Solid and Volatile Engine Particulate Emissions from F-T, HEFA, JP-8, and Blends

August 1, 2012

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DISTRIBUTION STATEMENT A - Unclassified, Unlimited Distribution

Alternative Aviation Fuels Experiment

- Test Setup
- Fuels Characteristics
- Impact Fuel Type on PM Emissions
  - Non-Volatile (solid) PM (1m)
  - Volatile PM (30m)
    - Sulfur studies
- Summary

Alternative Aviation Fuels Experiment AAFEX II

Objectives

- Evaluate engine performance with alternative fuels
- Determine the effects of alt fuels and ambient conditions on BC and gas phase emissions
- Study volatile aerosols that condense in plume and impact of fuel composition

Evaluations

Fuels

- JP-8
- JP-8/HEFA Blend
- Tallow HEFA
- Sasol FT (coal)
- Sasol FT + ~1000 ppm sulfur (*tetra-hydrothiophene*)
- Shell FT (natural gas) AAFEX 1

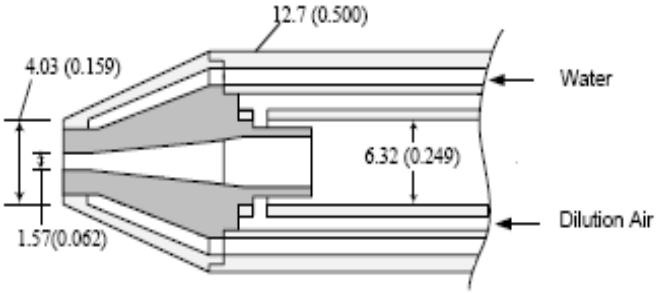
Engine Conditions (rated thrust)

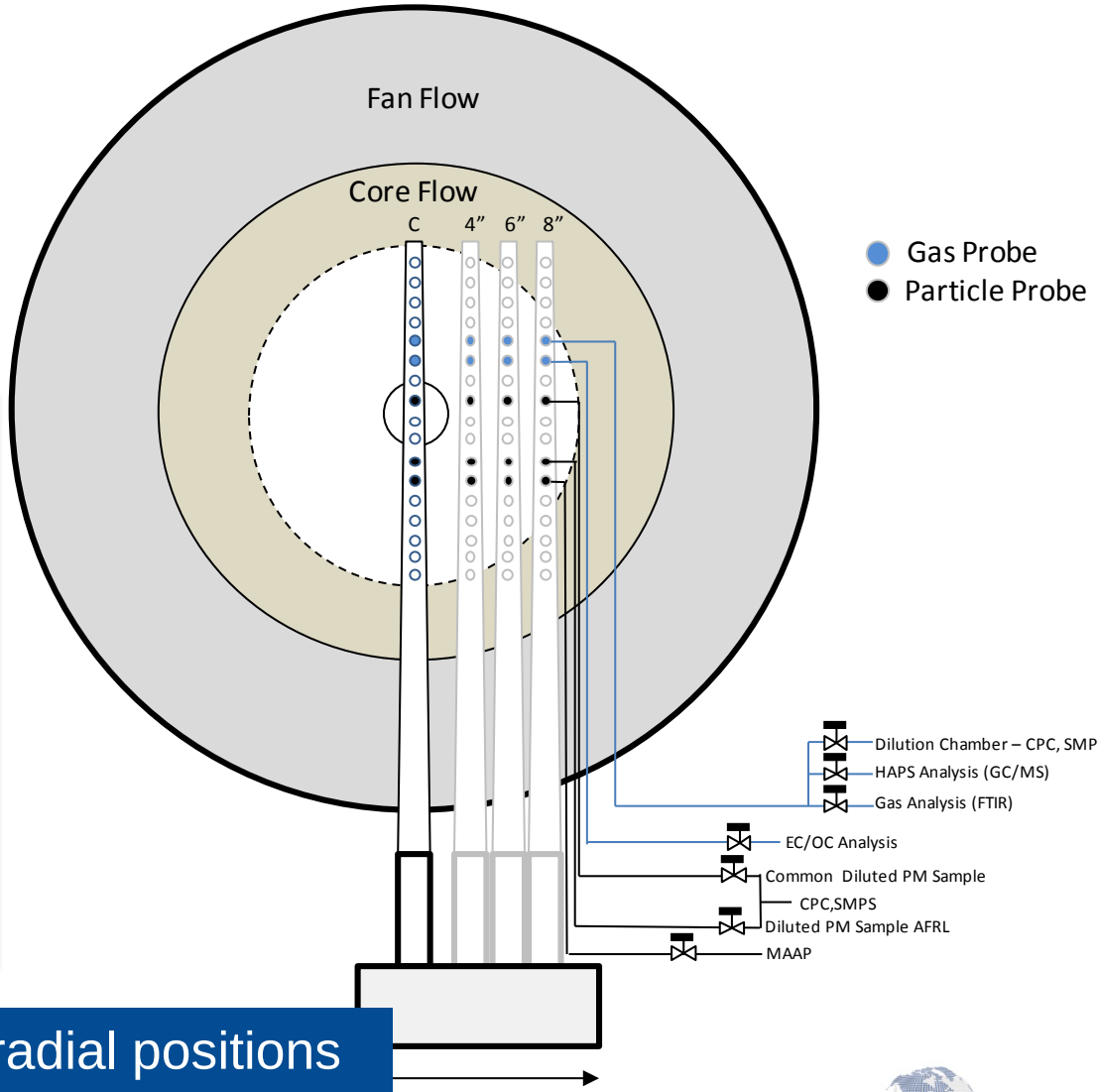
- 4%, 7%, 30%, 65%, 85%, 100%

NASA DC-8 Aircraft with CFM56-2C Engines
AAFEX II Tests Conducted on 26 Mar – 1 Apr 2011

Emissions Sampling Setup
AAFEX II

Particle Probe





- Probe rake translated to three radial positions
- Multiple gas and particle probes

Fuel Specification Tests Results

Test	JP-8	HRJ	FT	HRJ/JP-8	FT+THT
POSF#	**7493**	**7495**	**7498**	**7500**	**7503**
ASTM D 2622 - 10 Sulfur (ppm mass)	188	6	4	276	1083
ASTM D 3242 - 08 Total Acid Number (mg KOH/g)	0.005	0.005	0.003	0.004	0.002
ASTM D 1319 - 10 Aromatics (% vol)	21.8	0.4	1.4	10.2	2.1
ASTM D 3227 - 04a Mercaptan Sulfur (% mass)	0.001	0	0.001	0.001	0
ASTM D 86 - 10a Distillation					
Initial Boiling Point (°C)	149	156	146	150	151
10% Recovered (°C) 205	168	176	164	166	164
20% Recovered (°C)	177	184	167	174	167
50% Recovered (°C)	201	209	177	204	177
90% Recovered (°C)	243	244	200	248	201
End Point (°C) 300	268	254	226	263	224
Residue (% vol)	1.3	1.4	1.4	1.3	1.4
Loss (% vol)	0.6	0.6	0.2	1.1	0.7
ASTM D 93 - 10a Flash Point (°C)	46	52	43	46	43
ASTM D 4052 - 09 Density @ 15°C (kg/L)	0.811	0.759	0.761	0.783	0.761
ASTM D 5972 - 05e1 Freezing Point (°C) -47	-53	-49	-76	-54	-77
ASTM D 445 - 10 Viscosity @ -20°C (mm^2/s)	4.1	4.8	3.7	4.3	3.2
ASTM D 3343 - 05 Hydrogen Content (% mass)	13.5	15.3	15	14.4	15
ASTM D 1322 - 08 Smoke Point	22	25	34	31	30
ASTM D 1840 - 07 Naphthalenes (% vol)	1.3				
ASTM D 130 - 10 Copper Strip Corrosion (2 h @ 100°C)	1a	1a	1a	1a	1a
ASTM D 3241 - 09e1 Thermal Stability @ 260°C					
Change in Pressure (mmHg)	0	0	0	0	0
Tube Deposit Rating, Visual <3 (Max) 1	1	1	1	<2	1
ASTM D 381 - 04 Existent Gum (mg/100 mL)	<1	1	<1	<1	<1
ASTM D 1094 - 07 Water Reaction Interface Rating	1	1	1	1	1
ASTM D 5006 - 10e1 FSII (% vol)	0.15	0	0.03	0.1	0.03
ASTM D 2624 - 09 Conductivity (pS/m)	608 X	44	129	297	80
ASTM D 4809 - 09a Net Heat of Combustion (MJ/kg)	42.8	44	43.8	43.3	43.8
ASTM D 1319 - 10 Olefins (% vol) Report Only	0.7	0.2	1.6	0.6	1.5

