	0.084	--

Normalized EIs: APEX vs Spicer et al.



Selected HCs vs HCHO EIs (4-15%)



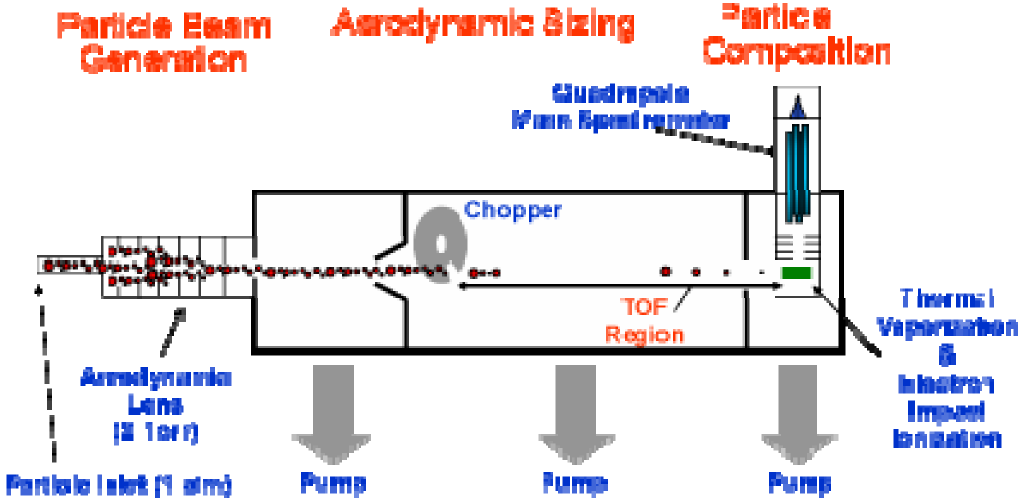
Summary for HAPs

- Excellent agreement with Spicer
  - Difficulties in capturing all HC species
- *Robust speciation profile across engines!*
  - Dependence on fuel/ambient T for lesser species?
- Dependence on power is significant at low powers (also ambient T!)
- Significance for developing inventories
  - Limits of ICAO-type canonical LTO cycle
  - Need realistic cycle, ambient conditions

Aircraft Volatile PM in Context

- Combustion-generated carbonaceous (soot) particles: “Non-volatile Particles” (refractory)
- Condensable species
  - Sulfate (H_2SO_4 from fuel sulfur)
  - Low vapor pressure HCs (large molecules, oxygen-containing species)
  - Vaporized lubrication oil (*c.f.*, diesel particles)
- Microphysical processing in plume (*and probe!*)
  - Nucleation of new particles
  - Condensation both on newly nucleated embryos and on carbonaceous particles
  - *(Interaction with background aerosol)*

Particle Chemical Composition Measurements:



- **Aerosol Mass Spectrometer (AMS)**
  - Non-refractory chemical composition: Mass spectra (1 to 300 amu) averaged 15 s.
  - Vacuum aerodynamic diameter: Chemically-speciated ToF (30 nm to 1000 nm) averaged 15 s.

Volatile

- **Multi-Angle Absorption Photometer (MAAP)**
  - Black carbon mass measurements with 1 s time resolution.

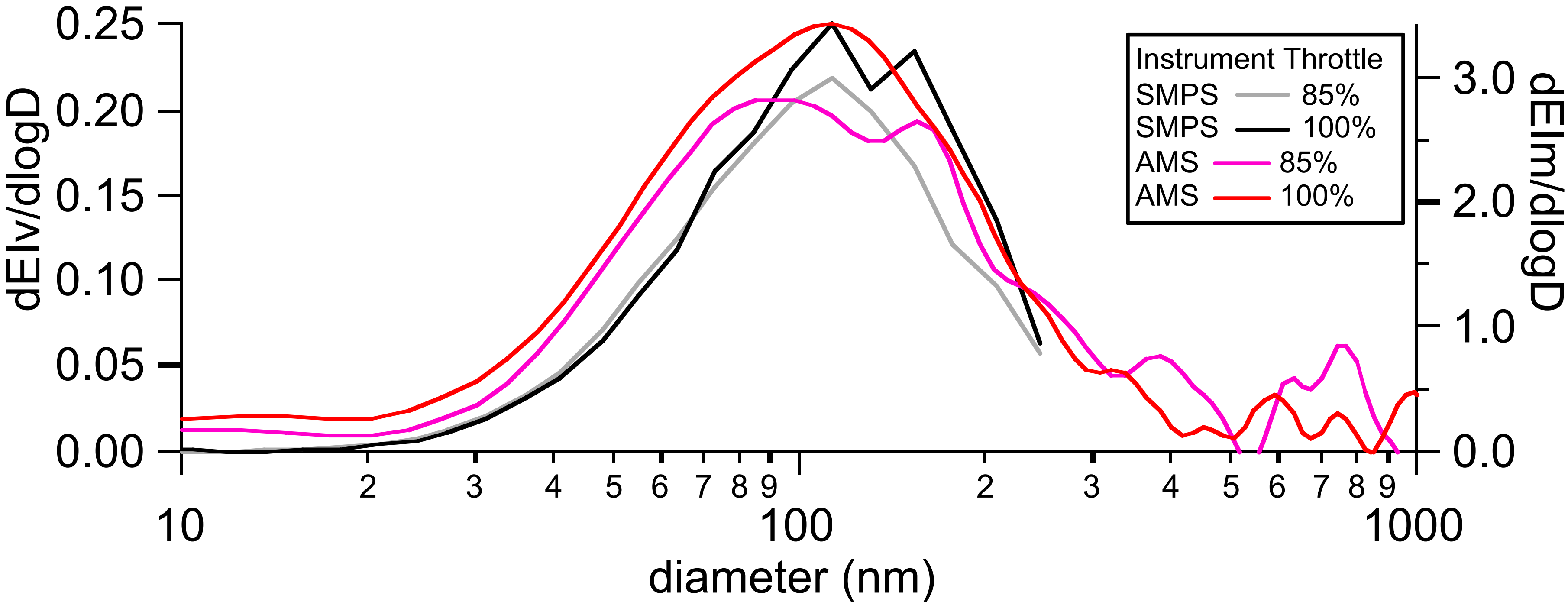
Non-volatile

- **Condensation Particle Counter (CPC)**
  - Particle number concentration measurements (>7 nm) with 1 s time resolution.
- **Differential Mobility Analyzer (DMA)**
  - Particle size and volume distributions

Size Distributions

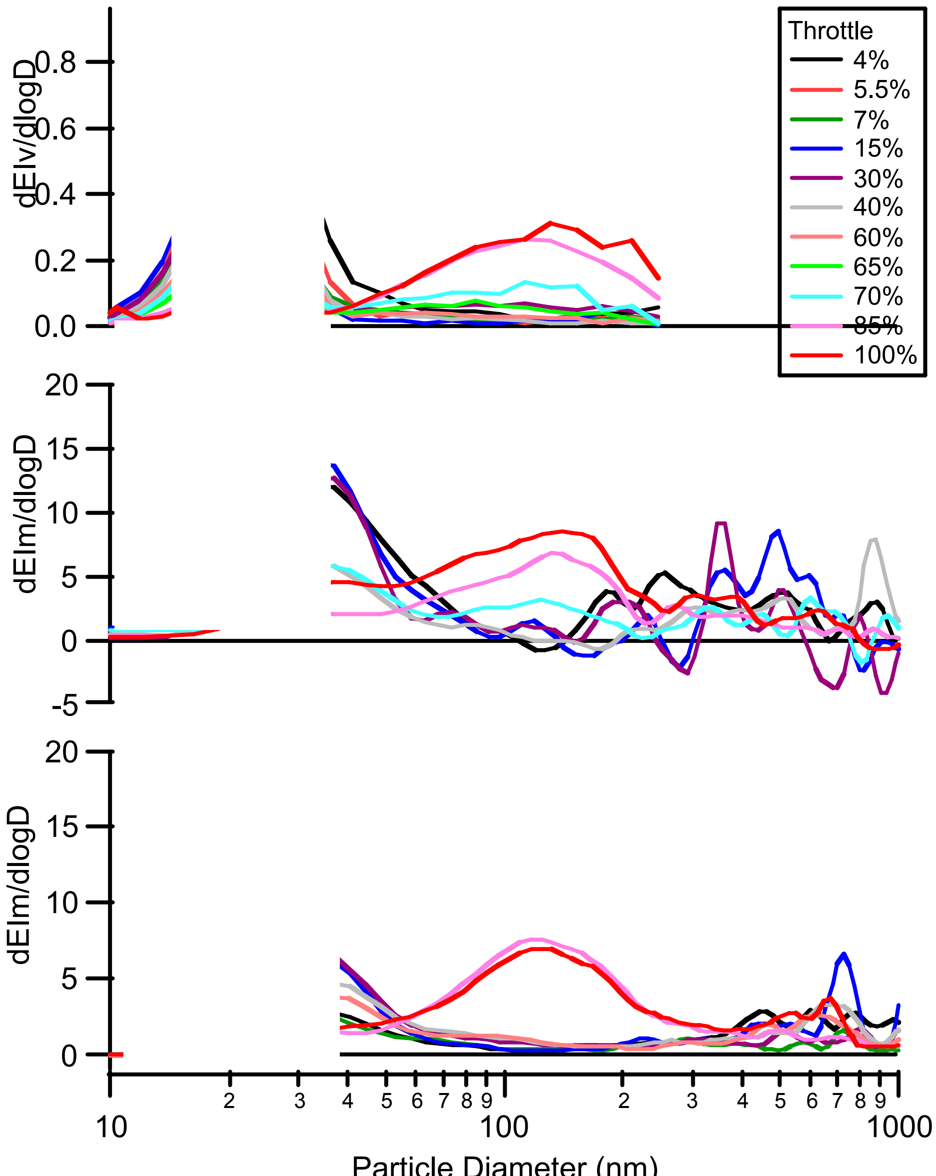
Comparison of AMS, SMPS at 1 m

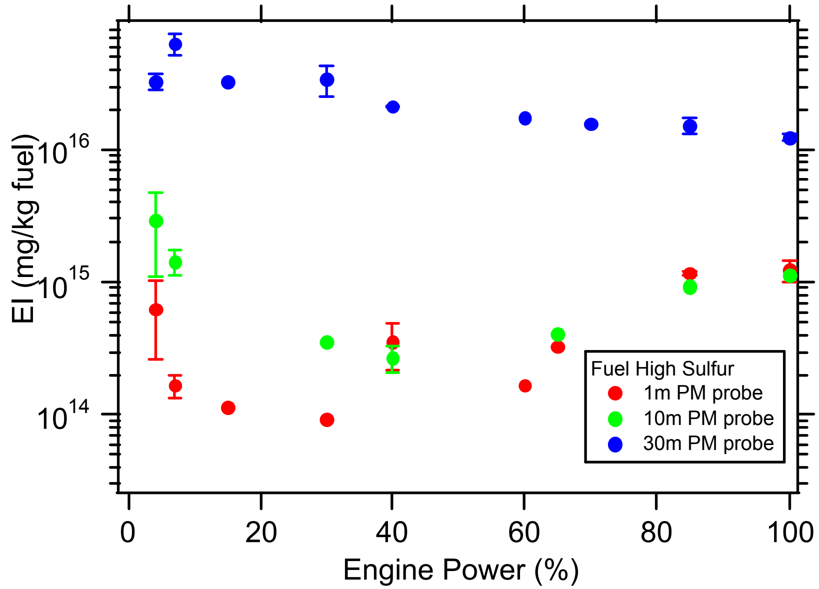
APEX 1 m probe data: high aromatic fuel



APEX results: Onasch et al., to be submitted to JPP

Condensed Mass: 'Total', organic, SO_4





↑APEX # EIs: high aromatic fuel

←APEX 30 m probe data

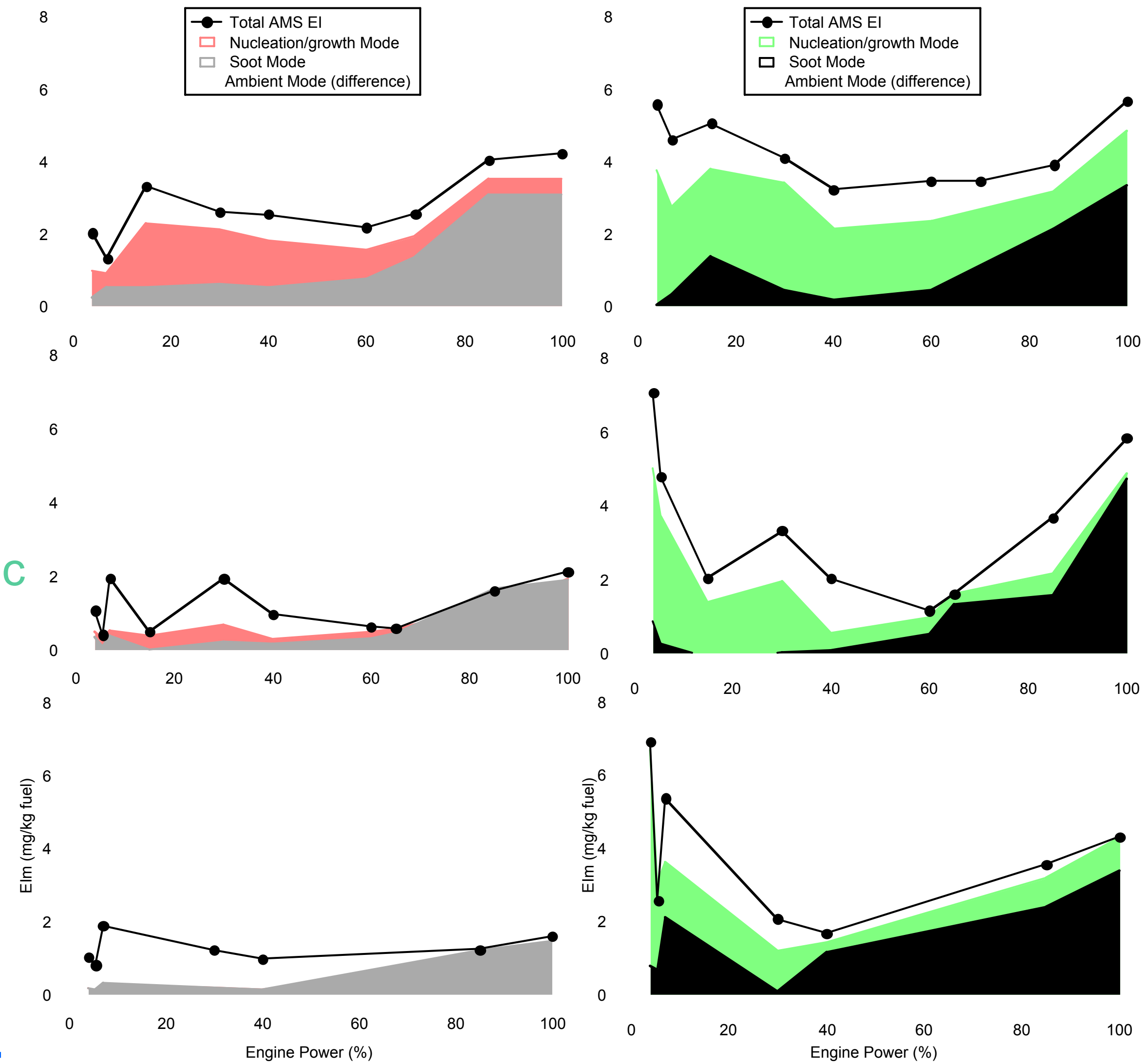
APEX results: Onasch
et al., to be submitted to JPP

