Concentrations and Characteristics of Particles within Commercial Aircraft Exhaust Plumes

B.E. Anderson, E.L. Winstead, G. Chen, C. Hudgins, K. Thornhill, and C. Wey, C.C. Wey, S. Herndon, R. C. Miake-Lye, J. Wormhoudt, D. Liscinsky, R. Howard, R. Heirs and Others

Test Venues

EXCAVATE

Hampton, VA; Jan ‘02

NASA LaRC B757

Rolls Royce RB211-535E4

40,100 lbs thrust

APEX-1

Edwards, CA; April ‘04

NASA DFRC DC-8

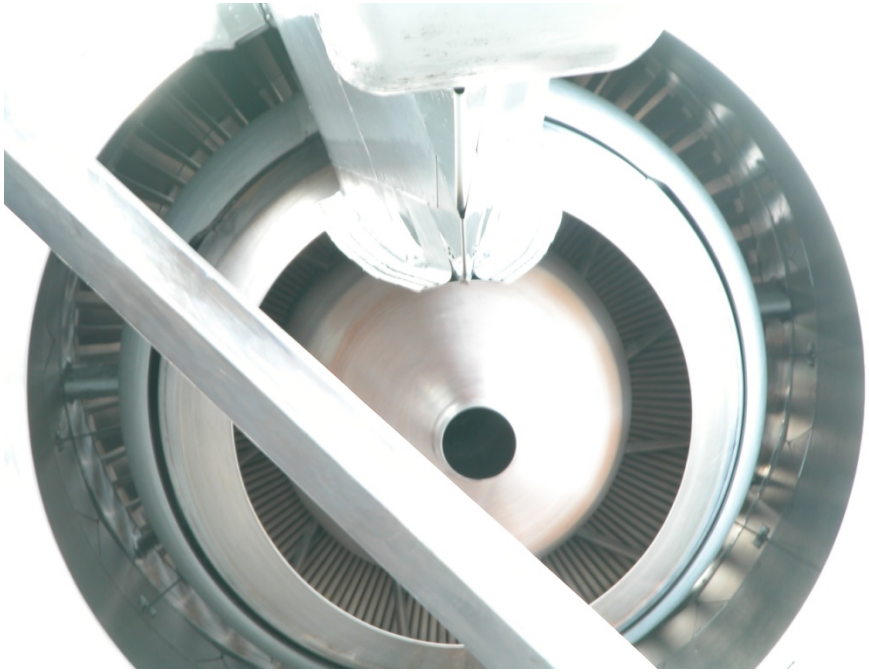
GEAE CFM56-5A engines

24,000 lbs thrust

Test Venues

JETS/APEX-2
Oakland CA; Aug '05
Four Southwest 737's with CFM-56-3-B1 or CFM56-7B24 Engines

APEX-3
Cleveland; November '05
9 Aircraft
CFM-56-3, CJ610, AE3007-A1E, PW4158, RB211-535E4 Engines



