Alternative fuel test on PW308 engine

A Collaborative effort

NASA, AFRL, ARI, UTRC and P&W

Anuj Bhargava

Aerodyne Research, Inc.

United Technologies Research Center

Tests performed to investigate impact of alternative fuels

- **Primary test objective: determine the impact of synthetic fuel on performance and emissions**
- Secondary test objective
  - Impact of heated fuel on emissions and performance
  - Spatial differences in emissions
- Measurements performed on PW 308 engine
- Sampling rake with multiple gas and particle probe used to collect sample at engine exhaust and at 50m
- Measurement team
  - NASA: PM and Gaseous emissions
  - AFRL: PM and Gaseous emissions
  - ARI: Volatile PM emissions
  - UTRC: Sampling System
  - P&W: Performance and test lead

All test objectives achieved

- Successful testing of all three fuels (JP8, Synthetic fuel or Fischer Tropsch (FT) fuel, and Blend)
  - No significant difference in engine performance or gaseous emissions with the three fuels
  - PM emission reduction with blend and synthetic fuel
  - Heated fuel had higher NO_x emissions
- Excellent set of data to validate models

Agenda

- Tests conducted
- Results
  - Engine performance and gaseous emissions with the different fuels
  - Difference in non-volatile PM emissions
  - Volatile PM emissions

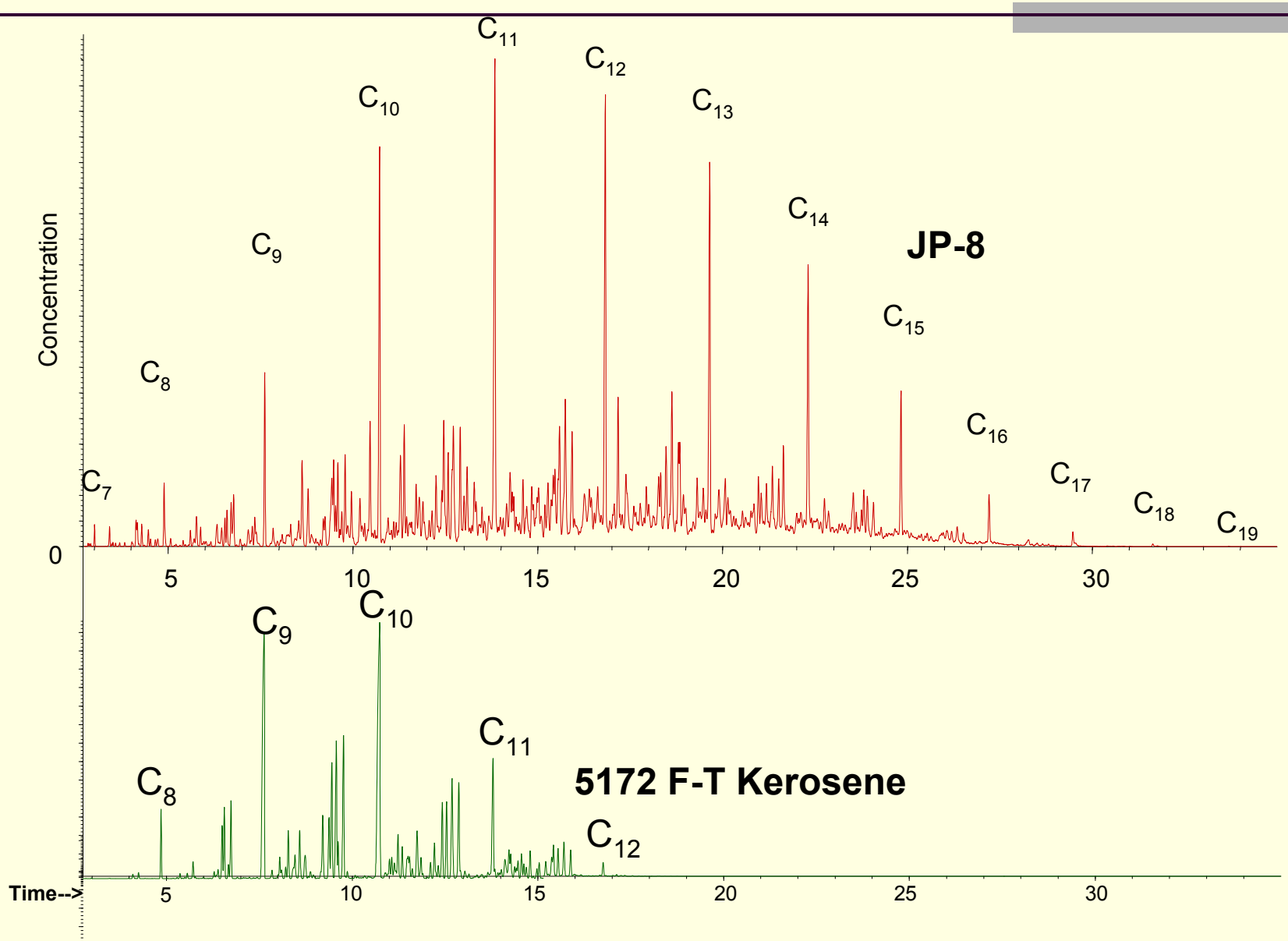
Agenda

- Tests conducted
  - Fuels tested
  - Sampling system
  - Test matrix
- Results
  - Engine performance and gaseous emissions with the different fuels
  - Difference in non-volatile PM emissions
  - Volatile PM emissions

Test setup

PW308 - B04 STAND - 03/27/08
NASA
COMPANY PROPRIETARY
08D8103-006

Composition of synthetic fuel looks different from JP8

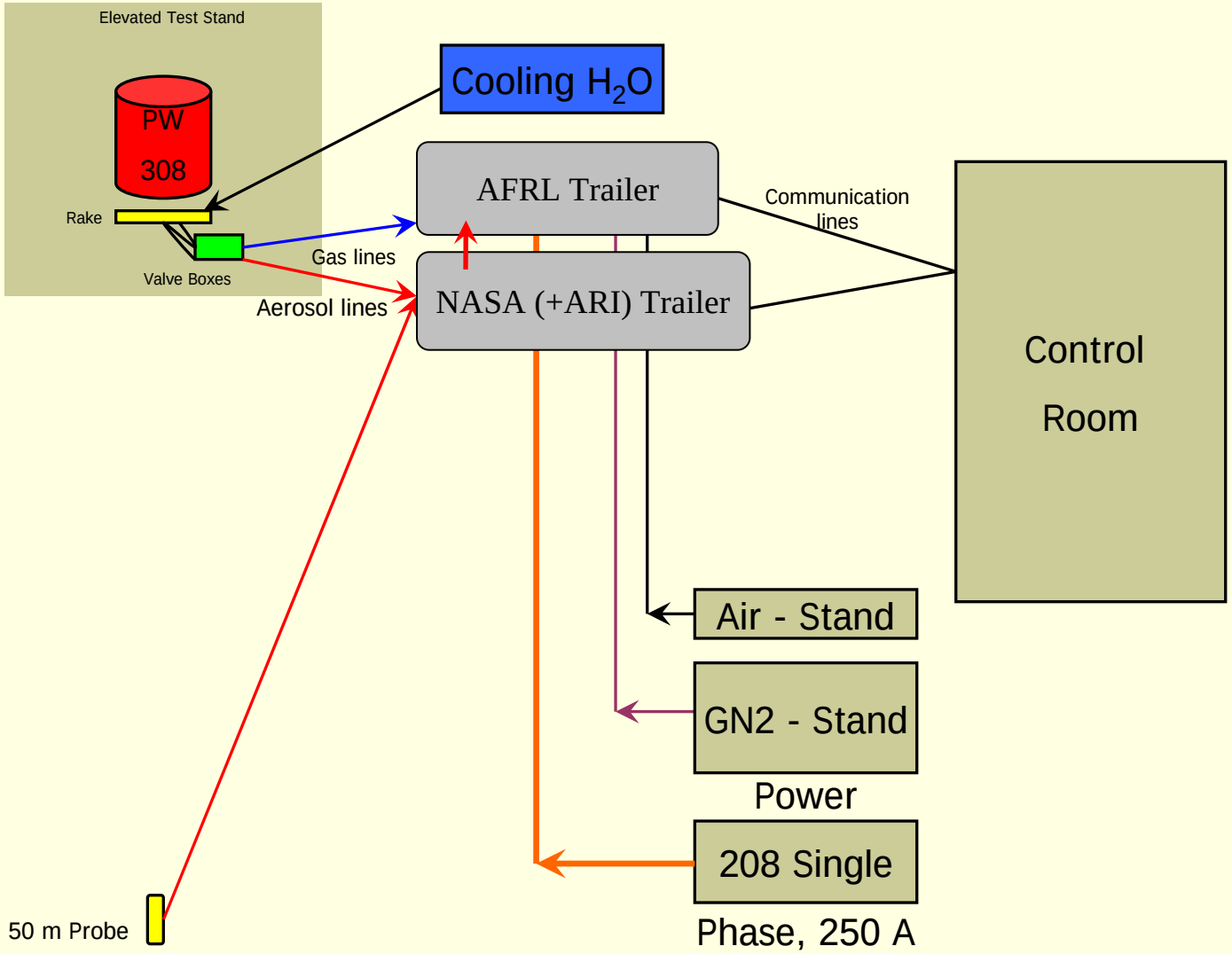


The three fuels have similar properties

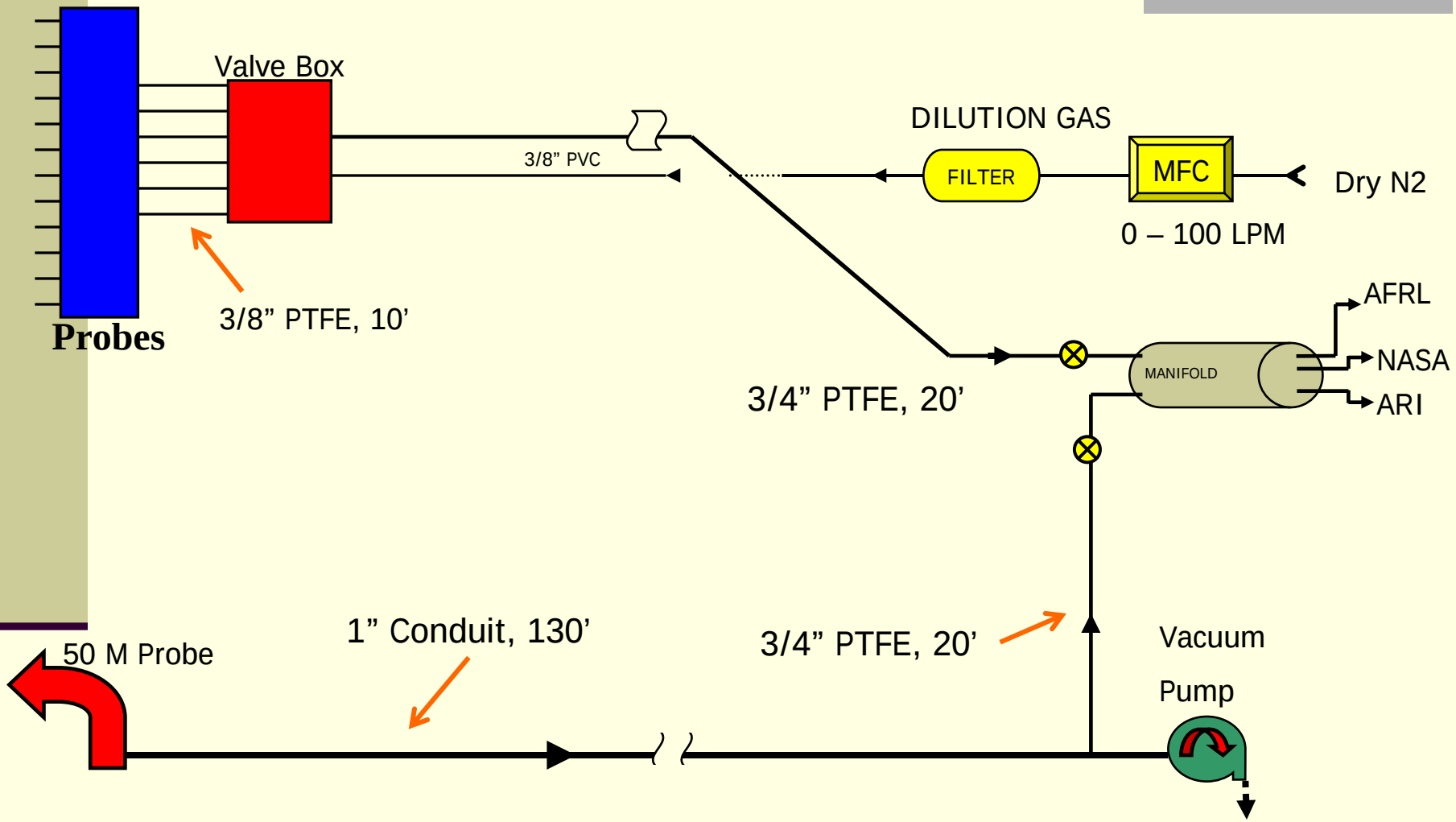
Property	JP-8	Blend	Synthetic
Viscosity (cSt)	1.38	1.14	0.96
Specific Gravity	0.8050	0.7734	0.7377
Net Heat of Combustion (Btu/lb)	18,533	18,735	18,960
Hydrogen % mass	13.95	14.78	15.71
Particulate contamination (mg/L)	0.71	0.21	0.11
Sulphur content (%)	0.123	0.065	0.003
Aromatic content (%)	19	10.1	0.17

Properties of the blend are within the Aviation fuel Specs
Synthetic fuel doesn't meet Aviation fuel spec

Test Setup

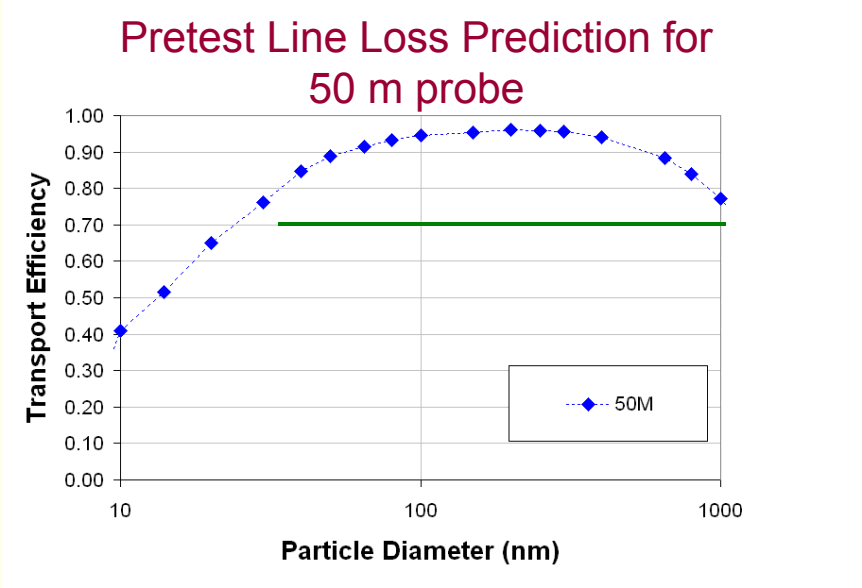

Elevated Test Stand
PW
308
Rake
Valve Boxes
Cooling H_2O
AFRL Trailer
Communication lines
Gas lines
Aerosol lines
NASA (+ARI) Trailer
Control Room
Air - Stand
GN2 - Stand
Power
208 Single
Phase, 250 A
50 m Probe

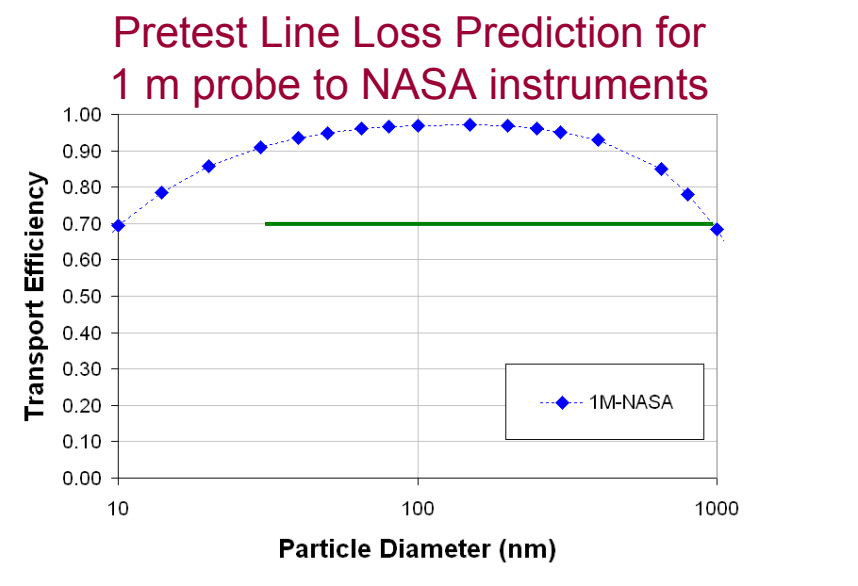
Particle Probe Plumbing designed to minimize particle losses