Fuel Specification Tests Results

	JP-8	HEFA	FT	HEFA/JP-8	FT+THT
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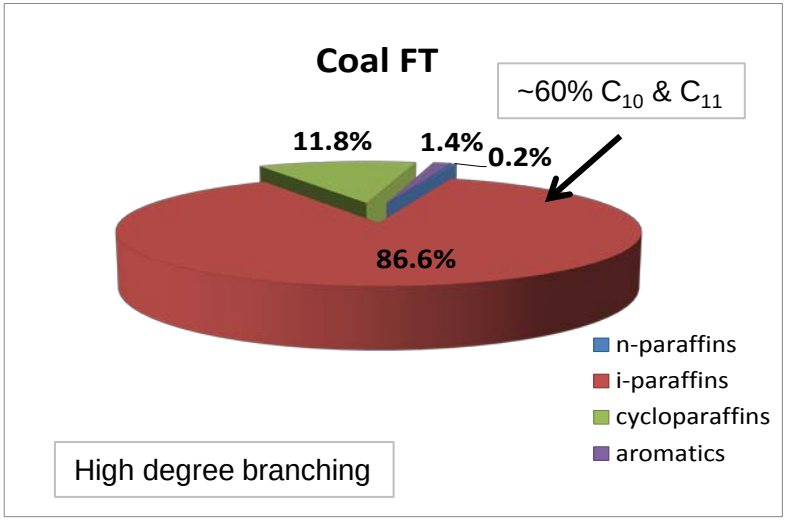
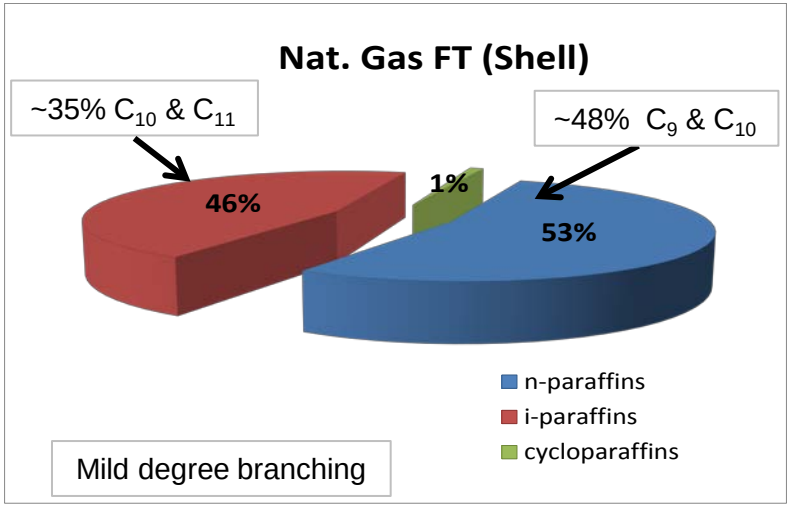
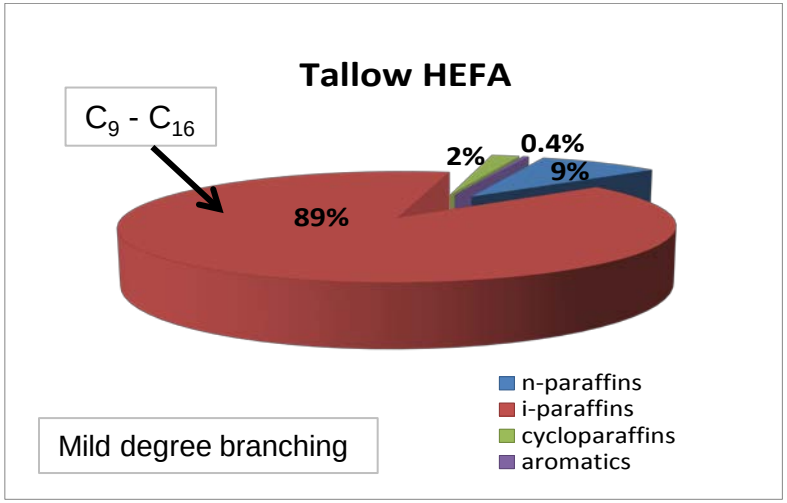
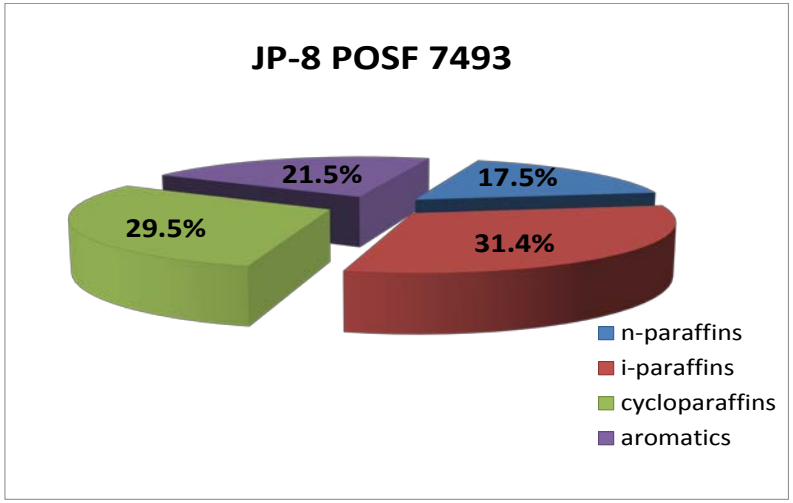
Alt Fuels Chemical Composition





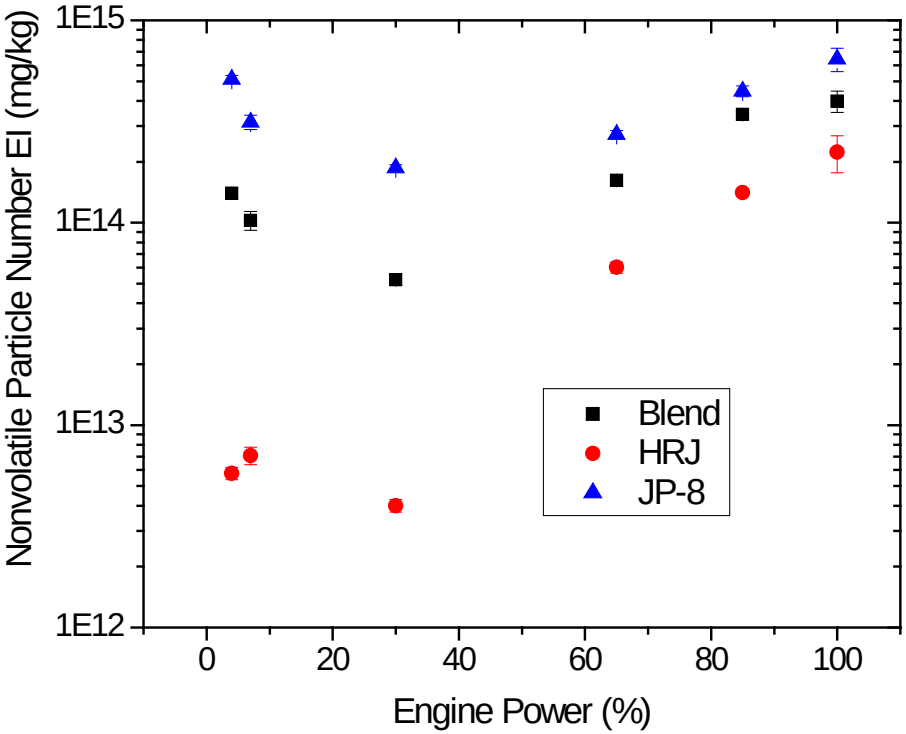




NOT ALL FT or SPK FUELS ARE THE SAME!