Experiment Details

EXCAVATE

Fuels: 810, 1050, 1820 ppmS

Inlets: 1, 10, 25, 35 m

Powers: 6,23,45,60,75%

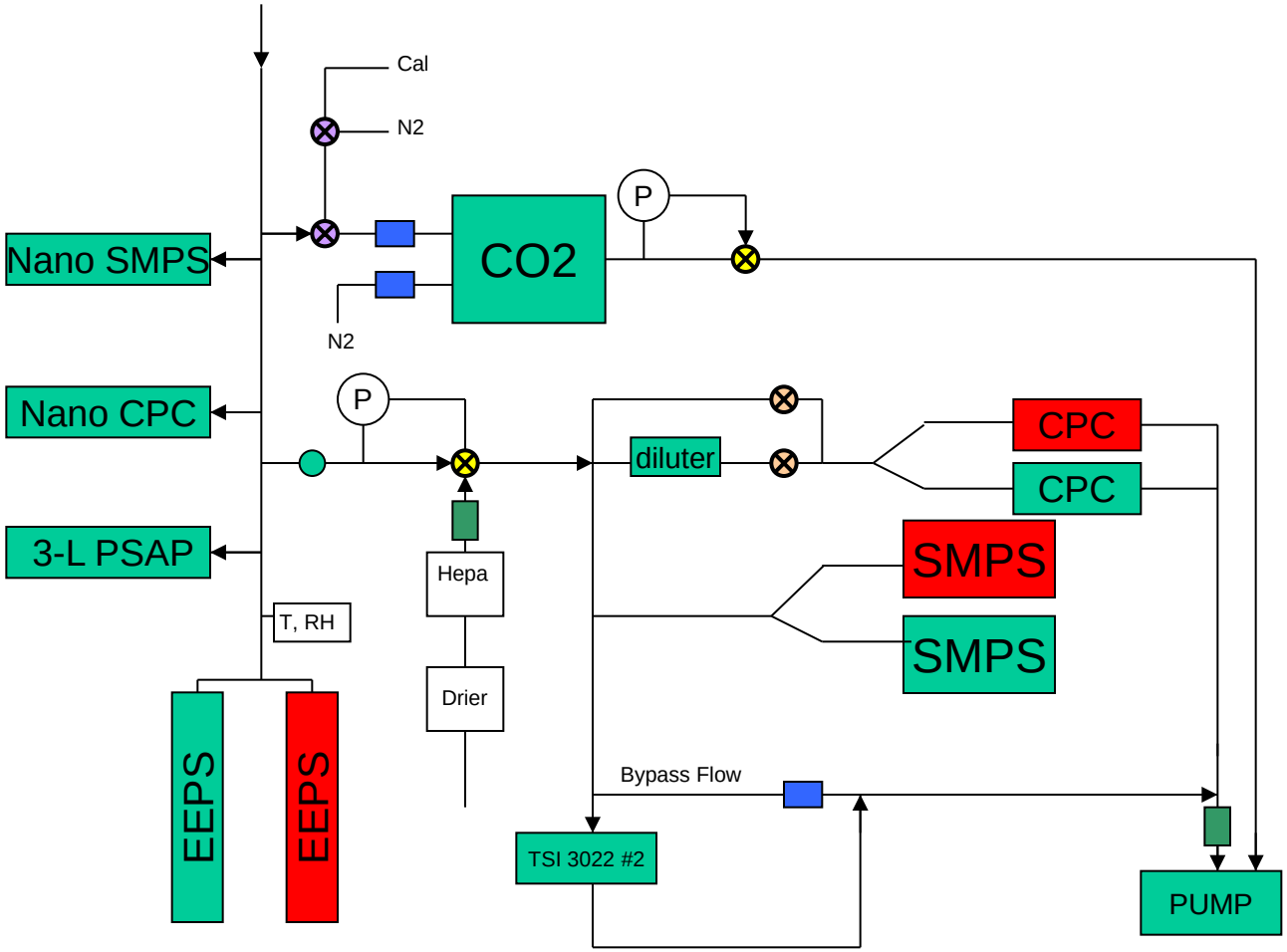
APEX-1

Fuels: 383, 530, 1595 ppmS

Inlets: 1, 10, 30 m

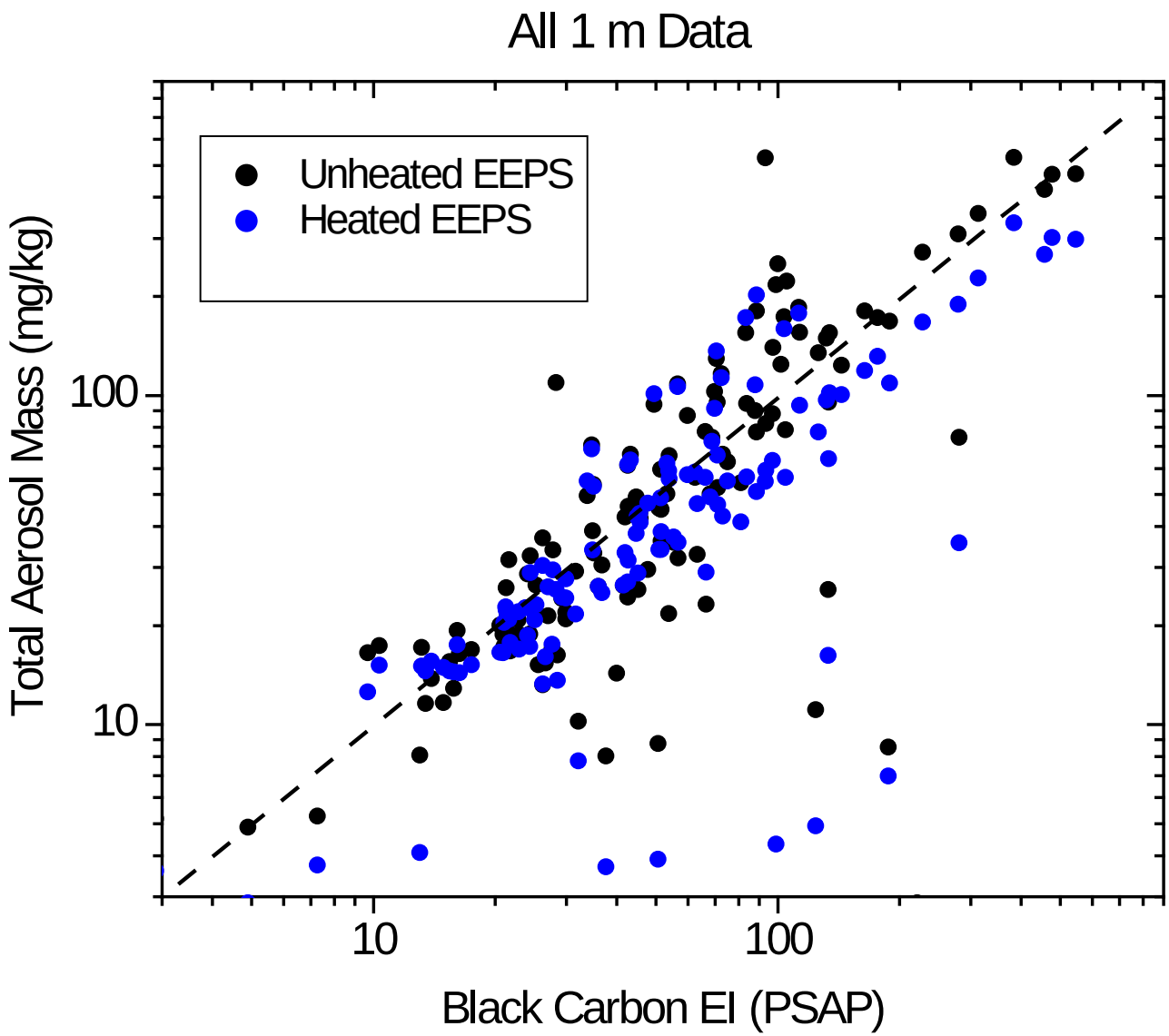
Powers: 4,7,30,45,65,85,100%

Aerosol Characterization Instruments

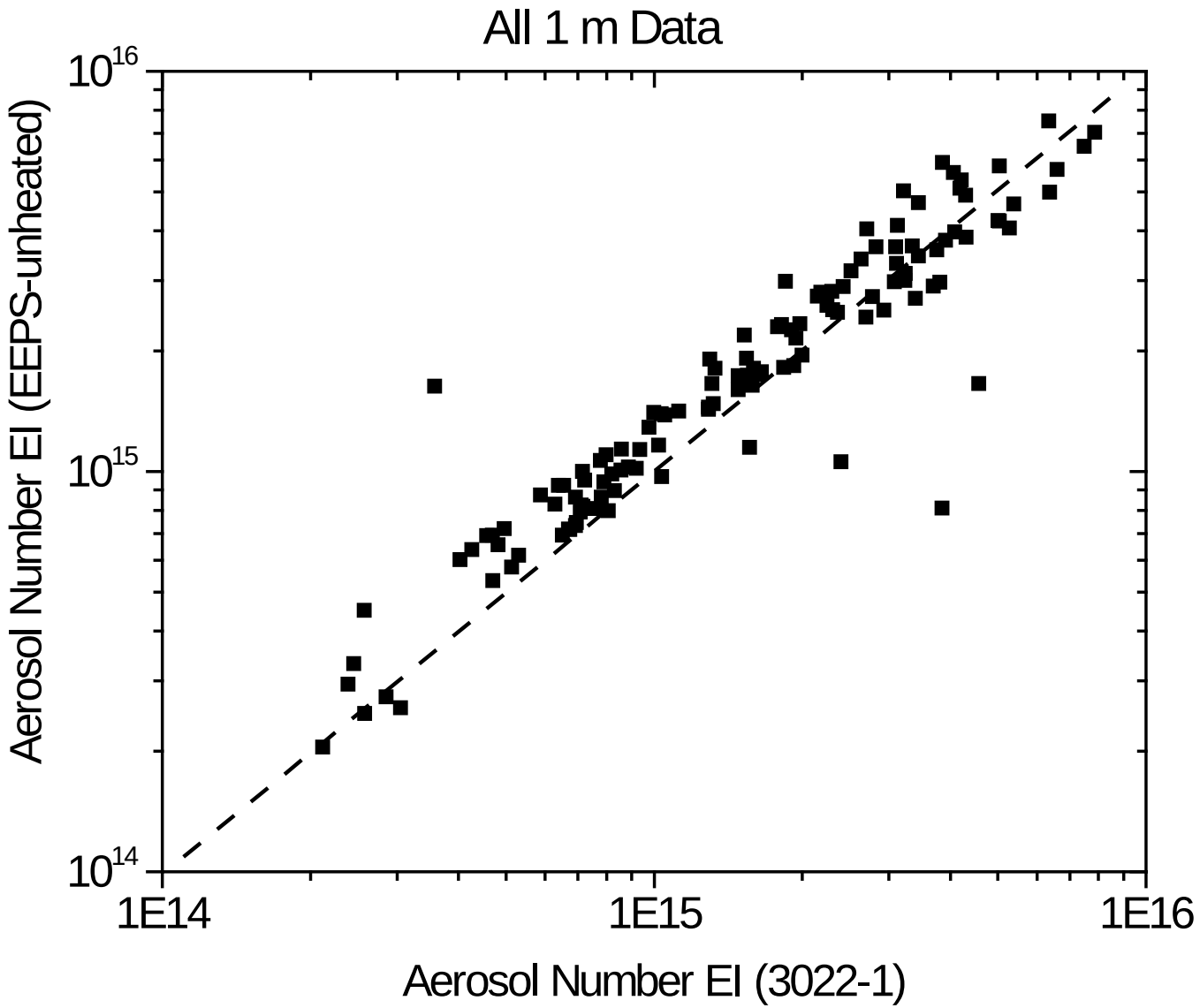


How sharp are our tools?

Mobility vs. Filter Techniques

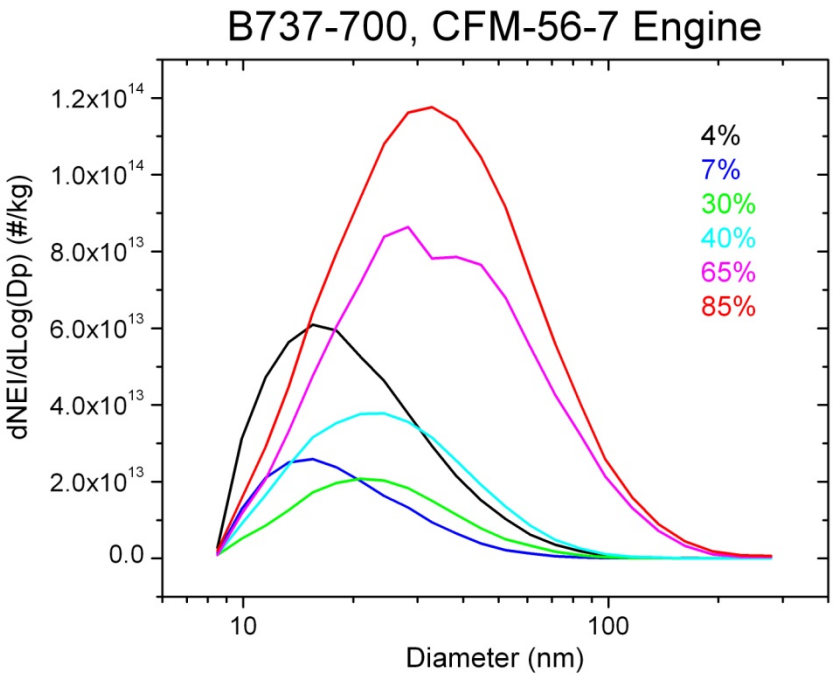


CPC vs Integrated Size Distributions

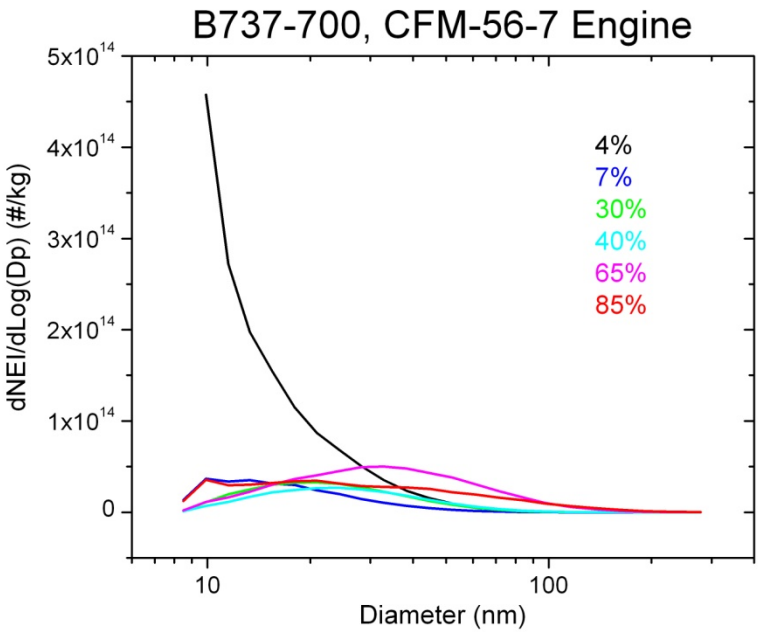


Size Distributions

APEX-2 CFM-56 Emission Characteristics

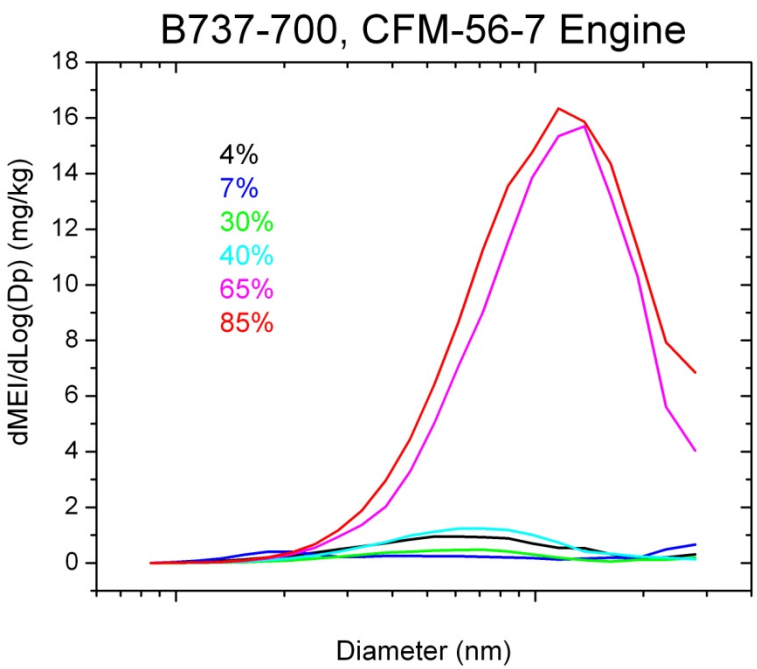


Nonvolatile Emissions @ 1 m
Size increases with power

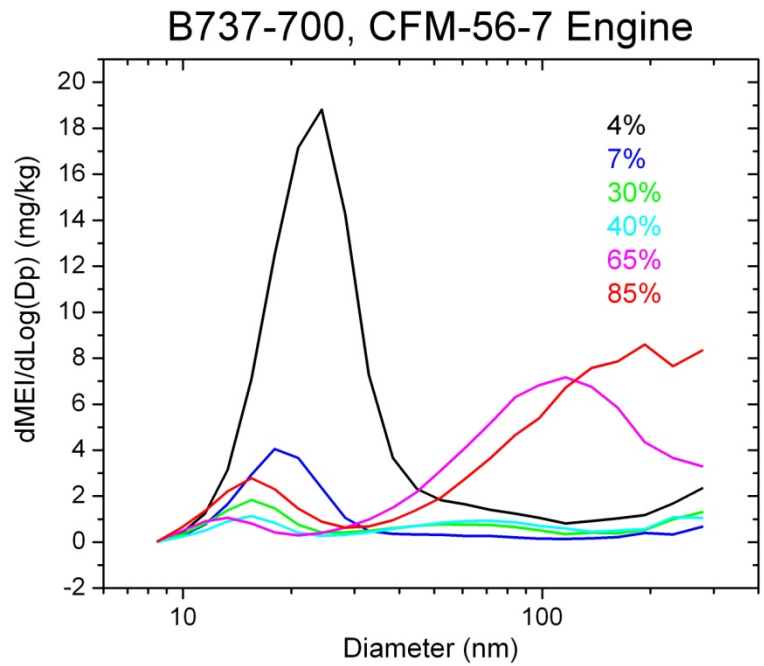


Size Distribution @ Idle
Nucleation mode seen in aged plume

APEX-2 CFM-56 Emission Characteristics

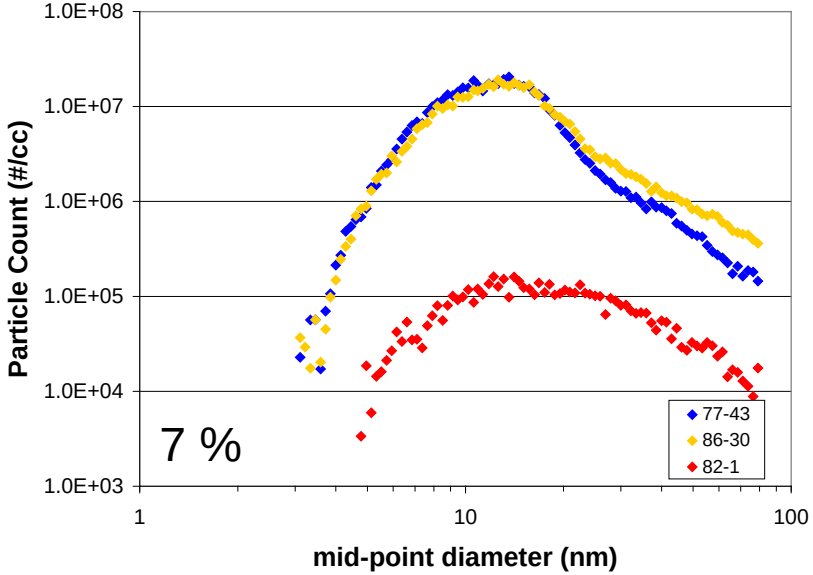


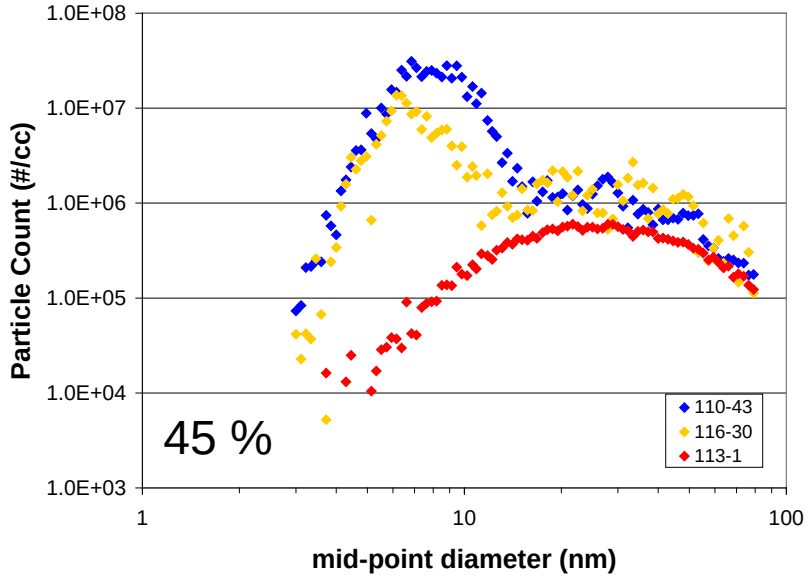
At 1m, mass emissions are dominated by soot
VMD ~60 to 120 nm