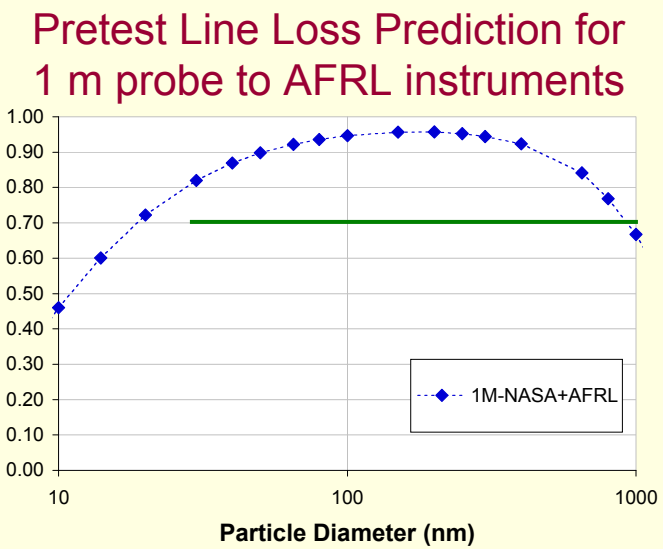


Considerable effort expensed to insure that the sampling methodology follows the recent advancement made in PM emission measurement

Line loss estimation model predicts line losses within acceptable limits

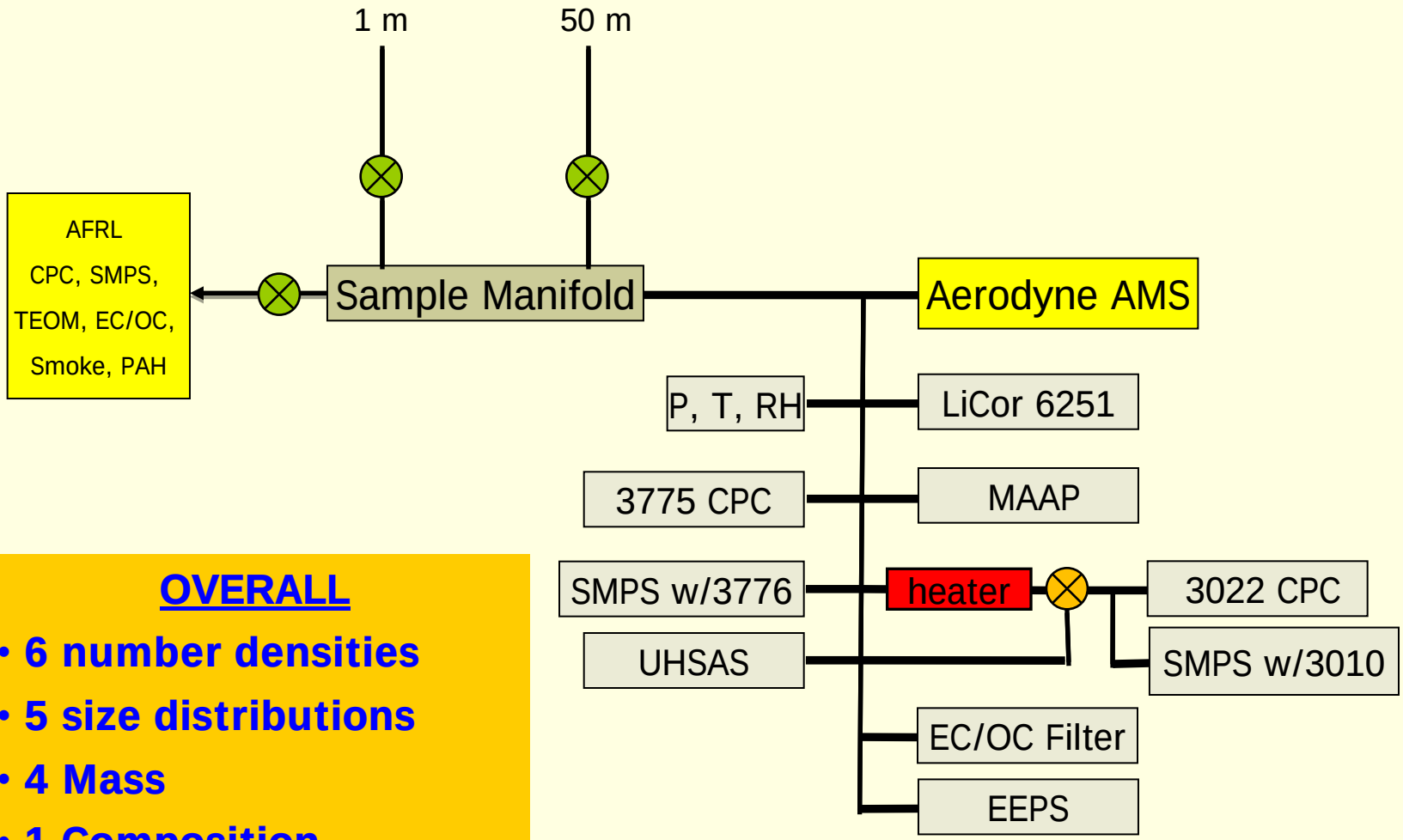






Acceptable limit

Full suite of Aerosol Instruments used to characterize emissions

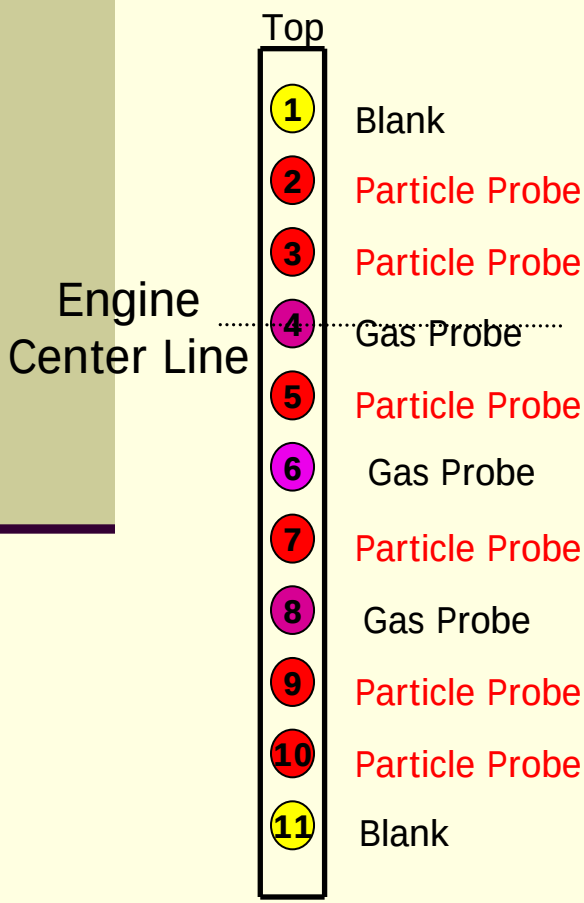


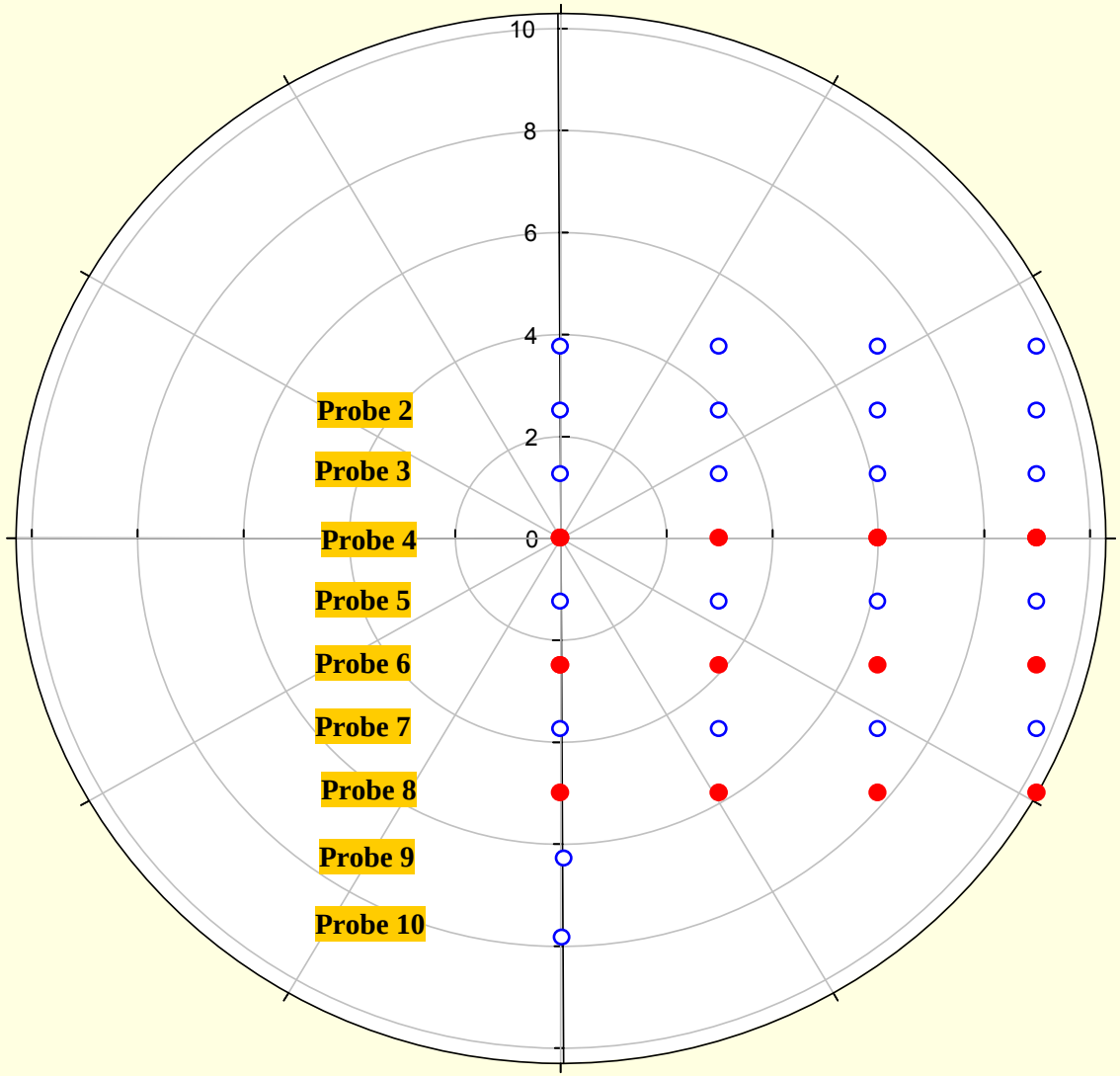
OVERALL

- **6 number densities**
- **5 size distributions**
- **4 Mass**
- **1 Composition**

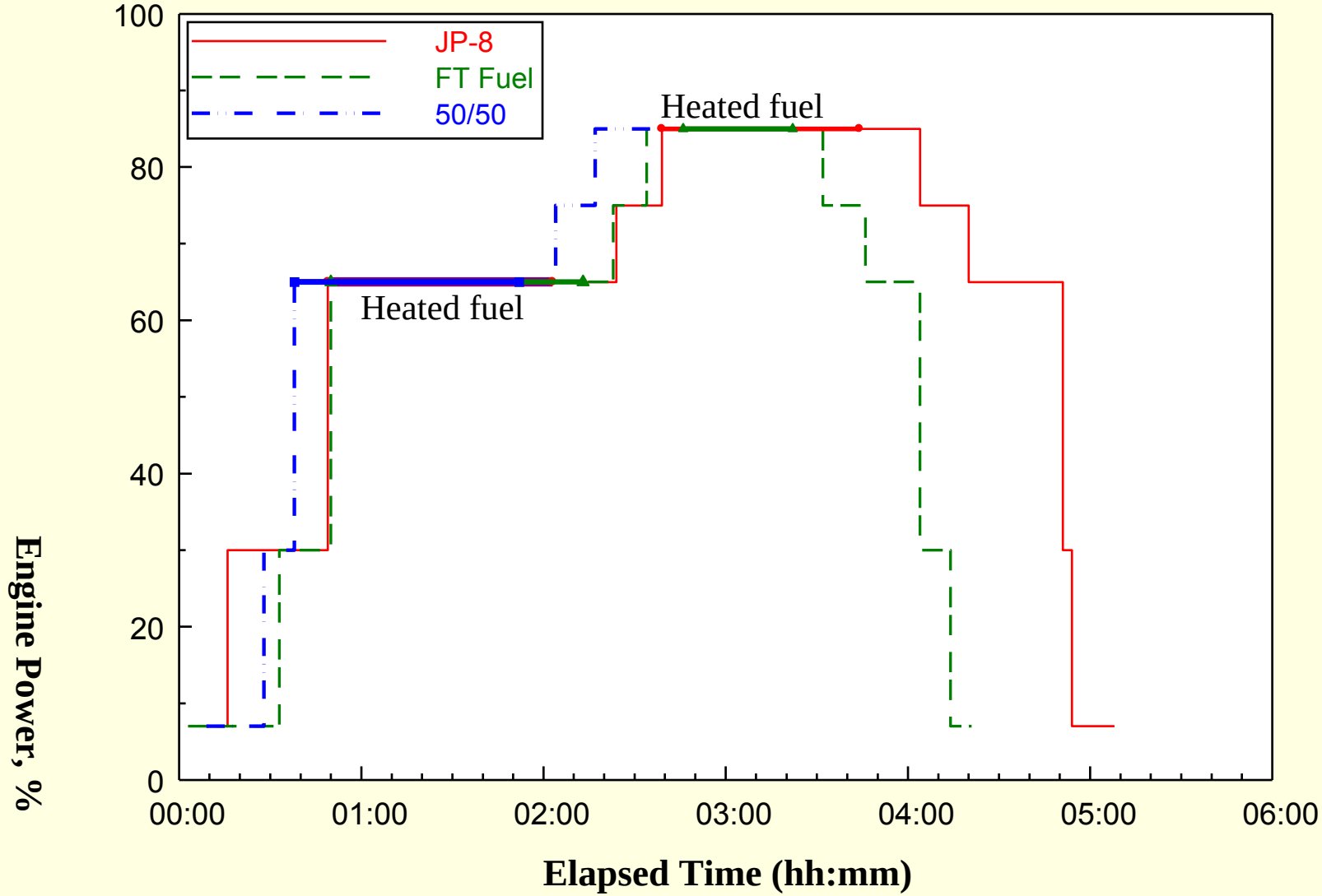
1 m Sampling Rake Setup

Each probe tip separated by 1.25”





PW308 Emissions Test Matrix designed to fulfill all objectives



Agenda

- Tests performed
- Results
  - Engine performance and gaseous emissions with the different fuels
- Difference in non-volatile PM emissions
- Volatile PM emissions

Engine and emissions data does not indicate major differences between the three fuels

	RATIO - Blend/JP8				RATIO – FT100%/JP8			
Thrust (Rotor Speed N1)	Fuel flow	NOx	CO	SO_2	Fuel flow	NOx	CO	SO_2
LOW (2200)	0.999	0.97	0.95	0.50	0.985	0.97	0.90	0.05
INTERMEDIATE (4500)	1.00	0.98	NA	0.54	0.982	0.97	NA	0.1
HIGH (5750)	0.995	1.0	NA	0.54	0.978	0.98	NA	0.1

