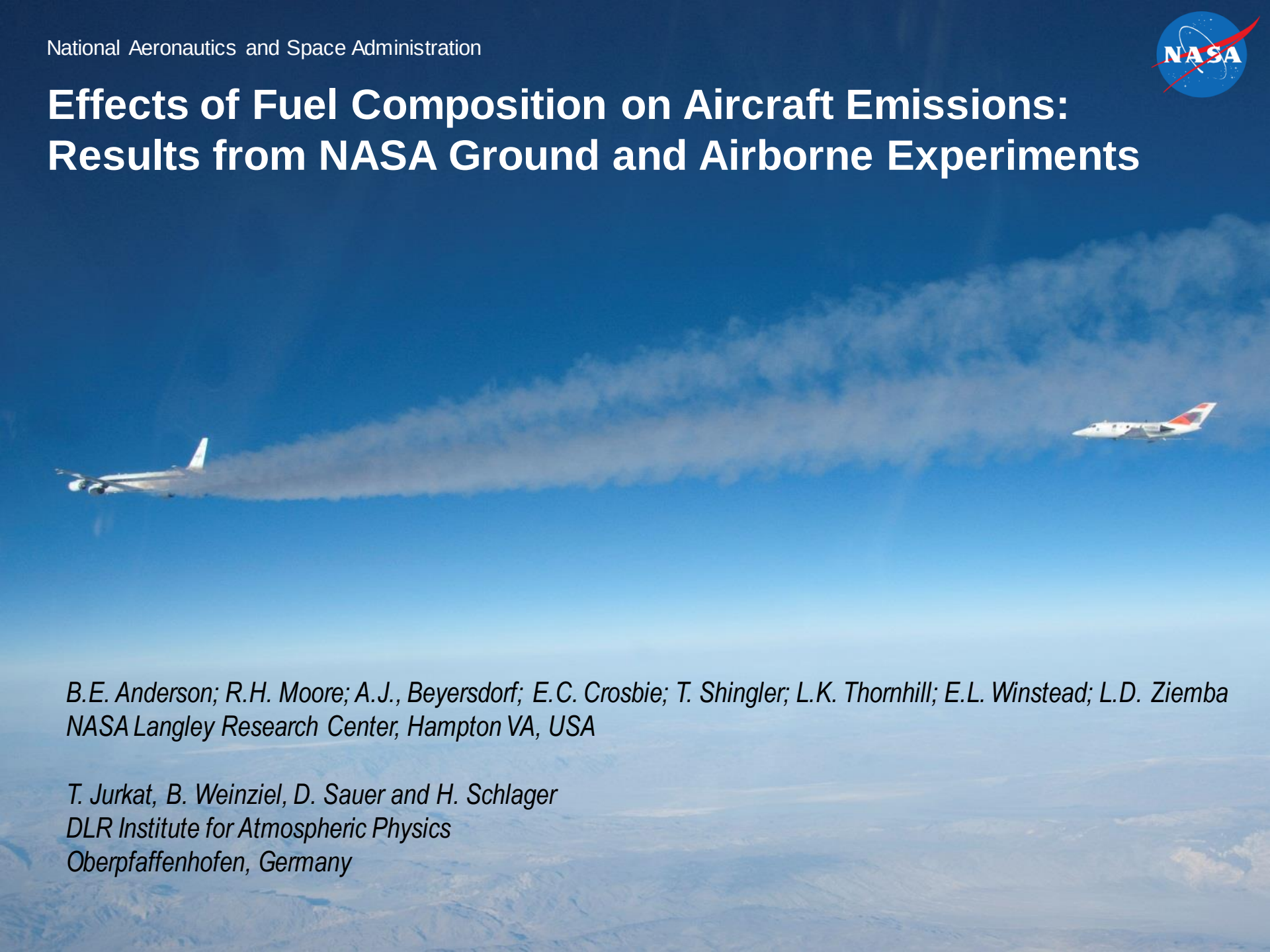
National Aeronautics and Space Administration

Effects of Fuel Composition on Aircraft Emissions: Results from NASA Ground and Airborne Experiments



B.E. Anderson; R.H. Moore; A.J., Beyersdorf; E.C. Crosbie; T. Shingler; L.K. Thornhill; E.L. Winstead; L.D. Ziemba
NASA Langley Research Center, Hampton VA, USA

T. Jurkat, B. Weinziel, D. Sauer and H. Schlager
DLR Institute for Atmospheric Physics
Oberpfaffenhofen, Germany

Motivation for Research

- Aircraft generate large numbers of black carbon and secondary aerosol particles which impact air quality and climate
- Aircraft also emit CO_2 and create contrails which enhance climate warming
- Airline traffic is increasing 2-3%/year and will probably double in the next 20 years
- New nonvolatile PM and CO_2 standards are being adopted by ICAO to mitigate aviation impacts
- Sustainable alternative fuels and more efficient propulsion systems will be needed to meet new standards
- Studies are needed to characterize engine PM emissions and how they change with fuel composition

Recent NASA Studies to Investigate PM Emissions

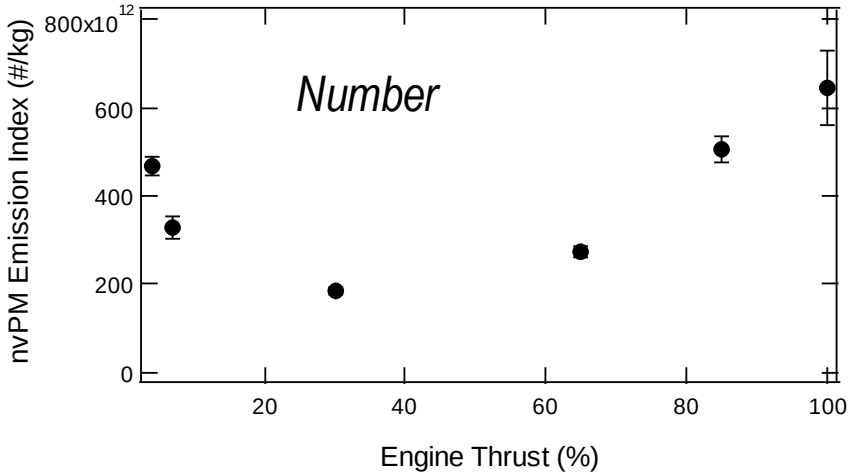
Year	Project	Location	Test Article	Fuels
2008	PW308	West Palm Beach	Pratt PW308	Jet A, FT, 50% FT
2009	AAFEX-1	Palmdale	CFM56-2C	Jet A, FT (gas), FT (coal), 50% blends
2011	AAFEX-2	Palmdale	CFM56-2C	Jet A, HEFA, 50% HEFA, FT (gas), Sulfur dopant
2013	*ACCESS-1	Palmdale	CFM56-2C	Jet A, 50% HEFA
2014	*ACCESS-2	Palmdale	CFM56-2C	Jet A, 50% HEFA
2015	CONEX	Cleveland	Honeywell APU	Jet A, Alt Fuels, Blends
2016	*ECLIF-1	Manching Germany	IAE2527-A5	2 Jet A ref fuels, 4 Blends