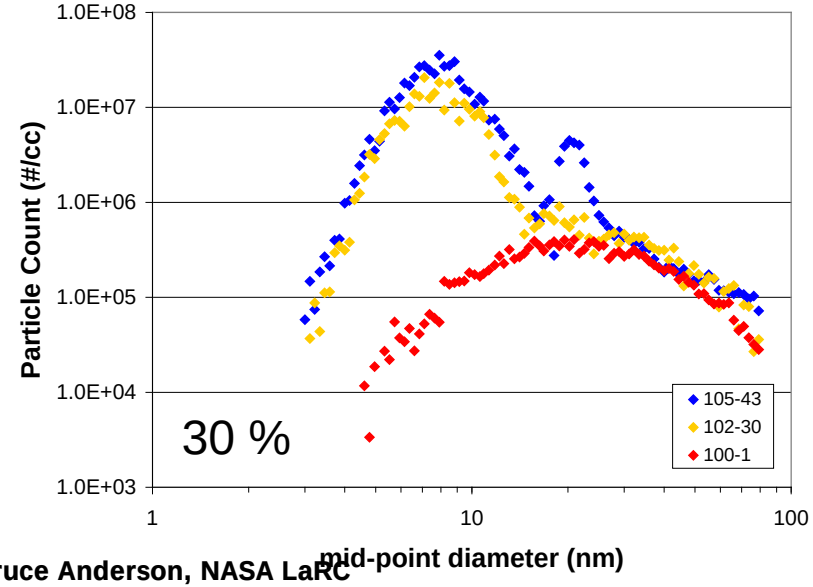


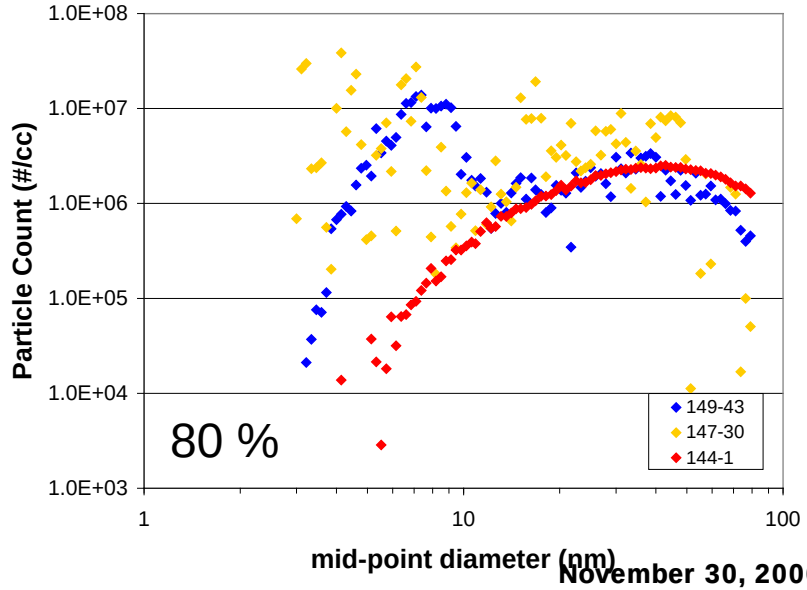
At 50m, mass emissions are dominated by soot at high power
Volatiles at low power

APEX-3 PW4158 Emission Characteristics

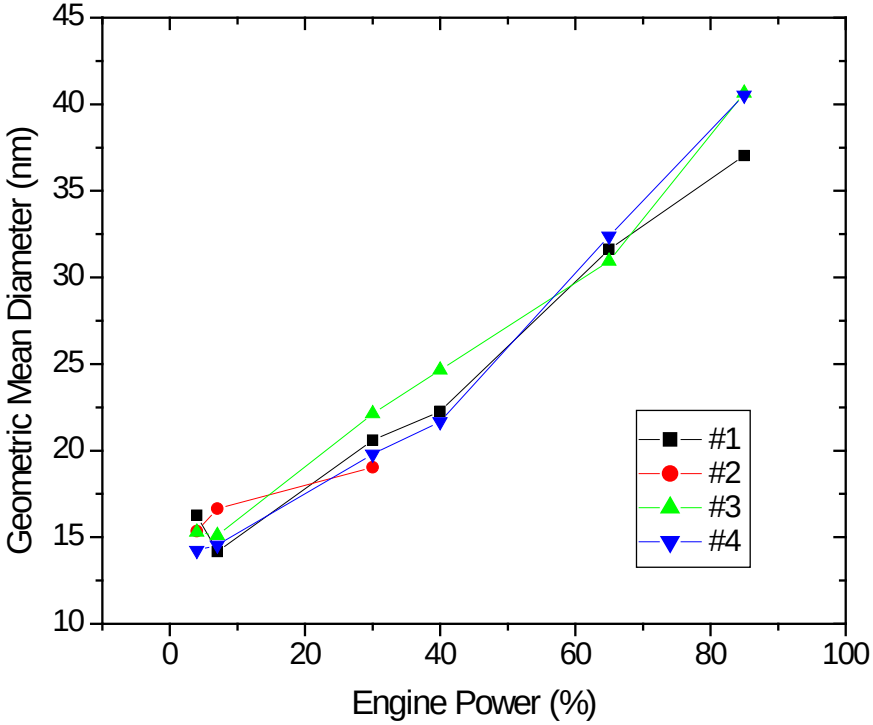




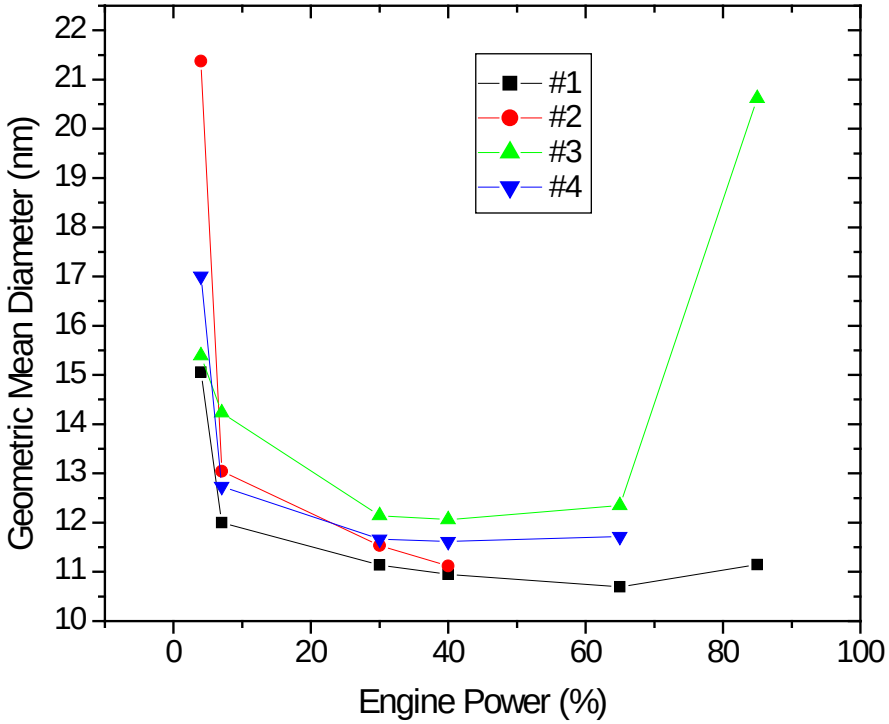




APEX-2 Aerosol Size Diameter



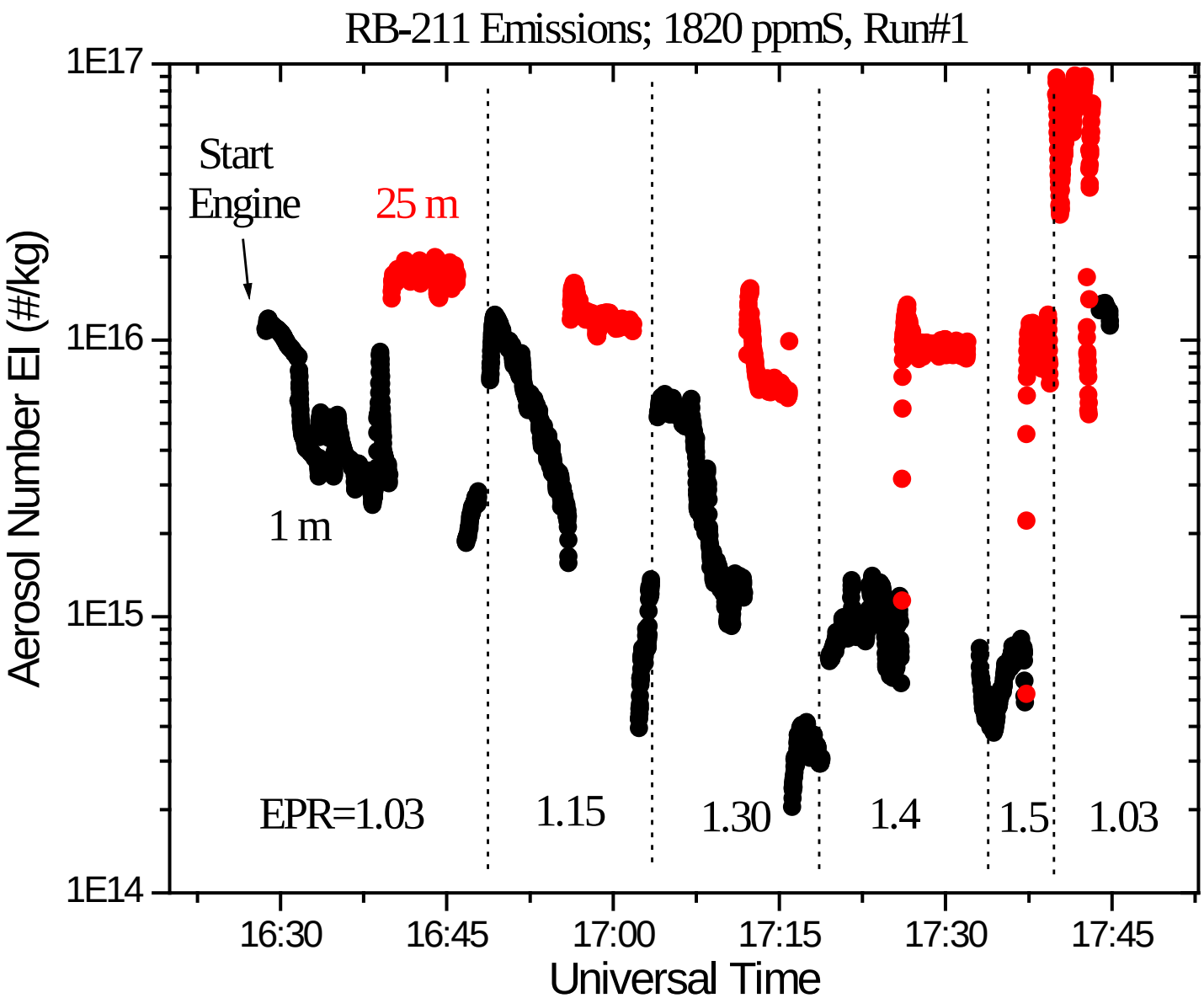
1 meter Rakes
CFM56-7B24: 15 to 40 nm
CFM56-3B: 15 to 40 mg/kg