GASEOUS EMISSIONS

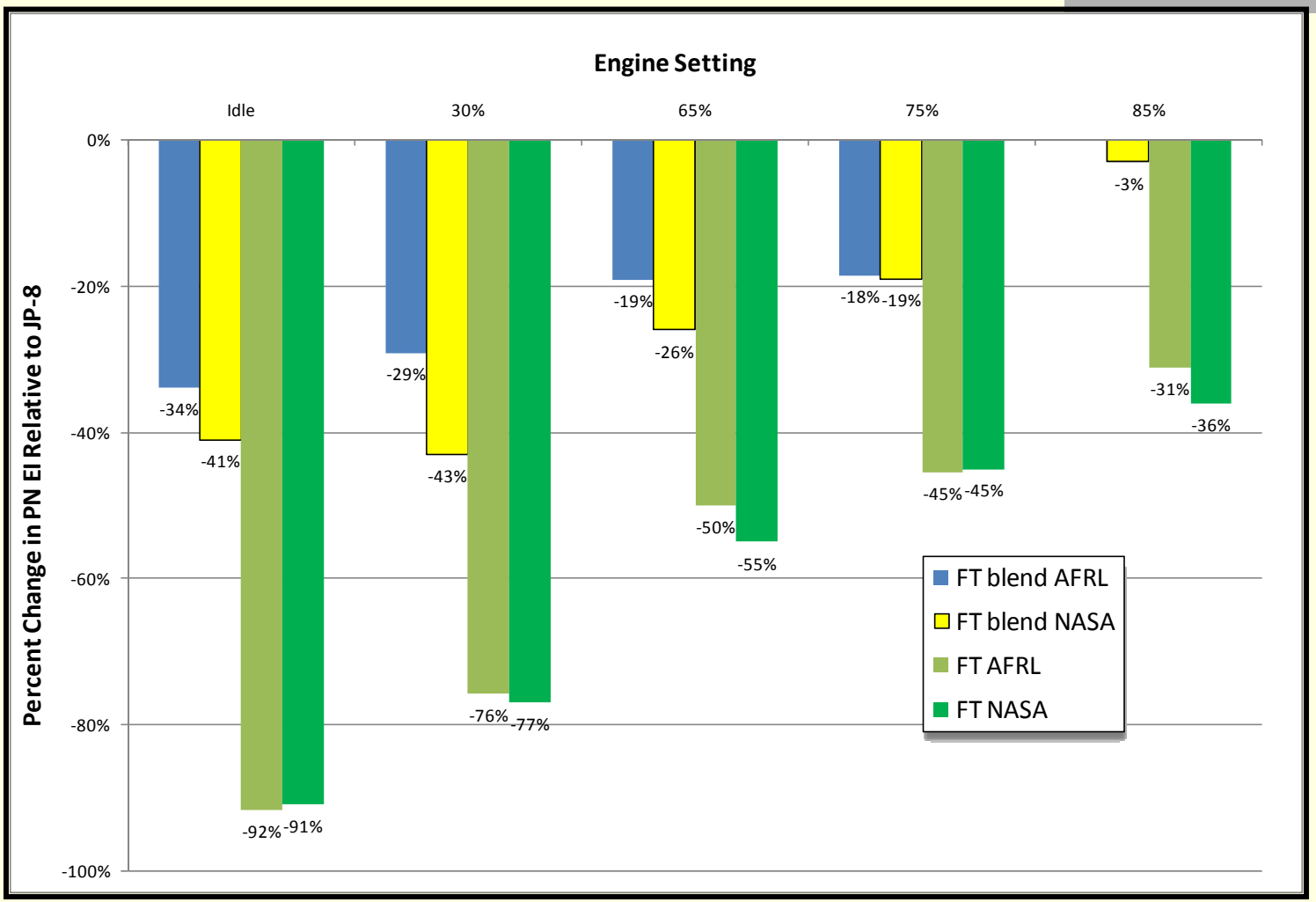
- At low power
  - NO_x emissions are within instrument measurement capabilities
  - Lower CO with FT/blend may be due to higher H/C ratio
- At intermediate/high power
  - Very low CO emissions make ratios irrelevant to evaluate differences between the fuels
  - No significant difference in NO_x emissions
- Negligible UHC at all power conditions for both fuels
- SO_2 emissions indicate Sulfur content of the blend to be around 50% of JP8 while for 100% FT fuel a value of 0.1% indicates contamination
- ~2% fuel flow benefit with 100% synthetic fuel can be attributed to the higher heat content of synthetic fuel

Negligible differences in gaseous emissions & performance as expected due to similarity in the physical properties of the fuels (like heating value, specific gravity)

Agenda

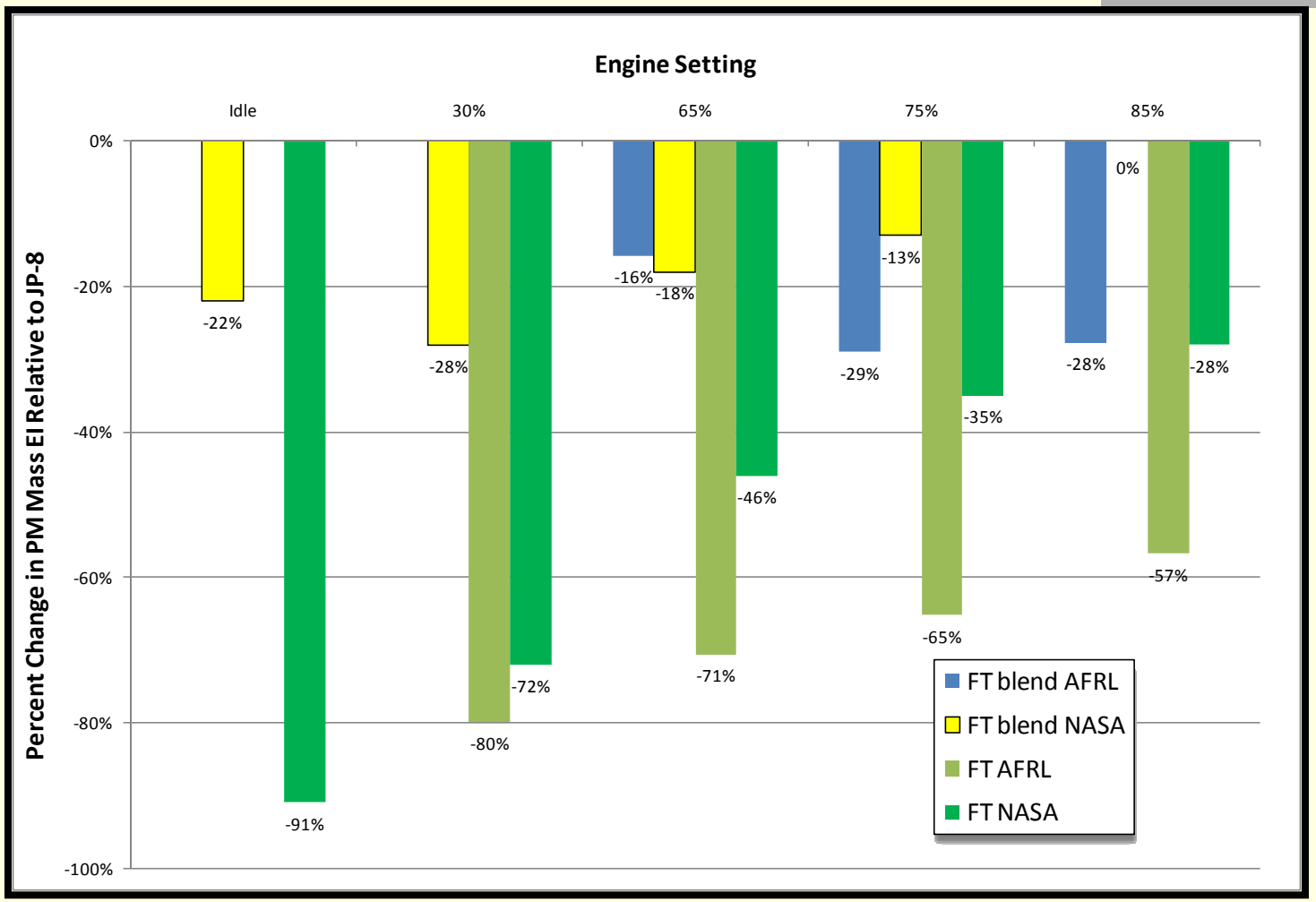
- Tests performed
- Results
  - Engine performance and gaseous emissions with the different fuels
  - Difference in non-volatile PM emissions
    - For the different fuels (JP8/Synthetic/blend)
- Volatile PM emissions

Synthetic fuel reduces Particle Number Emission Index



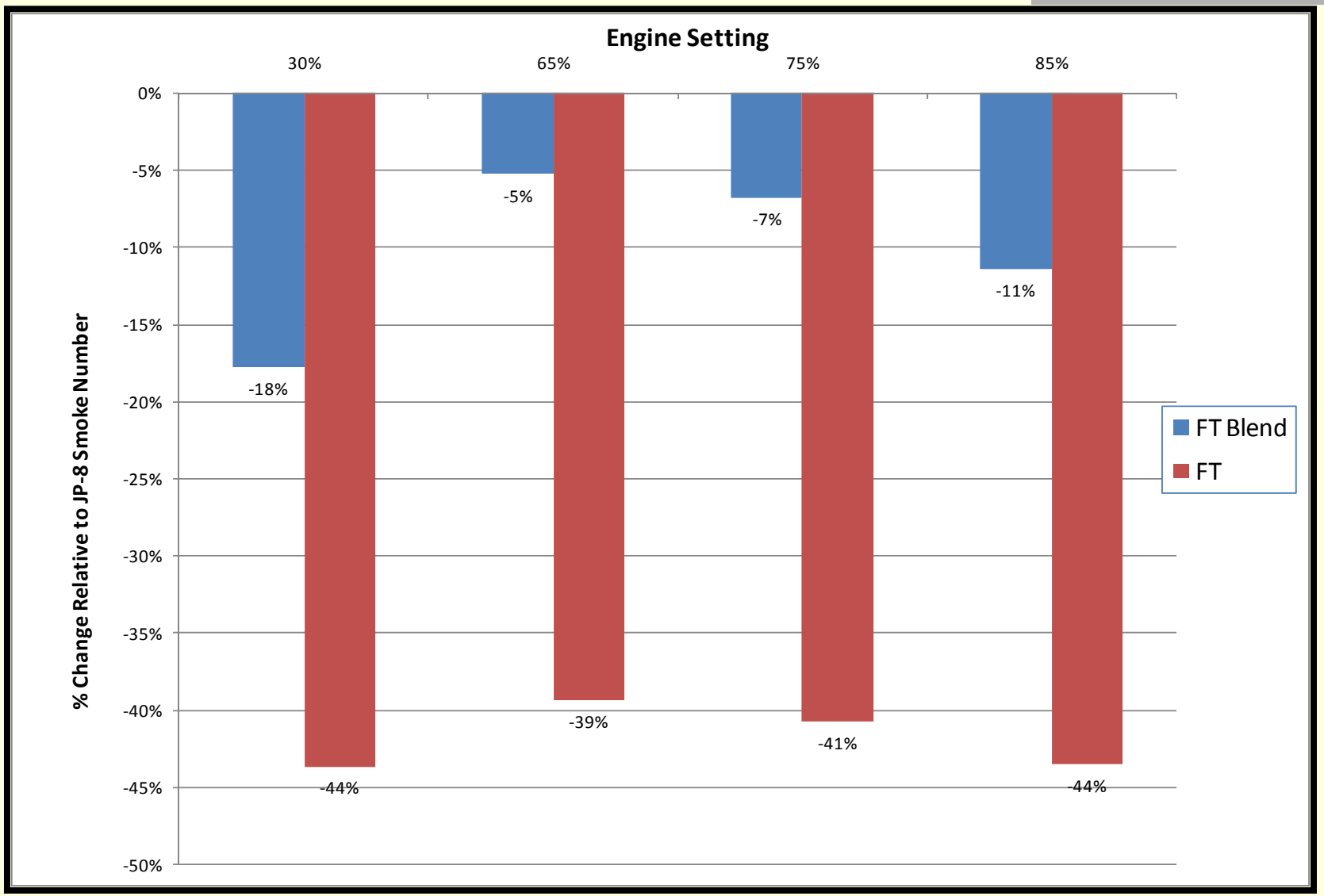
As expected lower PM emissions with synthetic fuel due to its chemical composition (higher H/C ratio and no aromatics/Sulfur)

Particle Mass Emission Index goes down with synthetic fuel

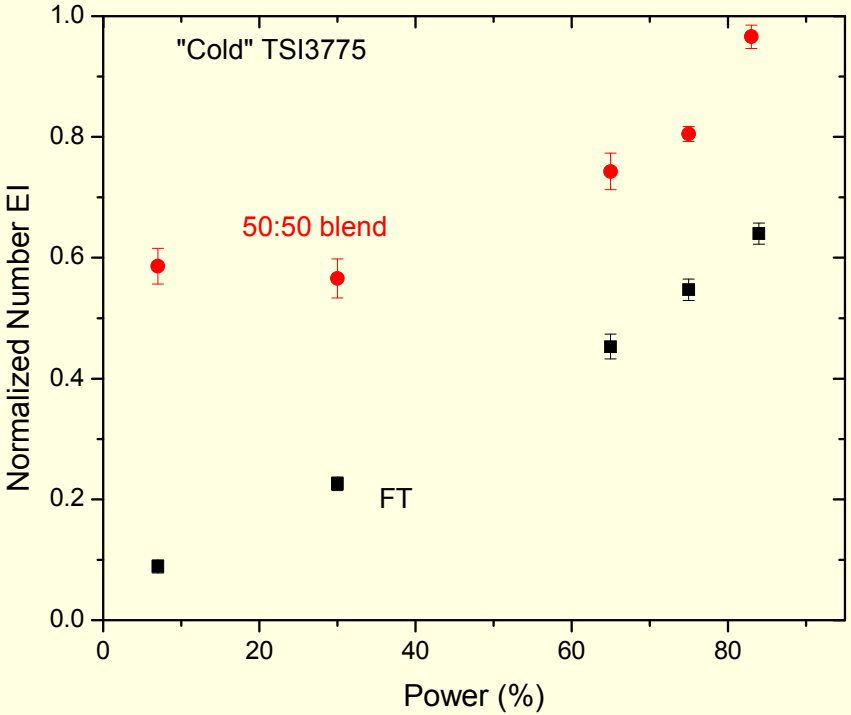


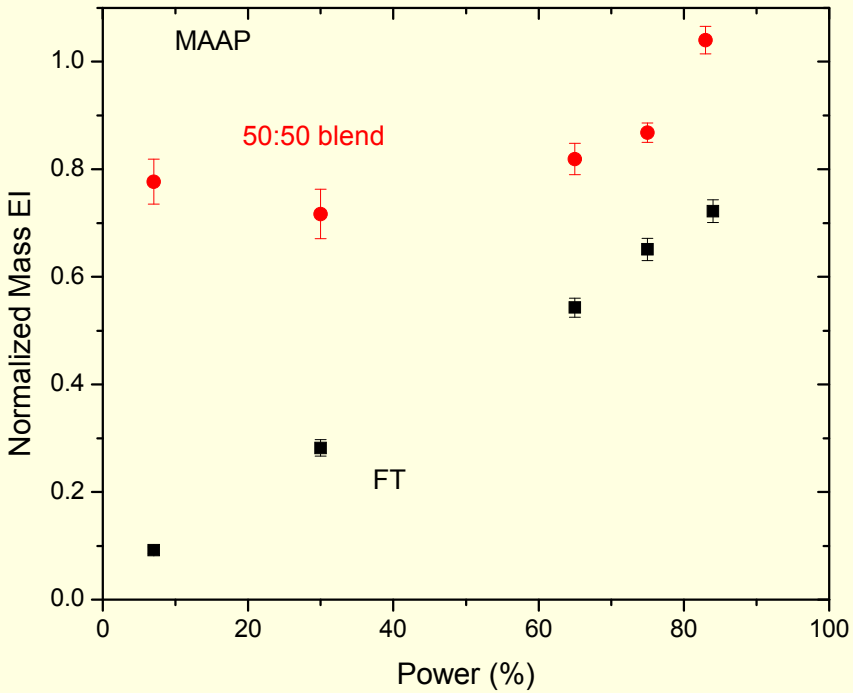
As expected PM emission reductions not proportional to the fraction of FT fuel
Greater discrepancy in the measurements between the different teams