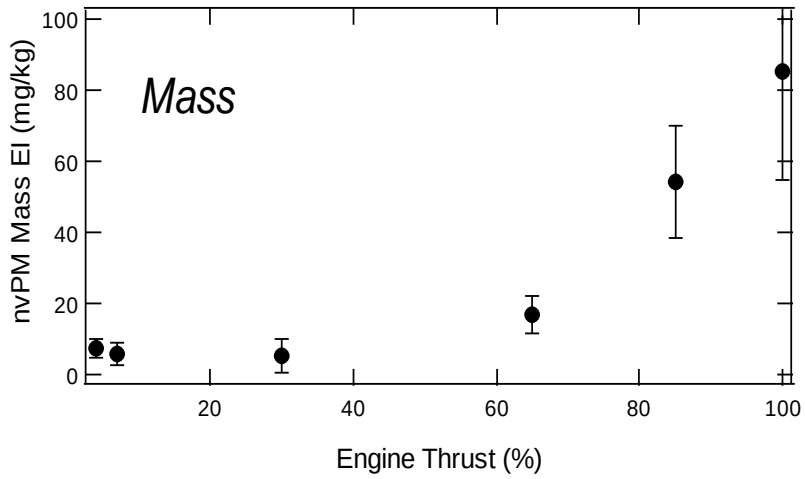
* Flight Projects

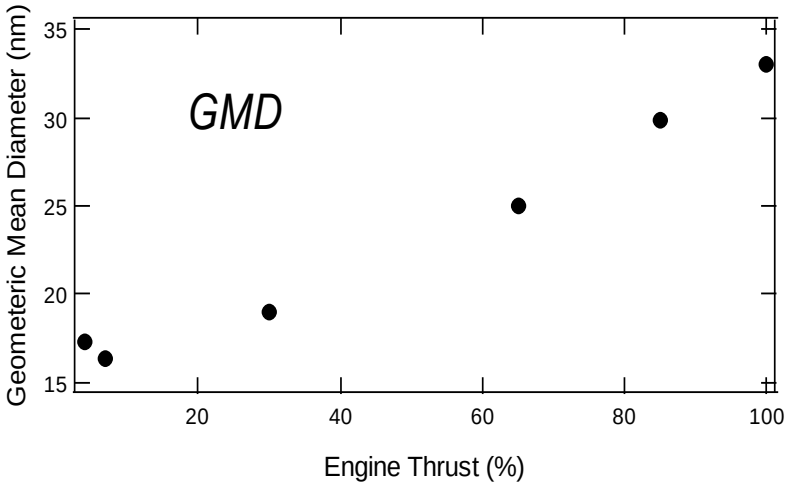
Studies of NASA DC-8 CFM56-2C emissions during ground and airborne operations

Characteristics of Gas Turbine nvPM Emissions

Measured nvPM emissions from a CFM56-2C Engine burning Jet A





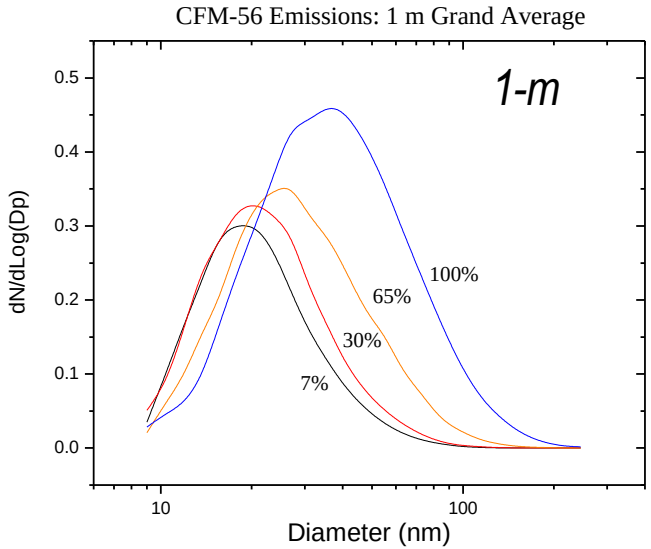


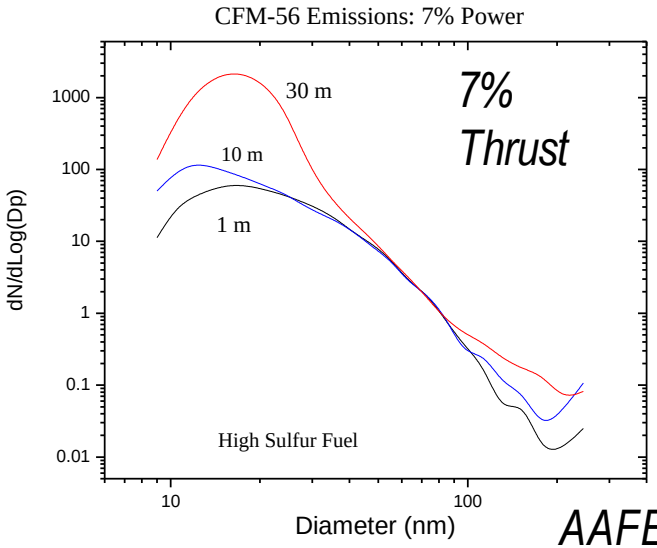
- RQL combustors exhibit highest nvPM number and mass emissions at TO and Climb thrust settings
- New lean-burn staged combustors exhibit maximum emissions at 30% thrust
- Soot emissions dependent on fuel aromatic content

Measurements from exhaust sampled 1-m behind engine exit plane.