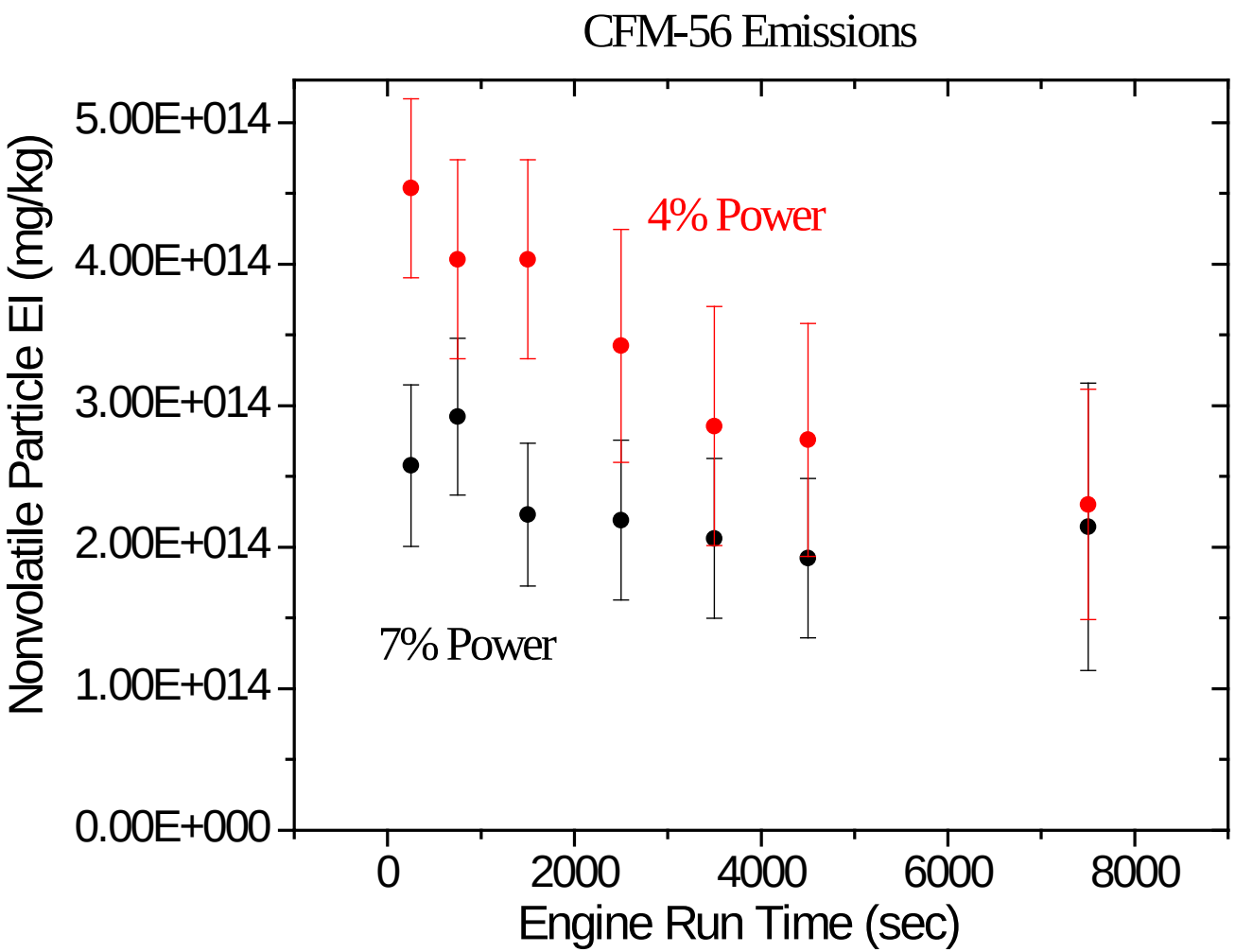
50 meter Rakes
CFM56-7B24: 10 to 20 nm
CFM56-3B: 11 to 20 nm

Number Emissions

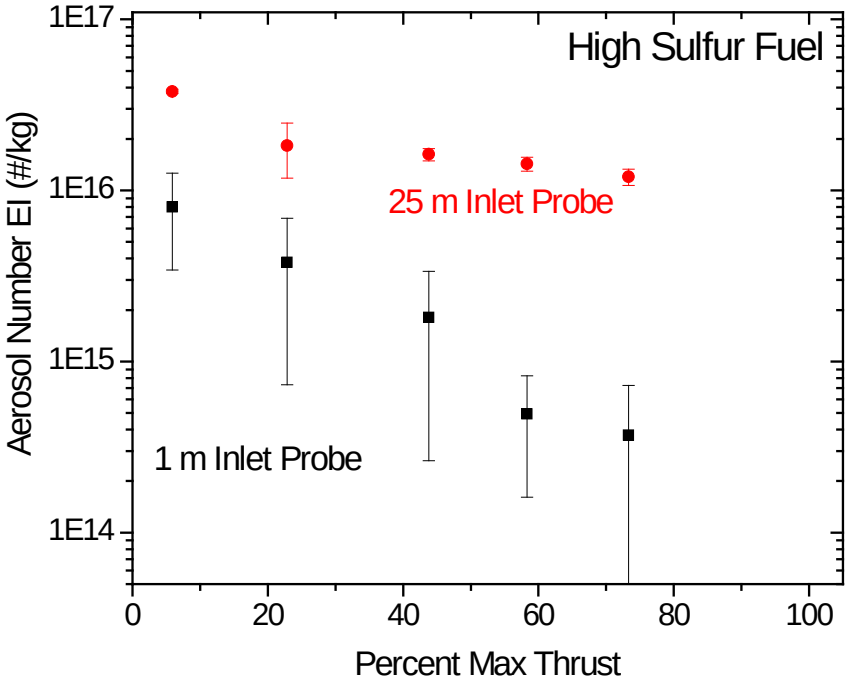
RB-211 Cold Start/Power Change Effects



CFM-56 Warm-Up Effects



EXC/APEX-1 Number EIs

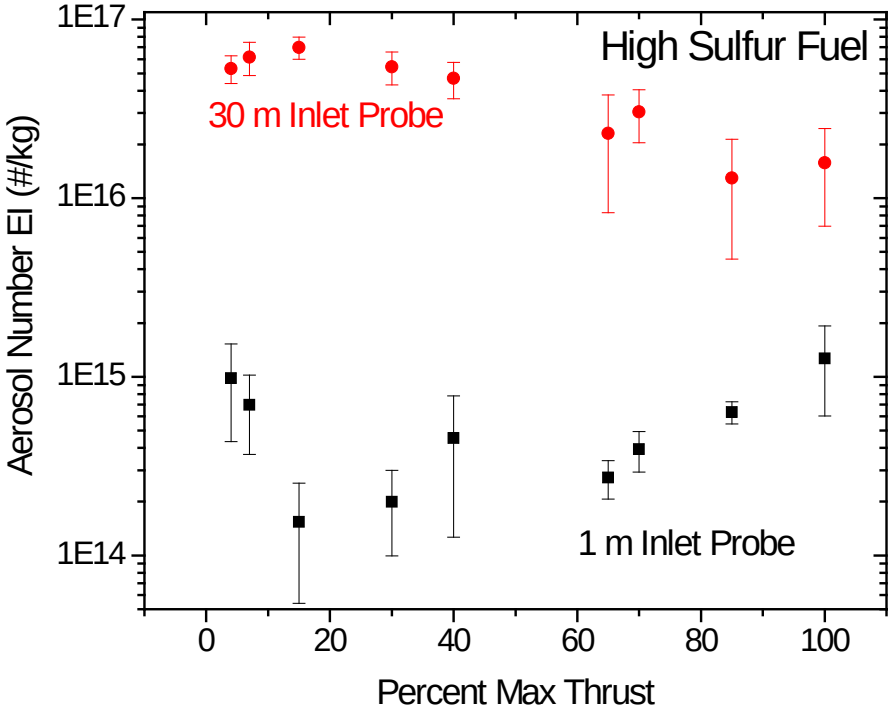


RB-211

~0.5 - 5 x 10^{15} kg^{-1} nonvolatile

10 - 50 x 10^{15} kg^{-1} volatiles

EI highly dependent on ppmS



CFM-56

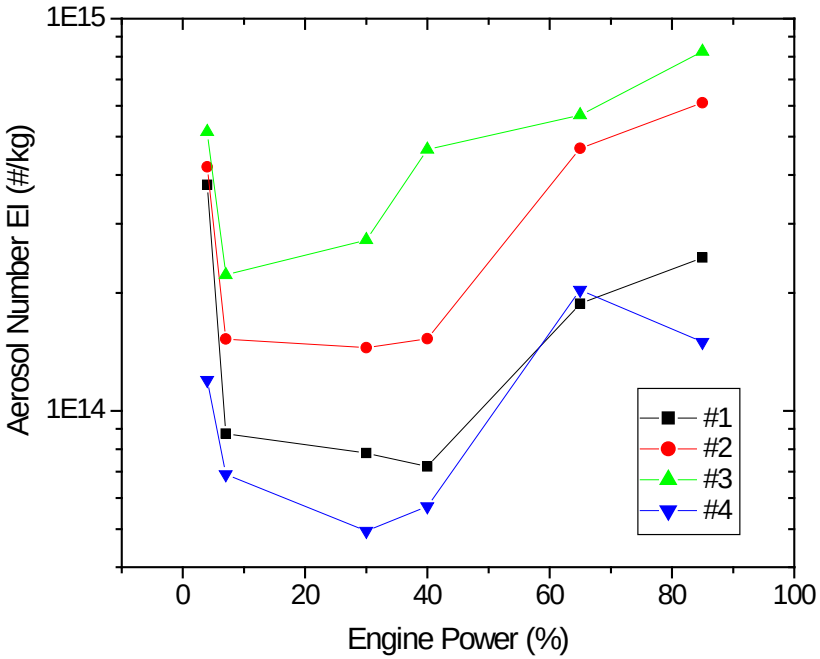
~0.5 - 2 x 10^{15} kg^{-1} nonvolatile

10 - 70 x 10^{15} kg^{-1} volatiles

EI highly dependent on ppmS

1 - 3 x 10^{7} new particles/cc!