As expected greater SN changes with 100% Synthetic fuelthan with the blend



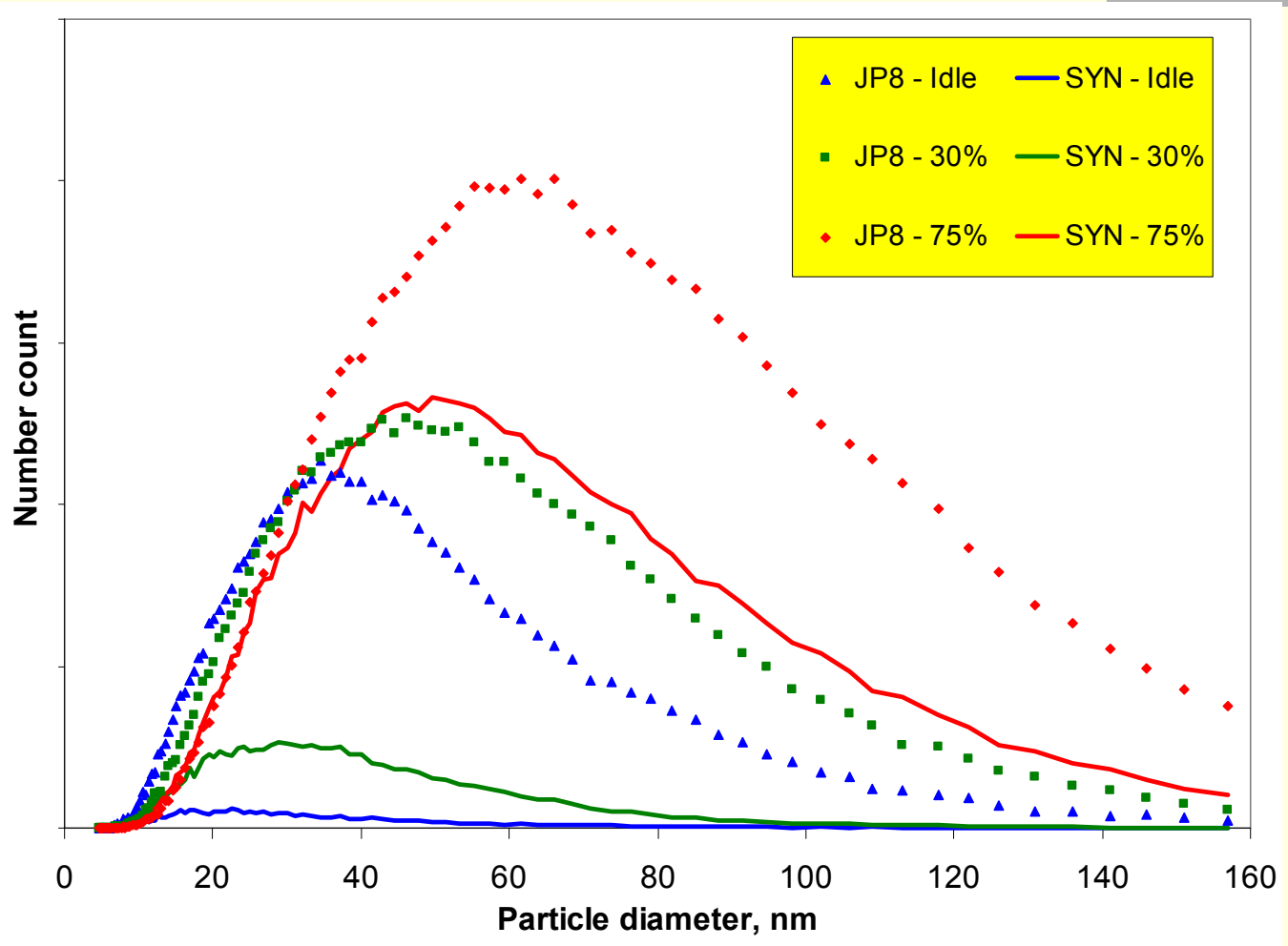
Measurement uncertainty is lower than PM EI reduction with synthetic fuel





FT produces >90% reduction at idle, 40% at high power

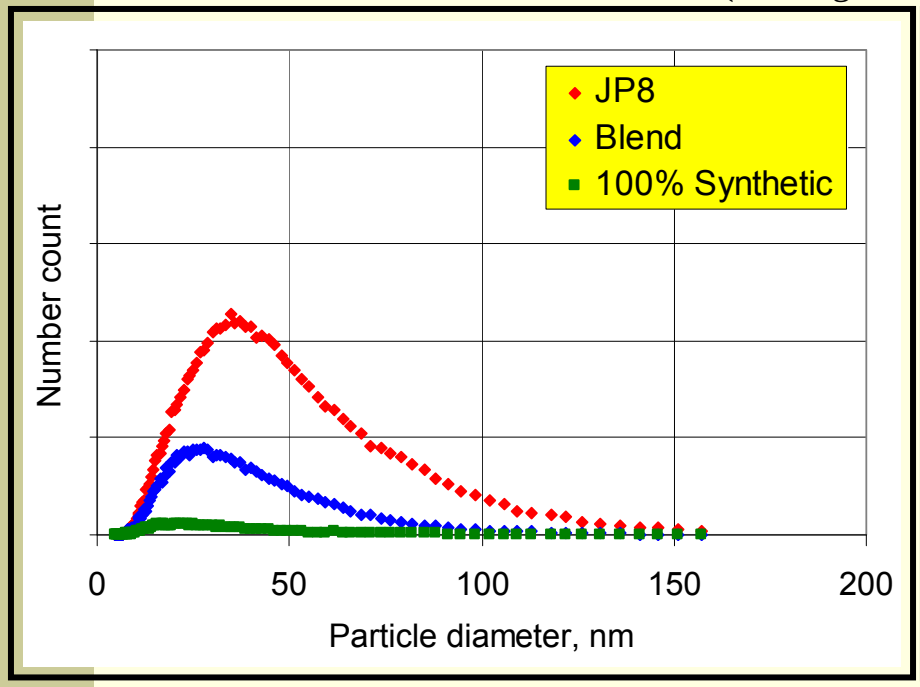
Particle size distribution for the different fuels at different powers show similar trends

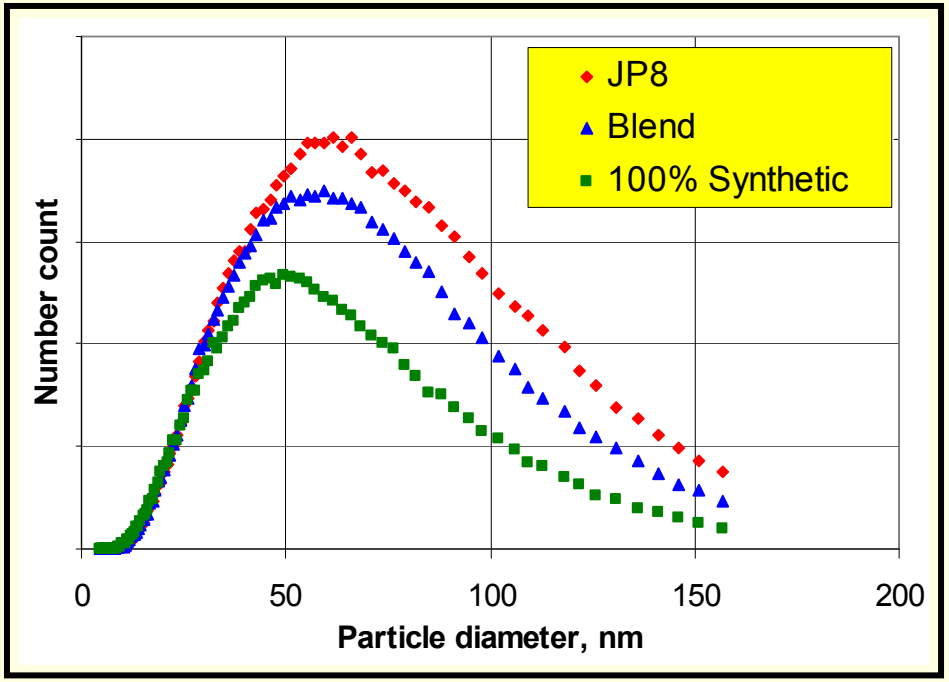


FT fuel makes lower number of particle emissions as well as particle of smaller size

FT fuels provide larger percentage reductions at lower power conditions

(both figures drawn to same scale)

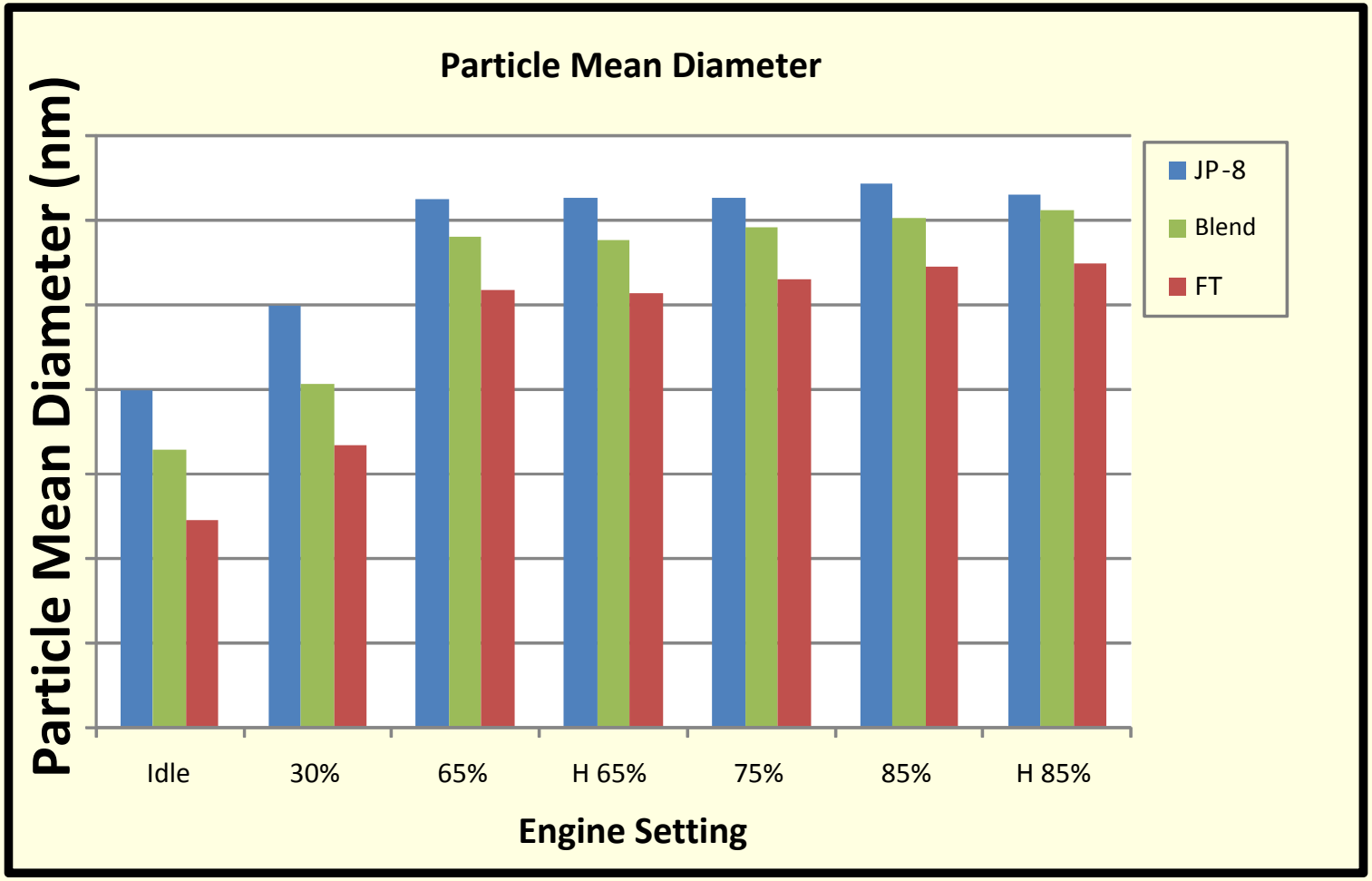




FT emissions are small, more difficult to discriminate from background at lower thrust conditions

Differences at higher thrust conditions are less

Particle mean diameter decreases with increase in FT fuel content

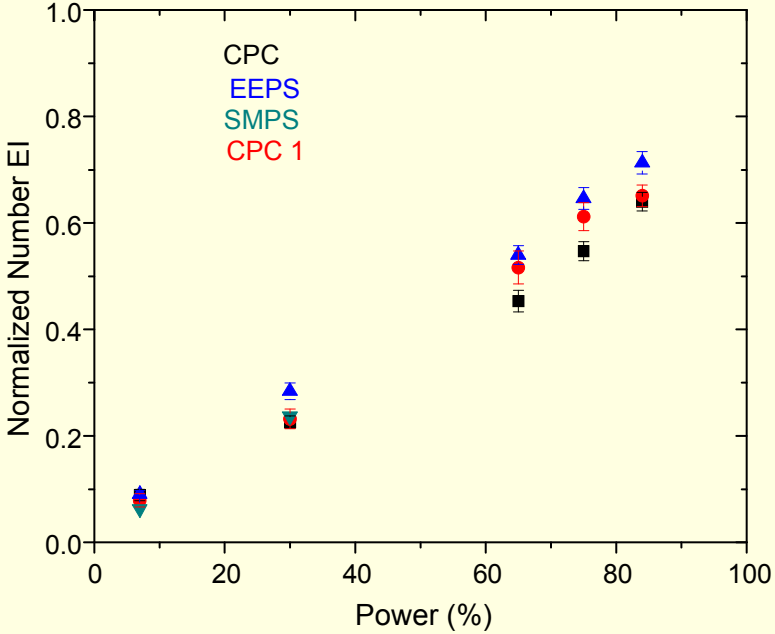


Particle mean diameter along with particle number count decreases from JP8 to Blend to FT fuel

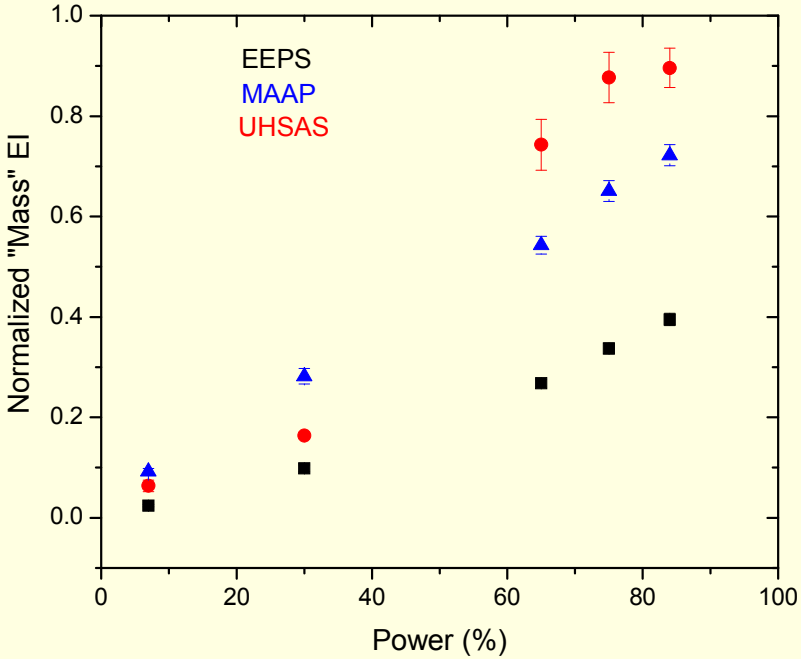
Mass variability for synthetic fuel for the different instruments not well understood

- Mass EI estimated or measured with different instruments
  - EEPS and SMPS measure size distribution and numbers. Mass estimated using volume of particles and density
  - MAAP and UHSAS measure mass more directly (based on reflectivity index)
  - Estimations based on the assumption that all particles generated by the different fuels have same physical/chemical properties
- The differences in the observed mass may be due to
  - Particles generated with the different fuels may have different physical or chemical properties
  - The different instruments have different cut-off size ranges