Sulfate (lft) and organic (rt) contributions

High Sulfur

High Aromatic

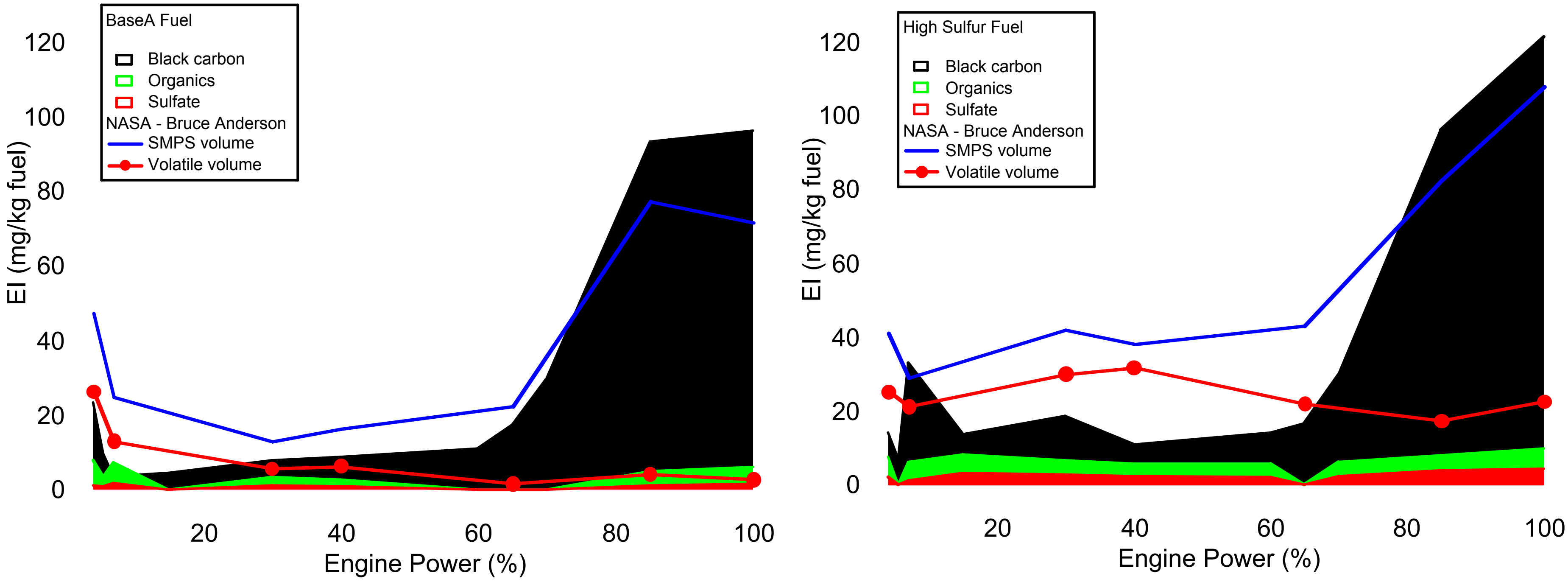
Base Fuel



APEX results: Onasch et al., to be submitted to JPP

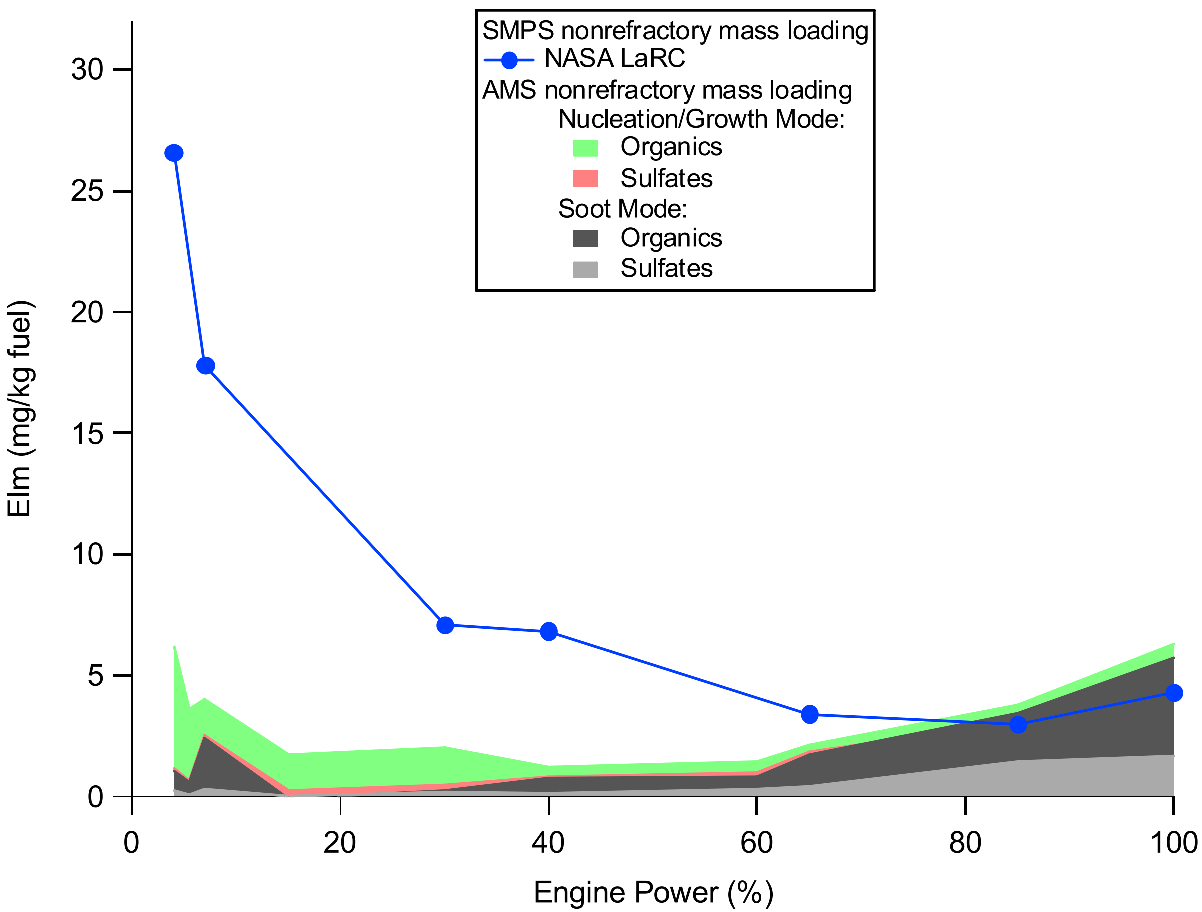
Composition of particle emissions

APEX 30 m probe data: base fuel and high sulfur fuel



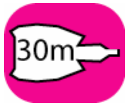
APEX results: Onasch et al., to be submitted to JPP

Volatile Components

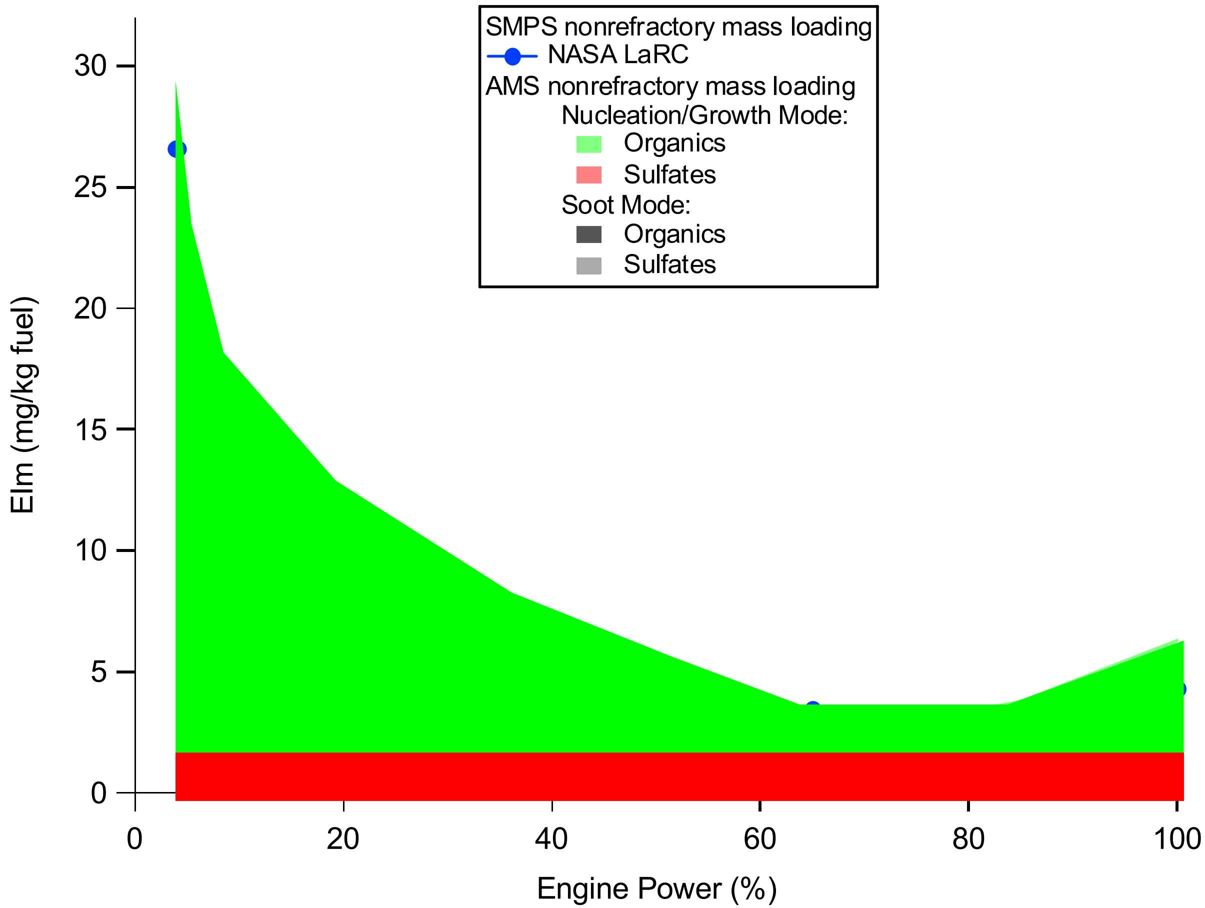


- Reasonable quantitative agreement between AMS mass and volatile SMPS volume at engine powers greater than 80% - insignificant nucleation mode

- Assume that S^{IV} to S^{VI} conversion does not change significantly with engine power – use AMS Sulfate EIm at high engine power



Volatile Components



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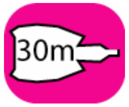
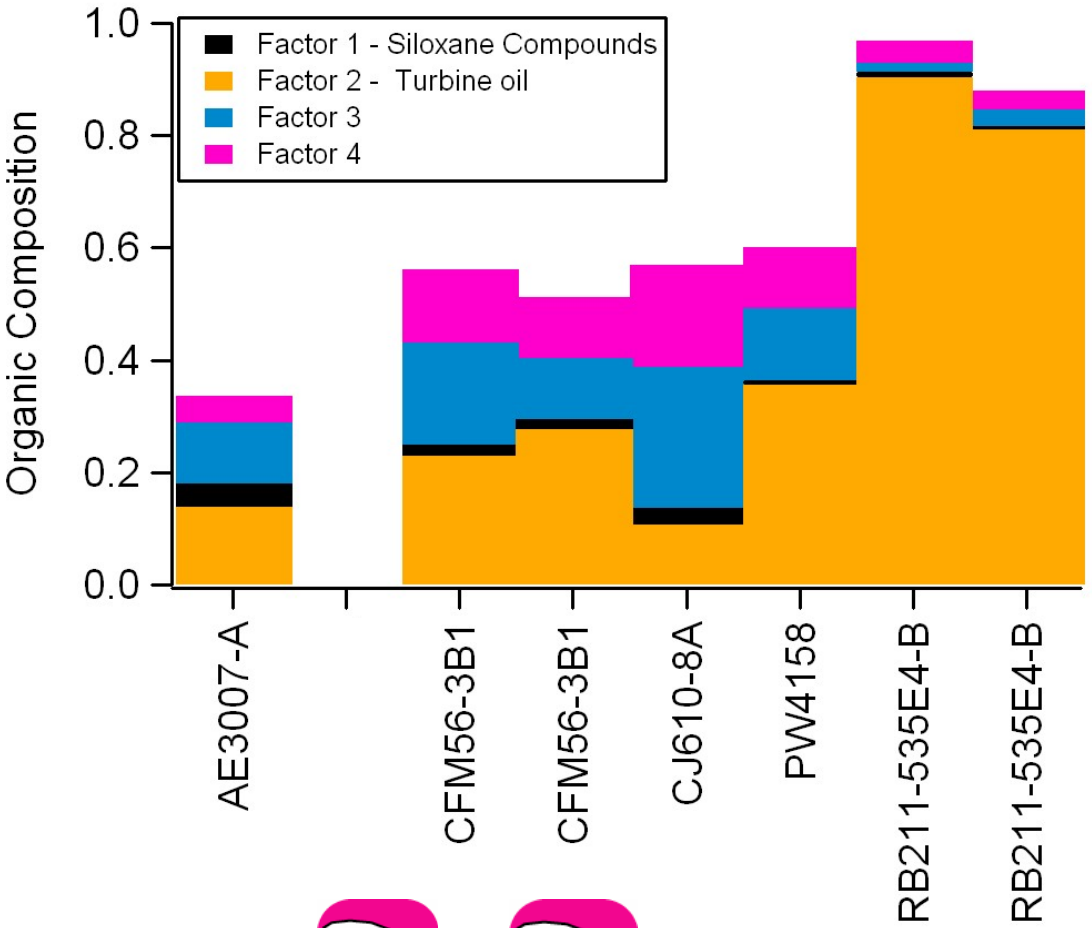


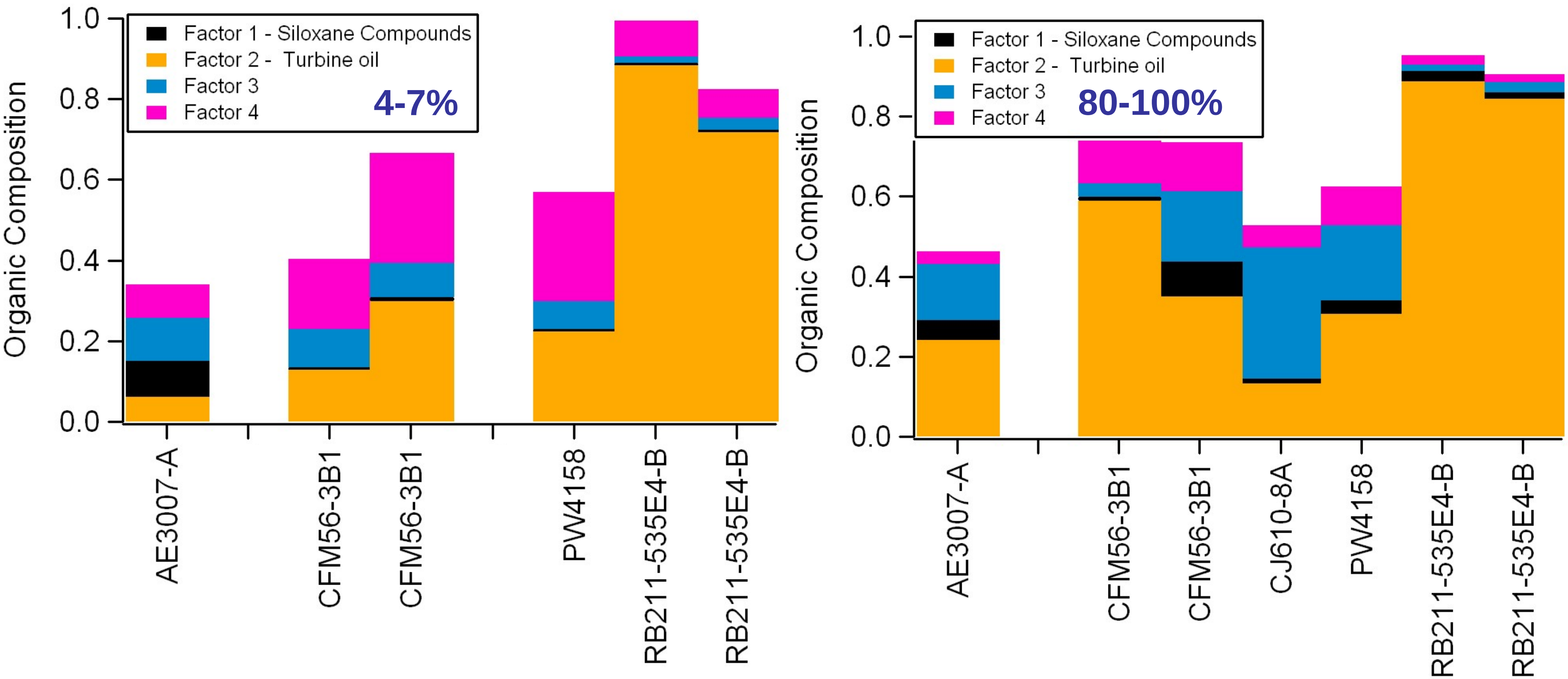
- Dominated by organics at low engine power and low fuel sulfur content

APEX3 PMF Analysis
Downstream Probes (30-43 meters)

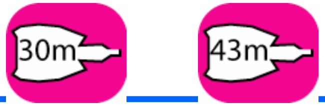


- First 2 factors account for 10-40% of condensable organic compounds measured for all but RB211 engines
- RB211 organic PM engine exhaust is dominated (80-90%) by the "EXCAVATE" specific turbine oil
- Factors 3, 4, and residual signals have not been positively identified
- A significant fraction of organic PM is composed of low volatile oil-related compounds and is NOT combustion related (potentially emitted by vents or heated surfaces within aircraft engines)

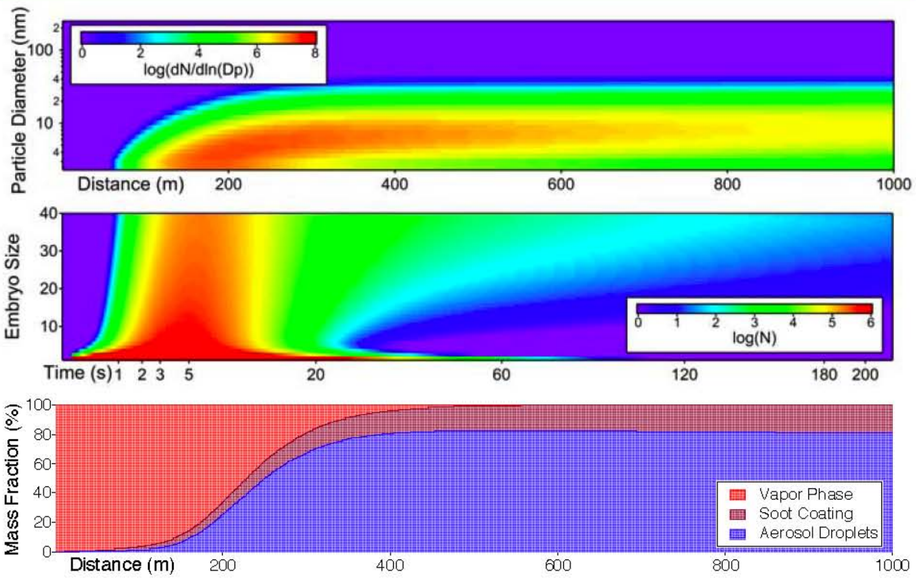
Composition of organic PM vs power *(30-43 meters)*



- EXCAVATE oil compounds appear to increase in proportions at higher engine powers (hotter engine surfaces?)