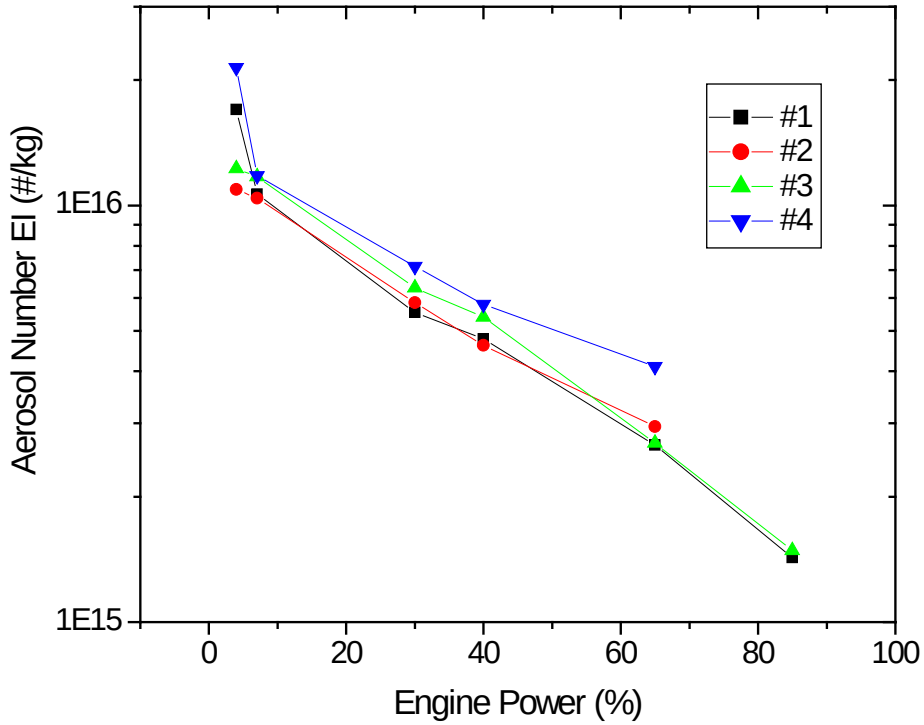
APEX-2 Aerosol Number Emissions



<u>1 meter Inlet</u>

CFM56-7B24: 0.6 to 2 x 10^{14} kg^{-1}

CFM56-3B: 1.5 to 8 x 10^{14} kg^{-1}

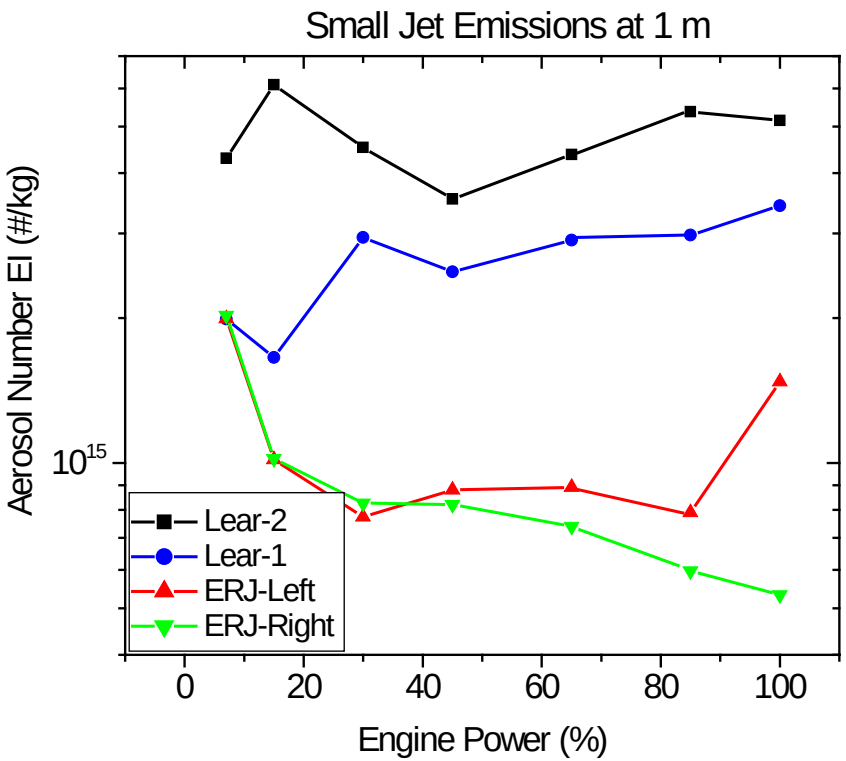


<u>50 meter Inlet</u>

CFM56-7B24: 2 to 20 x 10^{15} kg^{-1}

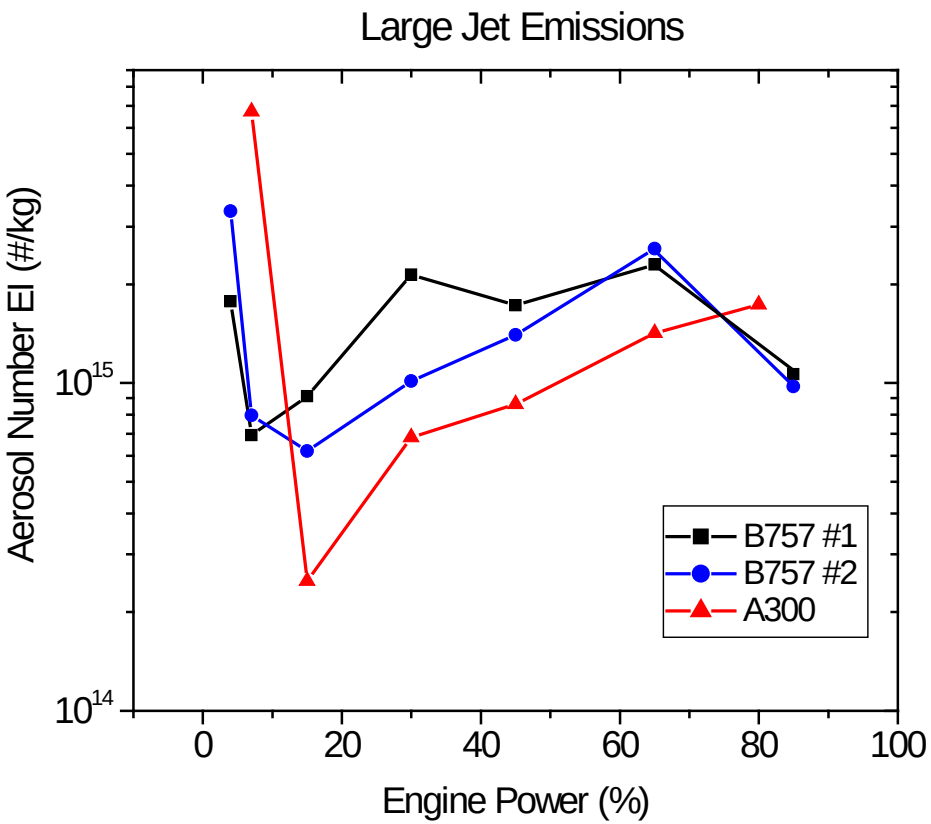
CFM56-3B: 1 to 15 x 10^{15} kg^{-1}

APEX-3 Number EIs



A3007 ~.7-2 e16/kg

CJ610 ~2-6e16/kg

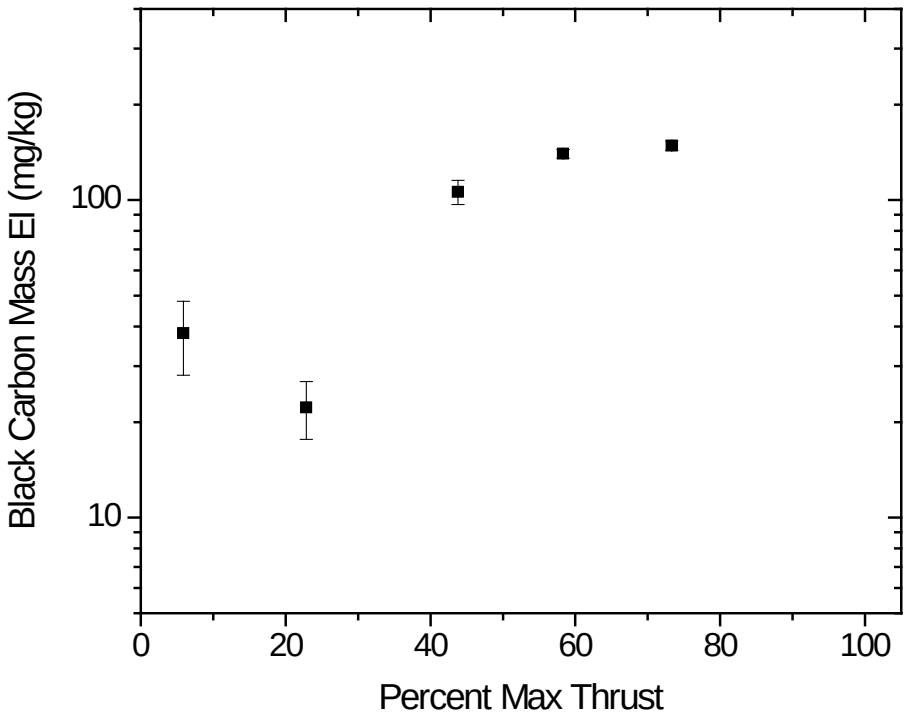


RB211 ~.8-3 e16/kg

PW4158 ~.2-6e16/kg

Black Carbon Emissions

EXC/APEX-1 Black Carbon Emissions