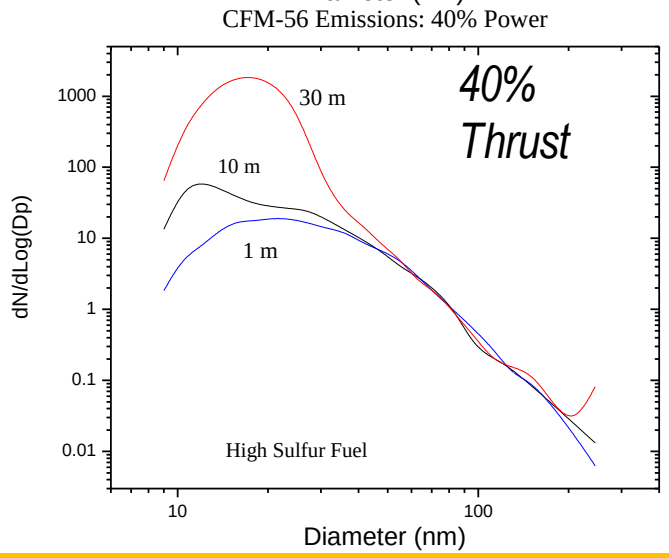
Volatile PM Form Rapidly in Cooling Exhaust Plume

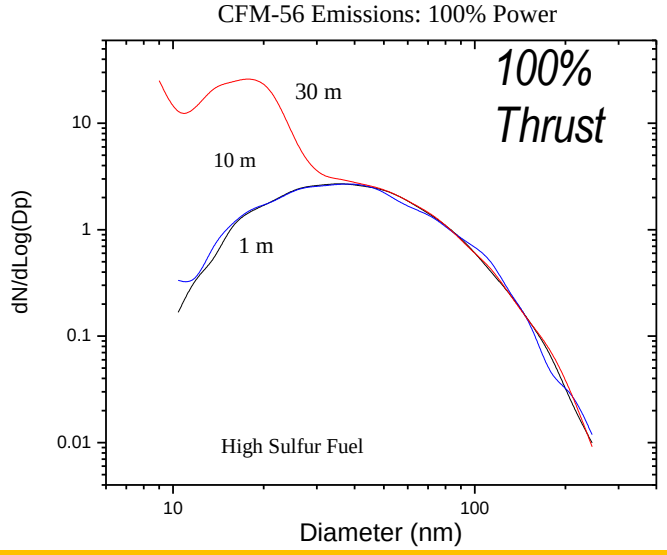
Measured PM emissions from a CFM56-2C Engine burning Jet A





AAFEX-I Results

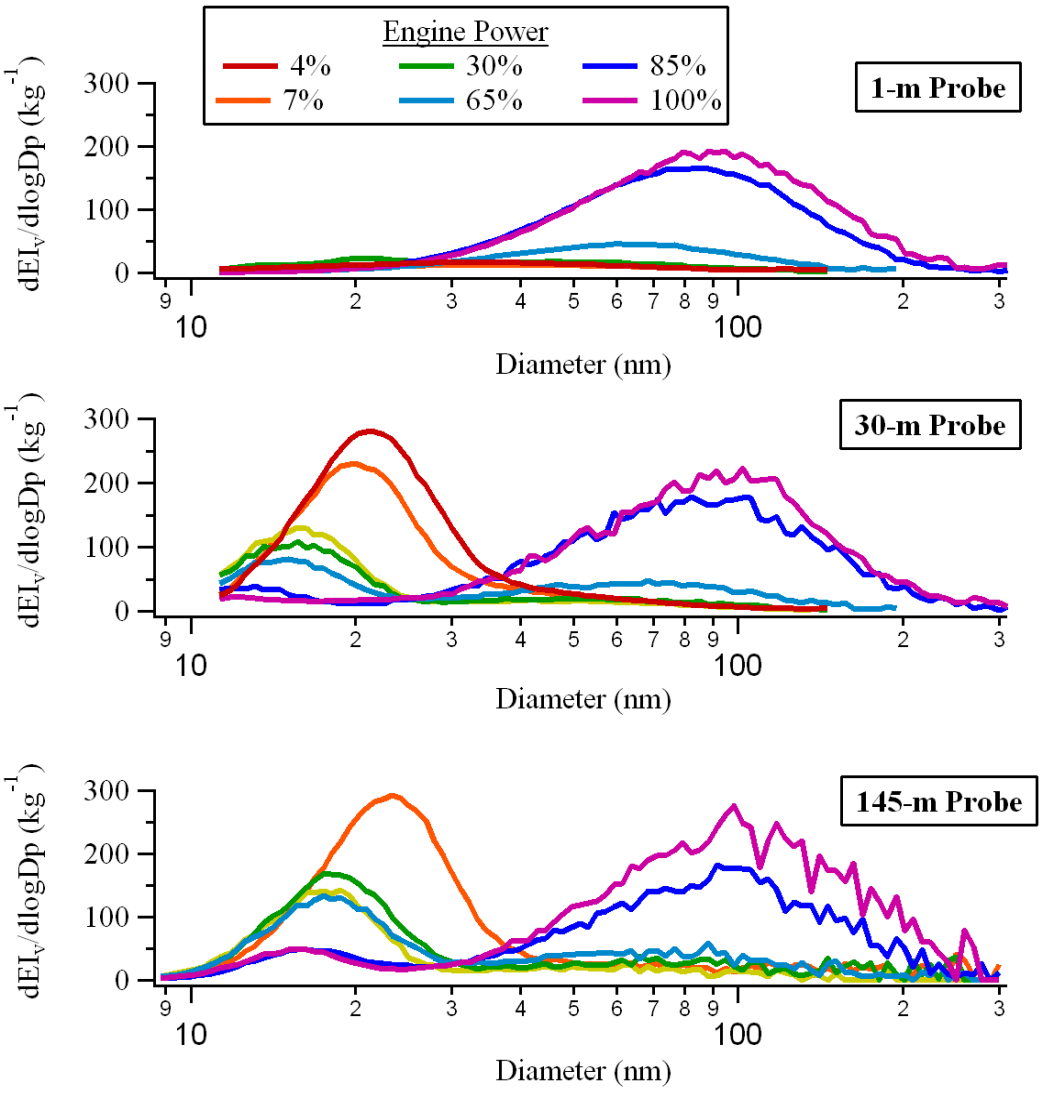




Mass of volatile aerosols dependent on fuel sulfur, ambient temperature and plume age