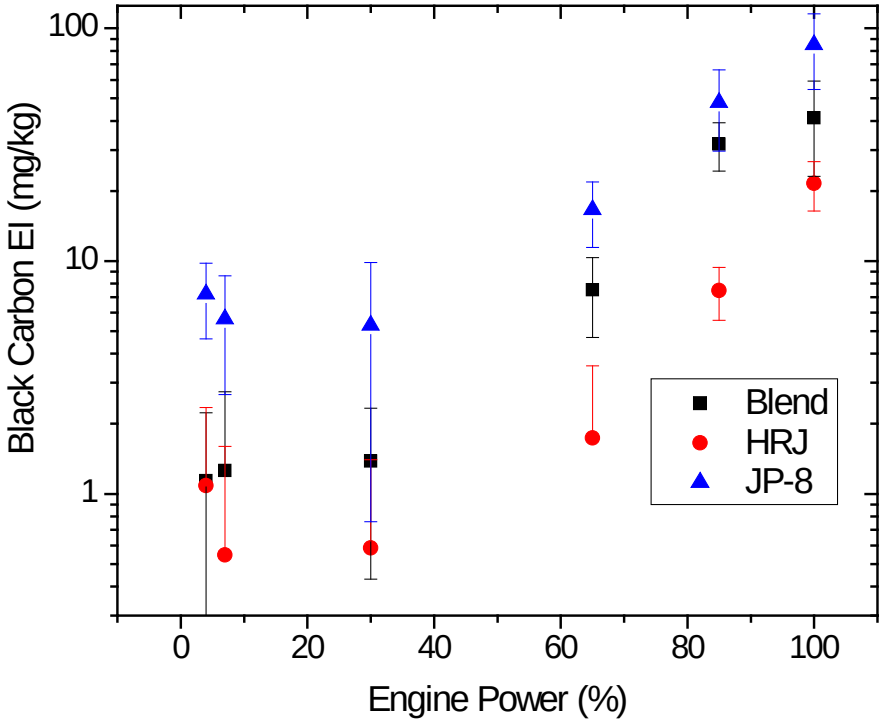
Non-volatile PM Data

HRJ (HEFA) Fuels Reduces PM Number & Mass

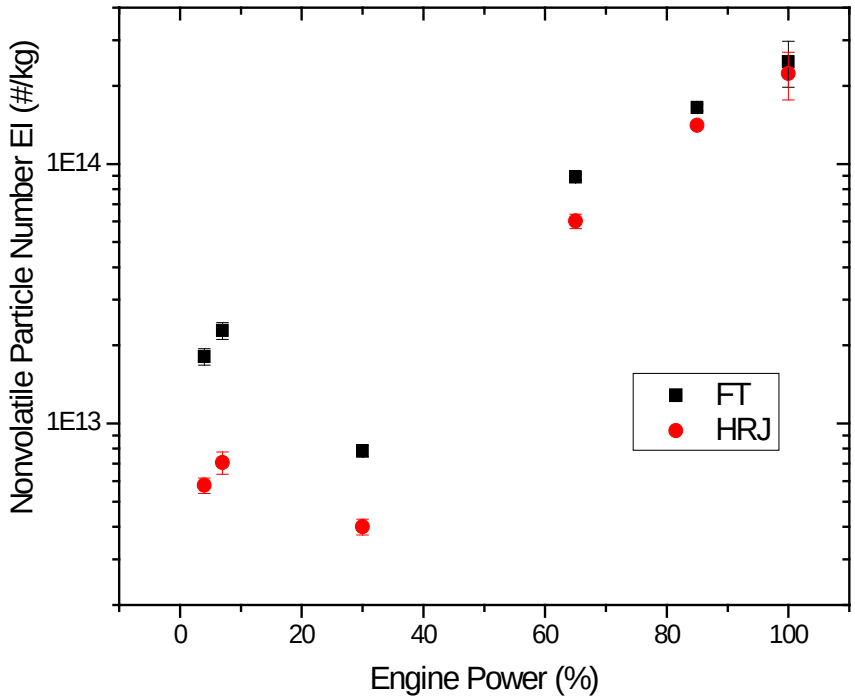


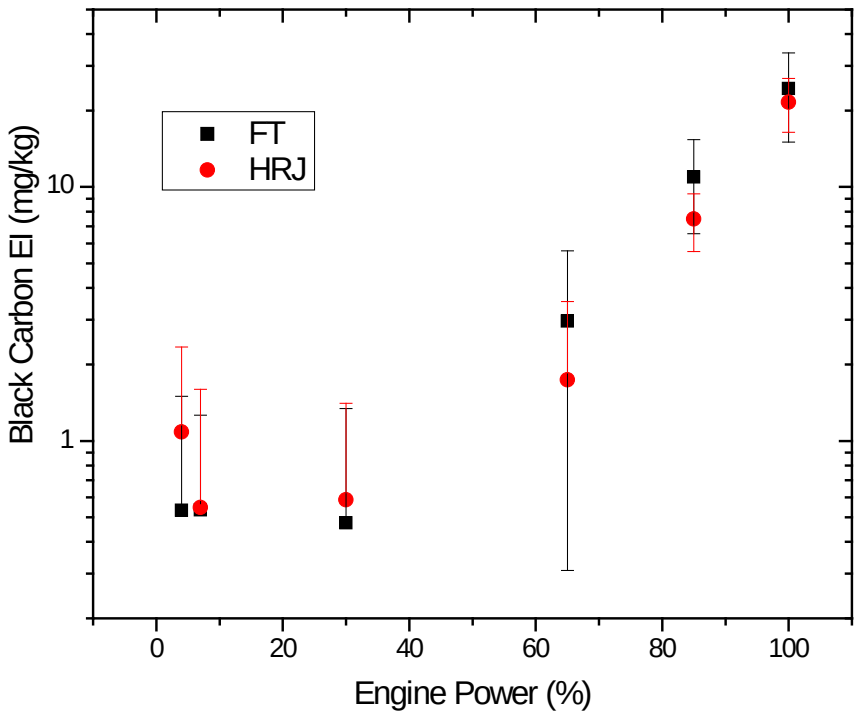
- Dramatically lower non-volatile PM with HEFA fuel and blend
- Lack of aromatics/higher H/C
- Differences greatest at idle, less at higher engine powers

- ~70-95% reduction in number & mass with HEFA
- ~30-65% reduction number & up to 80% reduction in mass with blend



Comparison of HRJ (HEFA) and FT2 PM Emissions

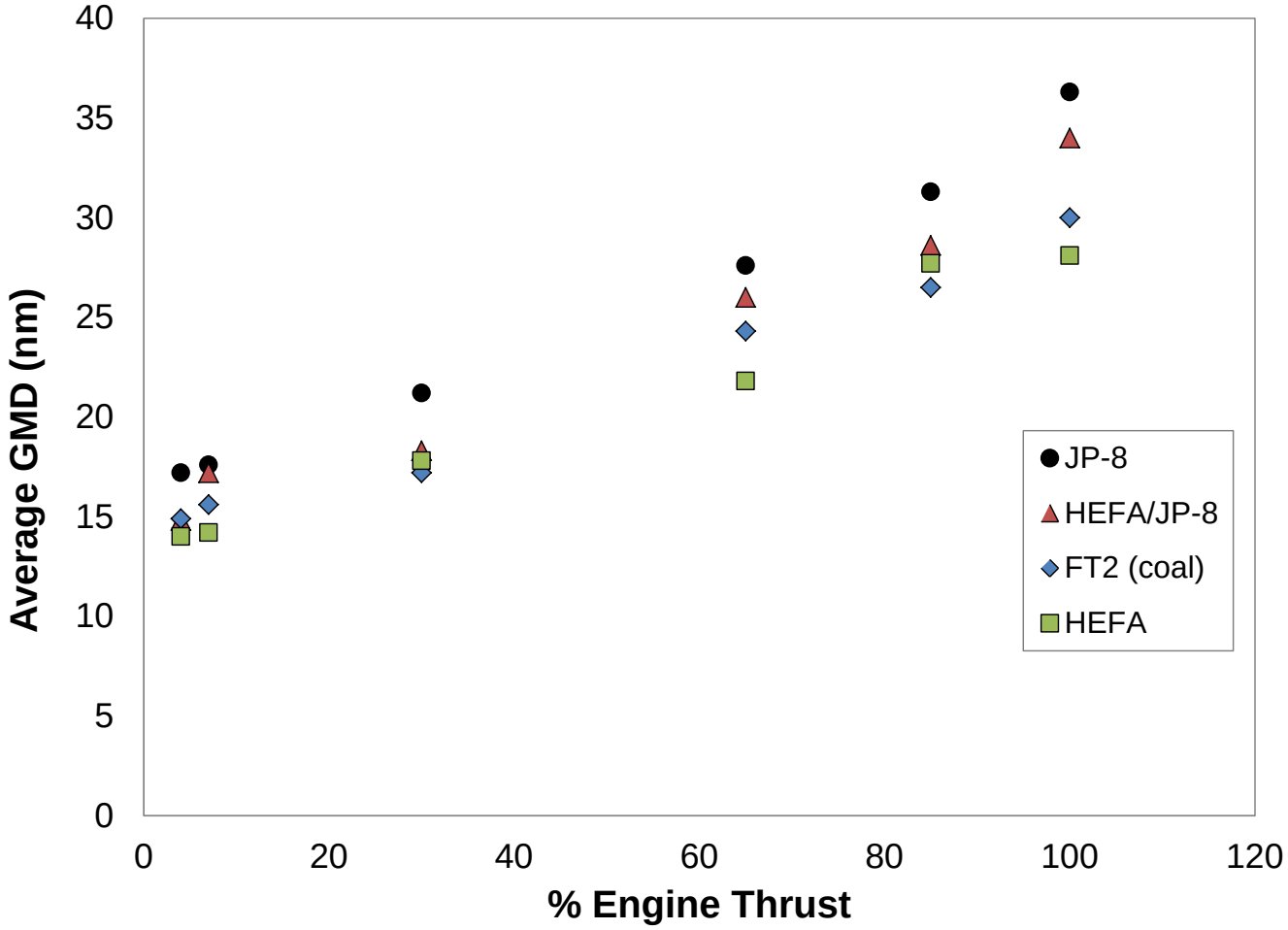




- HRJ (HEFA) PM Number EIs 2-3X lower than FT2 at low engine powers
- HEFA mildly branched iso-paraffins and n-paraffins less prone to soot formation than highly branched iso-paraffins in FT2
- Alt fuels produce similar PM at high powers – Less dependent on chemistry
- Very low PM mass formation for both fuels