Mass EI data for 100% synthetic fuel sensitive to instrument selection

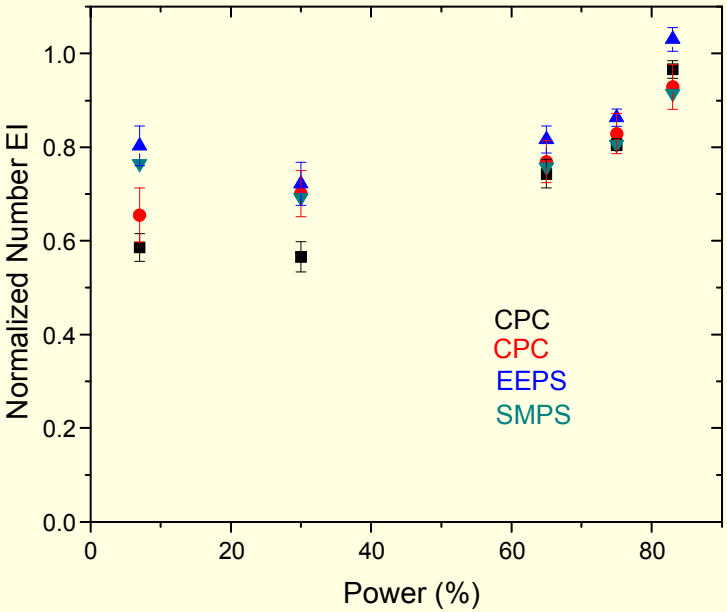


Reduction in number EI very similar for the different instruments



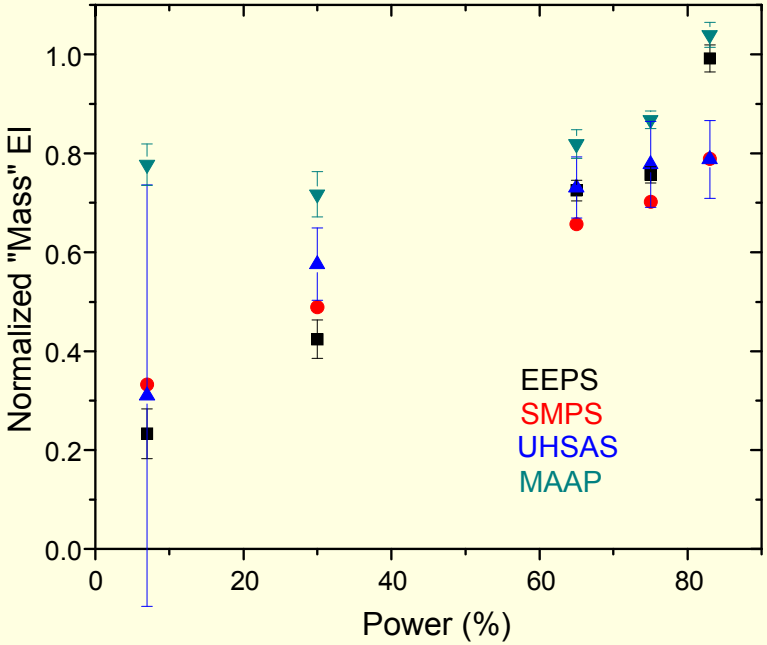
Reduction in Mass EI much more sensitive and variable for the different instruments

Blend data shows more variability at low thrust while high thrust data similar to FT fuel

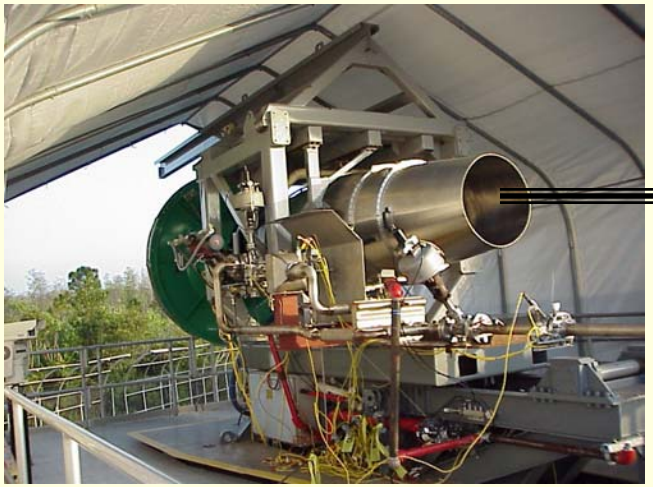


Number EIs variability probably because of variations in instrument sensitivity

Ratio of "Mass" EIs quite variable at low power, background particles may be a contributing factor

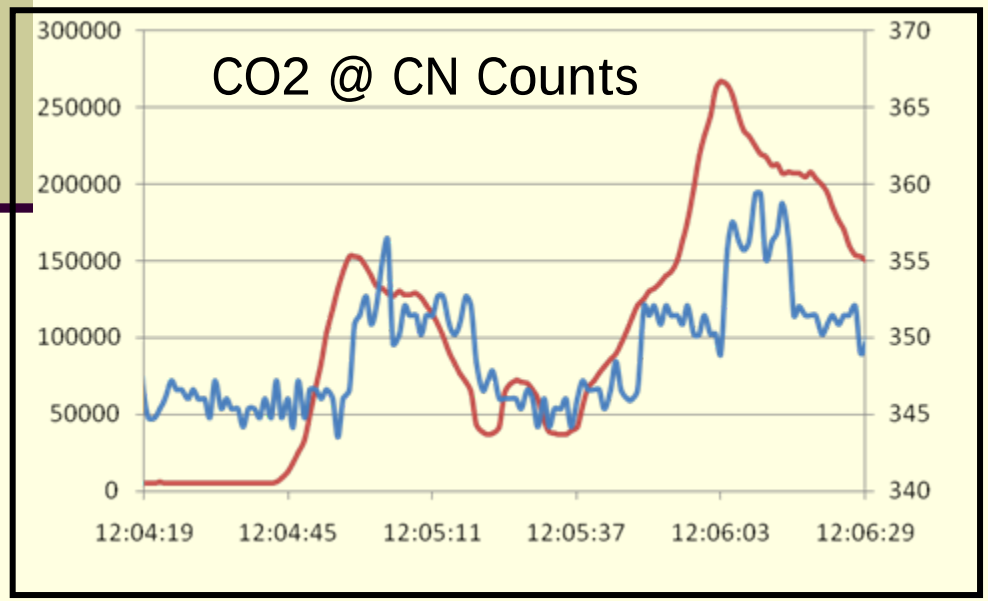


Measuring PM emissions at 50m is difficult



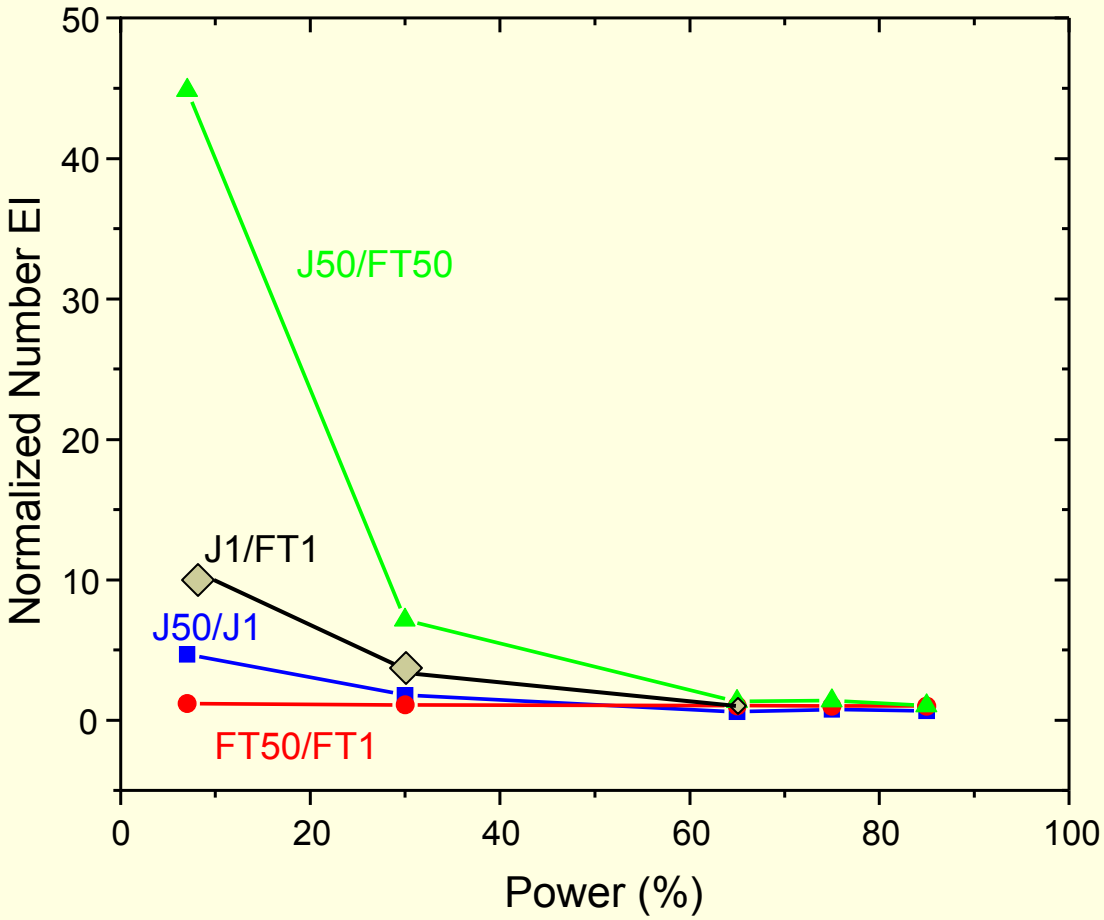
50 m

Probe



Wind causes plume to waver back and forth across 50 m inlet probe

Comparison between 1m and 50 m data reveals useful information on PM formation

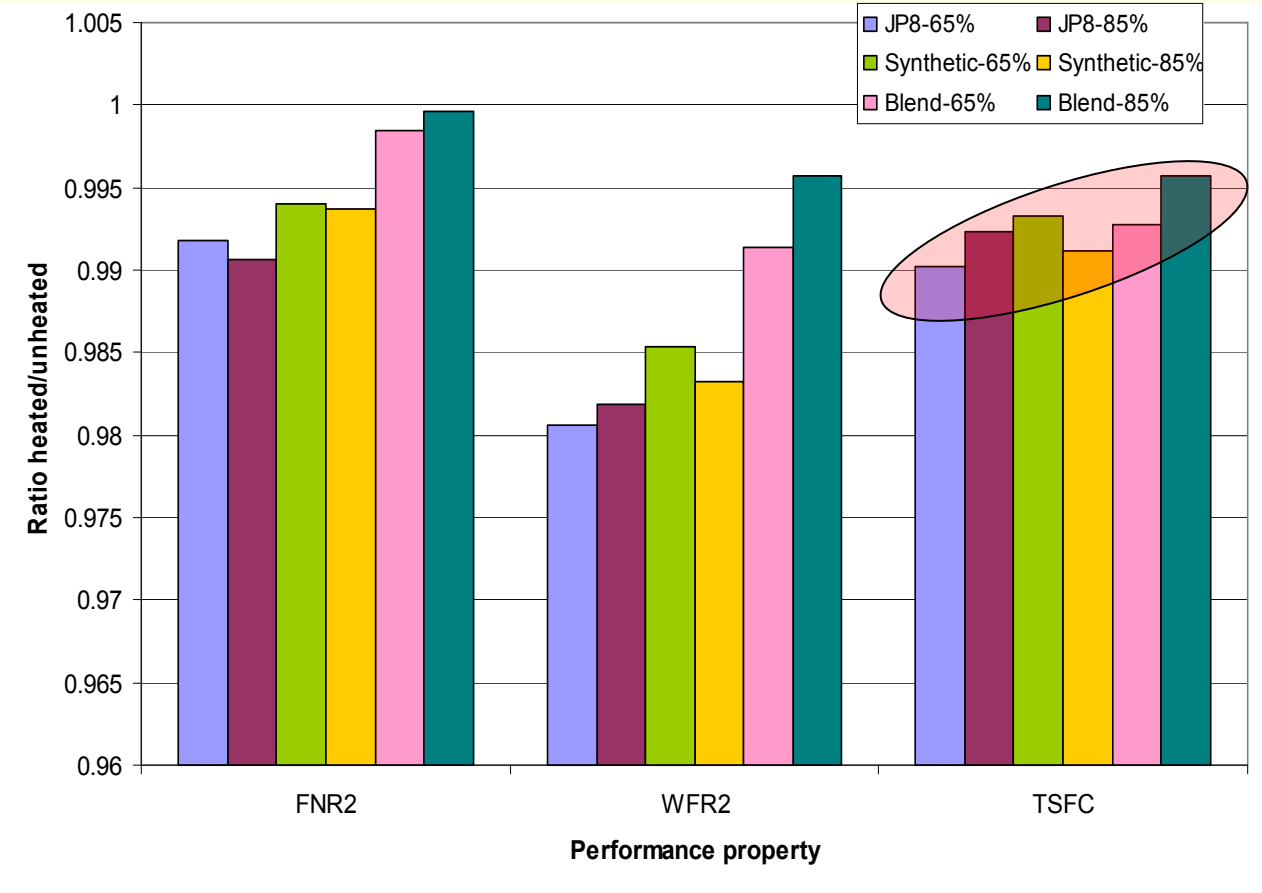


FT fuel produced significantly lower volatile PM emissions at 1m and 50m

Agenda

- Tests performed
- Results
  - Engine performance with the different fuels
  - Difference in non-volatile PM and gaseous emissions
    - Between hot and cold fuel
- Volatile PM emissions

Heated fuel (600 F) gives slightly better SFC



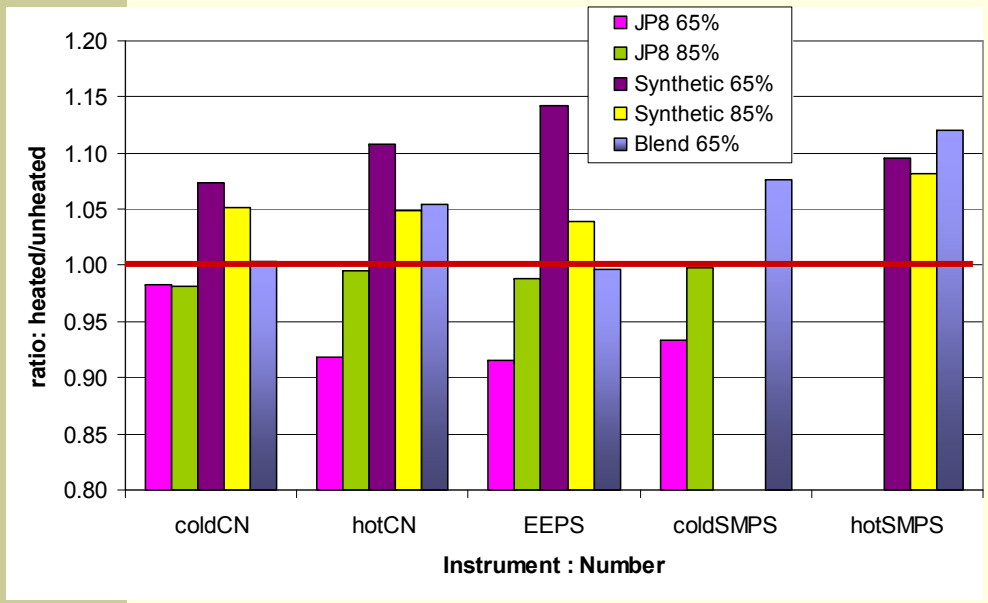
Heated fuel led to higher combustor inlet temperature and hence improved SFC by 0.5-1%

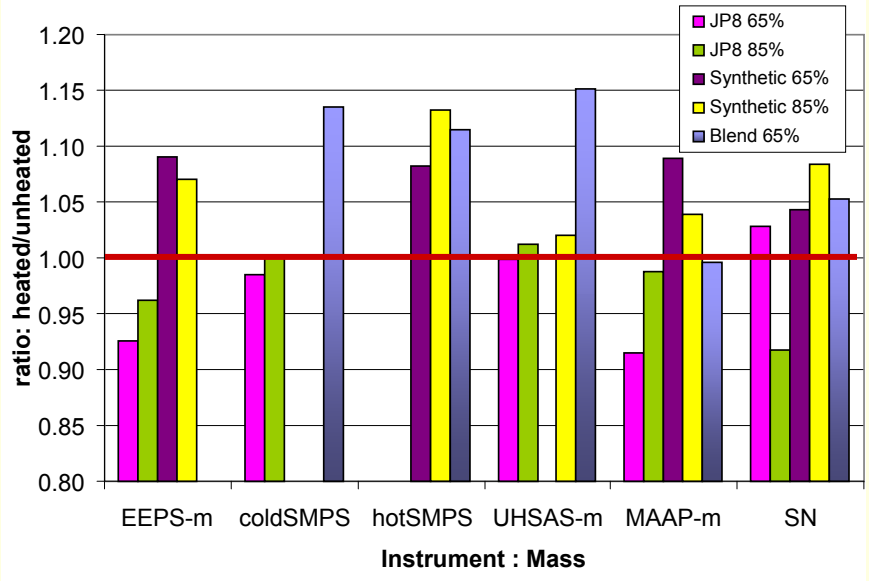
Heated fuel produced more NO_x and slightly higher SN

heated/unheated		
	SN	EINOx
JP8 65%	1.03	1.16
JP8 85%	0.92	1.15
Synthetic 6	1.04	1.15
Synthetic 8	1.08	1.2
Blend 65%	1.05	1.13
Blend 85%	1.03	