Wake Calculations – 1000 m Downstream
93% Thrust, T_a = 286K, RH = 80%



Wake Calculations – 1000 m Downstream
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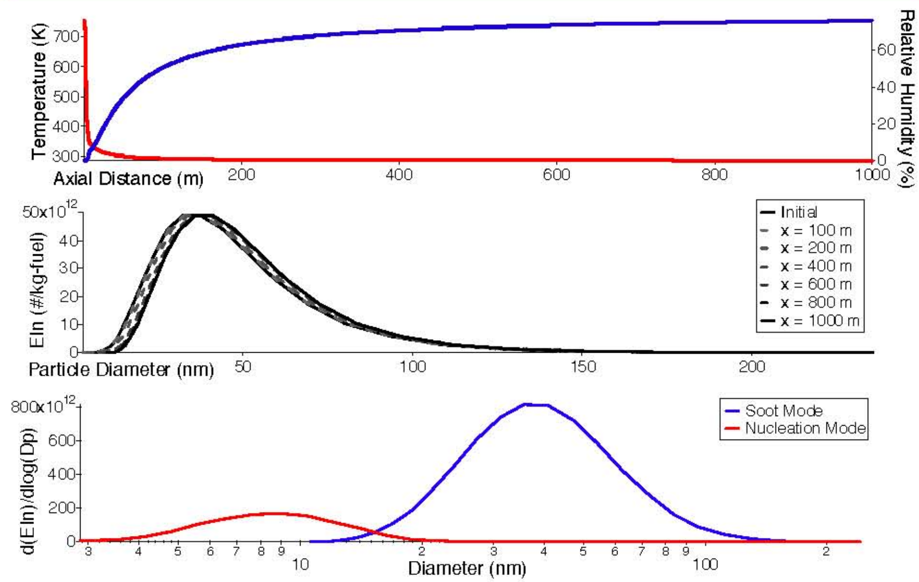
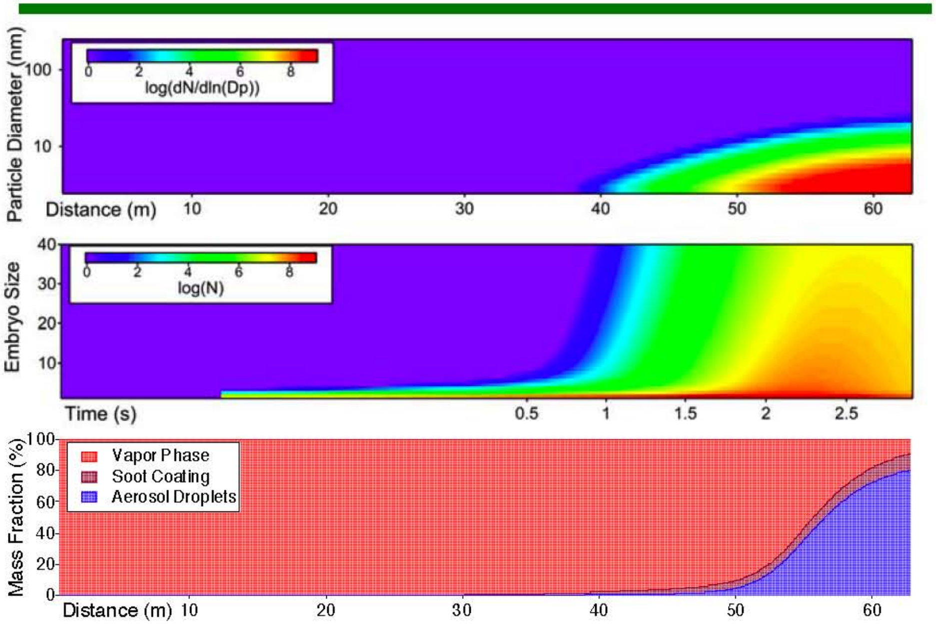


30 m Probe Calculations
93% Thrust, T_a = 286K, RH = 80%



30 m Probe Calculations
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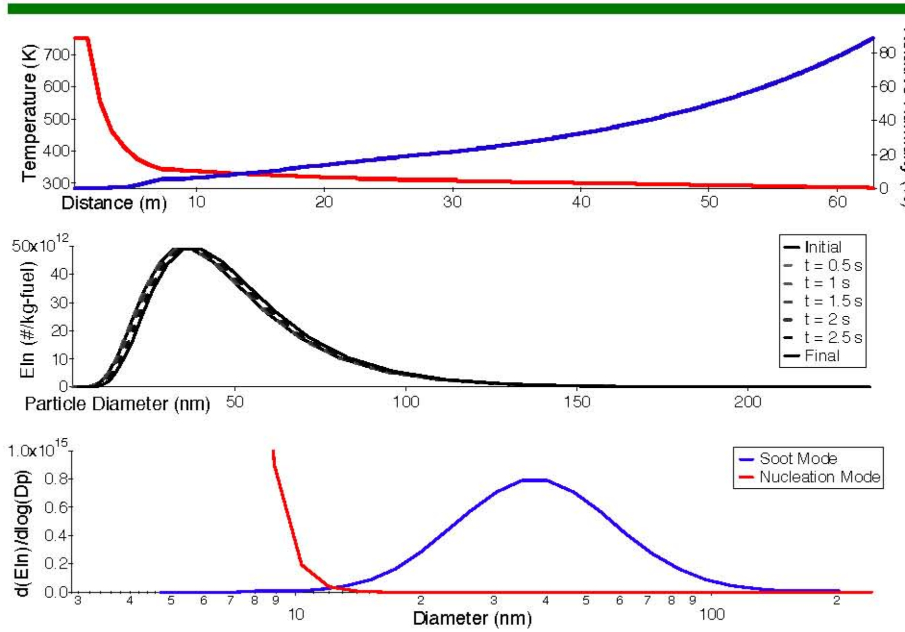
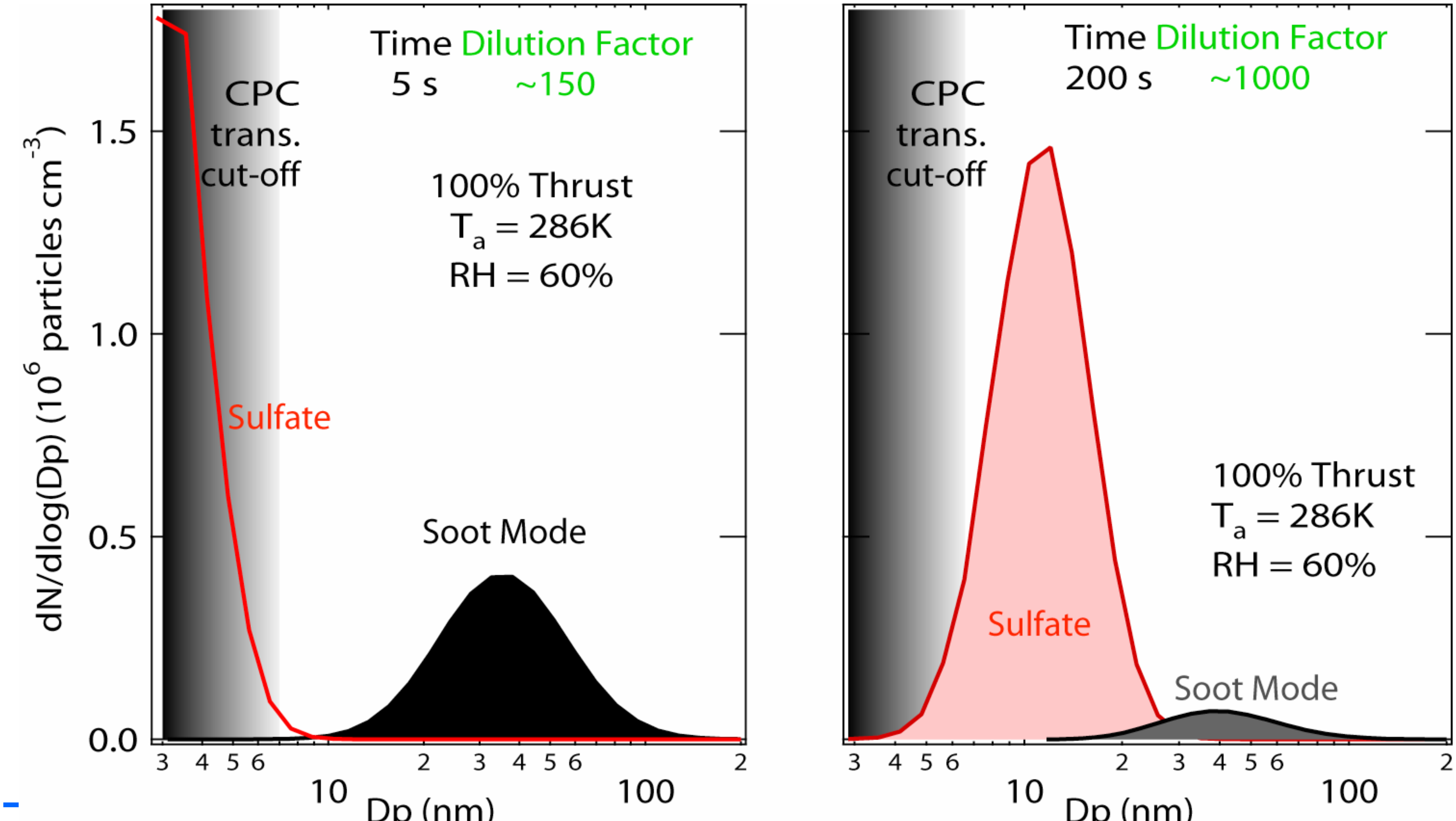


Volatile particle evolution: Cross Cove



Airport Studies

ARI Suite
0.5 - 1 Hz Measurements
CO_2
NO, NO_2
CO, HCHO, C_2H_4
PTR -MS (HC species)
CPC (# cm^{-3})
Aerosol Mass Spec
- Organic, Sulfate (μg cm^{-3})

MAAP (BC ng cm^{-3})

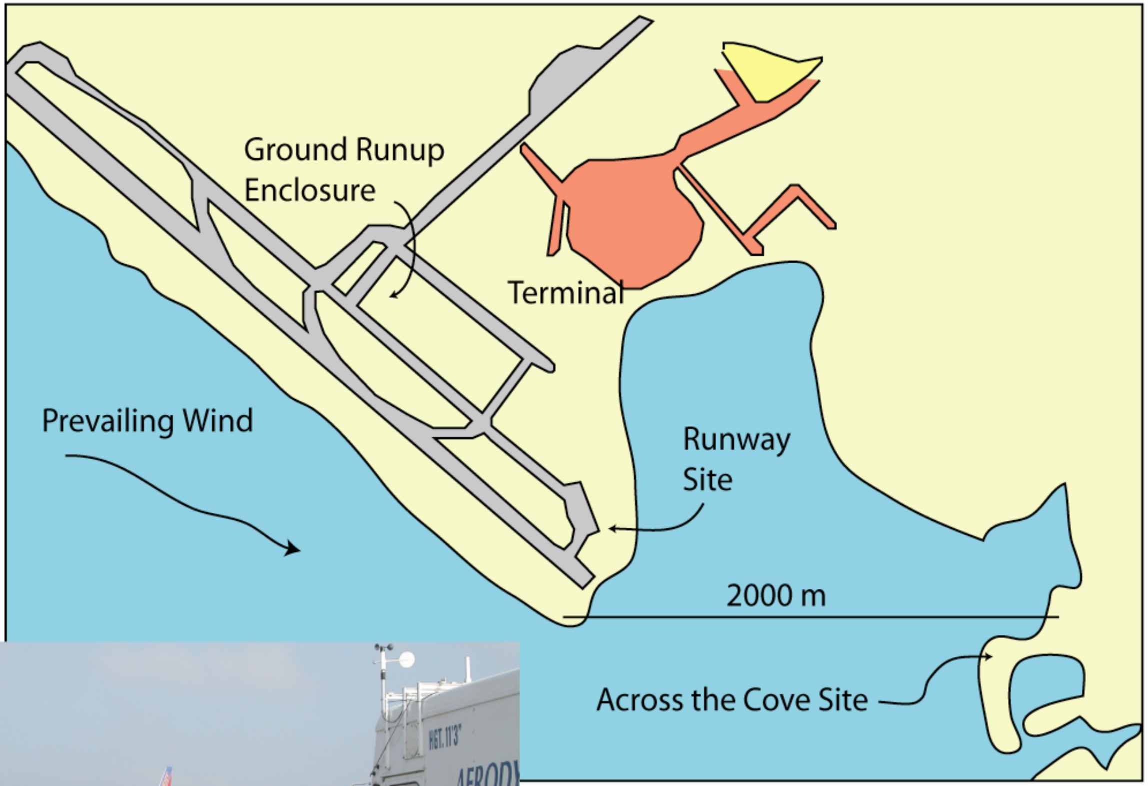
1 minute
Size Resolved (# cm^{-3}) with SMPS
(Various 12 VOC Canister)