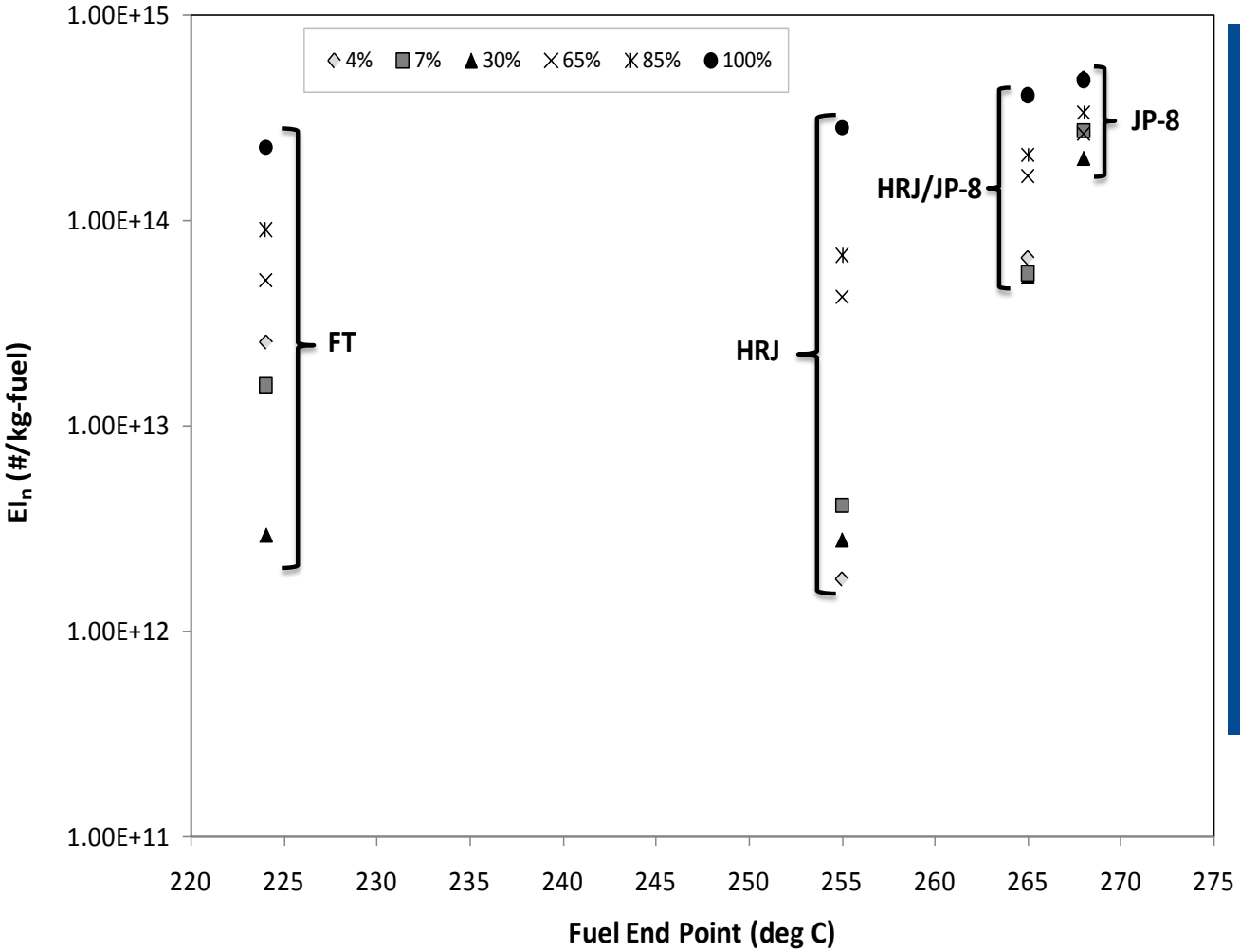
Mean Particle Diameter CFM56-2

1m Data



- Reduction in geometric mean diameter with alt fuels
- Fewer non-volatile particles for agglomeration and volatile species available for growth

Effect of Fuel End Point on Non-volatile Particle Number EI



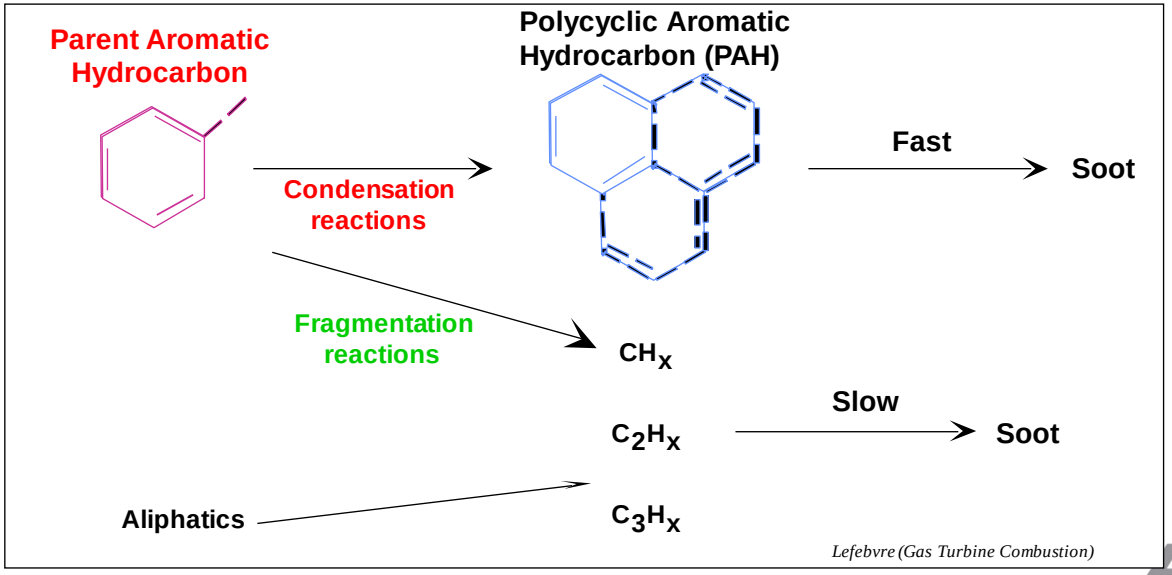
- Wider range of EI_n for fuel with lower fuel end point
- Lower fuel end point improves vaporization, promotes combustion & decreases volatile PM precursors
- Chemical composition of fuel also influences range of EI_n (aromatics, iso/normal paraffin ratio)

DISTRIBUTION STATEMENT A - Unclassified, Unlimited Distribution

Fuel Impact on Non-volatile PM Emissions Dependent on Combustion Conditions

- Higher impact at lower engine power
  - Most soot formation by aromatics (faster condensation route)
  - Improved fuel combustion – reduced HC aerosols
- Lower impact at higher engine power (combustion temperatures)
  - Higher combustion temperatures increase rate of soot formation by paraffinic species (fragmentation – polymerization route)
  - Reduced relative soot production rates of aromatics