Nucleation Mode Continues to Grow with Age

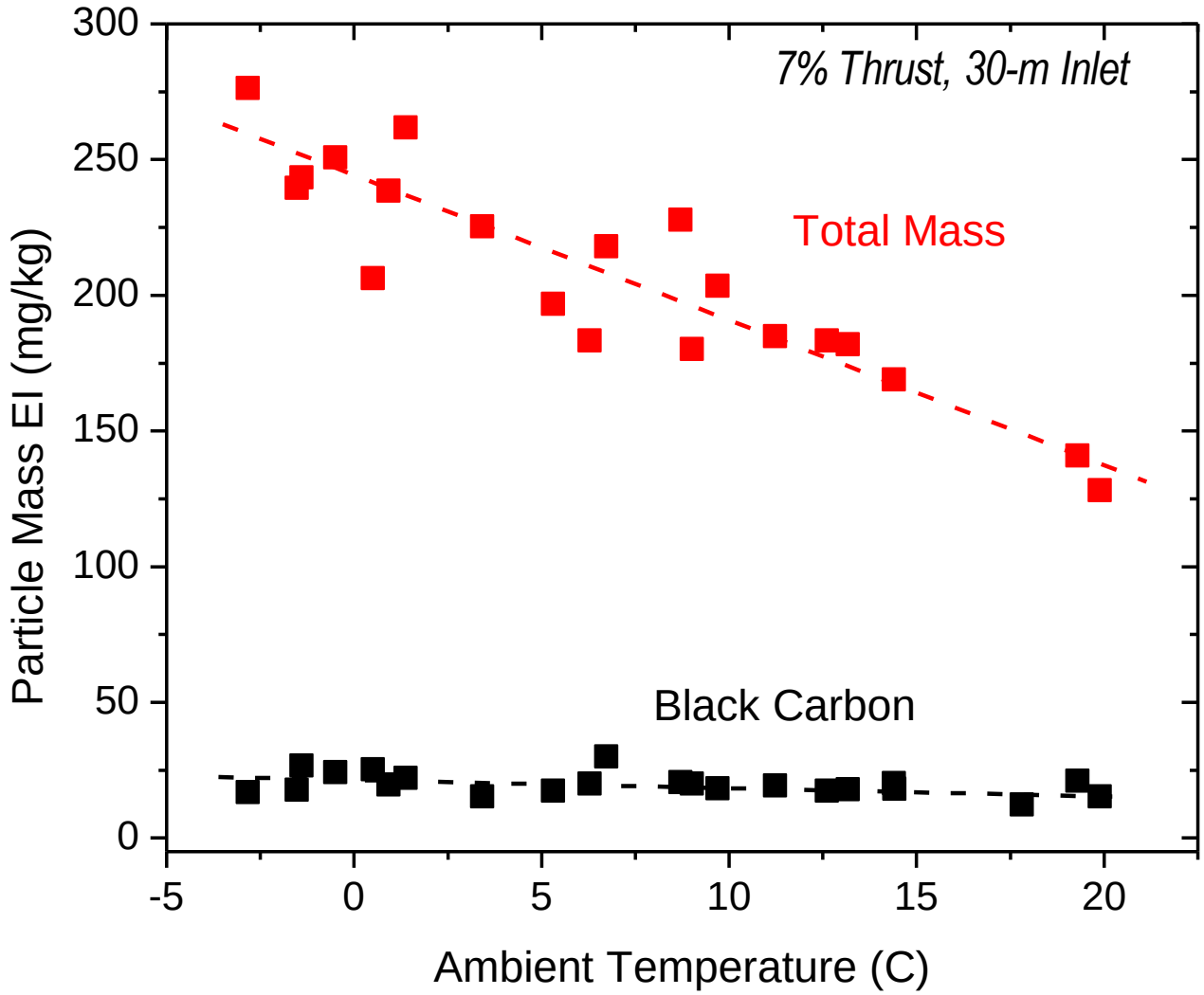
Measured PM emissions from a CFM56-2C Engine burning Jet A



- *Studies show sulfur oxidation mostly independent of engine thrust*
- *Nucleation mode less prominent at high thrust levels because vapors tend condense on soot surfaces*
- *AMS data show organics have greater tendency to condense on soot-mode particles*

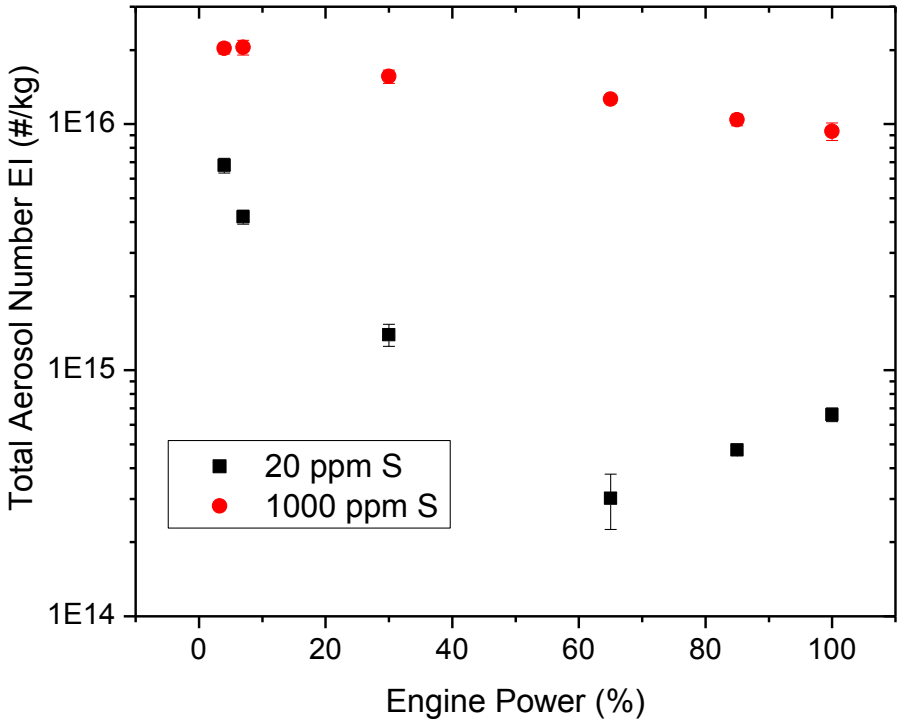
Volatile PM Mass EI depends on Ambient Temperature