Aerodyne and
University of Missouri-Rolla
Portable Laboratory Platforms

Emissions events:
-idle and taxi
-take-offs
-landings

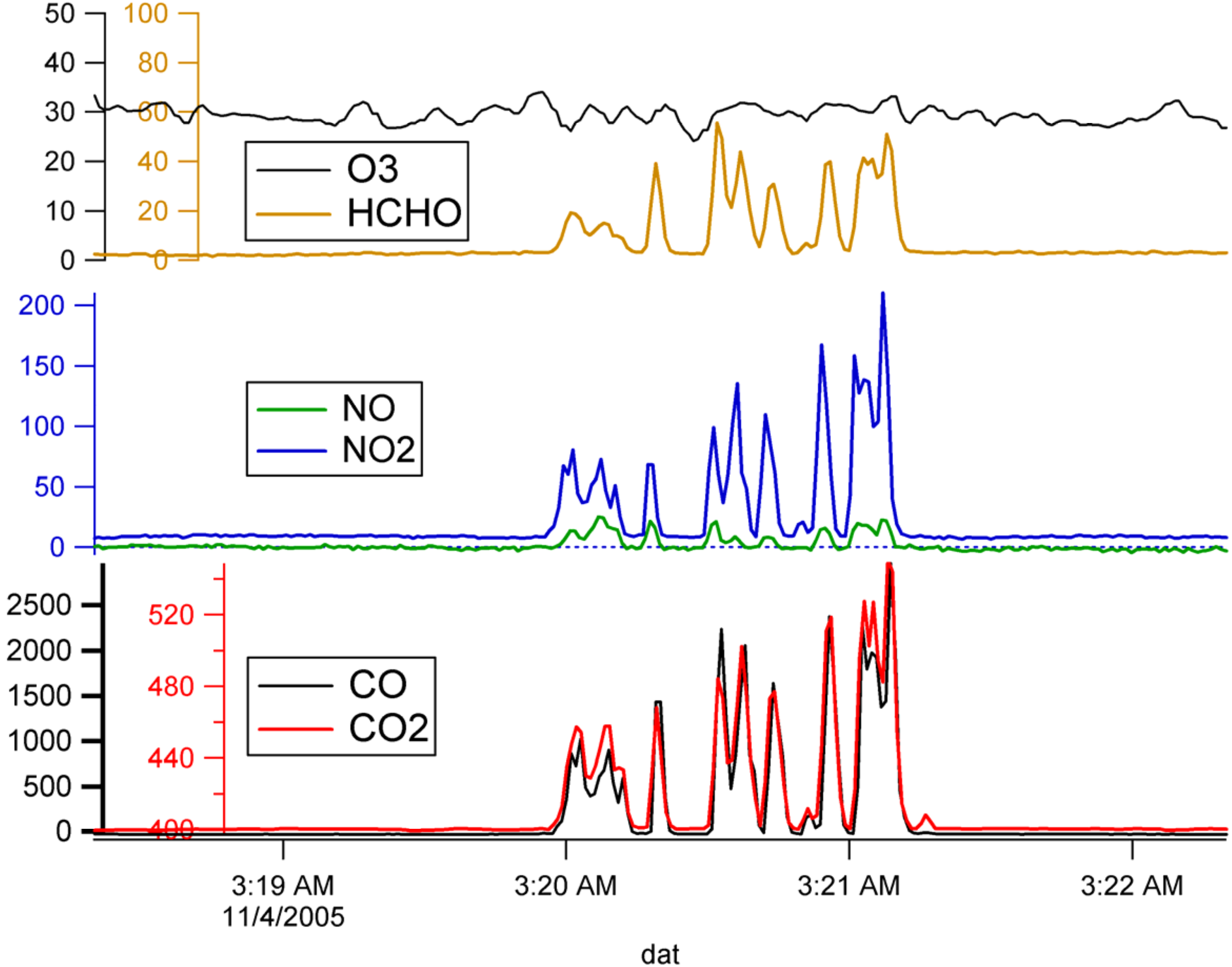
Airport Runway Studies at Oakland, CA

Oakland International Airport 8/2005 Measurements JETS/APEX-2



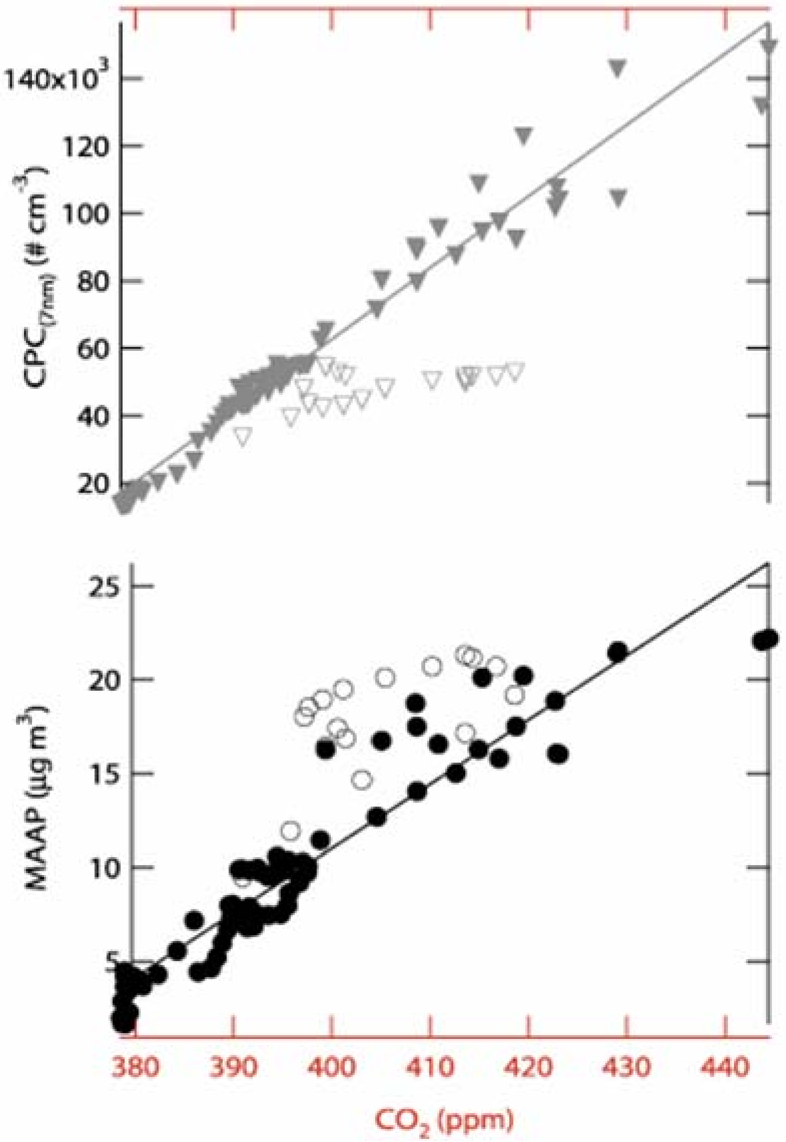
At JETS/APEX-2, GRE measurements similar to Approach II were performed
Advected plumes were sampled at the runway and across-the-cove sites

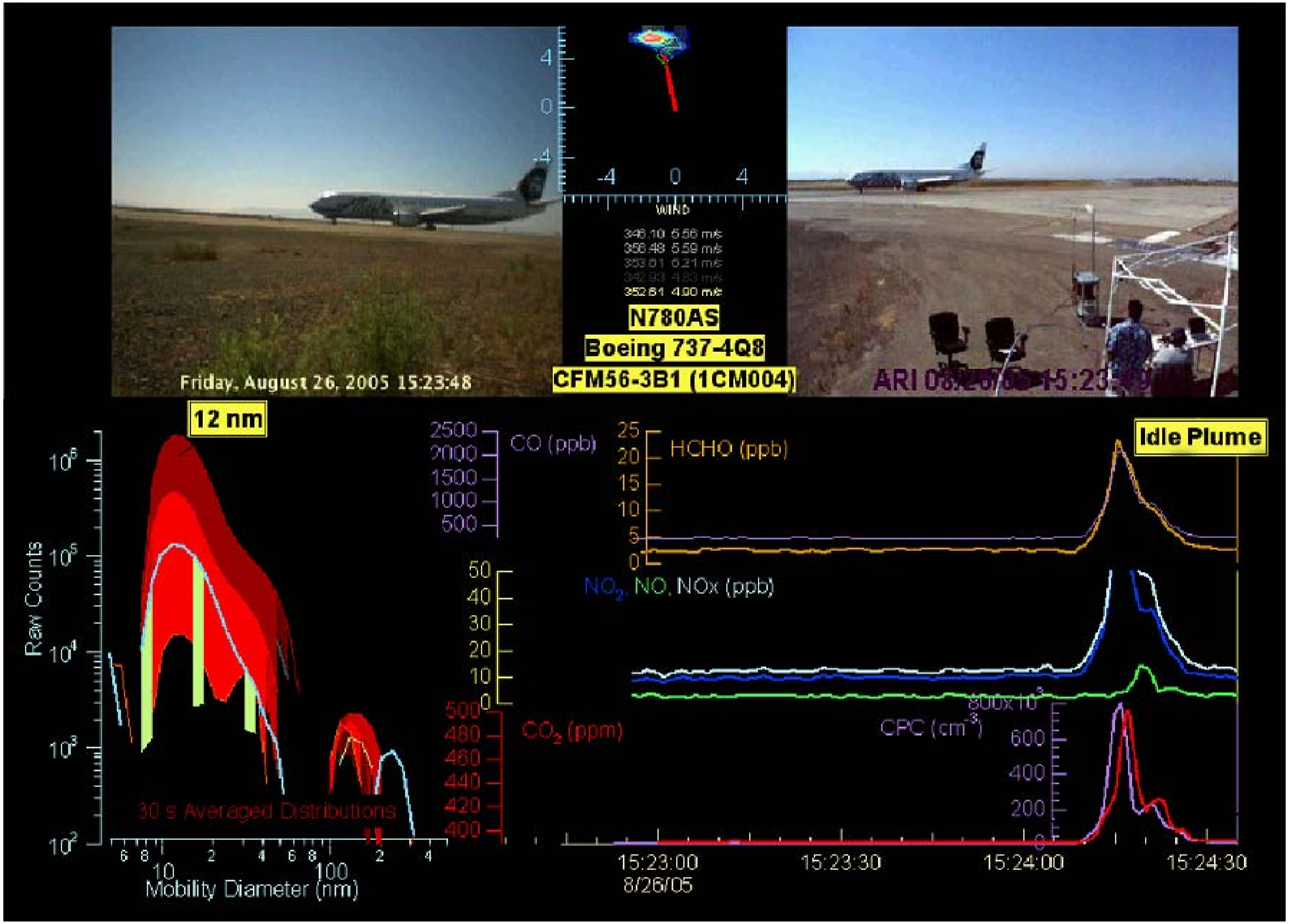
Emissions in plume of taxiing airplane



PM Emission Ratio Determination

With time varying signals, ERs and EIs can be derived by plotting concentration of an emission versus CO_2. Slope gives ER/EI, background levels also obtained.

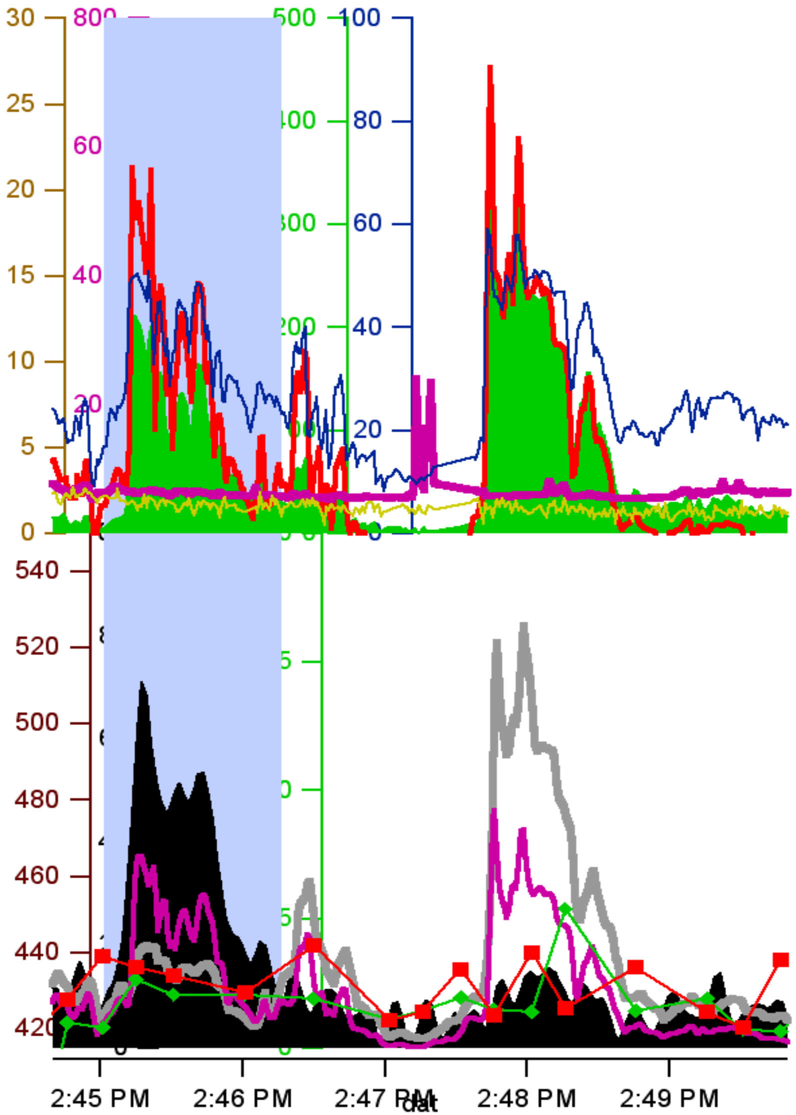


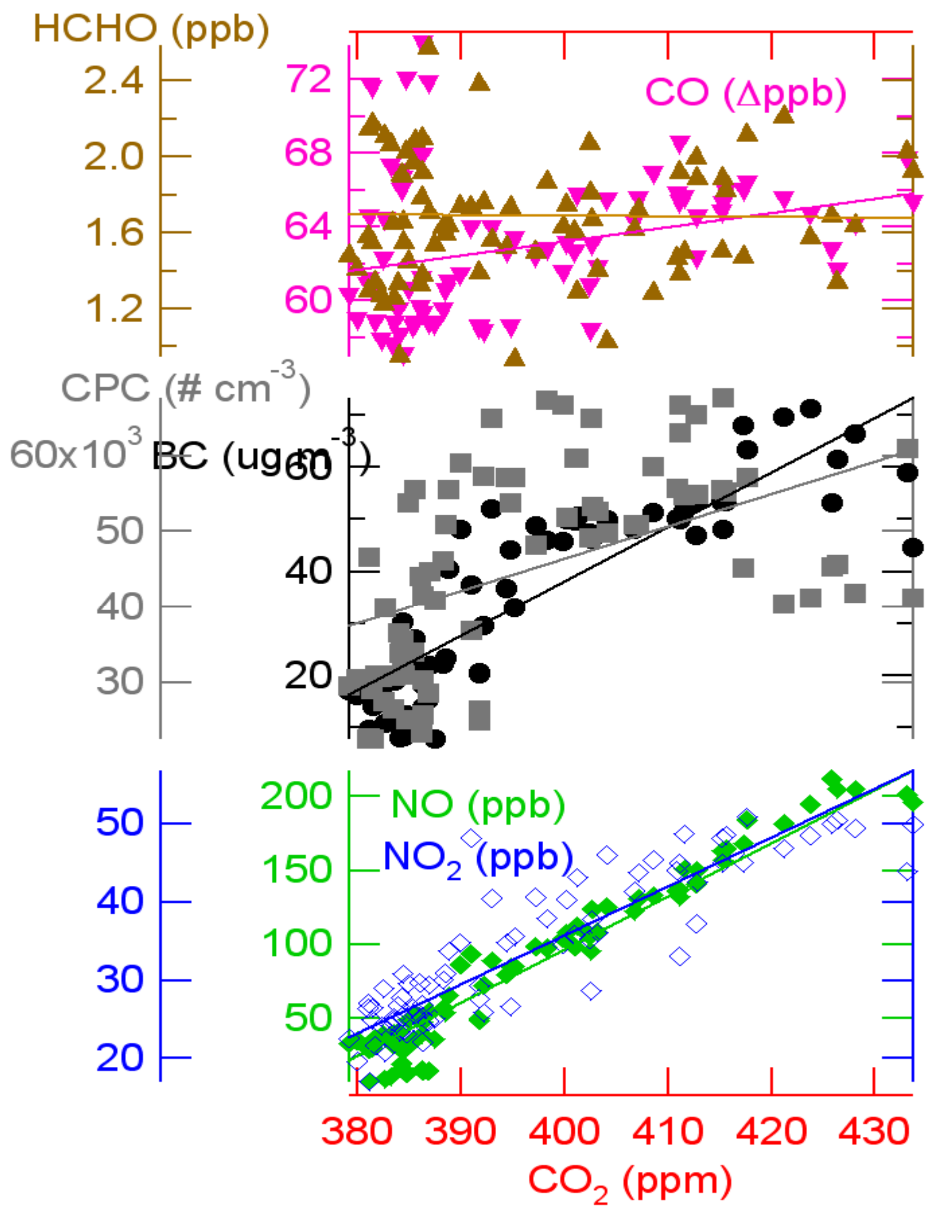


Friday, August 26, 2005 15:23:48
WIND
N780AS
Boeing 737-4Q8
CFM56-3B1 (1CM004)
12 nm
Raw Counts
Mobility Diameter (nm)
30 s Averaged Distributions
CO (ppb)
HCHO (ppb)
Idle Plume
NO2, NO, NOx (ppb)
CO2 (ppm)
CPC (cm-3)
15:23:00
8/26/05
15:23:30
15:24:00
15:24:30

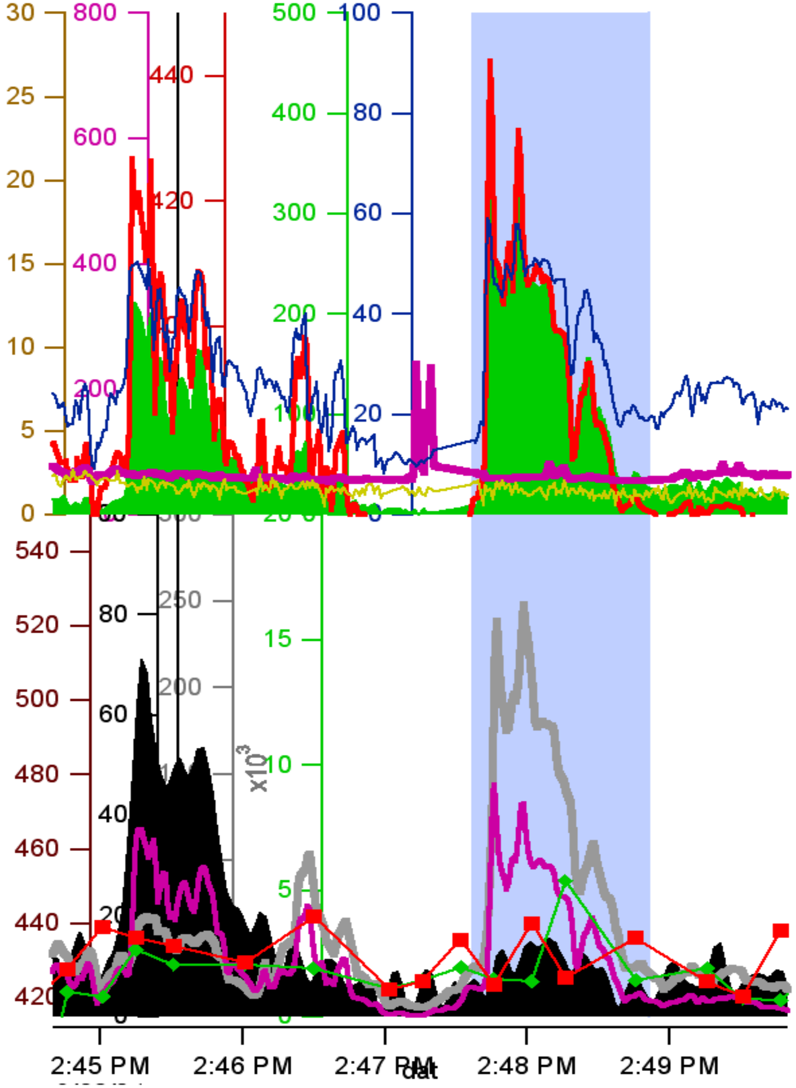
Video clip

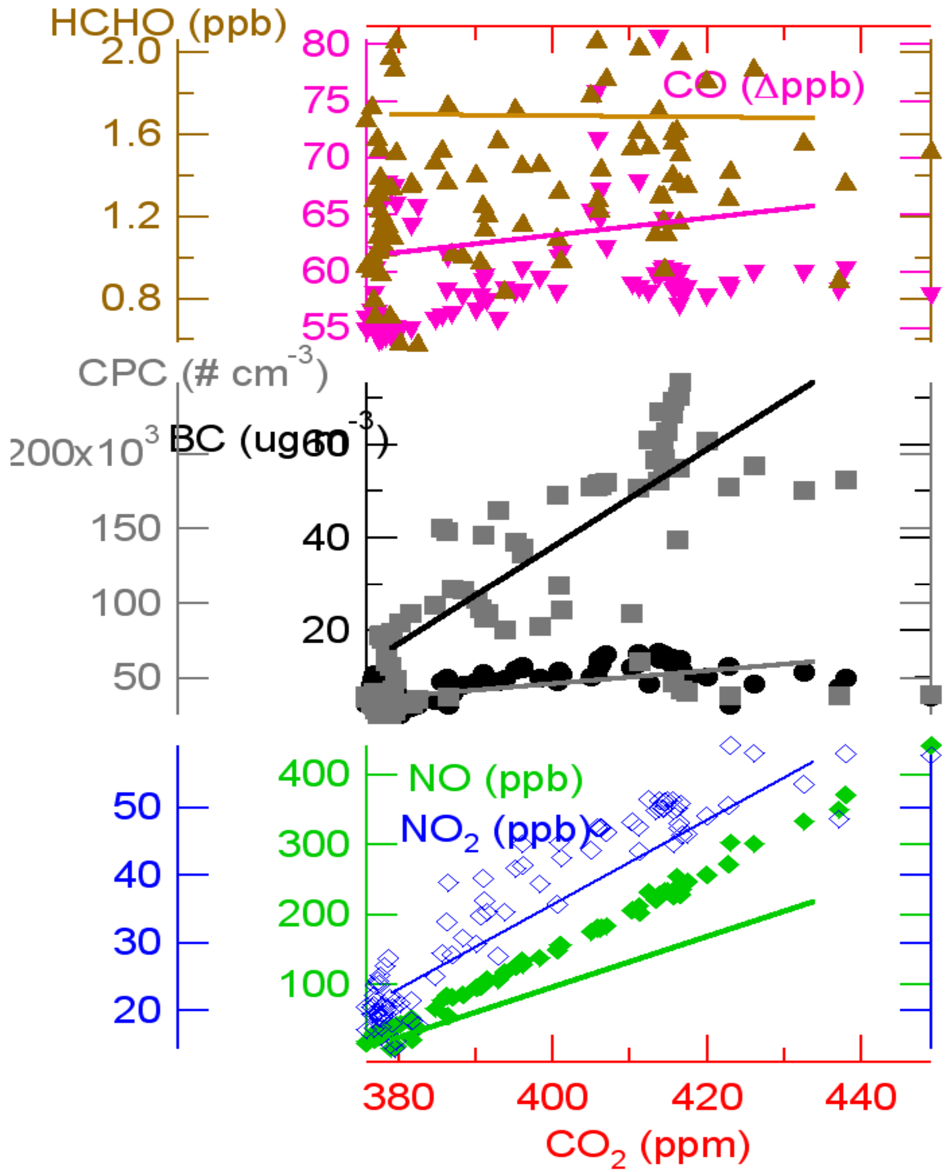
Take-Off Data "First"