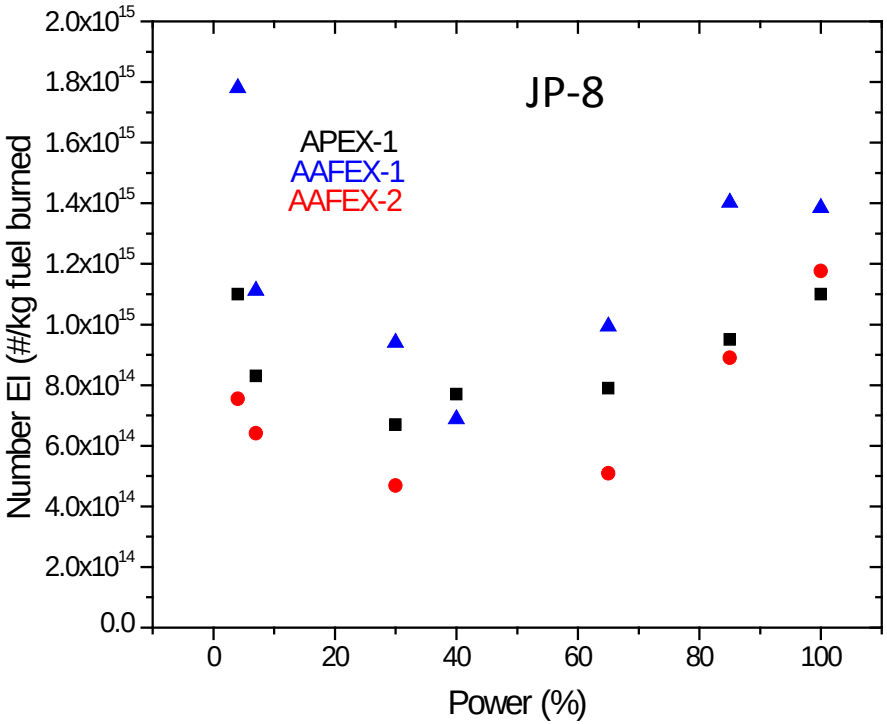
Simplified Soot Formation Mechanism

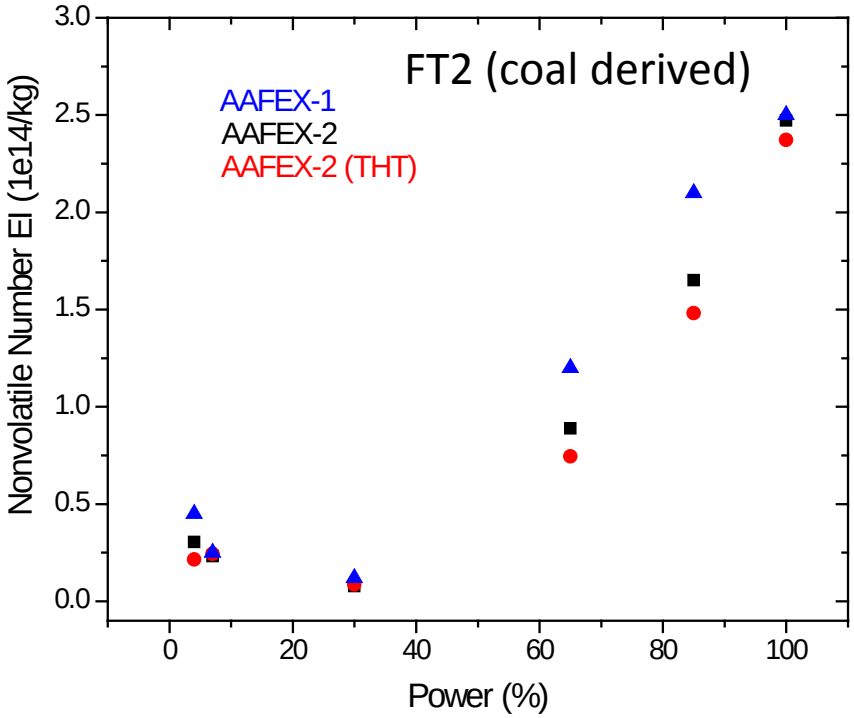


Lefebvre (Gas Turbine Combustion)

Are PM Measurement Consistent Between Tests?

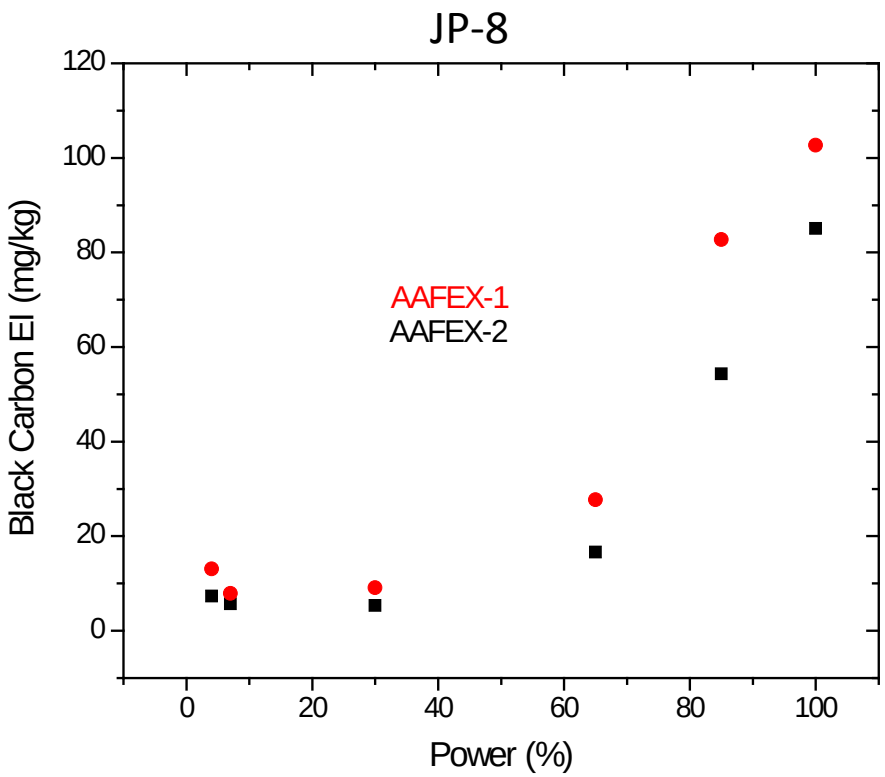
Particle Number EI Comparisons

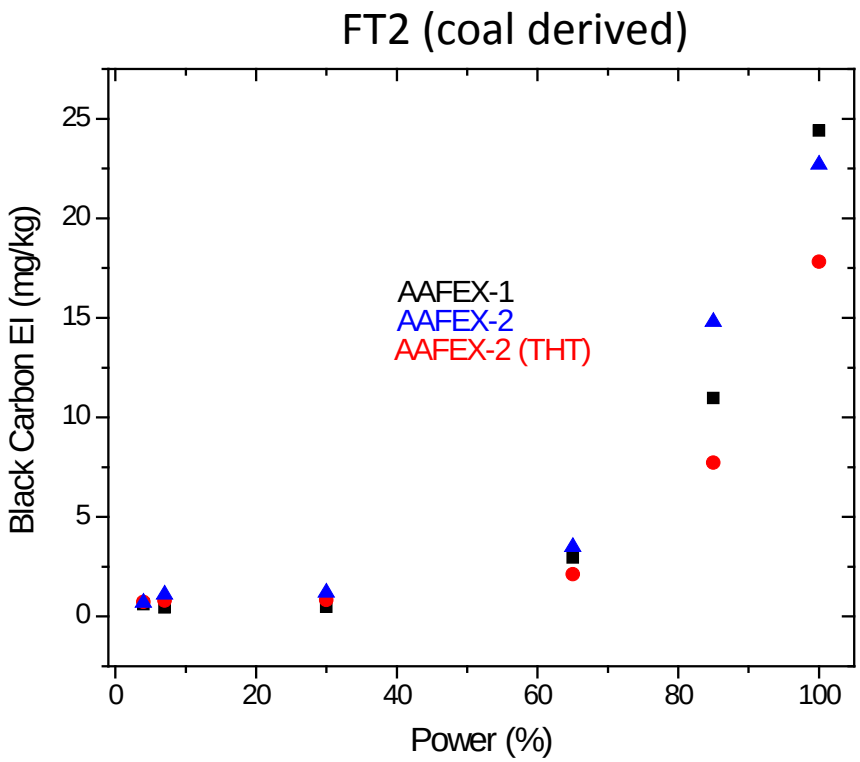




- Colder conditions during AAFEX-1 produced higher PN relative to AAFEX 2
- Temperature impact on PN lower with FT2 than with JP-8
  - Lower volatile fraction

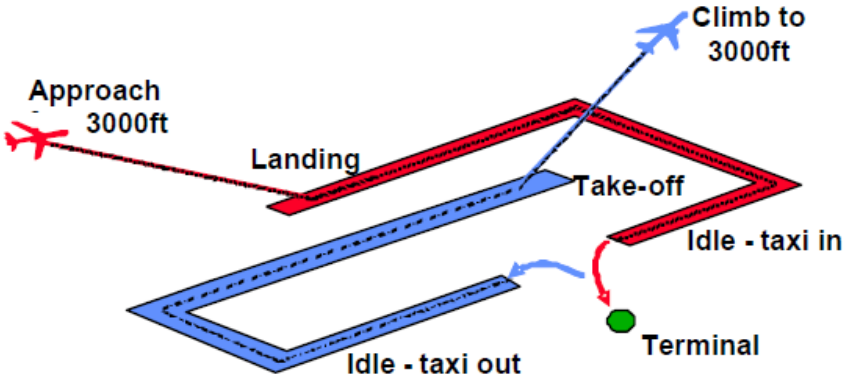
Black Carbon Mass Comparison AAFEX I & II