DC-8 CFM56 engine emissions while burning JP-8 fuel with 700 ppm S



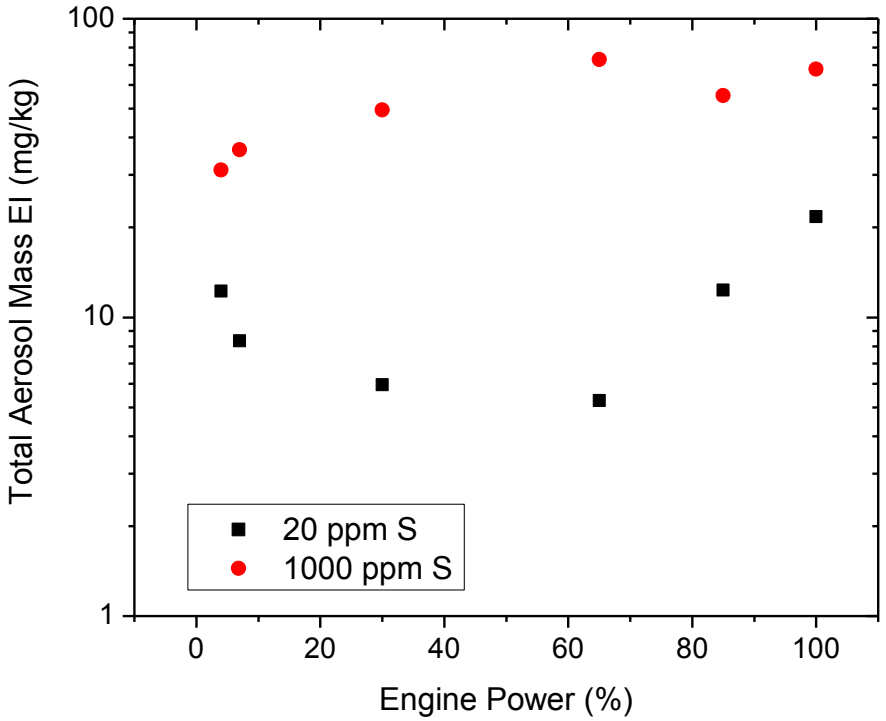
AAFEX-I Results

0.5 to 2% of Fuel S Oxidized to Sulfate in Exhaust

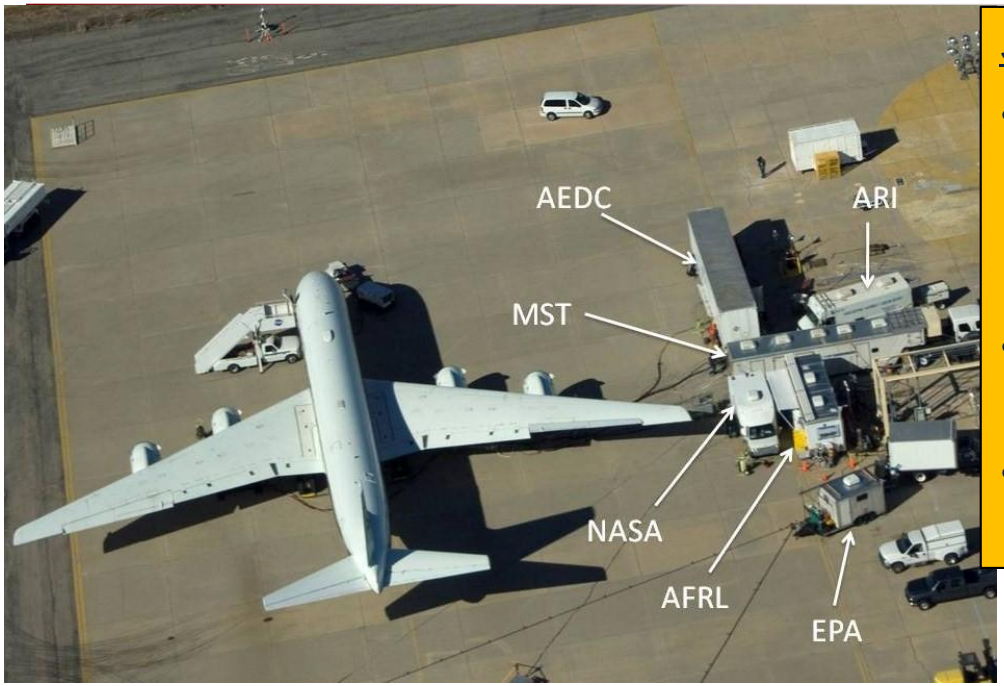


Relatively high ambient temperature suppressed volatile formation, but difference still profound

40 mg/kg ~ 1% S(IV) conversion to S(VI)



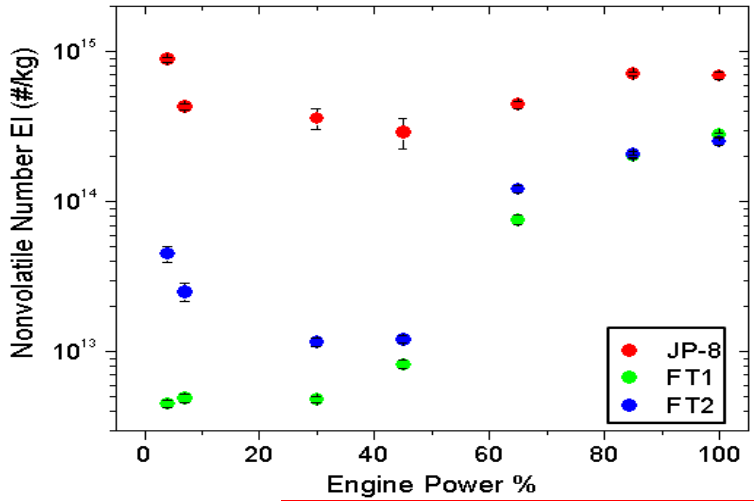
AAFEX-1 Demonstrated Alt Fuel Emission Reductions

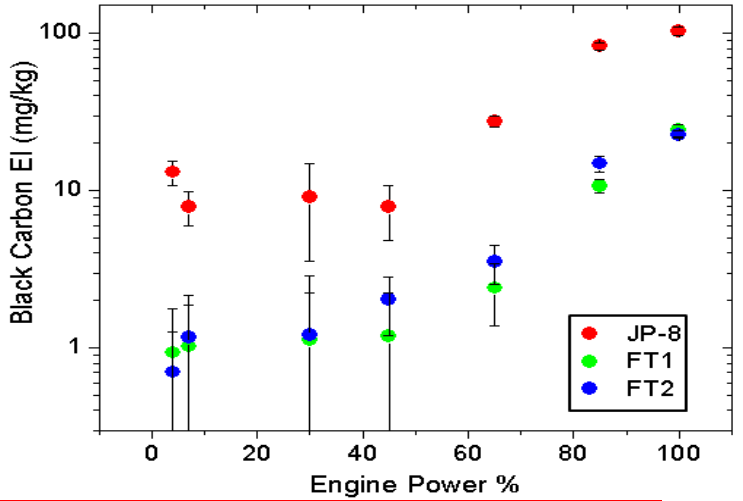


Summary

- *Studied emissions from DC-8 CFM56 engines while burning JP-8 along with natural gas and coal-based Fischer-Tropsch fuels*
- *Data recorded at 6 thrust levels for pure fuels and 50:50 blends with JP-8*
- *Measurements made at 1, 30 and 143-m behind engines*