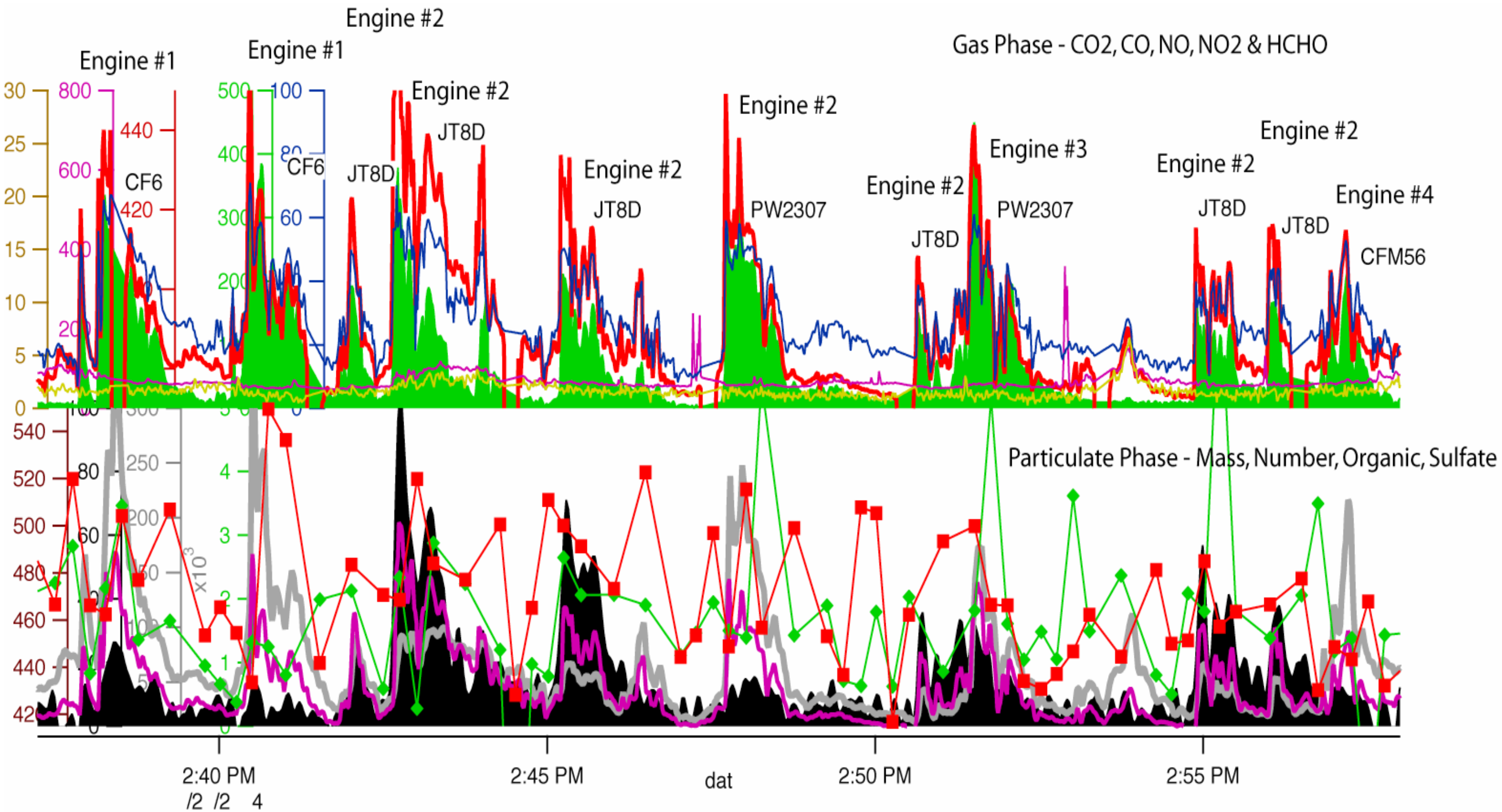


Take-Off Data “Second”



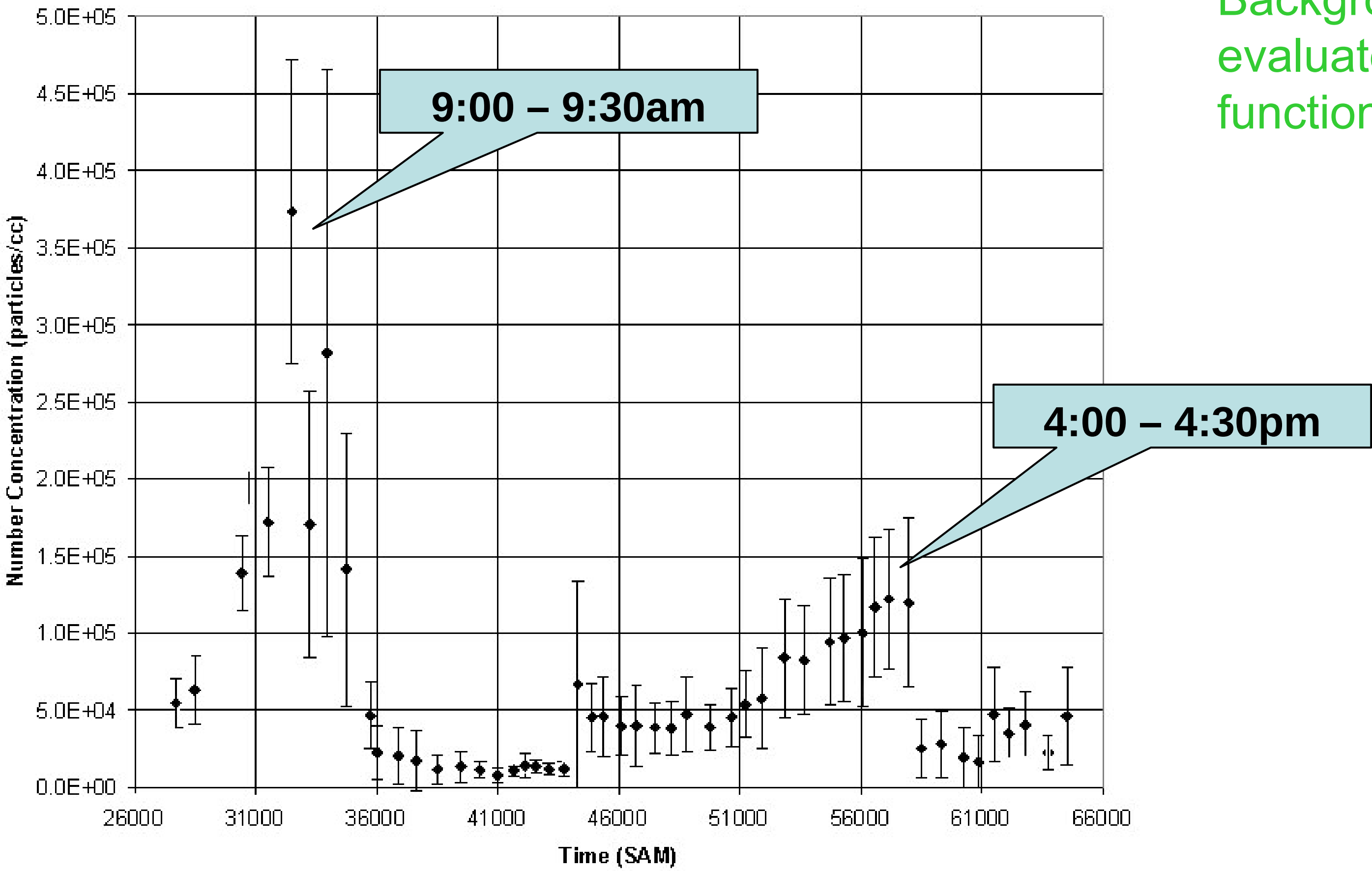


Continuing analysis…Engine Signatures



Background Emissions

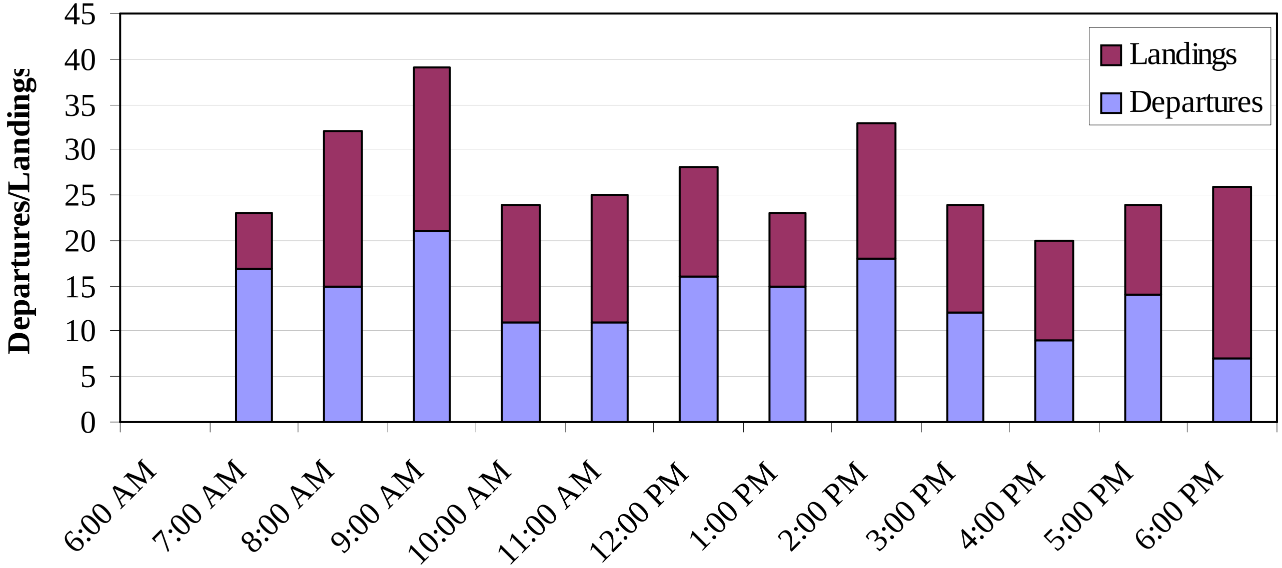
Integrated over size

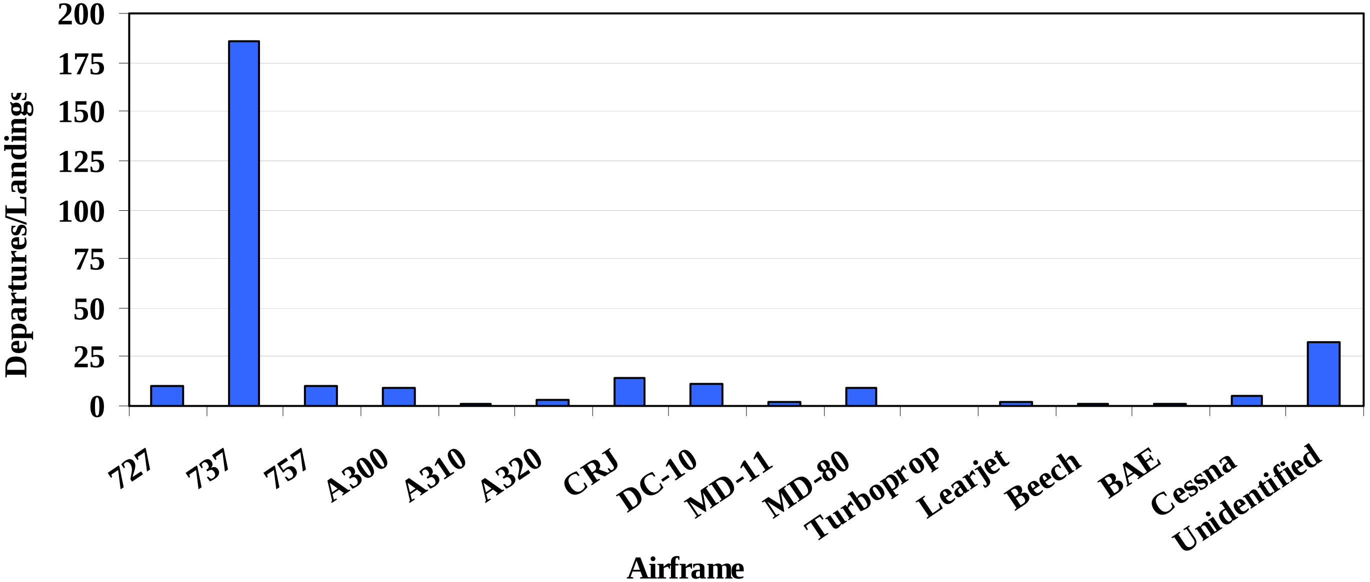


Backgrounds are evaluated as a function of size.

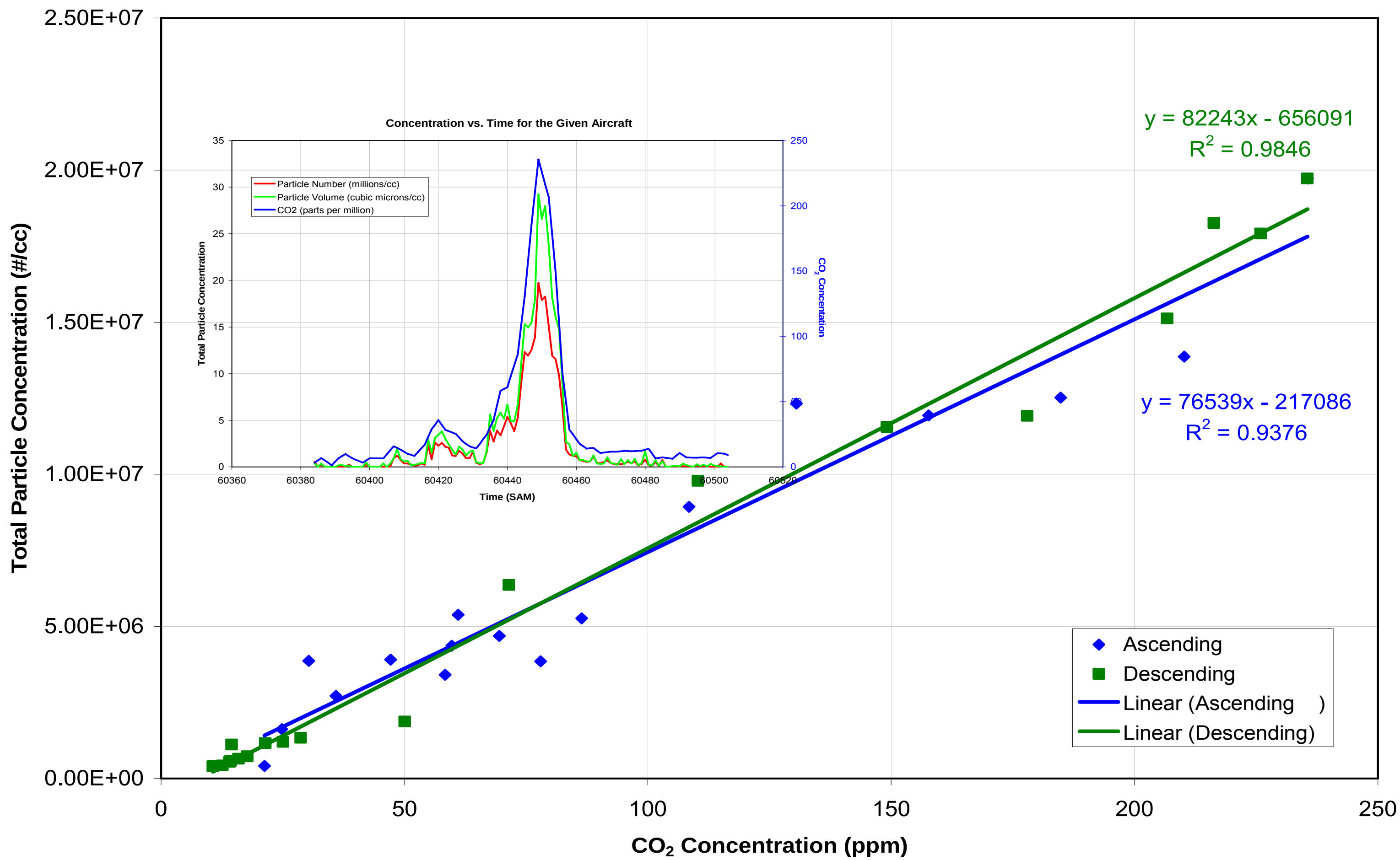
60 sec averages centered at point shown for periods where no aircraft were in the vicinity of the sampling system.