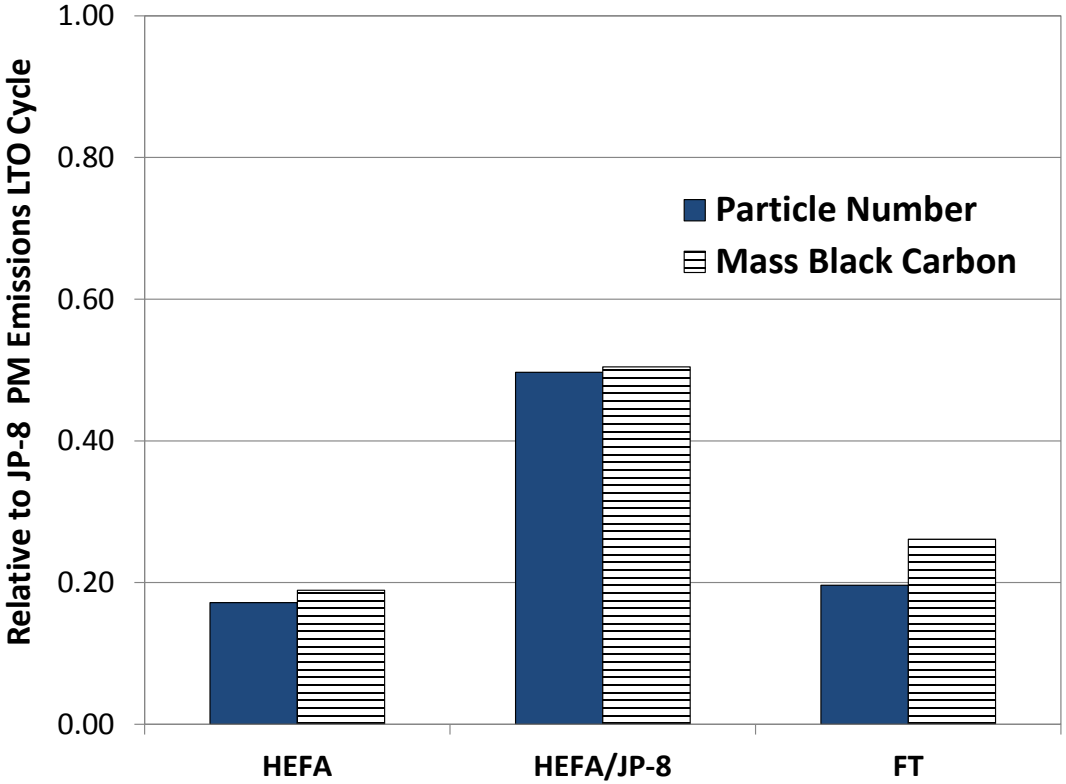


- Colder conditions during AAFEX-1 has minor impact on BC
- Overall good data agreement between campaigns

Significant Reductions in LTO PM Emissions with Alt Fuels



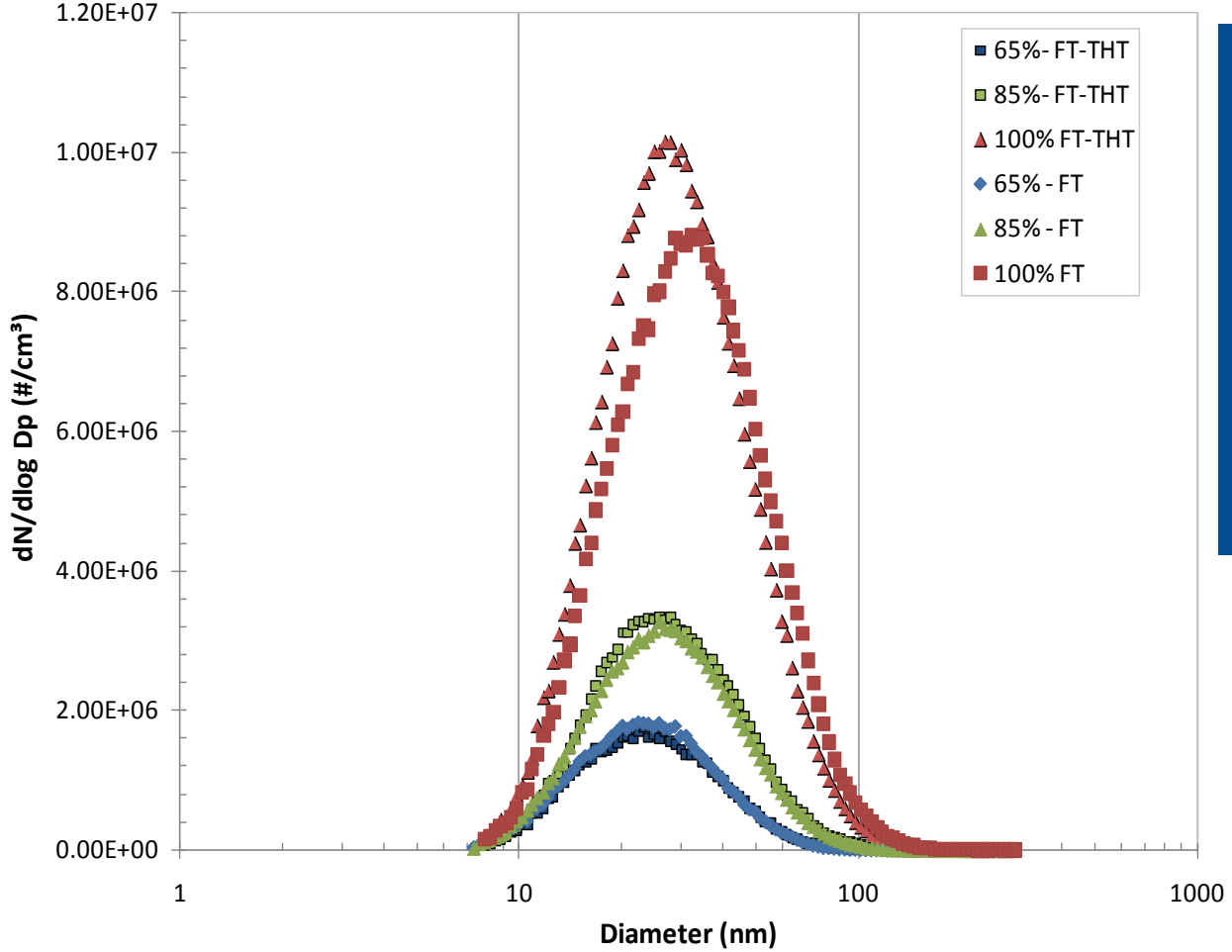
Operating Mode	Thrust Setting	Time in Mode (m)
Taxi/ground Idle	7	26.0
Approach	30	4.0
Climb	85	2.2
Take-off	100	0.7



- **Reductions of 50% in PM BC mass and particle number with 50/50 Blends of Alt & Conv. Fuel**
- **75-80% Reductions in PM with neat FT and HEFA**
- **Similar alt fuel effect expected for other engines**

Impact of Fuel Sulfur on Non-volatile PM

Comparison of PSD for 1m Sampling
CFM56-2 – FT+THT & FT (65-100% Thrust



- Negligible impact of sulfur in FT fuel on Particle Size Distribution for near field sampling
- Sulfur species do not impact non-volatile PM