- SN differences between the heated fuel and cold fuel was on the order of $\pm$10% which is within measurement uncertainty
- NO_x for heated fuel was ~15% higher for heated fuel
  - Combustor (nozzles) are not optimized for heated fuel
  - Higher stoichiometric flame temperature with heated fuel

Differences between heated and unheated fuels within experimental uncertainty



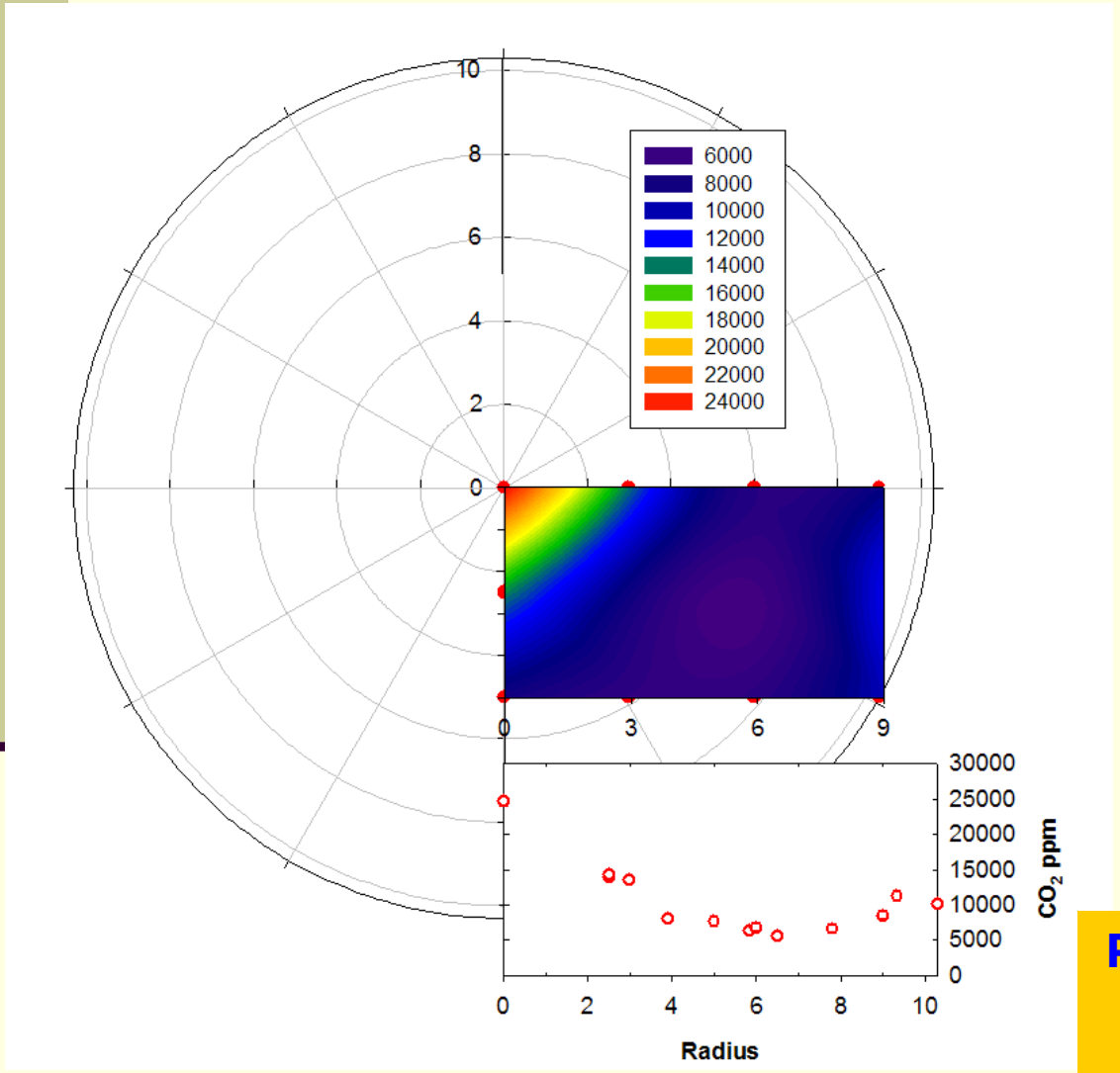


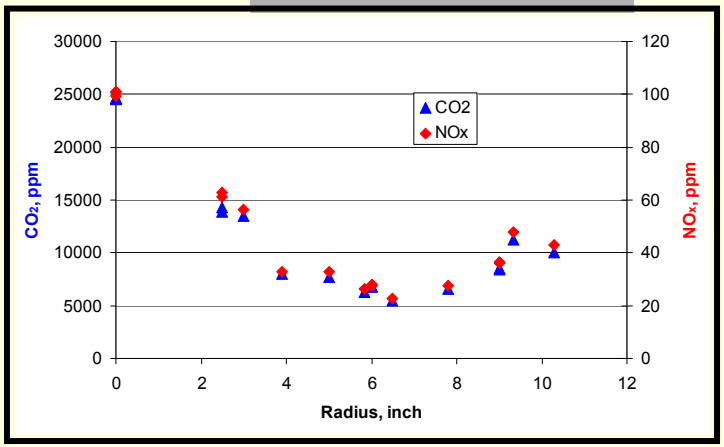
PM emission measurements indicate no significant difference between heated fuel and unheated fuel

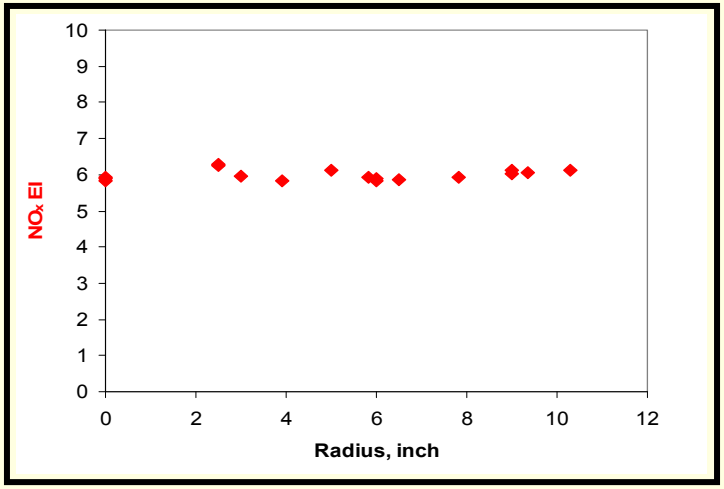
Agenda

- Tests performed
- Results
  - Engine performance with the different fuels
  - Difference in non-volatile PM and gaseous emissions
    - Spatial variation
- Volatile PM emissions

Spatial variation in the data captures the partial mixing of core and bypass stream

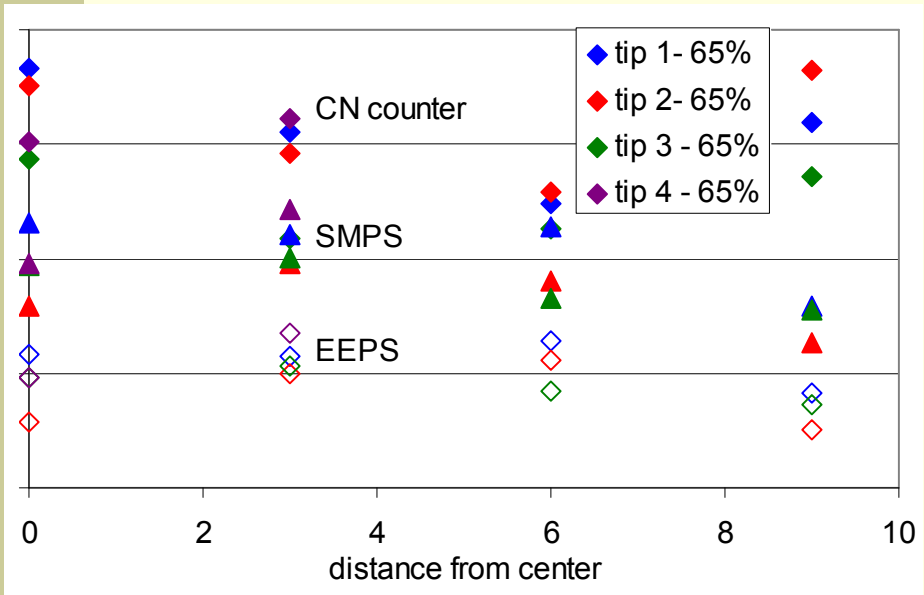




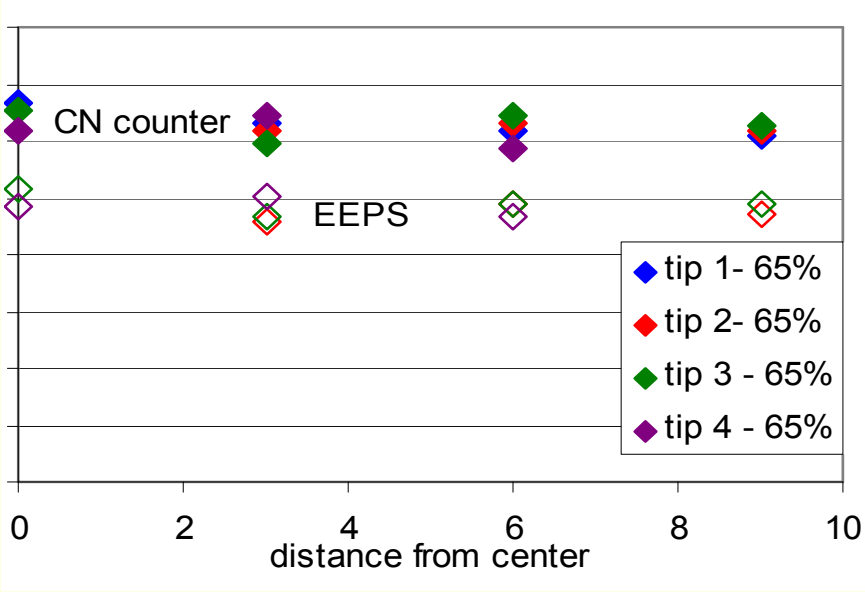


Partially mixed exhaust leads to variation in actual emissions but EI's are consistent across the exhaust

Just like gaseous emissions, PM number EI indicate little spatial variation



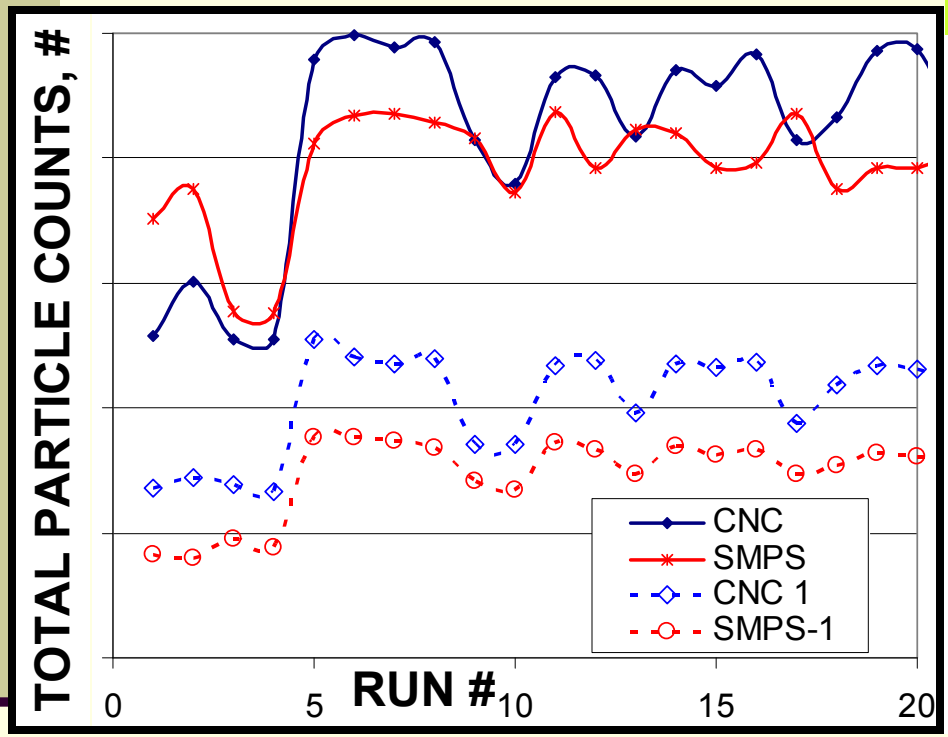
JP8



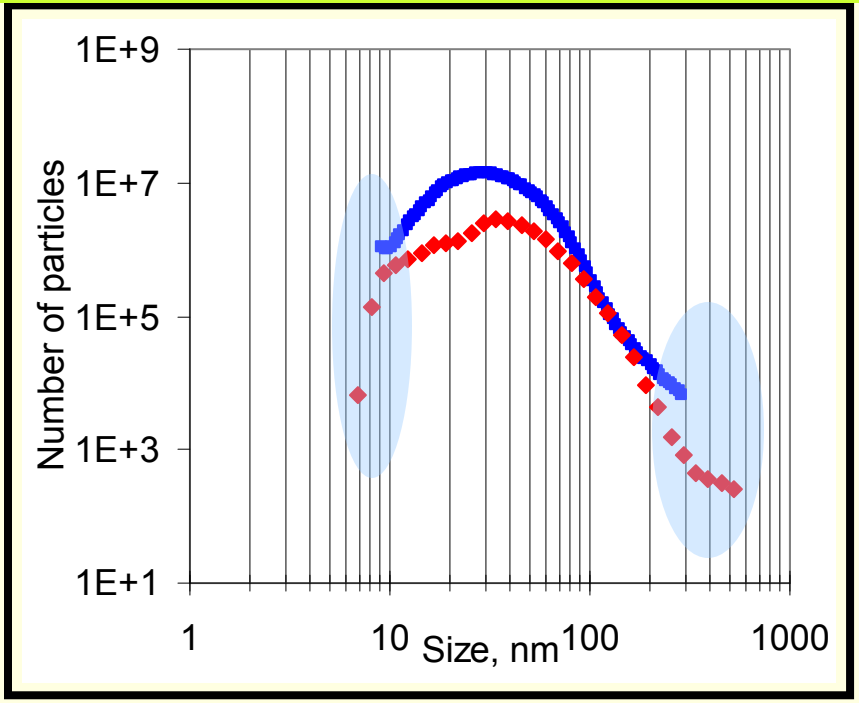
Synthetic

Instrument-instrument variability much higher then spatial variation

PM emissions with different instruments may not give same answers if instrument size cut-off is different



Two SMPS with different size cut-offs



Differences in total number count between different instruments can be attributed to differences in instruments "cut-off" sizes

Summary of Non-volatile PM

- Negligible Thrust and Fuel Flow impact of FT fuel as compared to JP8
- No significant difference in Gaseous emissions for the different fuels
- PM emissions for the different fuels
  - Pure FT EI values are an order of magnitude lower in both number & mass at idle relative to JP8. Differences between the fuels diminish with increasing power.
  - Changes in observed Number EIs largely independent of instrument; “mass” EIs sensitive to measurement technique.
  - FT particles much smaller, appear to be more dense than JP8
  - Emission reductions not proportional to the fraction of FT
  - FT suppresses volatile aerosol formation in plume
  - At the 50 meter probe, JP8 idle Number EIs 45 times higher that FT; differences decrease with power.