OAK Runway Activity - August 26, 2005

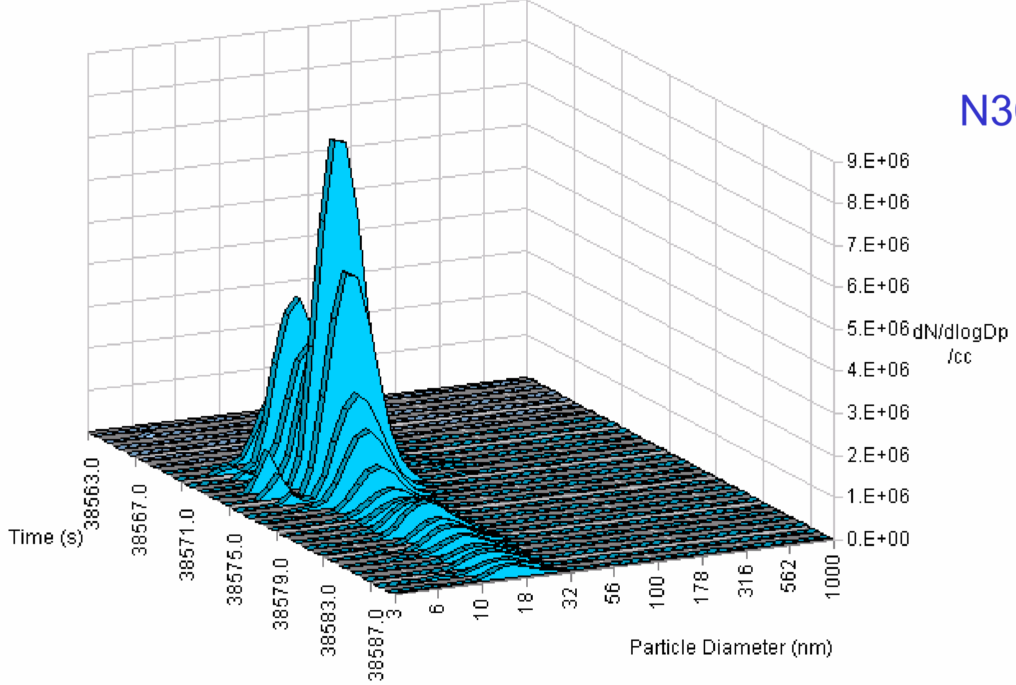


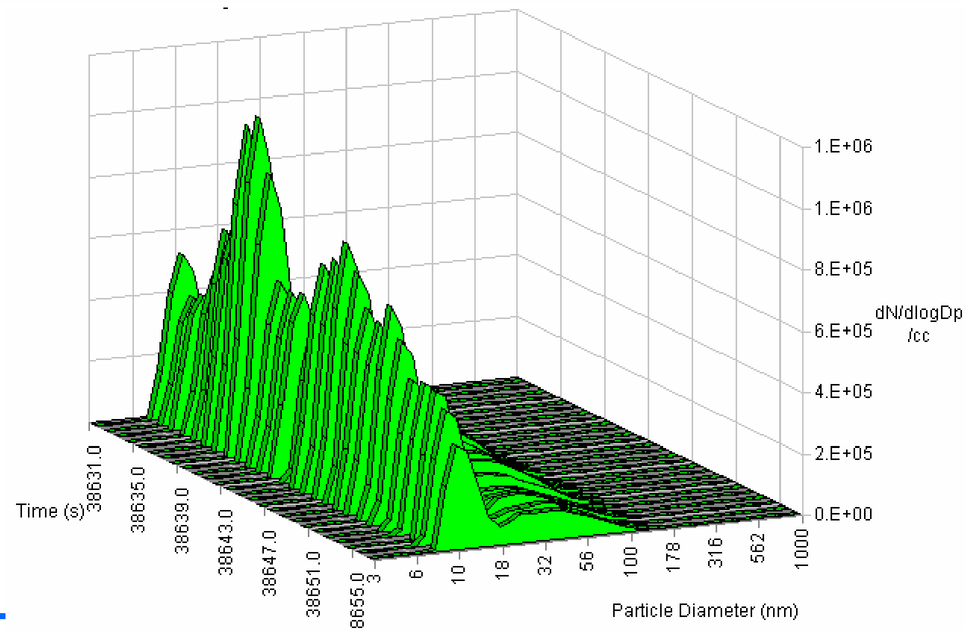


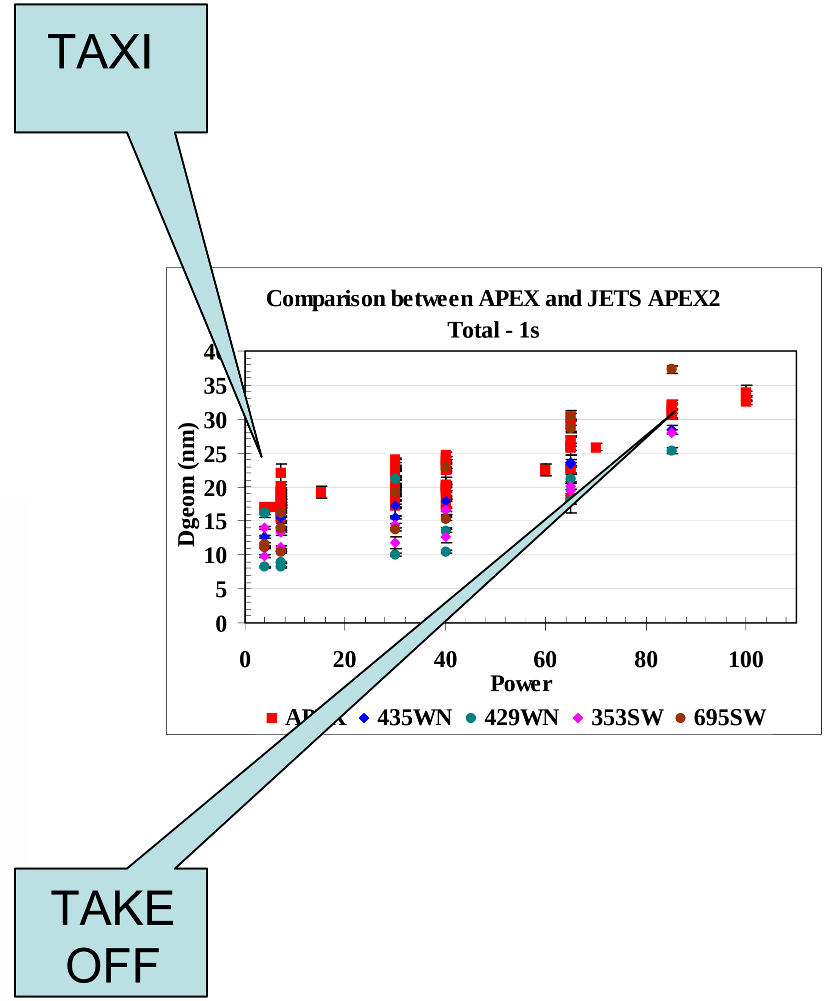
Plume Identification



N309SW(B737-300, CFM56-3B1) Events

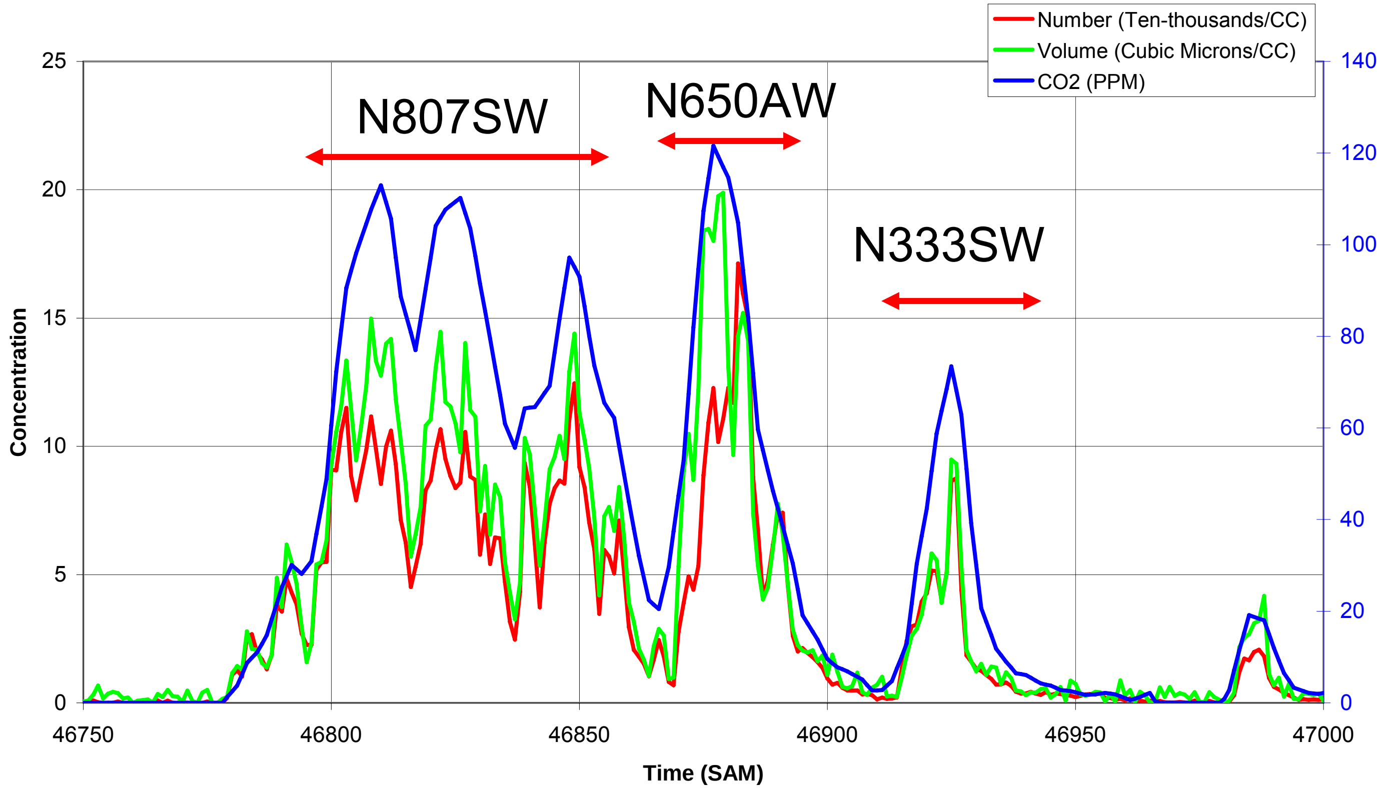




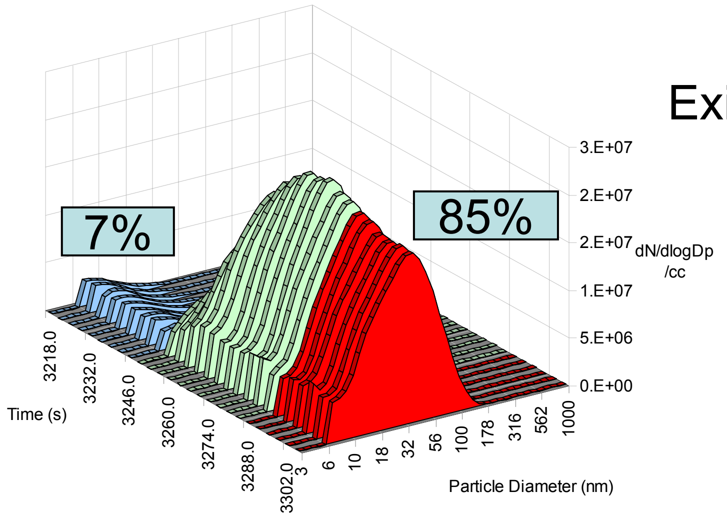


Sample Events - B737, A320, B737

N807SW: Landing, N650AW: Landing, and N333SW: Taxi
(Boeing 737-300, Airbus A320-200, and Boeing 737-300)
(CFM56-3B1 Engines, V2527-A5 Engines, and CFM56-3B1 Engines)

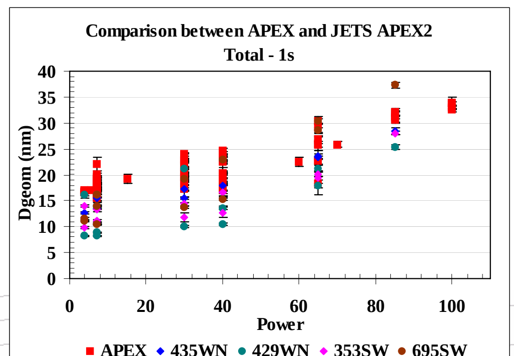


PM Number-based Data N309SW (B737-300, CFM56-3B1)



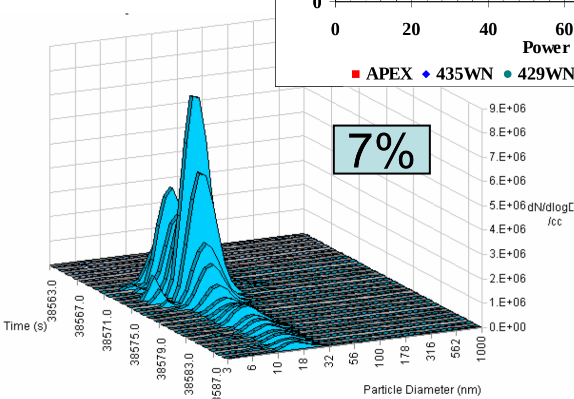
Exit plane size distributions

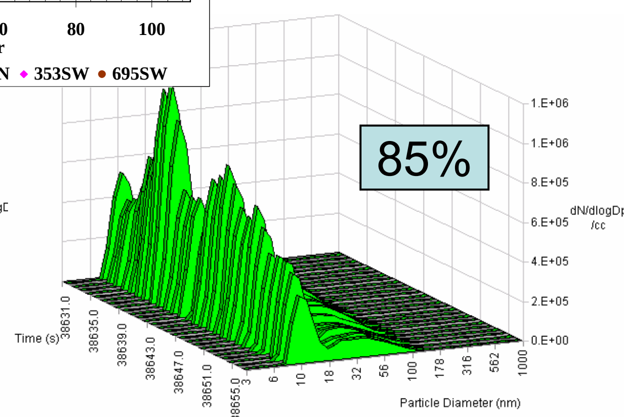
When sampling at or close to the exit plane (within 1m), emitted particles are log-normally distributed within a single size mode.