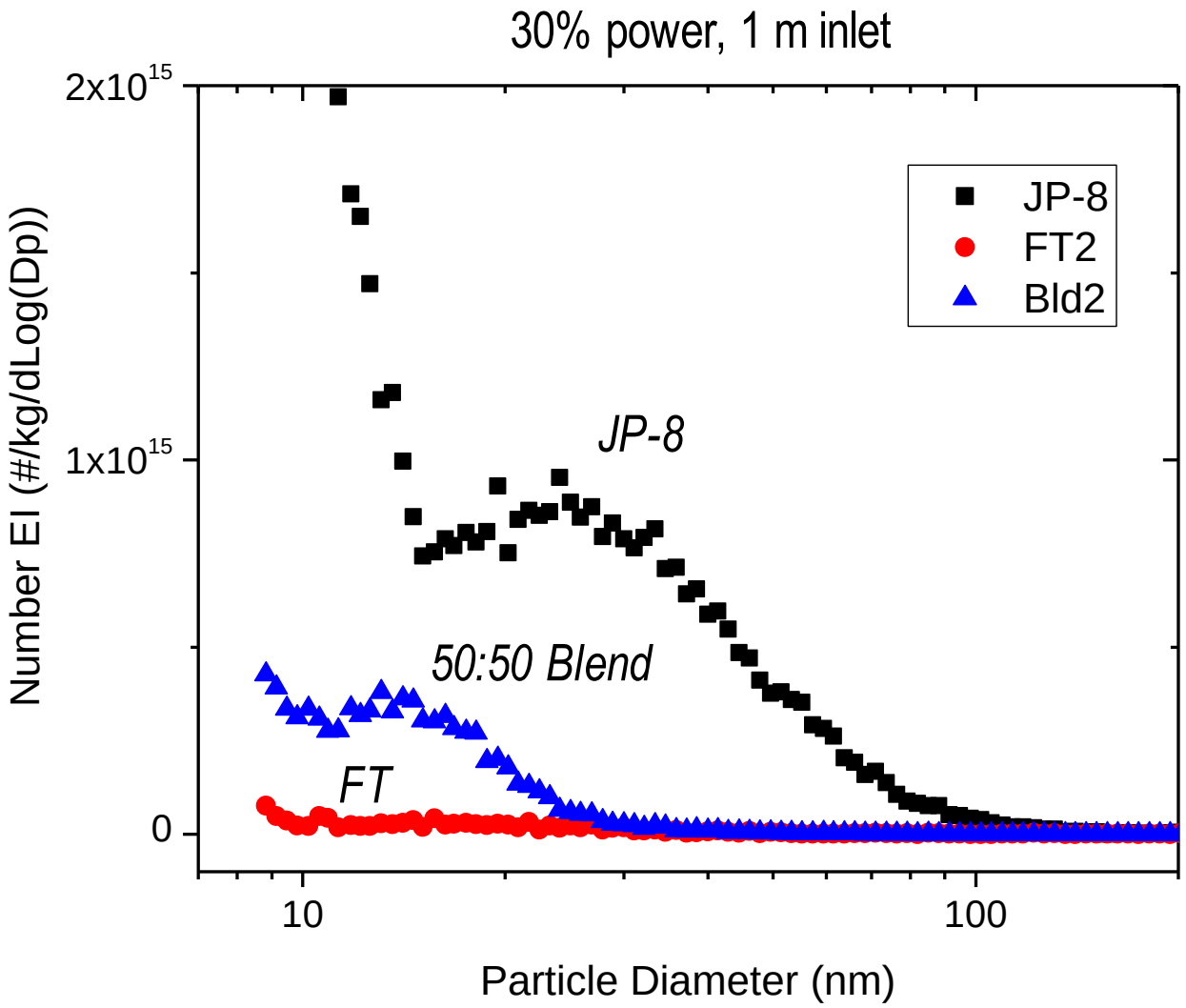
Anderson et al., NASA/TM-2011-217059, 2011





Huge nvPM Emission Reductions Seen when Using Alt Fuels

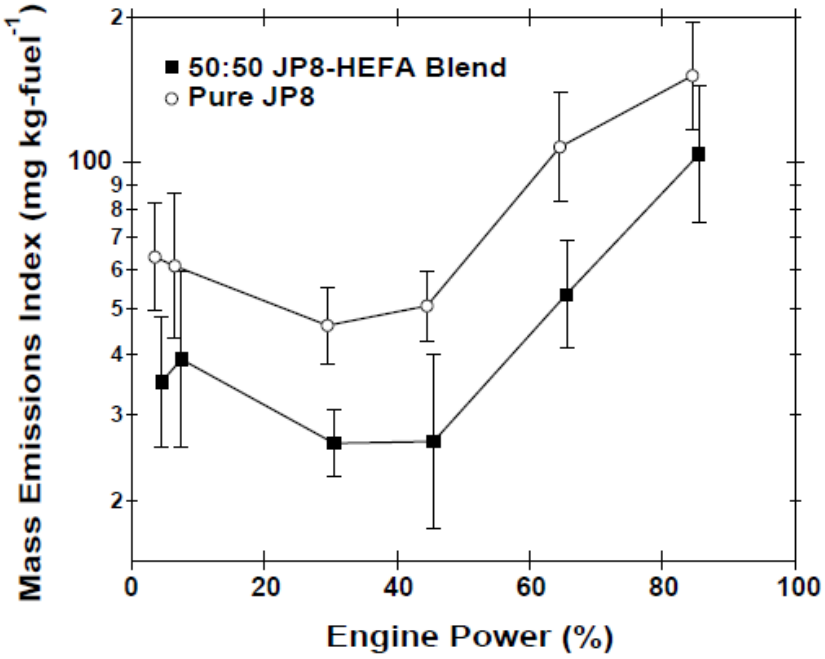
Lack of Aromatics Reduces nvPM Size



AAFEX-I Results

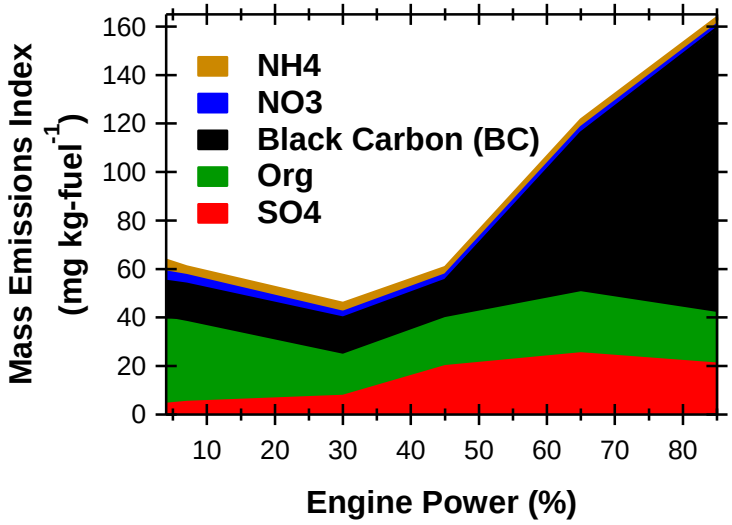
Reduced particle size leads to greater reductions in mass than in number EI

Fuel blending reduces overall particle mass emissions index by 30-50%, both soot and SO4 mass are decreased by two-fold.