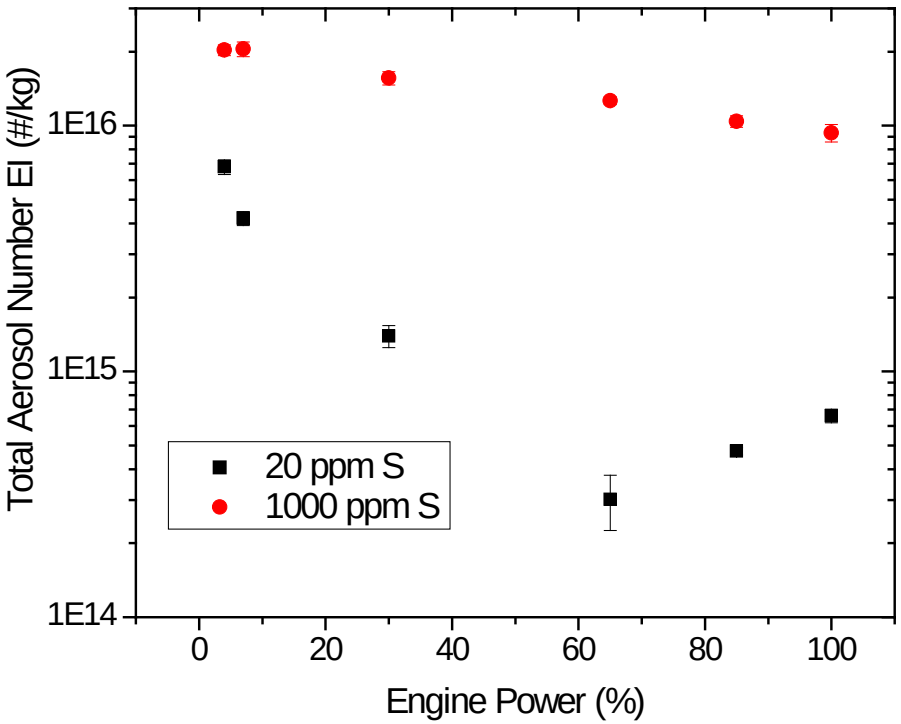
Volatile PM Emissions

Sulfur Impacts

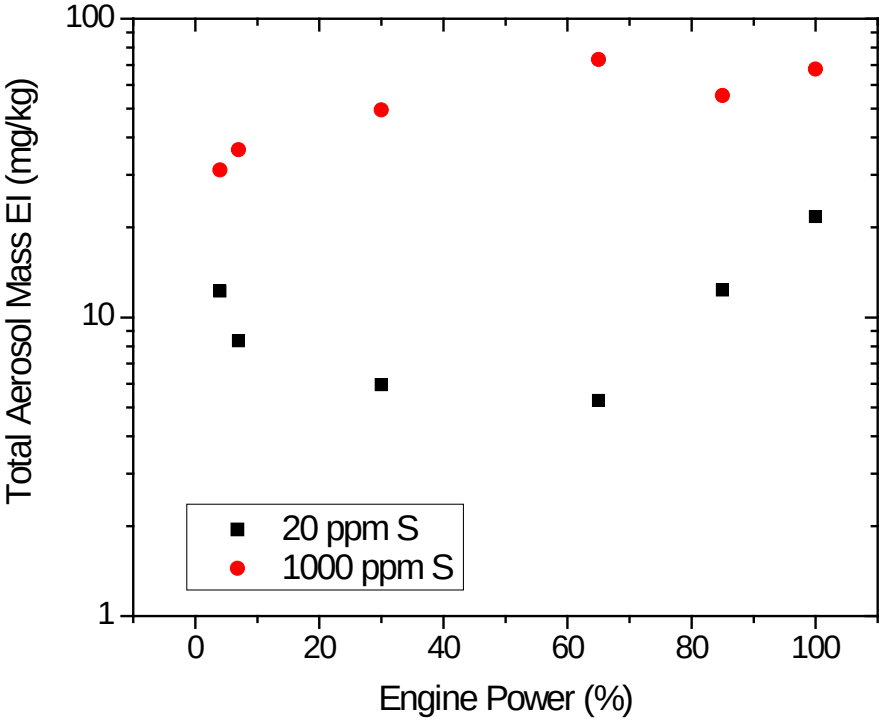
1 m vs 30m

Sulfur Plays Significant Role in Volatile PM

Data from 30 m inlet

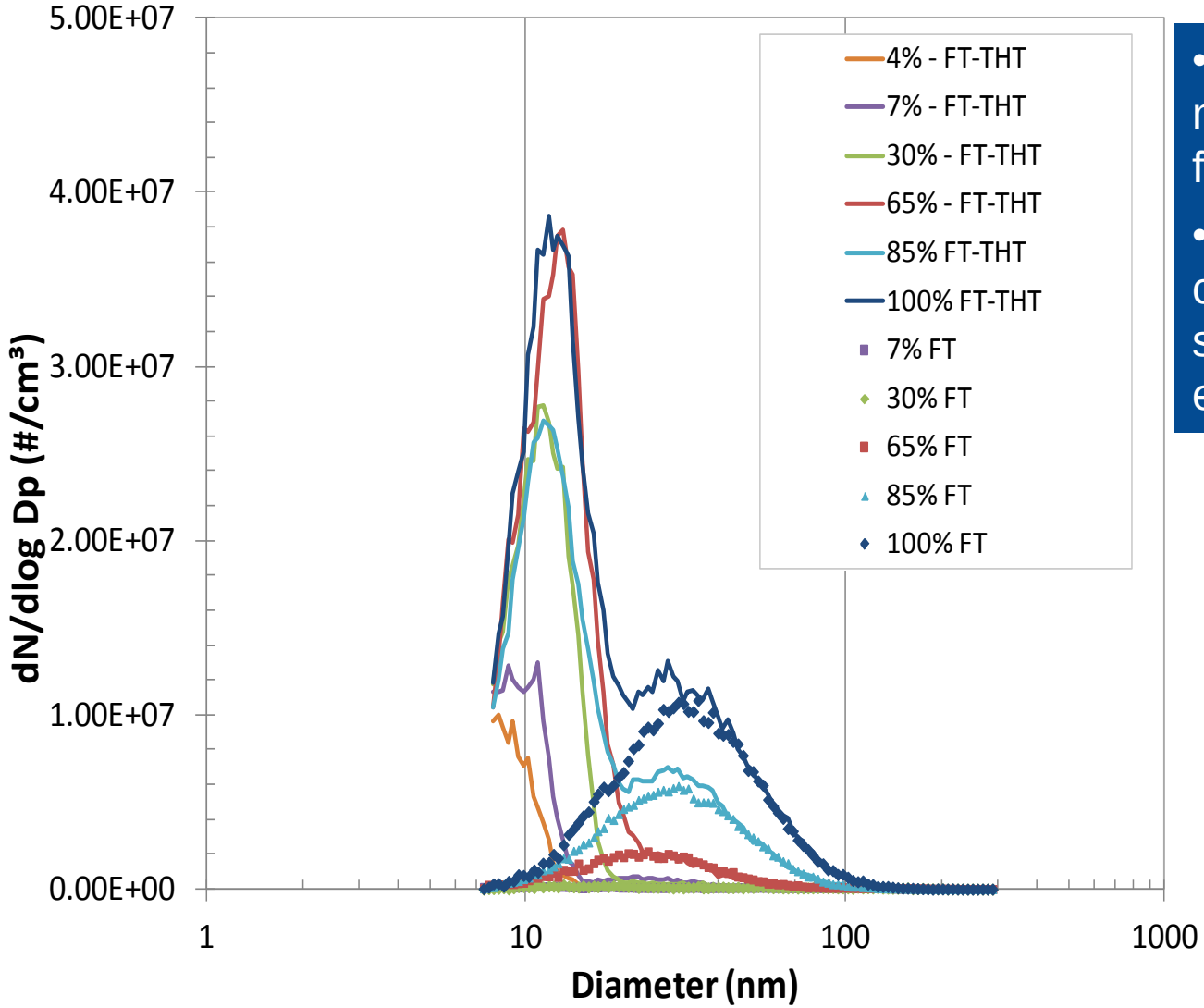


Relatively high ambient temperature suppressed volatile formation, but difference still profound



Difference in 30 m PN and mass not proportional to sulfur content in fuel

Comparison of PSD for 30 m Sampling CFM56-2 Sulfur Impacts



- Significant nucleation mode with sulfur-doped fuel at 30 m
- Larger PN for all power conditions for 30 m sample versus sample at engine exit plane