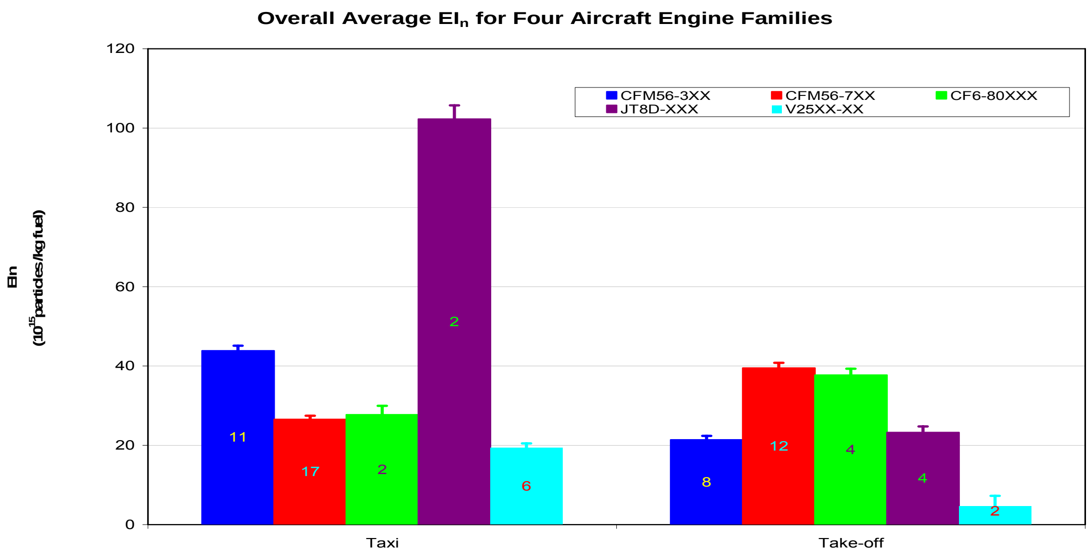
JETS APEX 2

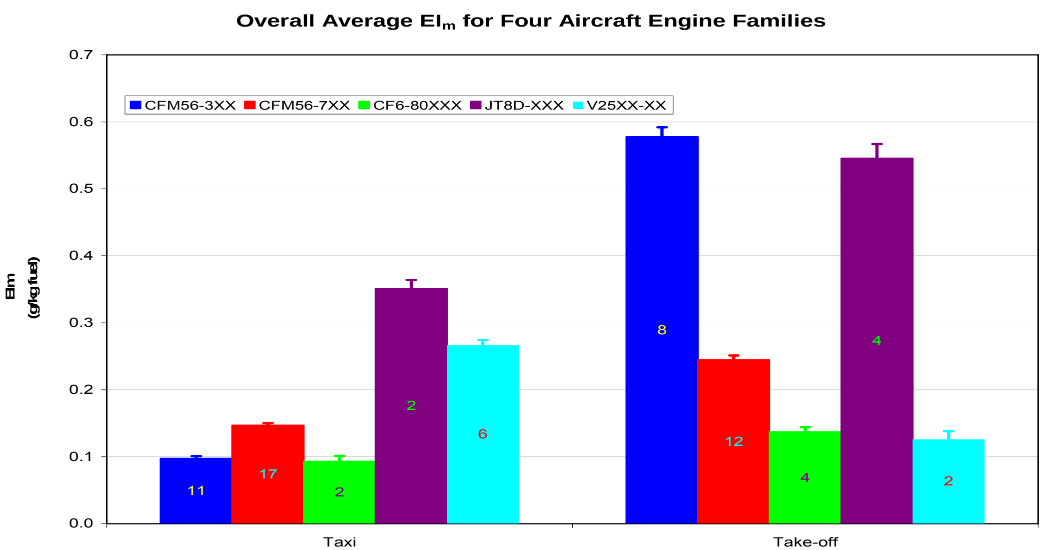
~200m downstream size distributions



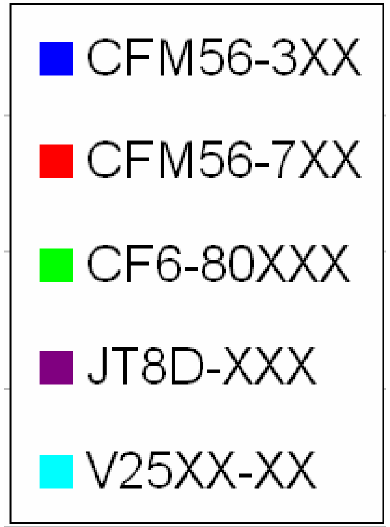


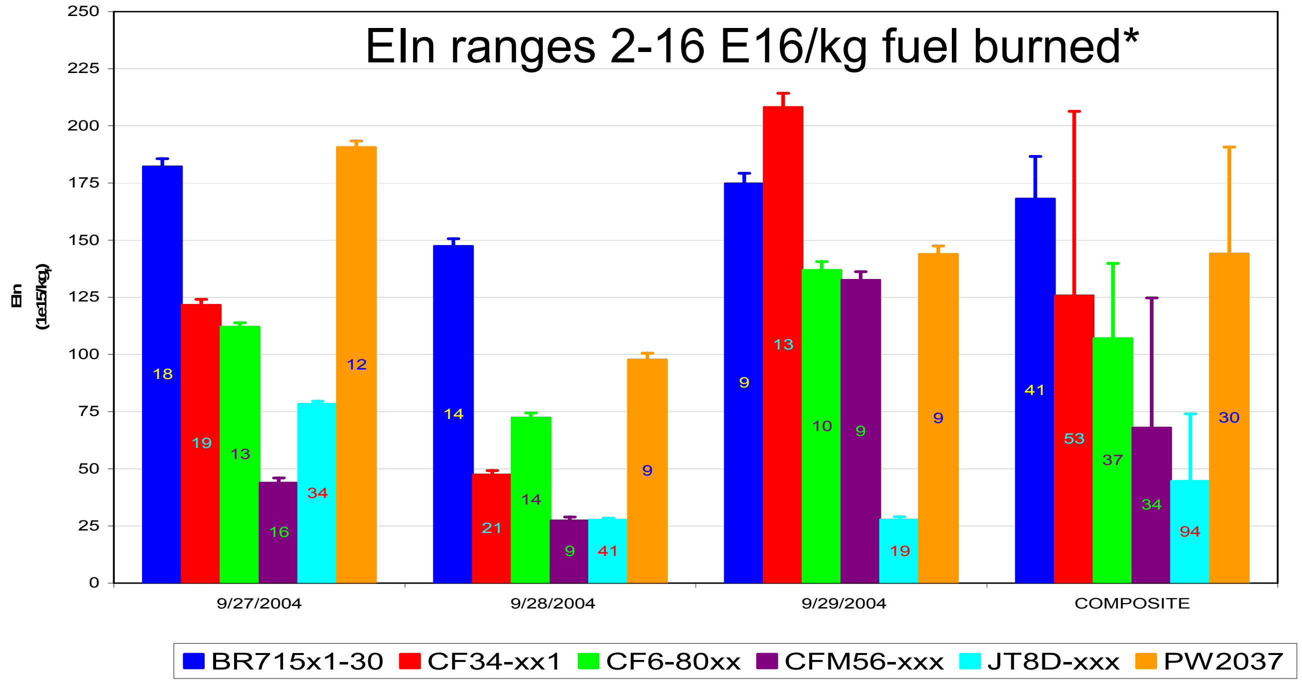
Downstream particle distributions typically exhibit two distinct modes, one corresponding to non-volatile particles and peaking at roughly the same diameters observed in the 1 m samples, and the other occupied by freshly nucleated sulfur and organic particles peaking at < 12 nm.

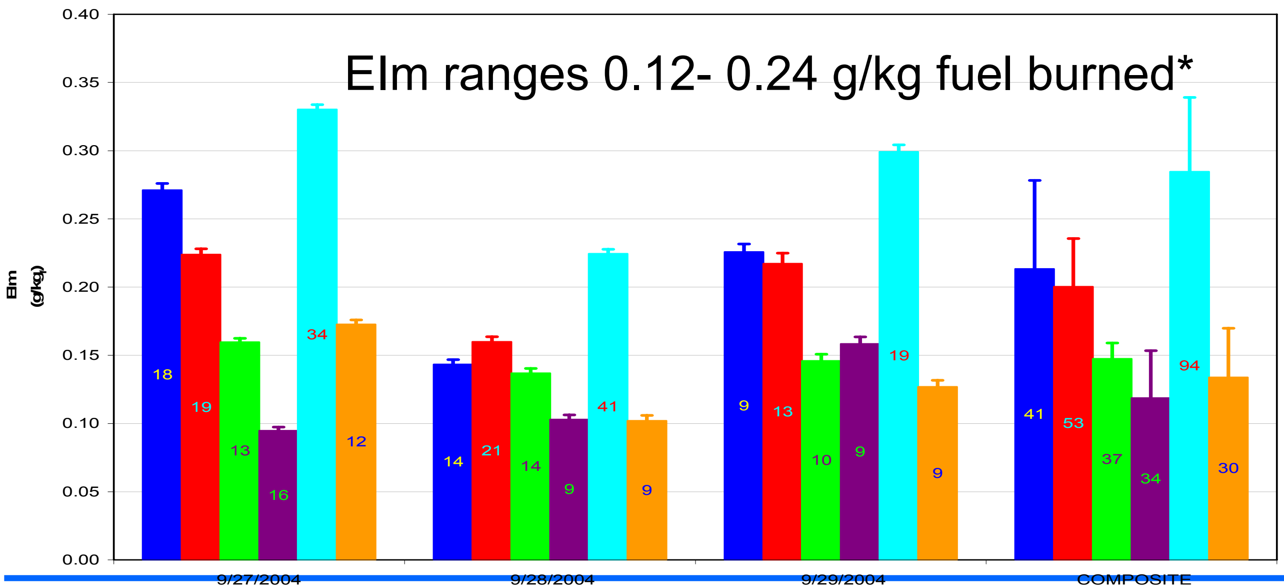




Average Emission Indices for engines at Oakland







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.

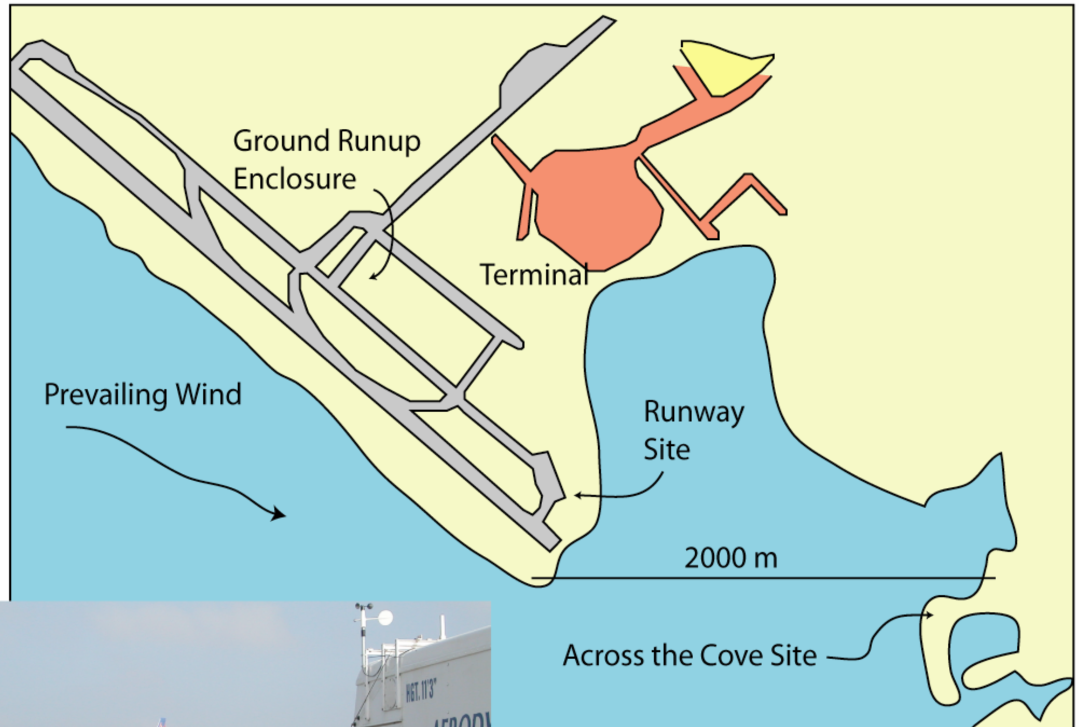
- Changes in ambient atmospheric conditions are likely to impact PM emissions. A larger impact would be expected on particle number than on particle mass as was observed in the advected plume data.

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

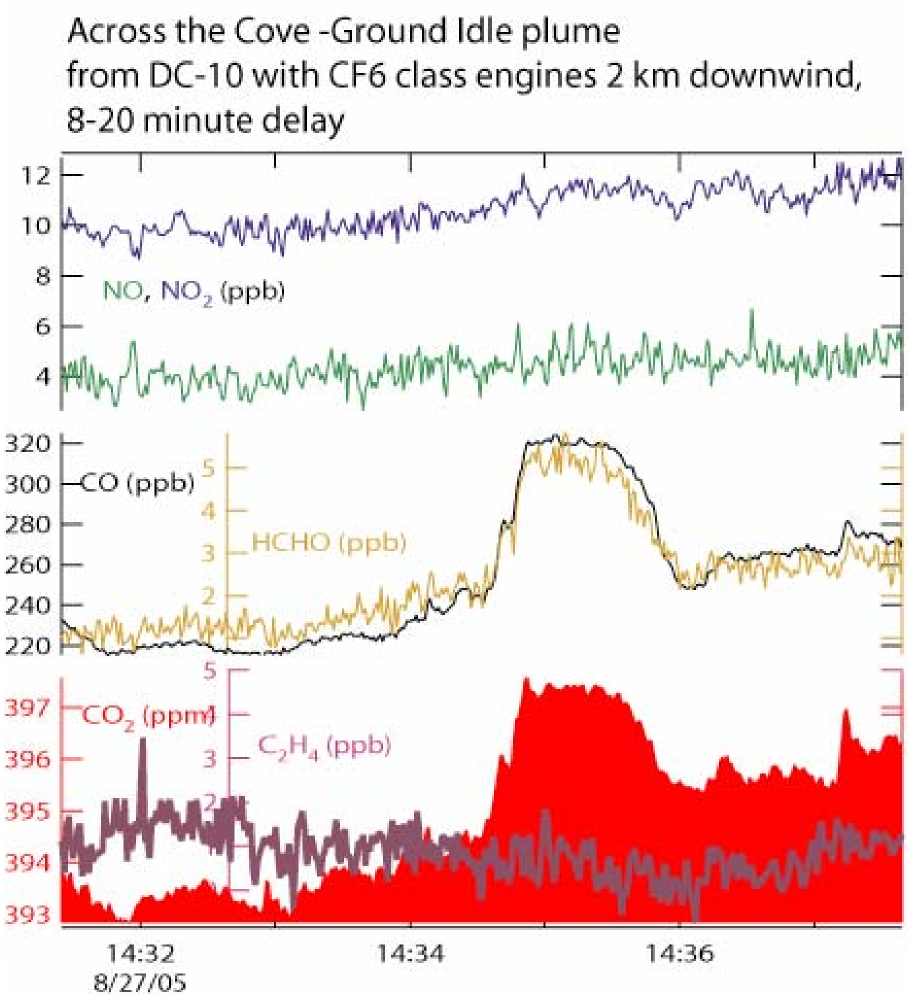
Downwind Sampling

Oakland International Airport 8/2005 Measurements JETS/APEX-2



At JETS/APEX-2, GRE measurements similar to Approach II were performed Advected plumes were sampled at the runway and across-the-cove sites

Downwind Site, DC-10



Formaldehyde
- 0.9 ppb ppm^{-1} CO_2
- 1.9 g kg^{-1} fuel

Carbon Monoxide
- 24.5 ppb ppm^{-1} CO_2
- 49 g kg^{-1} fuel

Ethylene
- ?

runway idle contained 1.3 x HCHO should be above detection sens.

Summary for Volatile PM

- New particles, soot, and ambient particles compete for condensable species
- Rates and resulting aerosol properties depend on ambient conditions and/or sampling
- Sulfate meditates volatile PM formation and growth: even organic contributions
- Organic has multiple components
  - Partially combusted fuel
  - Lubrication oil contributions
- How to measure and quantify volatile contribution? What can be standardized?
- C.f. secondary ambient aerosol processes?


HGT. 11'3"
AERODY

Major Conclusions:

•Measurement of NOx indicated that the general emissions performance of the engines was in keeping with certification measurements for the engines studied.

•Measurements of individual hydrocarbon species suggest that the Emission Indices for most of the major species decrease with increasing engine power, in proportion to each other, and specifically with formaldehyde, which is one of the most plentiful emitted hydrocarbons and can be measured accurately.

•The particle composition includes both sulfate and organic volatile fractions at downstream distances, adding to the carbonaceous aerosol that is present already at the engine exit plane.

•The sulfate contribution has little dependence on engine power, while the organic contribution is greatest at low engine powers.

Conclusions continued

•The relative distributions of the substituted naphthalenes to non-substituted naphthalenes for the idle modes are in general agreement with the work from Spicer et al.1992, 1994.

•Chromium (VI) results revealed ambient levels.

•The major three contributors to the carbonyl emissions are formaldehyde, acetaldehyde, and acetone.

•Formaldehyde and acetaldehyde are most dominant carbonyl species in the aircraft exhaust emissions

Conclusions continued

•The aerosol properties were calculated for the entire aerosol size distribution and not individual size modes.

•Size distributions for exit plane were generally lognormal. Strong and sometimes non-linear dependencies were observed with engine power settings.

•The onset of gas-to-particle conversion was apparent at 50m for low to medium powers. In this data non-lognormal size distributions were often observed, where the mean sizes decreased and EIn increased relative to the 1m size distributions.

Recommendations

- The results of this study proved that accurate emission factors can be acquired in a cost effective manner. Since the data is clearly engine/airframe specific, studies of this nature should now be performed on other important engine/airframe combinations e.g. B747/CF6-80.

- The GRE at Oakland proved to be an ideal open air laboratory for dedicated aircraft engine emission studies in the exhaust nozzle and near field plumes for B737 commercial transports.

- The weather conditions and prevailing winds experienced on the east side of San Francisco Bay in late August were also favorable. These factors lead to the recommendation that the GRE at Oakland should be considered a high priority venue for any future scheduled tests.

- It should be noted that the mix of transports routinely operating in and out of Oakland will limit the range of engines/airframes that can be studied. For future studies where B747, B757, B767, and B777 and the larger Airbus transports A320, A340 etc. are anticipated test vehicles, it will be necessary to consider attracting other aircraft to the Oakland test site or using GREs located at other airports provided appropriate weather conditions prevail.