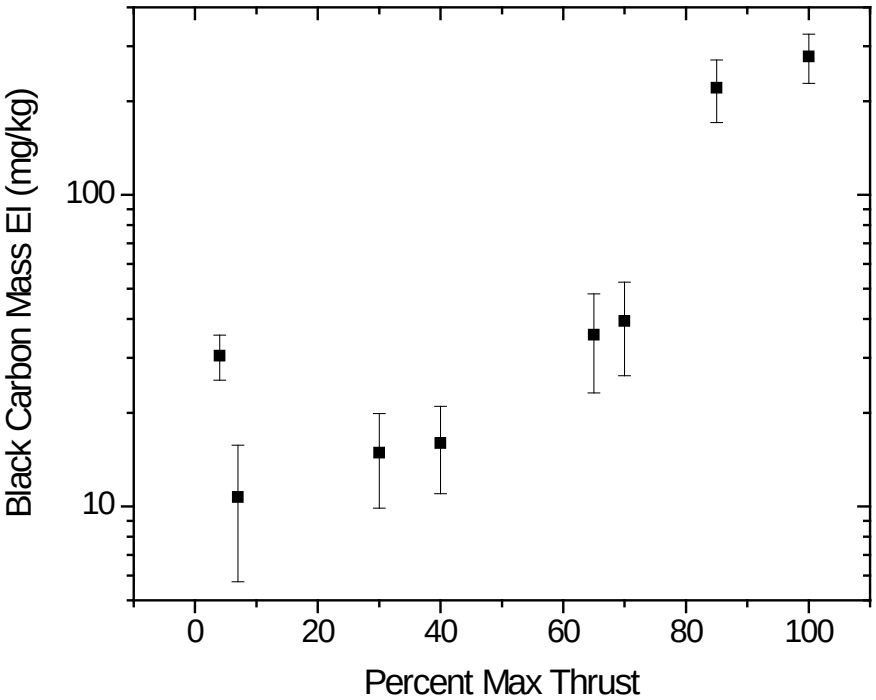


EXCAVATE RB-211

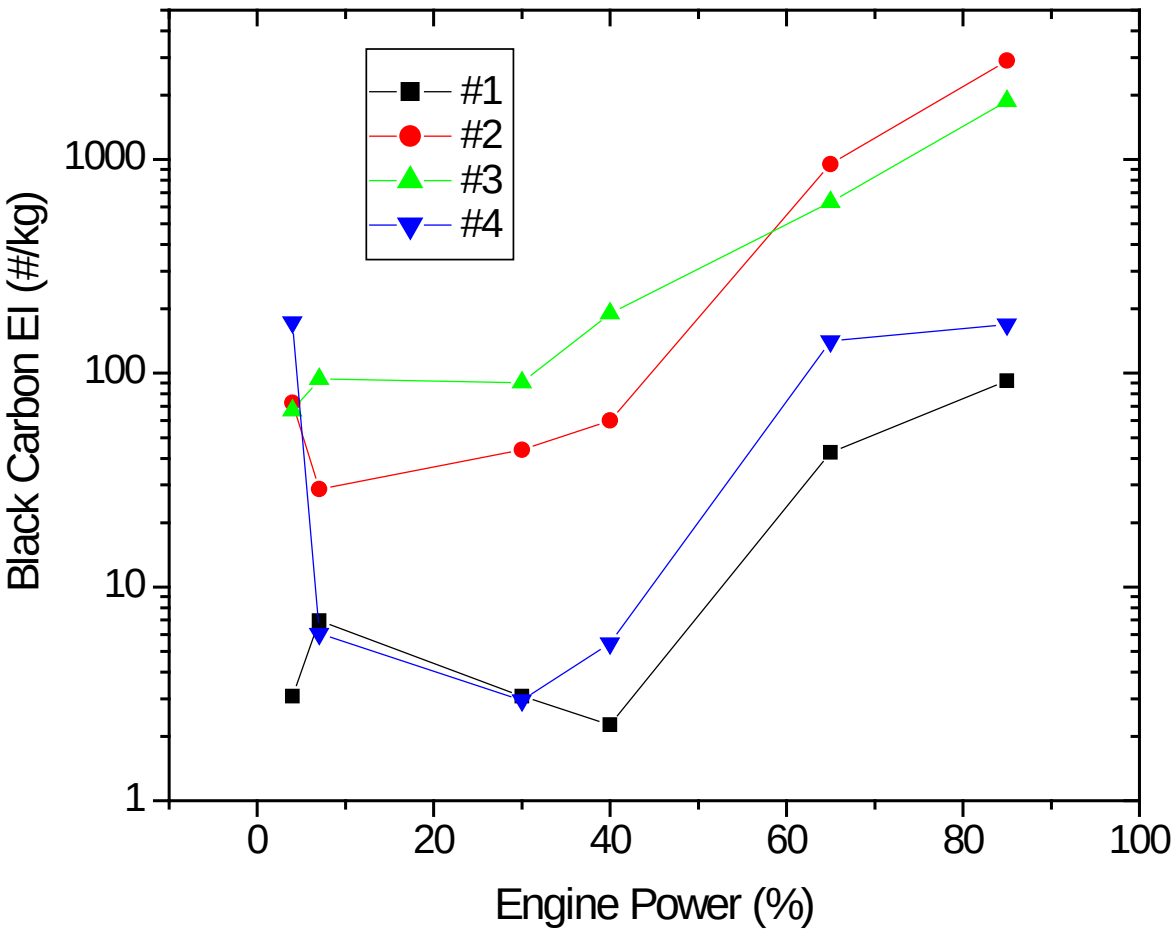
~20-200 mg/kg fuel

APEX-1 CFM-56-2

Revised: 3-150 mg/kg fuel



APEX-2 Black Carbon Emissions

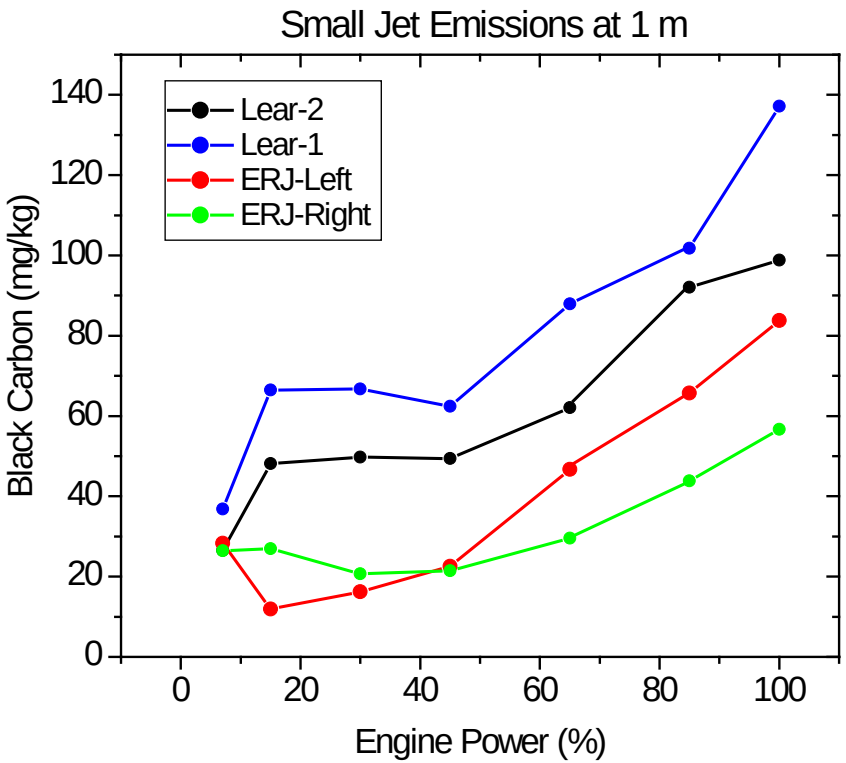


Revised BC EIs

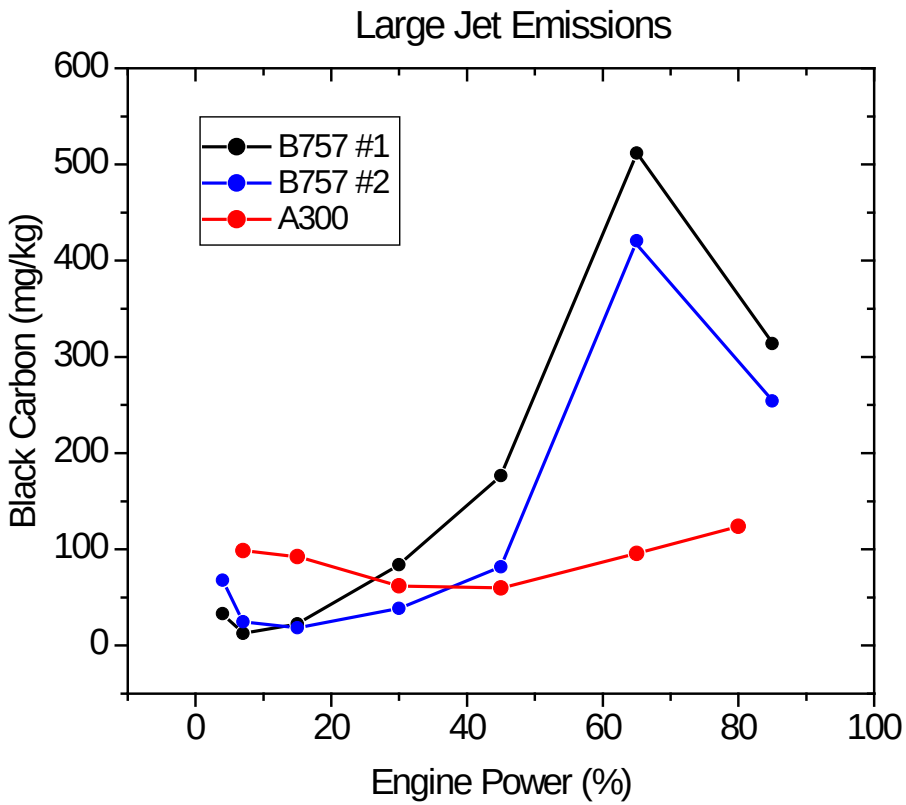
#1,#4: CFM56-7B24: 3 to 75 mg/kg

#2,#3: CFM56-3B: 20 to 300 mg/kg

APEX-3 Black Carbon Emissions



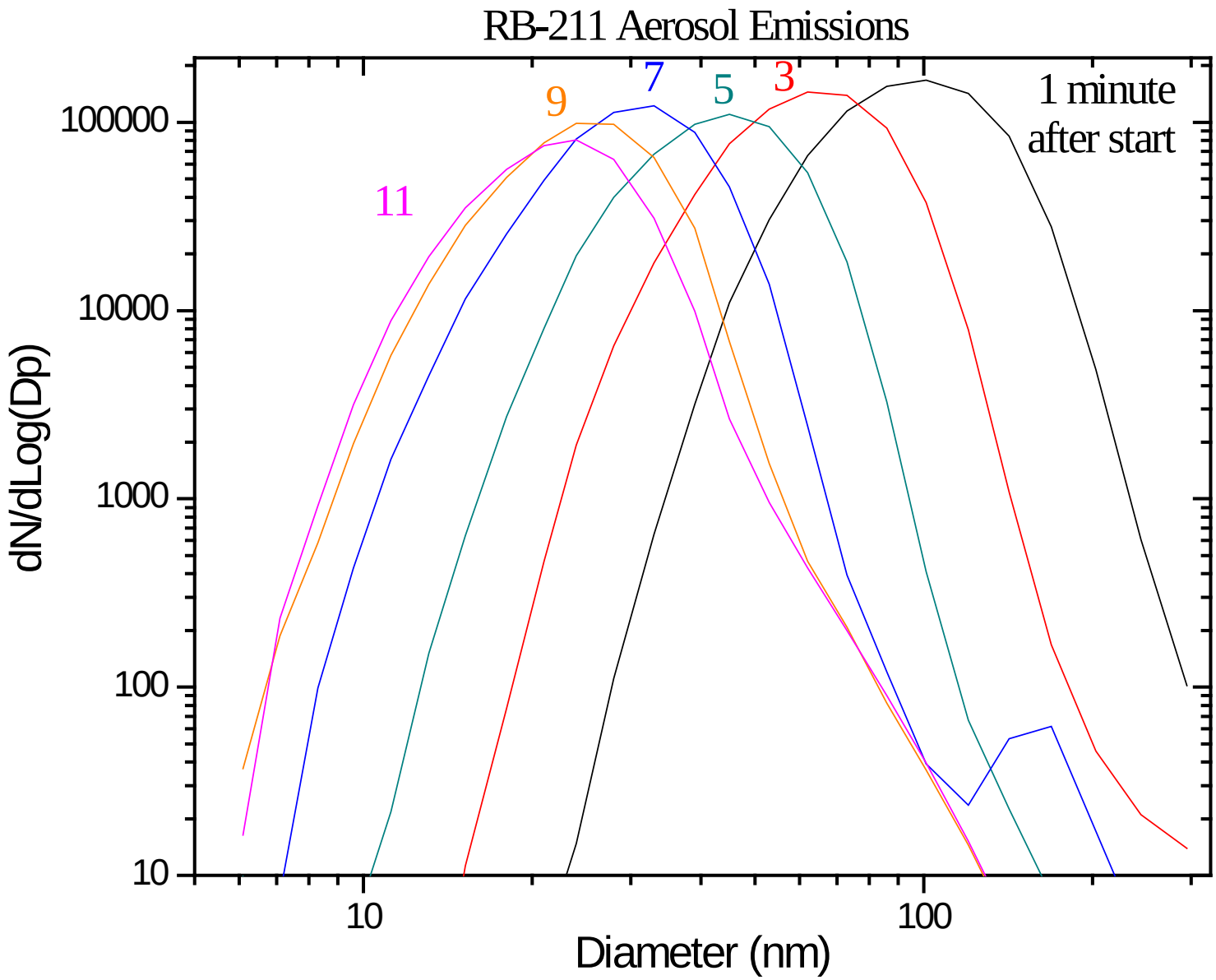
A3007: ~20-80 mg/kg
CJ610: 40-140 mg/kg



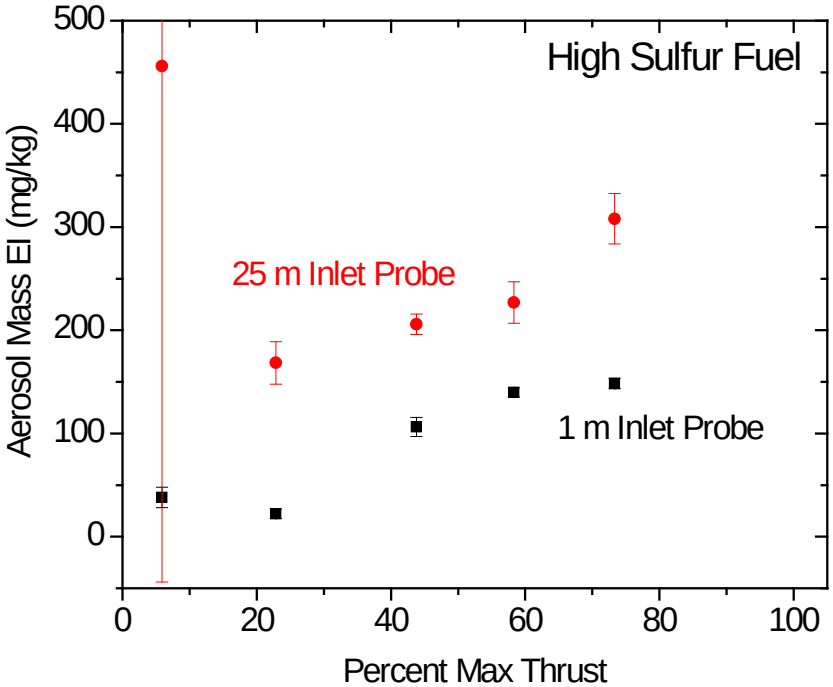
RB211: ~10-500 mg/kg
PW4158: 40-120 mg/kg