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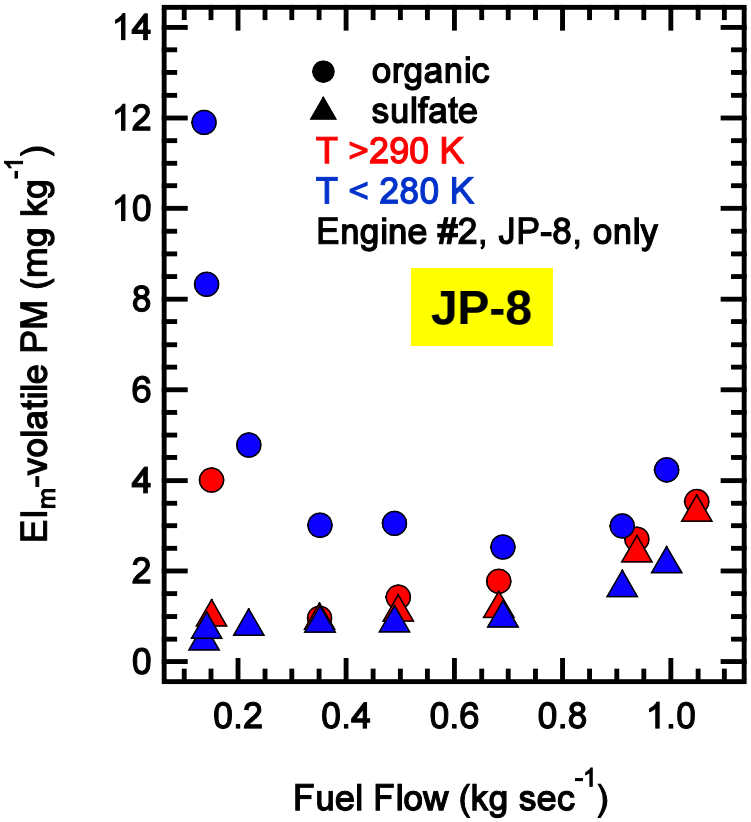
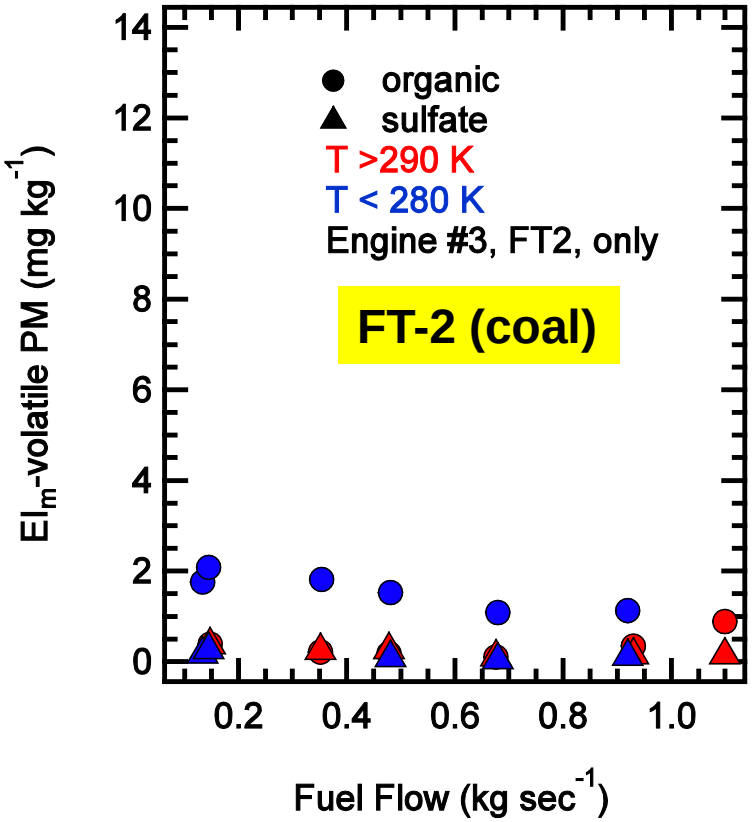
AMS Volatile PM Mass Measurements

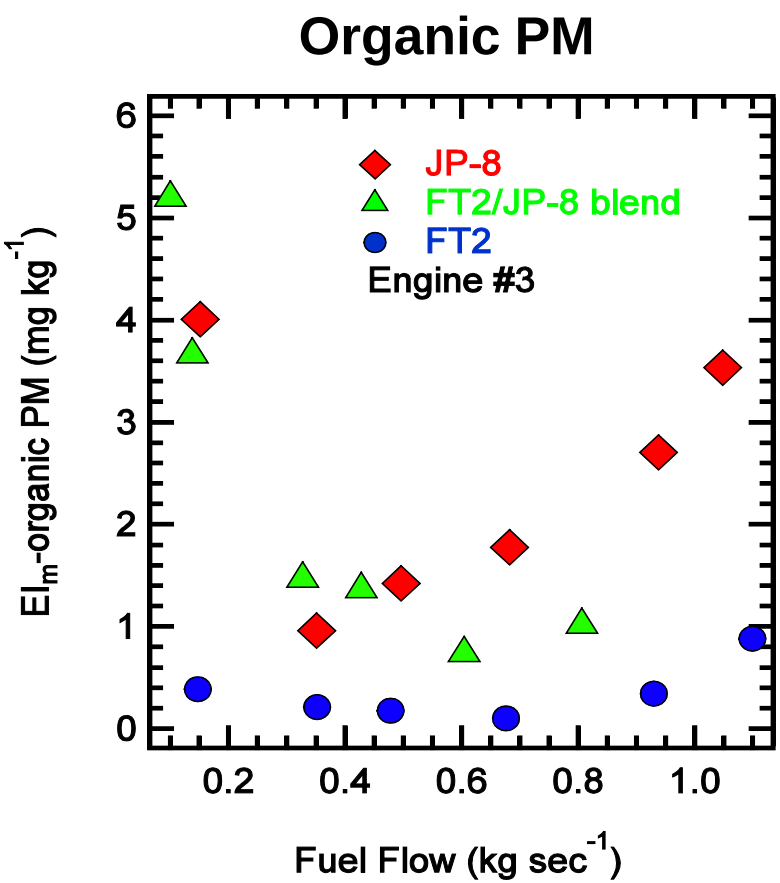


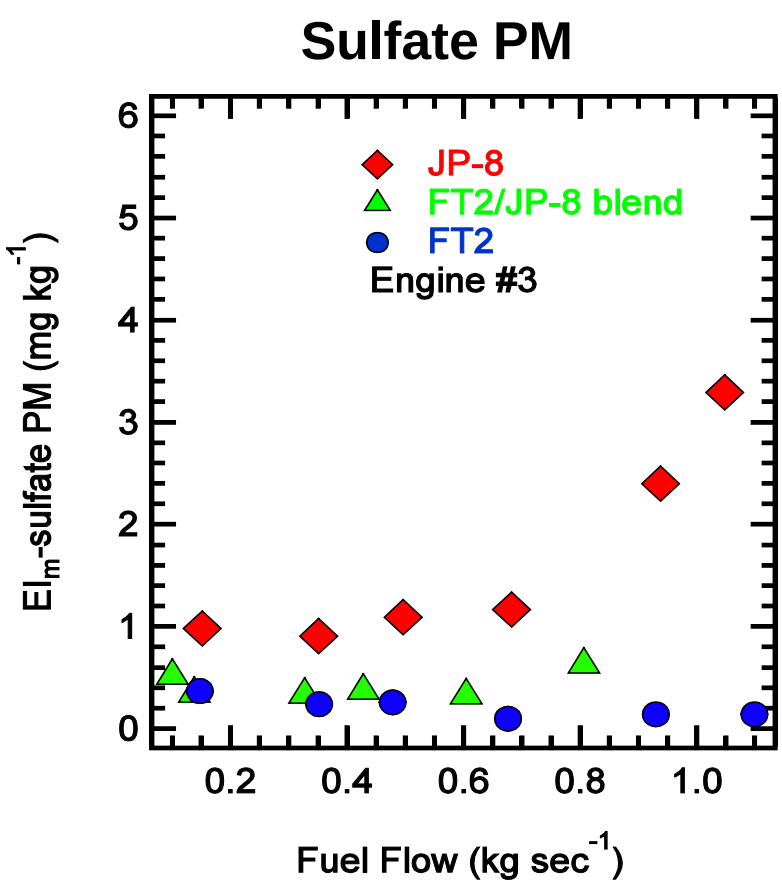


Aerosol Mass Spectrometer (AMS) measures size-resolved volatile PM (70-700 nm species that vaporizes under vacuum at 600C) such as sulfate and organics

- Both organic and sulfate volatile PM mass reduced for combustion of alternative fuel
- Ambient temperature affects volatile PM mass emissions and speciation
- Organic PM mass increases with decreasing temperature, whereas sulfate is less strongly affected.

Fuel Flow Dependence on AMS Volatile PM Mass





- Reduction in organics and sulfates in FT blend not directly proportional to FT fuel concentration
- Very low concentrations of organics and sulfates in FT exhaust
  - Lower molecular weight compounds - No aromatics
  - Negligible sulfur

Summary

Alternative Fuel Effects on Non-Volatile PM Emissions

- Significant reductions in non-volatile EI_n compared to JP-8
  - Higher impact at low power, but still significant EI_n at high power
  - 50% reduction with blend and >75% reduction in PM in LTO
- Fuel with lower end point produce lower EI_n at low engine power
- HEFA produces lower PM at lower power, similar at high power
- Non-volatile number/mass/size emissions for same fuels comparable between different experiments, indicate measurements reproducible

Alternative Fuel Effects on Volatile PM Emissions

- Fuel sulfur responsible for rapid volatile PM formation in plume
- Number EIs do not vary linearly with sulfur content
- Sulfate aerosols create nucleation mode and coat soot particles
- Organics have lower impact on volatile PM