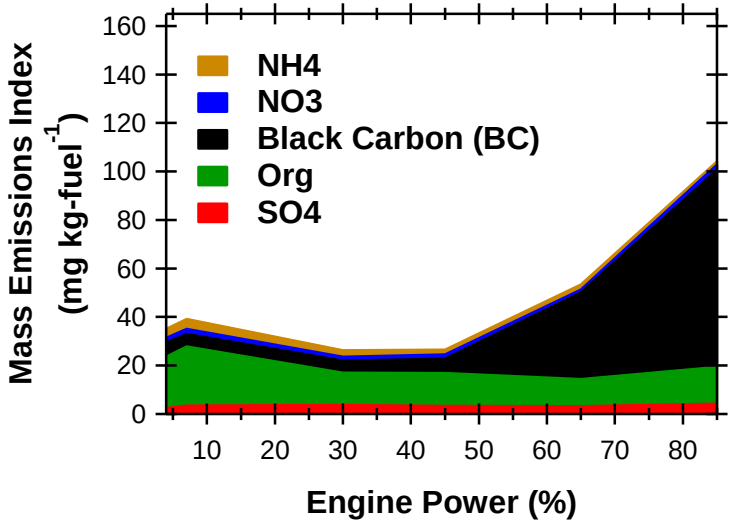


ACCESS-1 Results

Pure JP8:



50:50 JP8-HEFA Blend:

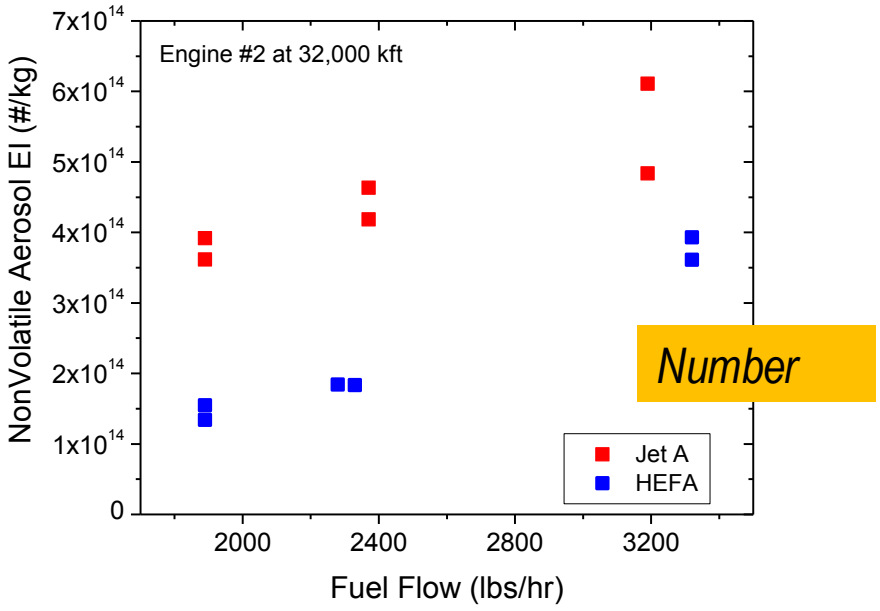


Ground Data

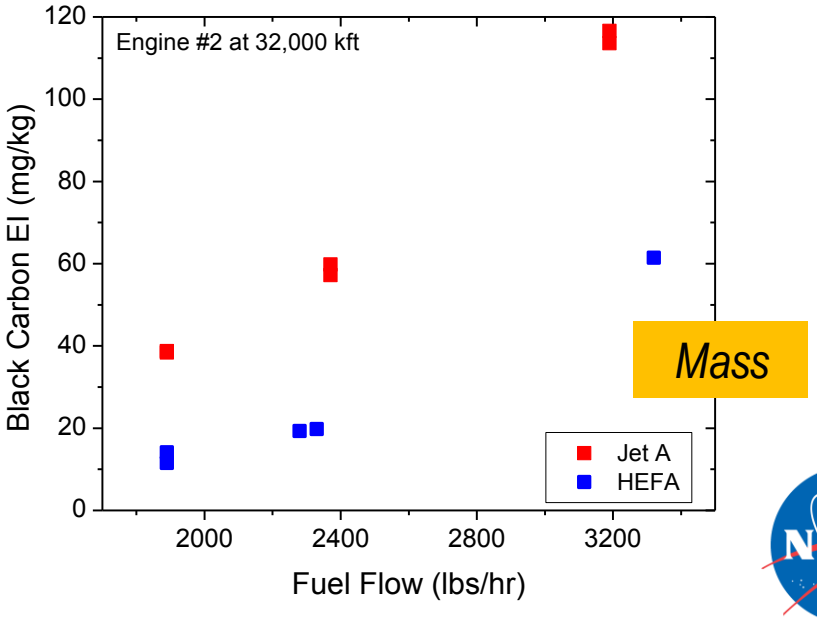
ACCESS-2 Demonstrated Alt Fuel Emission Reductions at Cruise

See Moore et al., NATURE, 543, 411-415, 2017

50:50 HEFA:Jet A Blend Reduces Black Carbon Number and Mass Emissions by 30 to 70% at Cruise



Number



Mass

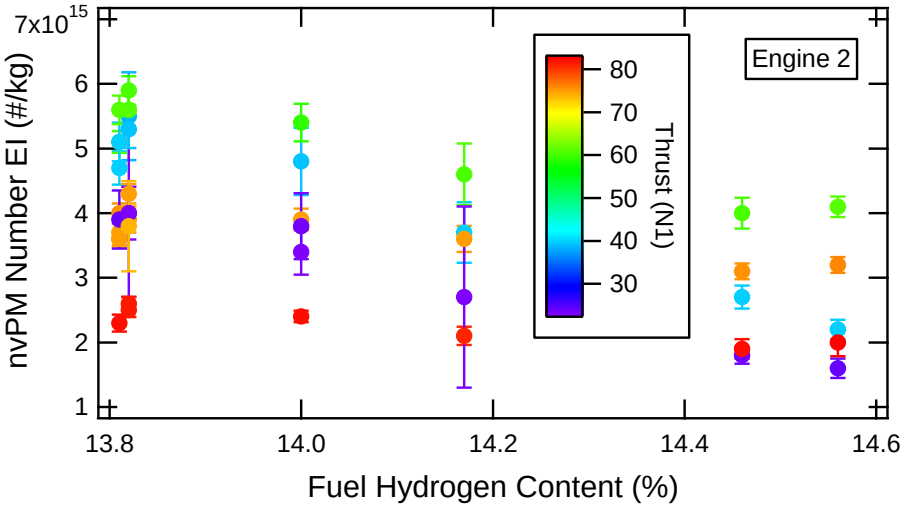
Emissions Decrease with Increasing Fuel H Content