Total Mass Emissions

EXC RB-211 Emissions After Cold Start



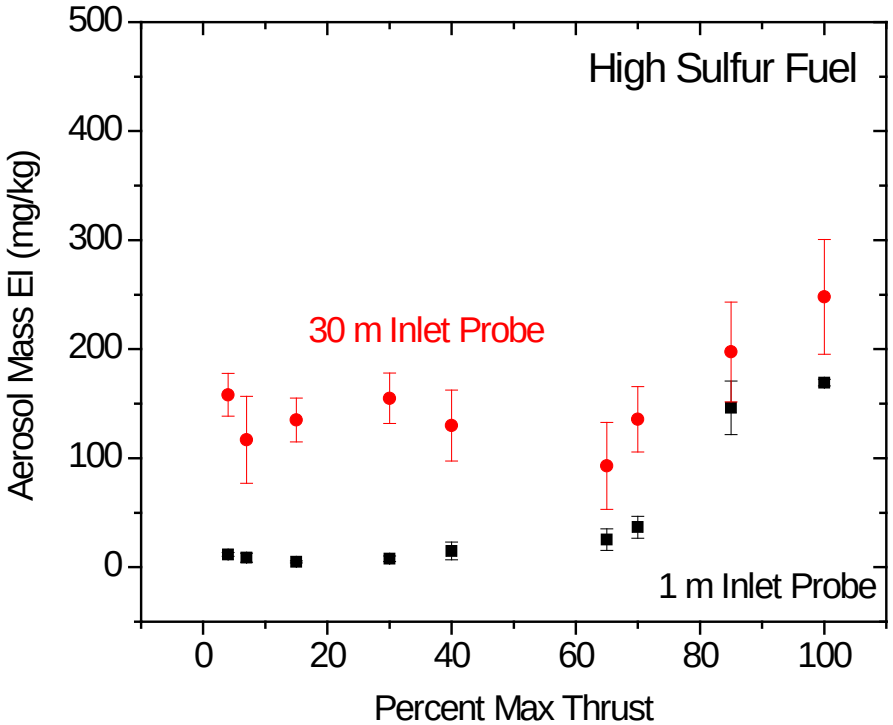
EXC/APEX-1 Total Mass Emissions



RB-211

20 – 1000 mg/kg @ idle

50 –100 mg/kg @ higher powers

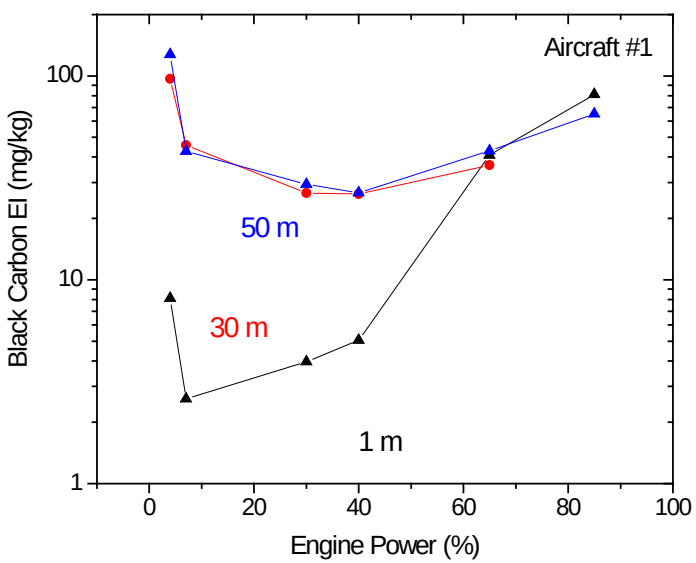


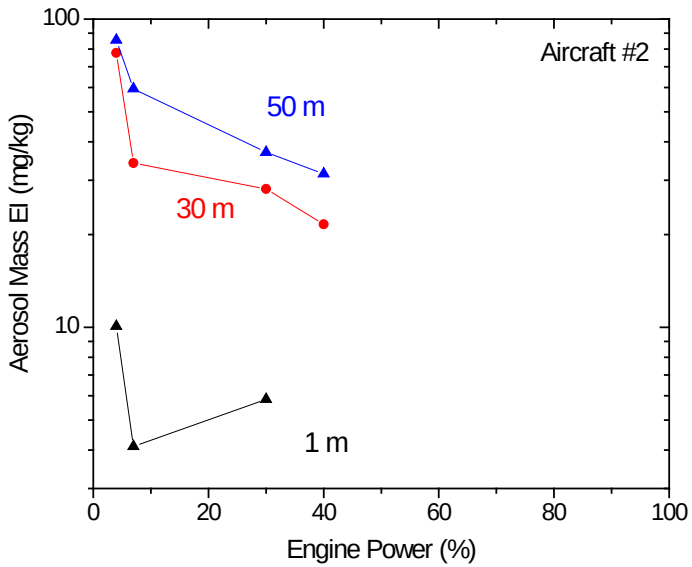
CFM-56

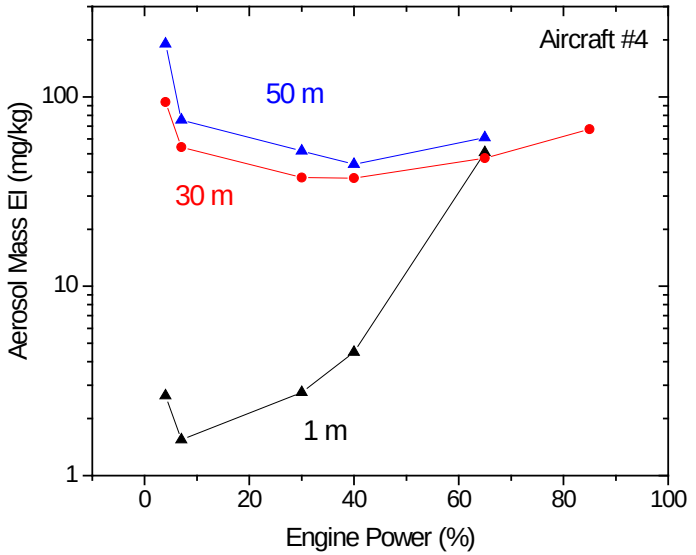
Revised:

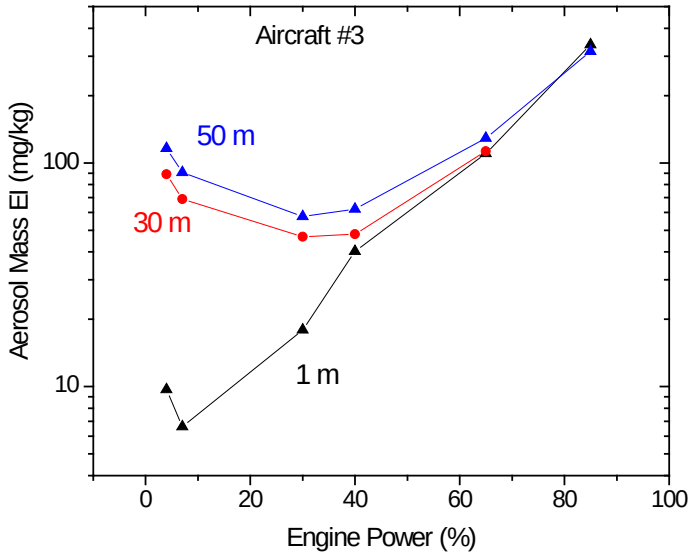
25 – 100 mg/kg

APEX-2 Aerosol Mass Emissions

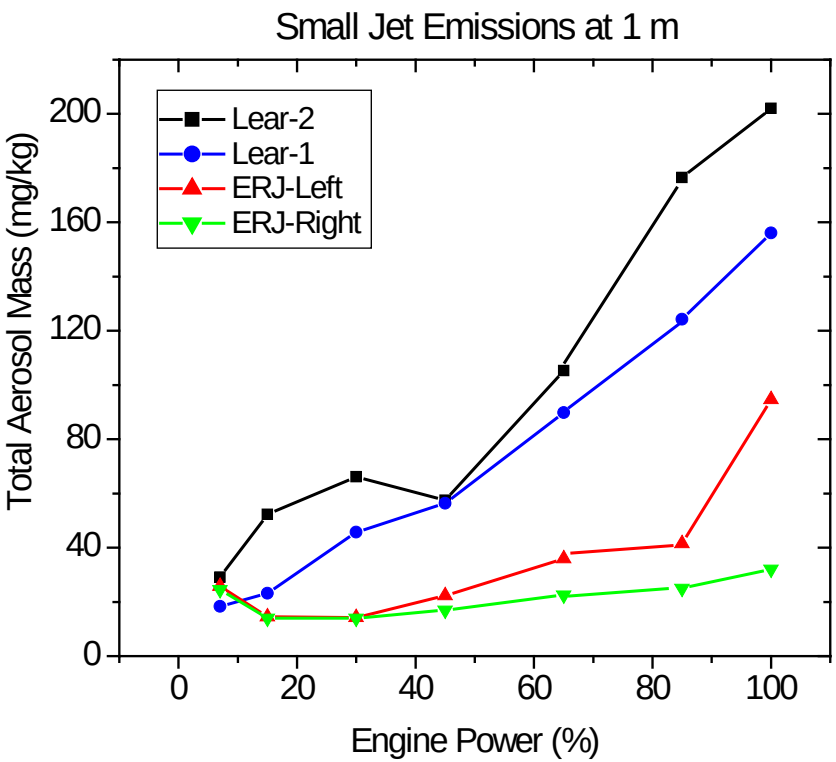






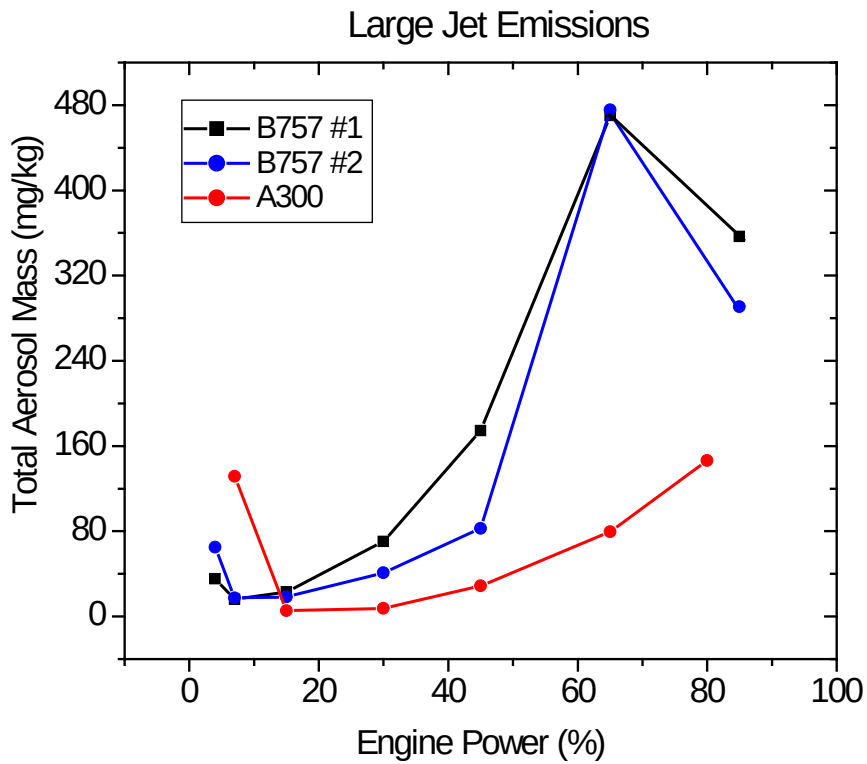


APEX-3 Total Mass Emissions



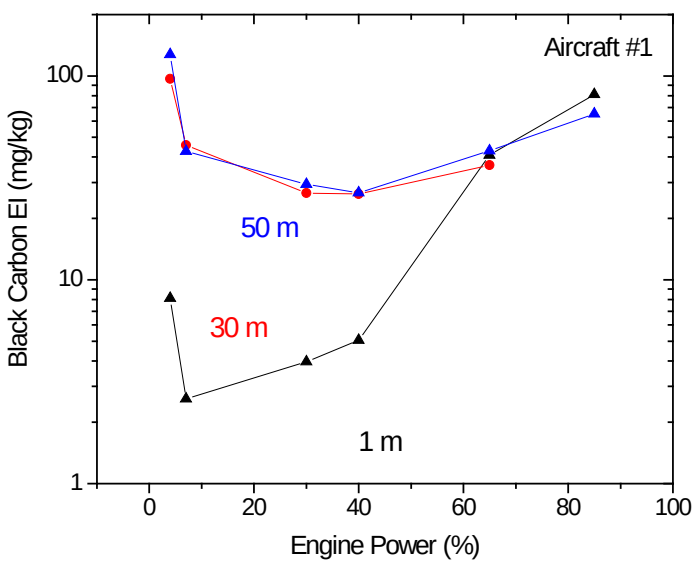
A3007 10 to 80 mg/kg
CJ610 30 to 200 mg/kg