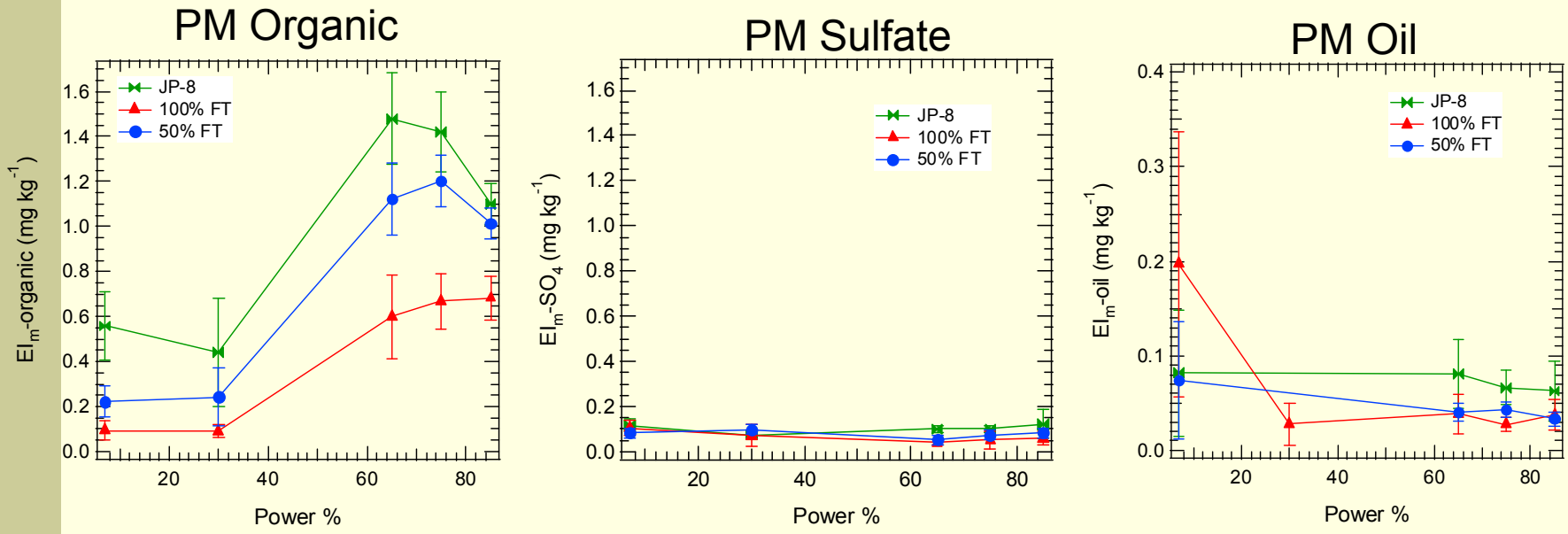
Summary of Non-volatile PM (cont.)

- Spatial variation in emissions indicates unmixedness. Constant Emission EI across the exhaust indicates all emissions vary in a similar fashion
  - Useful information to determine mixer efficiency
- Heated fuel had a higher NOx EI than unheated fuel
- Excellent set of data to model/develop combustion kinetics and impact of fuel composition, thrust (temperature/pressure) on PM emissions
  - Consistent trends with changes in fuels (JP8 vs. blend vs. 100% FT fuel) can be used to resolve the impact of fuel composition on PM emissions
  - Heated unheated fuel data can be used to model impact of temperature on gaseous as well as PM emissions
  - Data collected at different power level can be used to model impact of f/a, temperature and pressure on emissions

Agenda

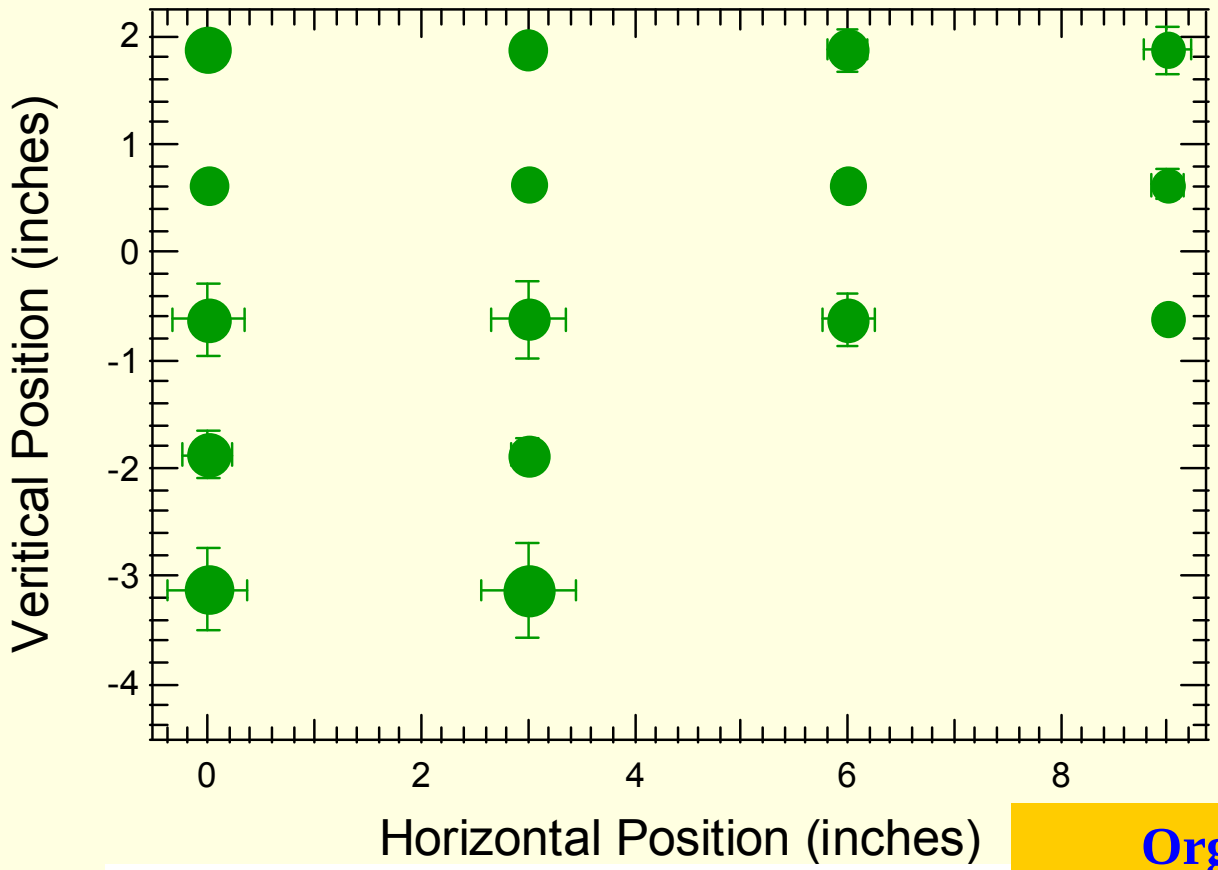
- Tests performed
- Results
  - Engine performance with the different fuels
  - Difference in non-volatile PM and gaseous emissions
  - Volatile PM emissions

Exit Plane Organic, Oil & Sulfate Emissions



EI_m-organic > EI_m-sulfate > EI_m-oil consistent with previous field measurements
Very little volatile PM emission concentration measured at engine exhaust

Detailed Spatial Profile of EI_M-organic made at engine exhaust



Organic EIs are relatively constant across the engine exit plane

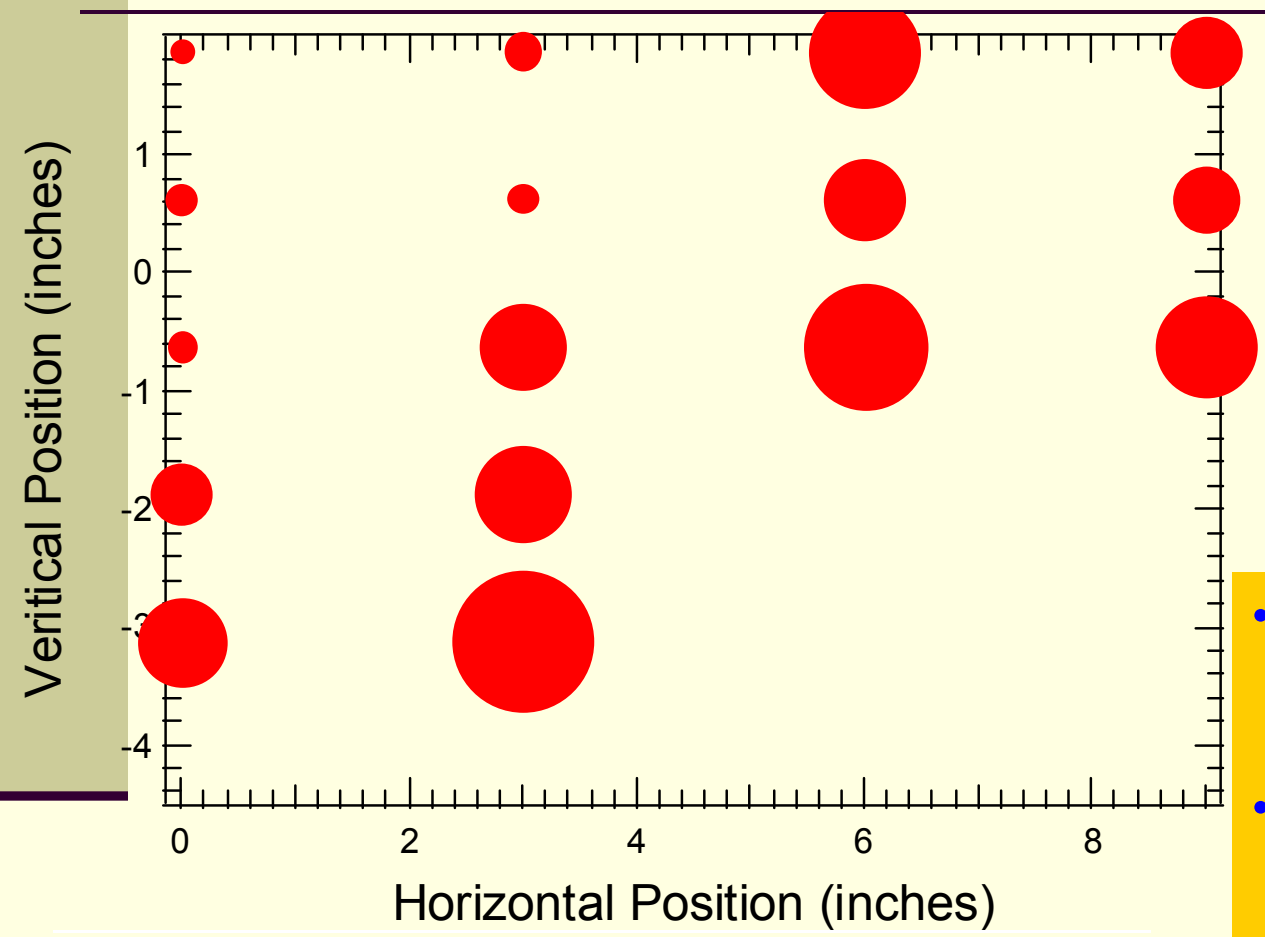
JP-8 85% power

Full scale is 0.02 to 2 mg kg^{-1}

Error bars scale with measurement uncertainty

Marker size scales with EIM-organic (ranges from 0.8 ± 0.14 to 1.3 ± 0.4 mg kg-1)

Re-scaled Profile of EI_M-sulfate



- **Plot shows that entrained bypass air is the source of sulfate at 1m**
- **Signal too weak to generate particle size distribution with AMS**

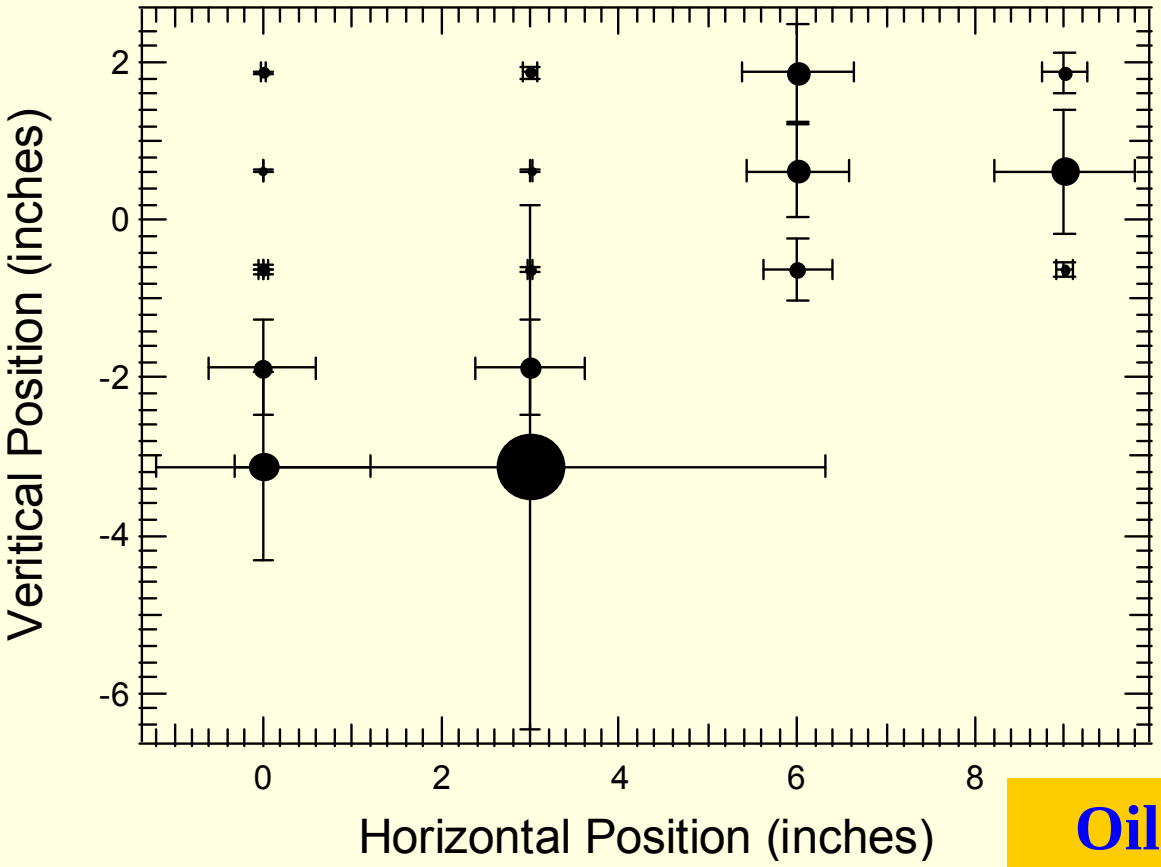
JP-8 85% power

Marker size scales with EI_M-sulfate (ranges from 0.06 ± 0.01 to 0.40 ± 0.06 mg kg^{-1})

Full scale is 0.02 to 0.2 mg kg^{-1}

Error bars scale with measurement uncertainty

Detailed Profile of EI_M-oil



Oil EIs are consistent with an intermittent source at the periphery

JP-8 85% power

Full scale is 0.02 to 2 mg kg-1

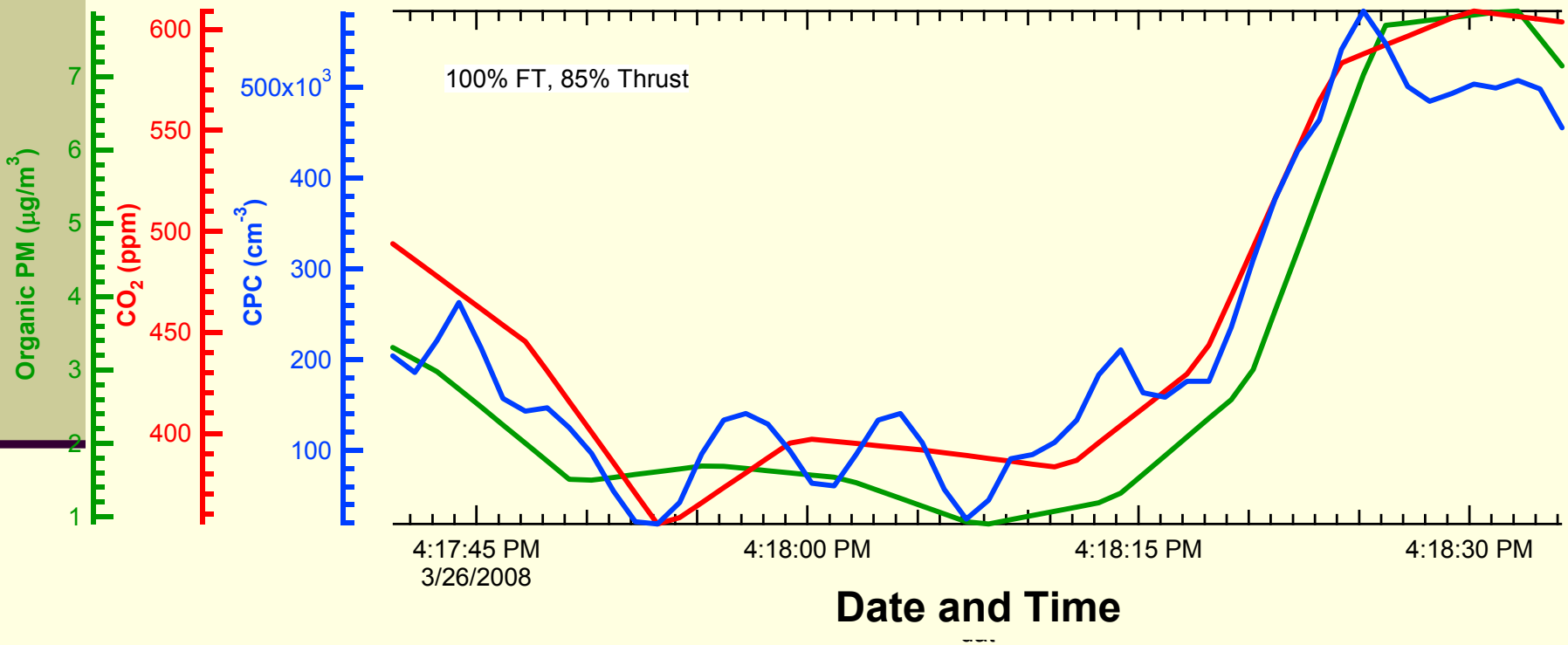
Marker size scales with EI_M-oil (ranges from 0.036 ± 0.006 to 1.9 ± 3.3 mg kg^{-1})