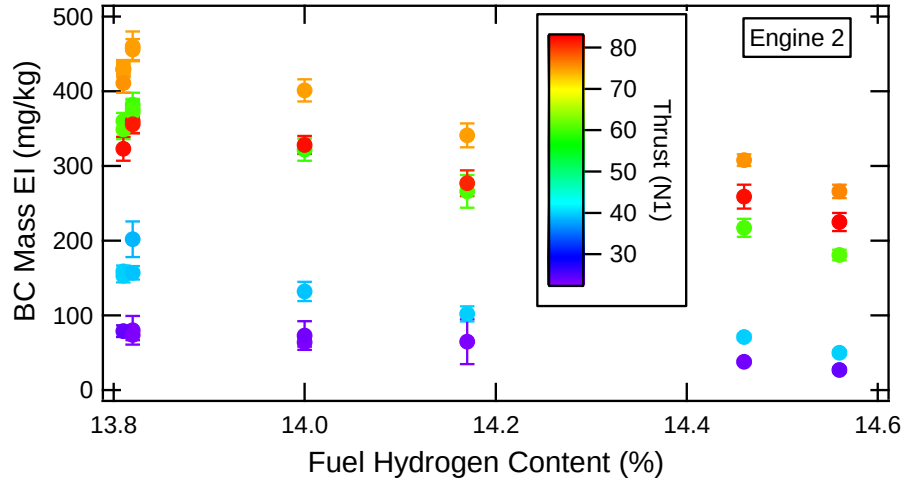
ECLIF-1 Experiment measured nvPM emissions from DLR A320 with IAE2527 engines in flight and during ground tests

DLR

Aircraft burned 6 different fuels with broad range of aromatic and hydrogen content

Papers and reports under development…..





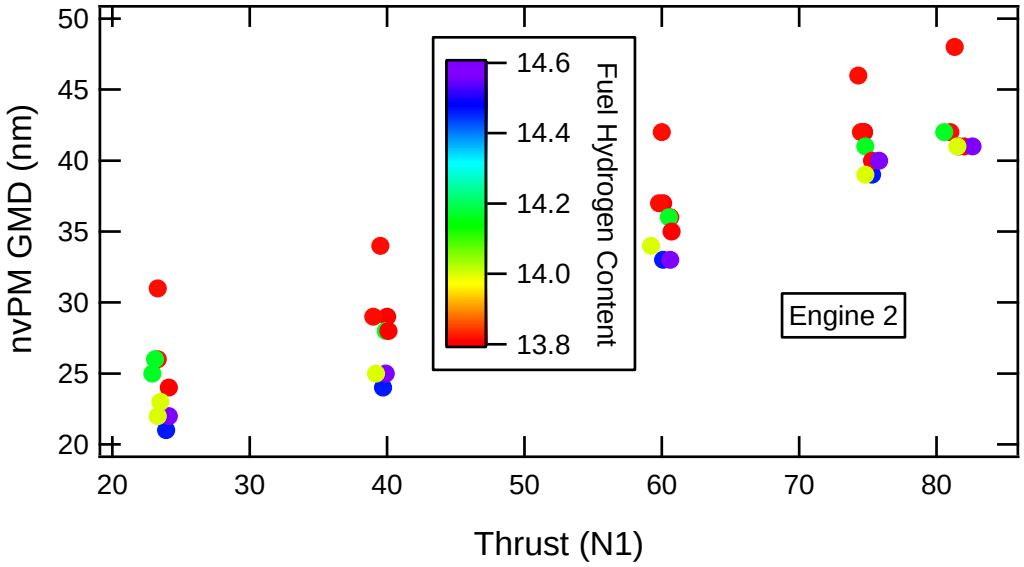
Ground-based measurements show nvPM number and mass anti-correlated with fuel H content

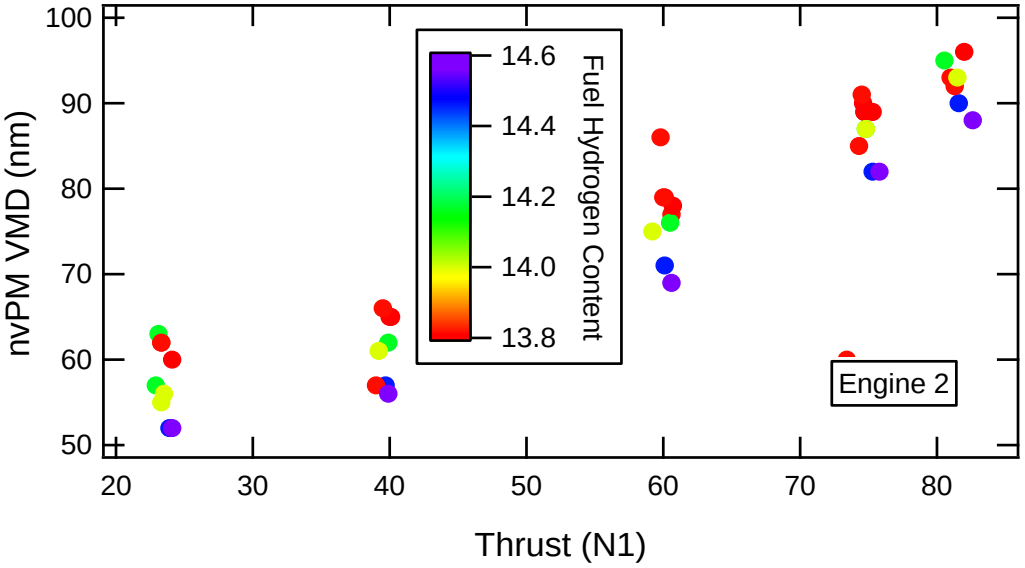
nvPM Size also Decreases with Increasing Fuel H Content

ECLIF-1 Experiment measured nvPM emissions from DLR A320 with IAE2527 engines in flight and during ground tests

Aircraft burned 6 different fuels with broad range of aromatic and hydrogen content

Papers and reports under development…..





Summary

- Aircraft Typically Emit 10^{14}-10^{15} nvPM per kg fuel burned during both ground and flight operations
- nvPM mass emissions range from 1 to 100 mg/kg fuel burned
- nvPM GMD and VMD range from 15-35 nm and 30 to 80 nm
- Volatile PM form rapidly in engine exhaust and typically outnumber soot by 10 to 1 in aged plumes
- ~0.5 to 2% of fuel S oxidized to form volatile PM
- Alternative fuels greatly reduce both nvPM and total PM emissions because of reduced aromatic and sulfur contents
- nvPM reductions anti-correlated with fuel Hydrogen content
- Low aromatic fuels produce smaller nvPM; combined with lower number, could significantly alter contrail ice number and size.

Questions?

Future Work: Emission and Climate Impact of Alternative Fuel—ECLIF-2, January-February 2018