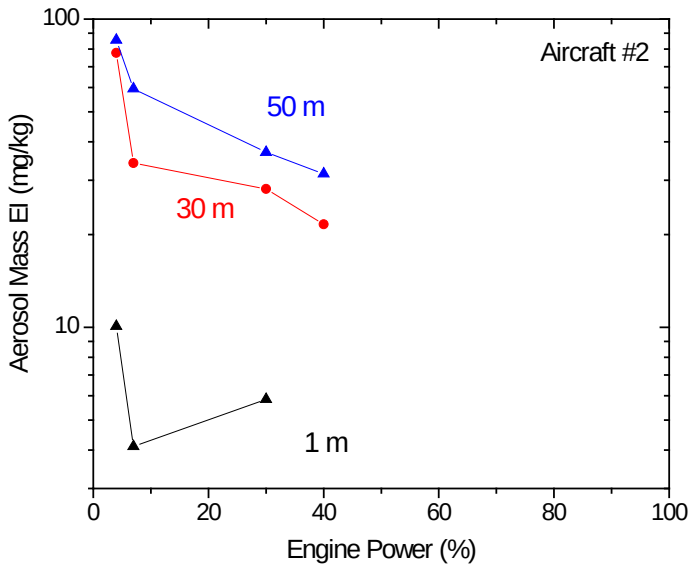
RB211: ~10-500 mg/kg
PW4158: 20-150 mg/kg

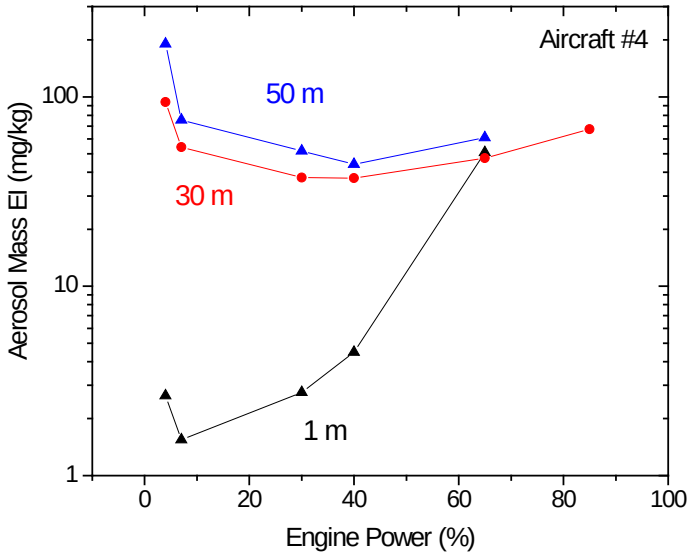


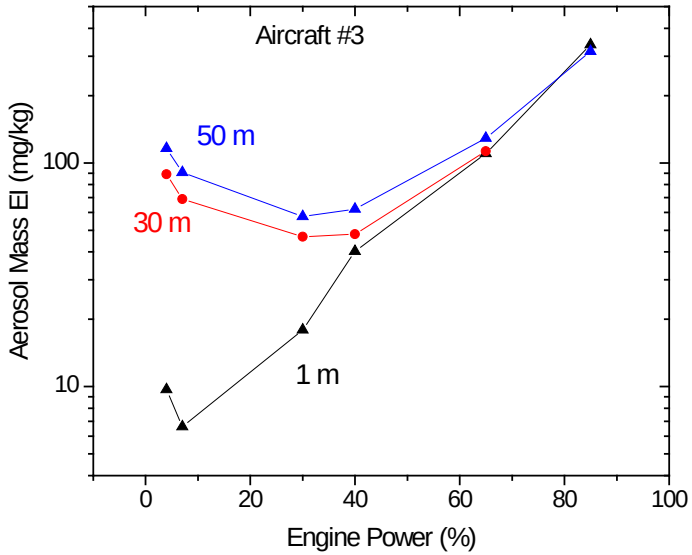
Volatile Mass Emissions

APEX-2 Aerosol Mass Emissions

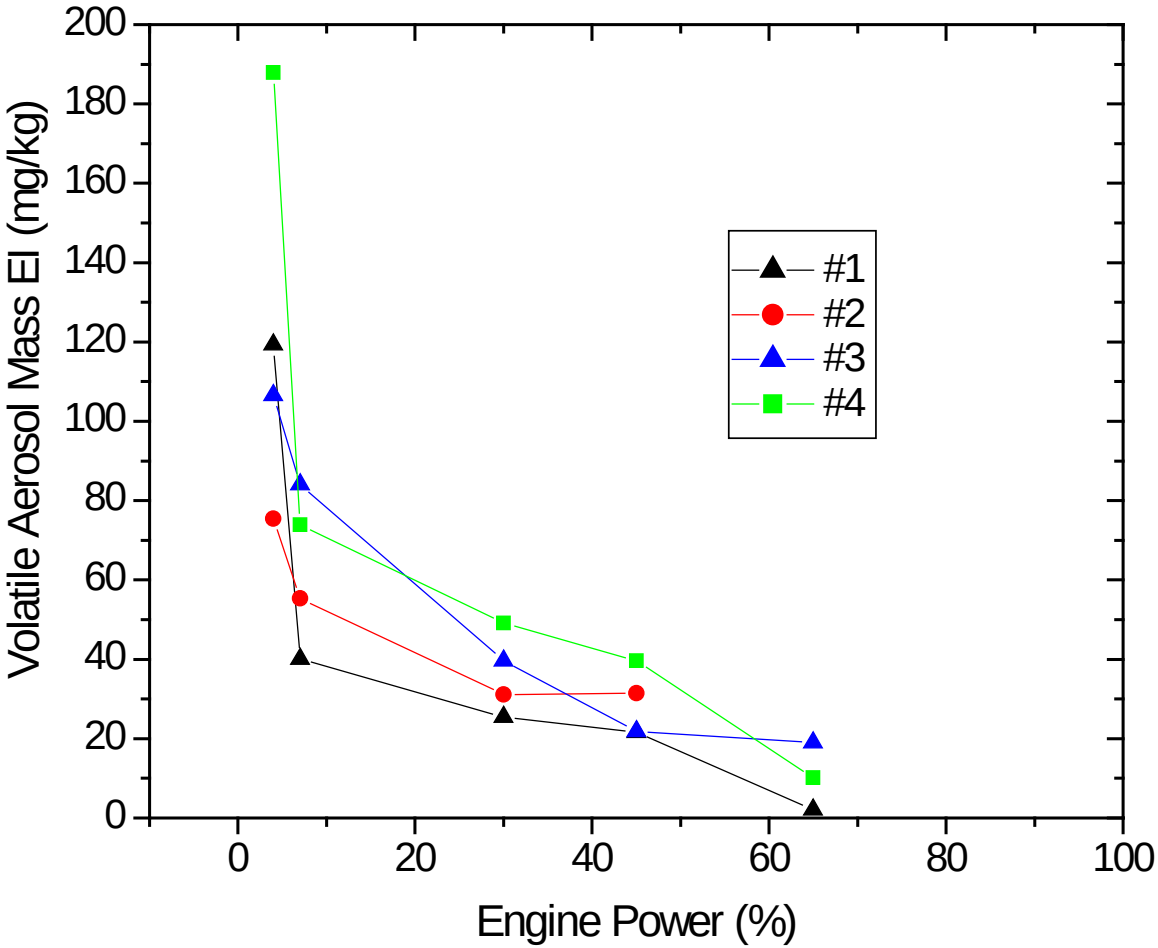








APEX-2 Volatile Mass Emissions

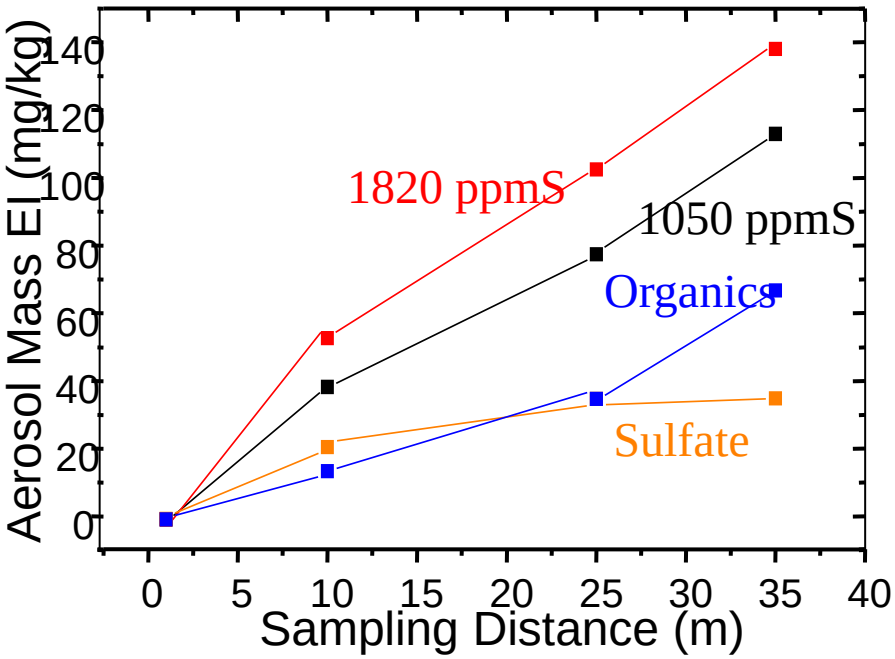


<u>50 meter Rakes</u>

CFM56-7B24: 0 to 200 mg/kg

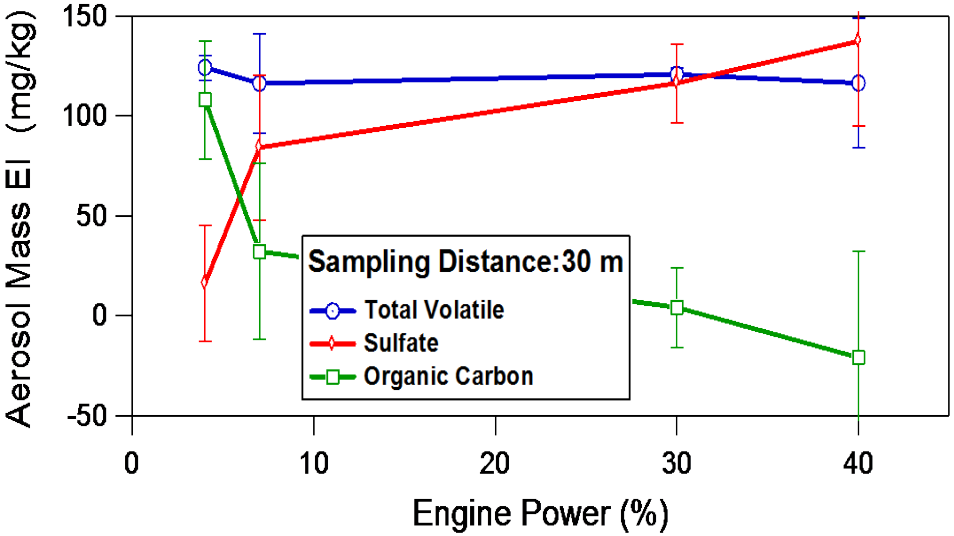
CFM56-3B: 10 to 110 mg/kg

EXC/APEX Volatile Mass Emissions



RB-211, 44% power
(1820 – 1080 ppm)
ε ~ 0.9 %

CFM-56
(1595 – 383 ppm)
ε ~ 0.5 - 1.5%



Summary of Results

- Modern engines emit 0.1 – 2 x 10^{15} kg^{-1} fuel burned of nonvolatile particles, depending on power setting
- Nonvolatile particle mass emissions range from 10 to 300 mg kg^{-1} and increase with power
- Nonvolatile particle size increases with power, with GMD's ranging from 15 to 45 nm
- Secondary aerosols form rapidly within the plume, with formation rates approaching 10^7 cm^{-3} s^{-1}; nucleation mode evident in all aged plumes
- Engines can potential emit huge quantities of PM on cold starts!
- Sulfur and organic species implicated in secondary aerosol formation; RB211 emits > 1000 mg kg^{-1} under some conditions
- Secondary aerosol number and mass concentrations are highly dependent on fuel S concentrations
- Volatile aerosol variation with fuel S consistent with conversion of 1$\pm$0.5% of fuel S to S(VI)