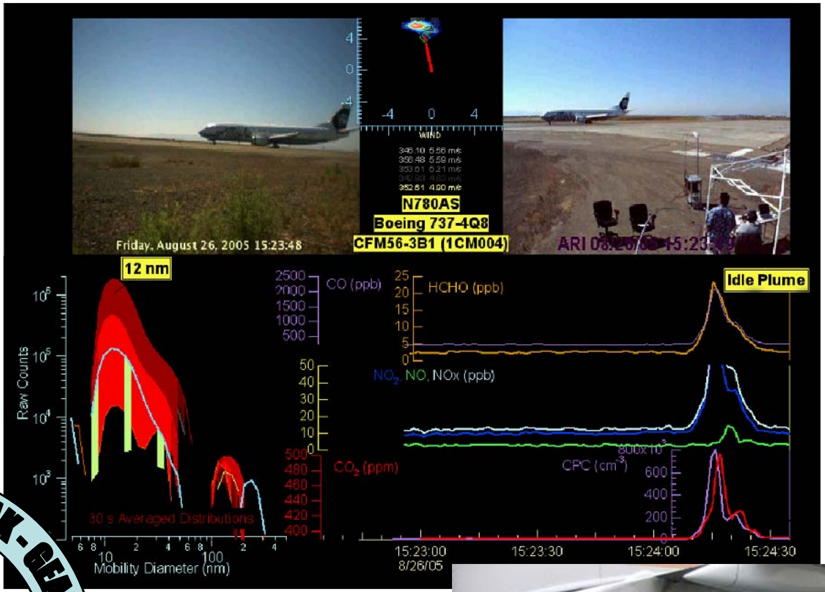
•In this study, engine operating conditions were recorded only once during each stable engine operating condition. In future tests it is recommended that high frequency data acquisition be employed for engine operating conditions. This may be difficult for older airframes but straight forward for newer additions to the commercial fleet that digitally record engine operating conditions.

•Most of the data was gathered and initially analyzed in real-time. However, this was not the case for the UCR samples that were analyzed off-site post test. For future studies efforts should be expended to assure that the analysis could be undertaken for these samples on-site. This would provide quasi-real-time feedback on the integrity of such samples.

•Engine to engine variability is difficult to estimate when the engine sample size is small (in this study ≤ 4 engines per model). The value of accurately estimating this parameter warrants the consideration of a longer period of study than the 4 days afforded this project, especially since the per-day costs are small compared to planning, preparation, set-up, and post test analysis costs.

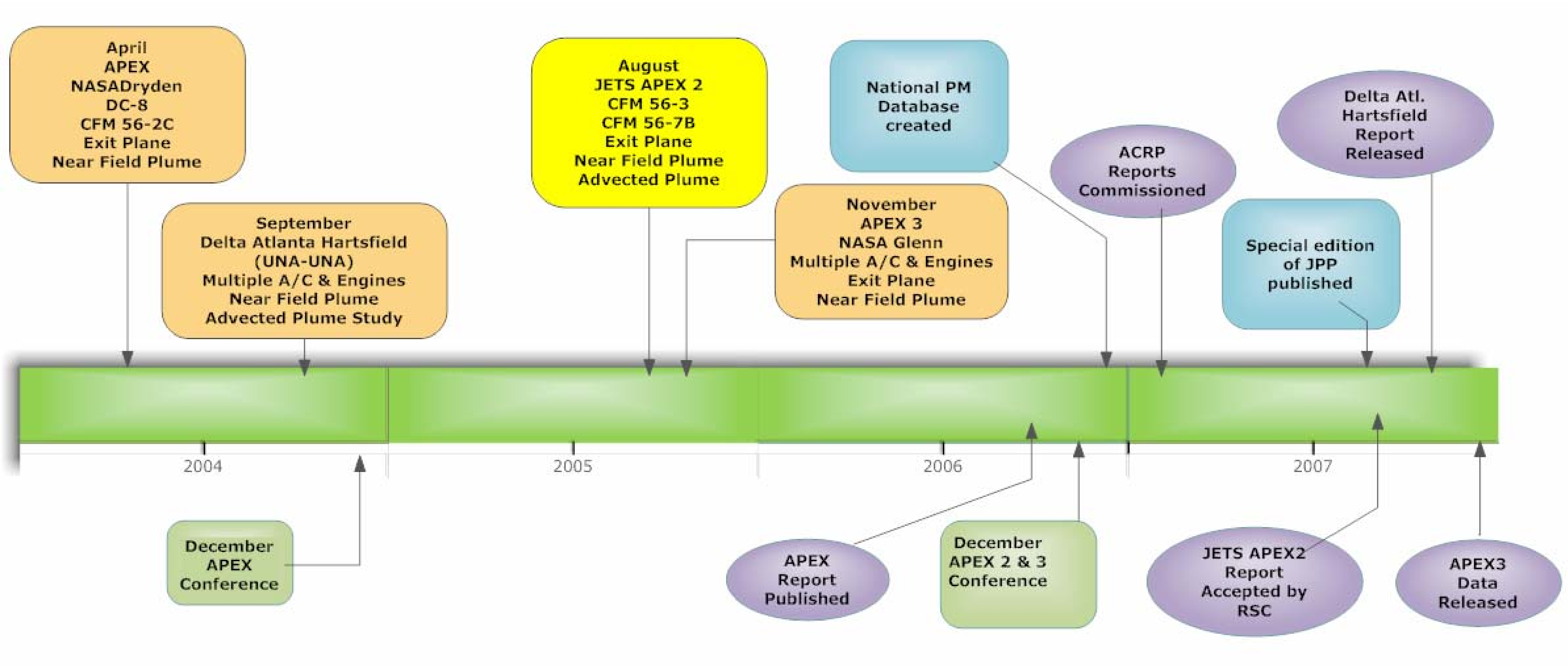
•Valid measurements for TOG and multiple significant speciated VOCs were not obtained because of sampling and laboratory issues for the light hydrocarbon and carbonyl analyses. These measurements should be repeated at a future engine test, when the opportunity arises, to get better estimates of TOG and speciated VOCs.

What is the national aircraft PM program?



Measurement Campaigns

Aircraft Particle Emissions eXperiment Timeline



How does JETS APEX2 fit in to the national aircraft PM program?

- An excellent starting point for the development of a national database that accurately represents commercial aircraft emissions.
- The successful completion of this project facilitates:
  - informed decision-making
  - accurate modeling of B737 type commercial jet engine exhaust emissions.
  - inventories and ozone estimation
  - detailed chemical speciation/source apportionment to assist in health risk assessments during the EIR process for airport expansion projects.

It should be noted that the data presented in this study are engine/airframe specific and do not necessarily represent gas turbine engine emissions in general and should not be applied to other engine/airframe types.

Acknowledgments

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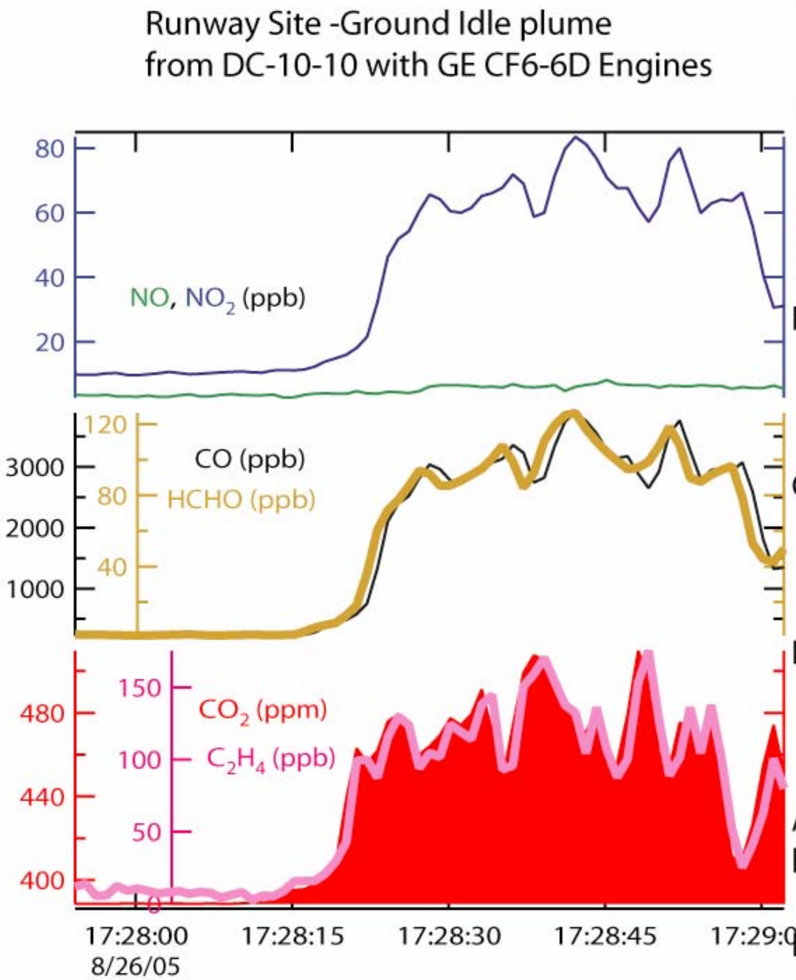
Dan Vickers at Frontier Analytical Laboratories;
Steve Church, Steve Francis, and staff at ARB;
Gary Kendall, Jim Hesson and staff at Bay Area Air Quality Management Dist.

JETS APEX2 Team

Back Up Slides

Runway Site DC-10



Formaldehyde

1.02 ppb ppm^{-1} CO_2

2.2 g kg^{-1} fuel

Carbon Monoxide

31 ppb ppm^{-1} CO_2

62.2 g kg^{-1} fuel

Ethylene

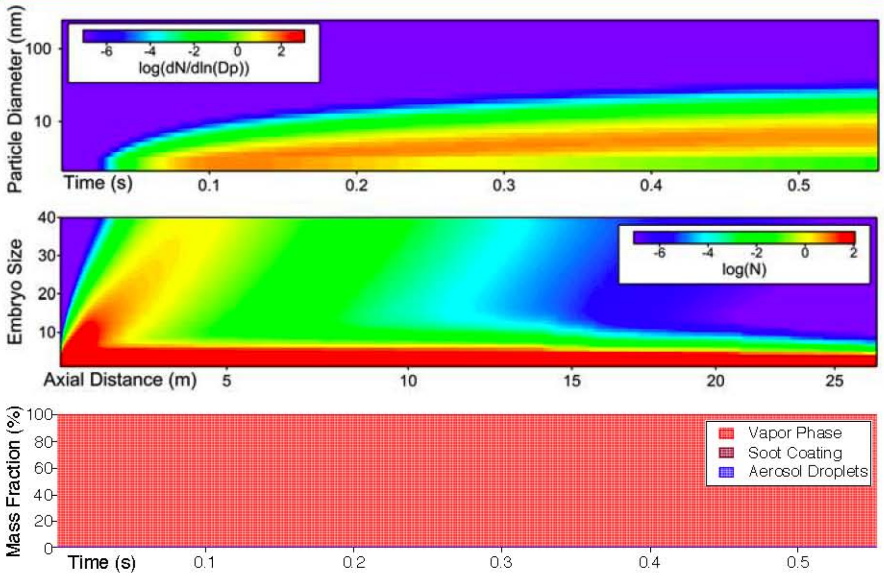
1.3 ppb ppm^{-1} CO_2

2.6 g kg^{-1} fuel

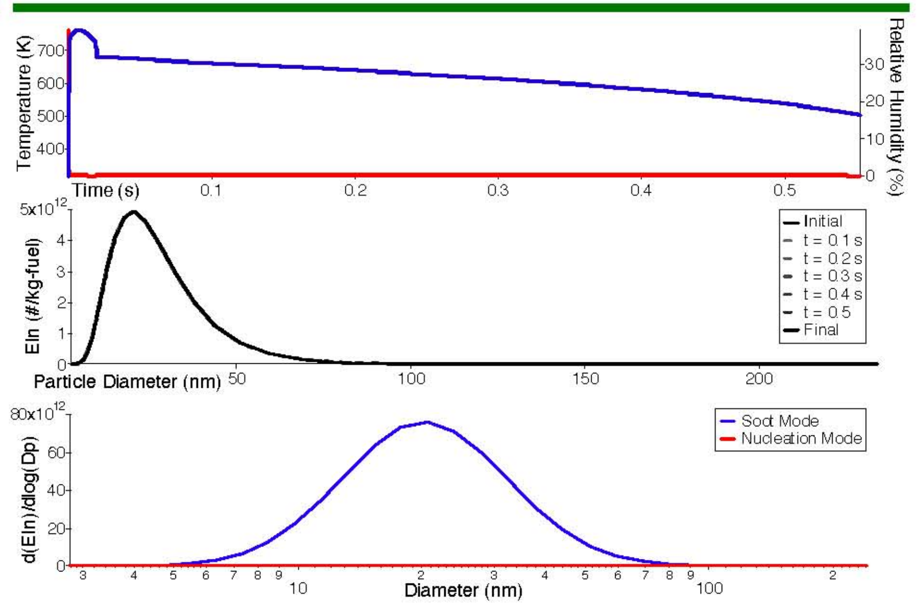
At 7% 'idle' the CF6-6D burns ~0.17 kg fuel s^{-1}

DC-10 has 3 engines

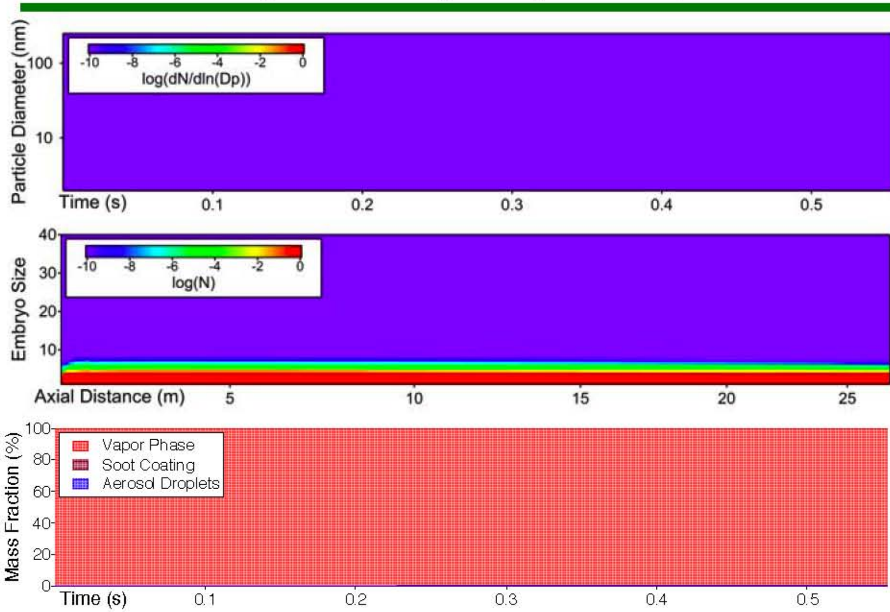
1m Probe with Polydisperse Soot Particles
α = 0.018, N=10^6 1/cc, GMDp = 20nm, RH= 80%



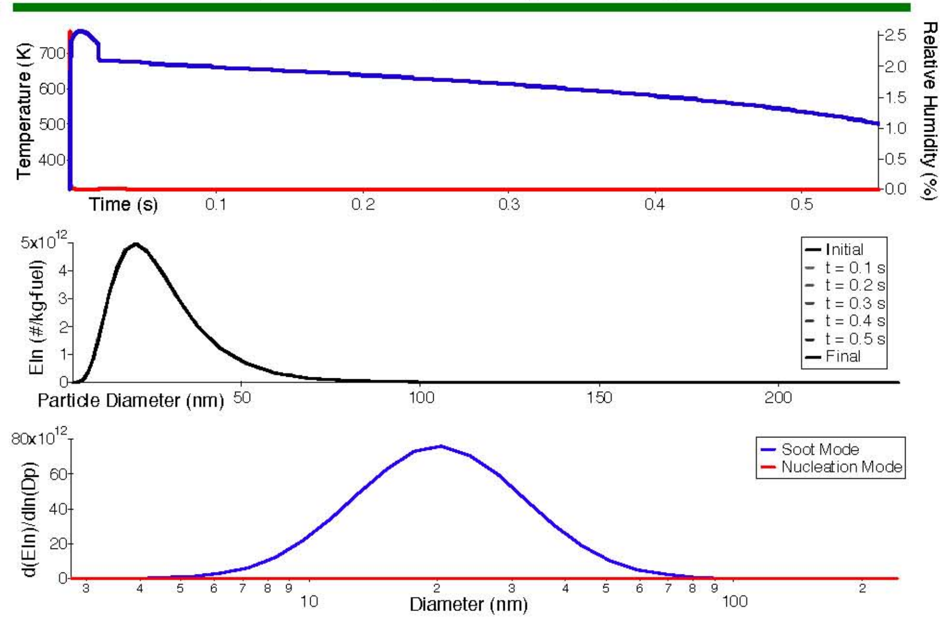
1m Probe with Polydisperse Soot Particles
α = 0.018, N=10^6 1/cc, GMDp = 20nm, RH= 80%



1m Probe with Polydisperse Soot Particles
α = 0.018, N=10^6 1/cc, GMDp = 20nm, RH= 0%



1m Probe with Polydisperse Soot Particles
α = 0.018, N=10^6 1/cc, GMDp = 20nm, RH= 0%




SOUTHWEST