Error bars scale with measurement uncertainty

Organic PM Emissions at 50m

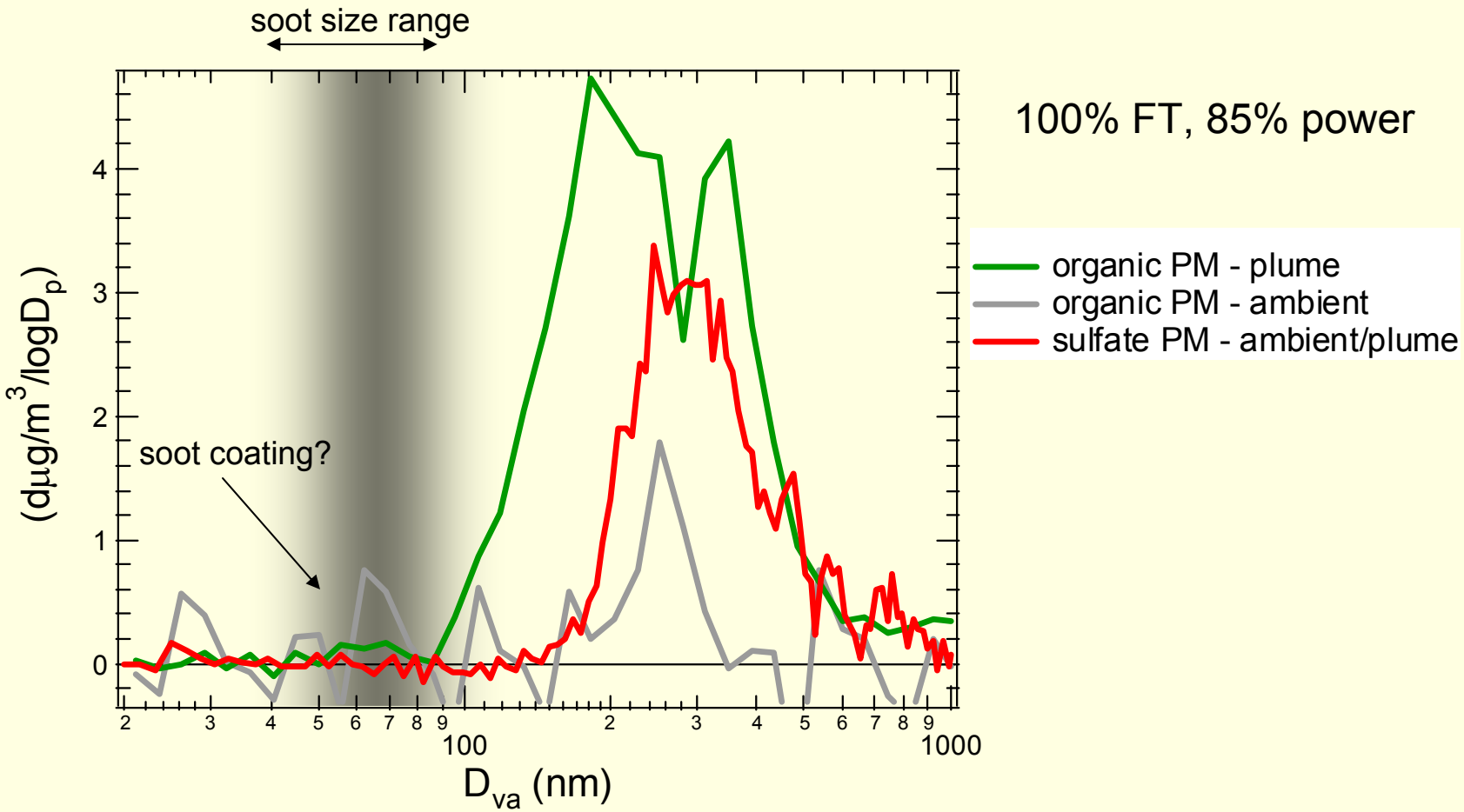
EI_m- organics ≈ 25 ± 10 mg kg^{-1}

- $EI_{organics}$ only a small fraction of total PM emissions
- Significant amount of lubrication oil (>75%)
- $EI_{organics}$ independent of thrust condition/fuel



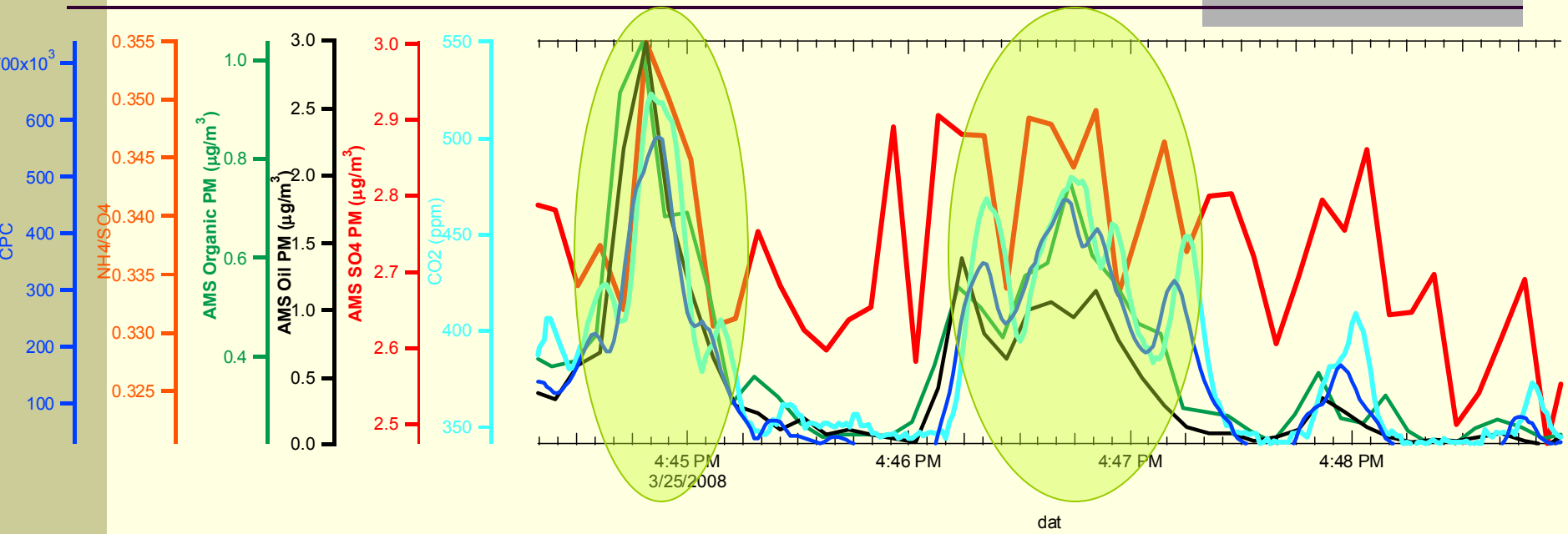
Unusual level of lube oil may be due to test engine configuration

Organic at 50m is larger than soot



Similar results found at other power conditions and for other fuels
Organics at 50m have same particle size distribution as periphery of engine exit plane
Oil is **not** coated on the soot – consistent with emission as liquid droplets

Plumes for JP8 shows contribution of sulfate particles



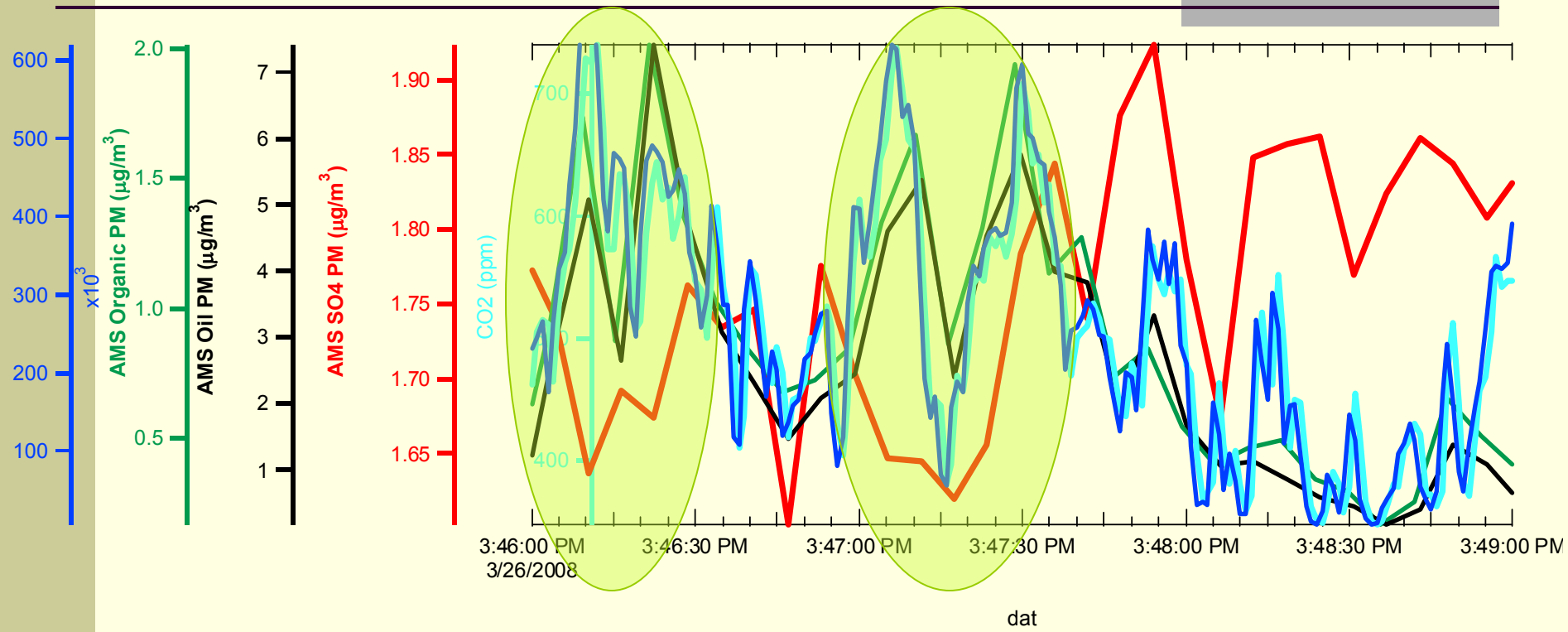
JP-8 – CO_2/number peaks coincide with sulfate peaks

EI_m-sulfate (JP8) = 3.5 ± 1 mg kg^{-1} (1200 ppm sulfur)

EI_m-sulfate (50% FT) = 1.5 ± 0.5 mg kg^{-1} (600 ppm sulfur)

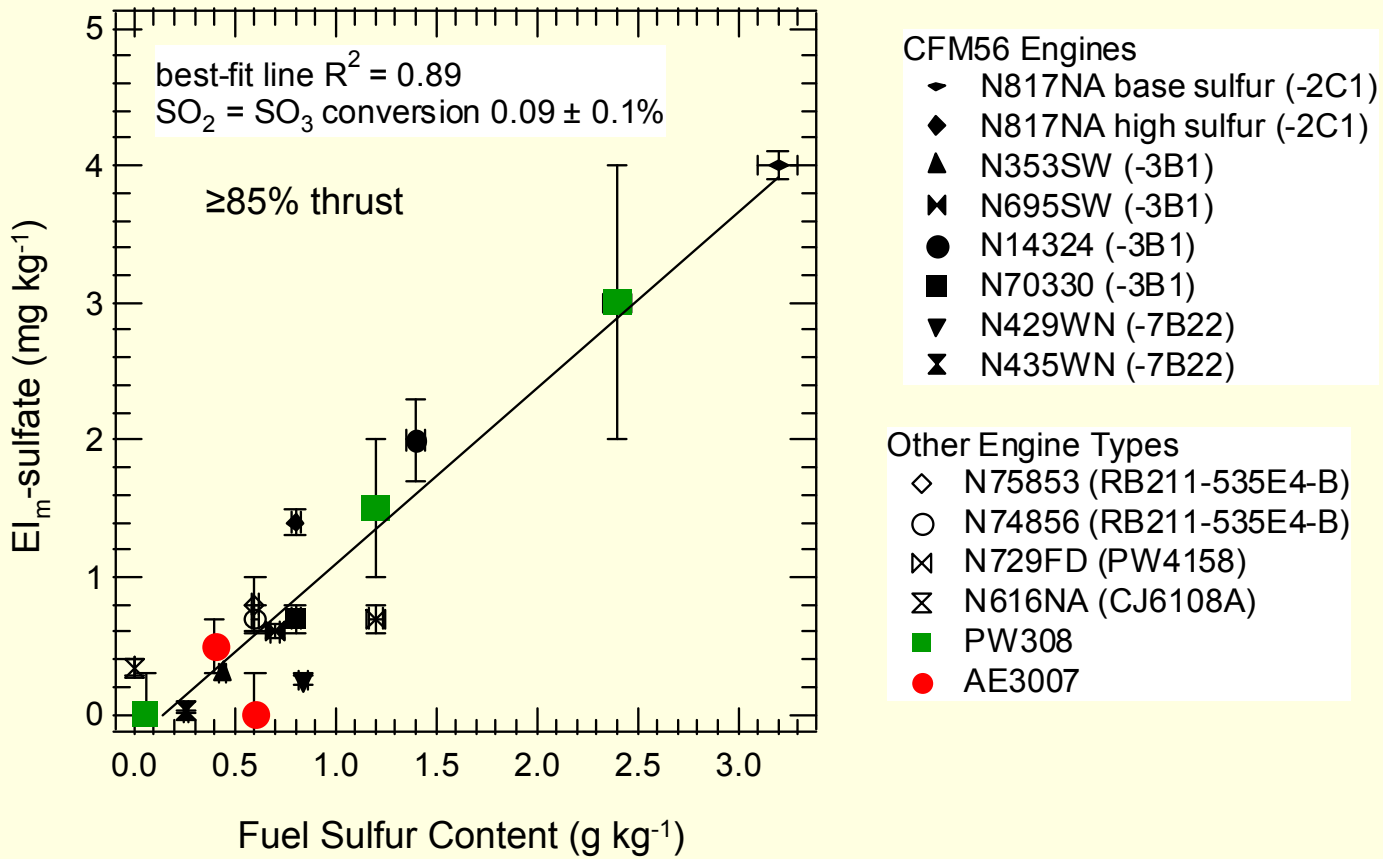
EI_m-sulfate (100% FT) < 0.05 mg kg^{-1} (30 ppm sulfur)

PM Plumes for 100% FT fuel shows sulfate concentration less than background



100% FT – CO_2/number peaks coincide with sulfate valleys, i.e. Sulfate concentration in plume is less than ambient sulfate levels

PW308 Sulfate PM data shows that sulfate PM emissions relate directly to fuel sulfur



PW308 sulfate data follows the trend seen in previous tests

Preliminary Data Interpretation

- Volatile content of PW308 “organic particles” is lubrication oil, partially burned fuel
- Lubrication oil emitted as 100-400 nm droplets in the bypass flow – EI_m-oil not a strong function of power or fuel
- Lubrication oil may be the dominant source of PM especially at low power conditions and especially for synthetic fuels
- Partially burned fuel characteristic of hydrocarbon
- At engine exit plane, partially burned fuel is coated onto soot
- At 50 m, EI_m-sulfate depends linearly on fuel sulfur content
- At 50 m, plumes generated by FT combustion contain “less” particle sulfate than ambient air

WOULD LIKE TO SAY

THANK YOU

TO THE WHOLE MEASUREMENT TEAM