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Center of Excellence for Aerospace Particulate Emissions Reduction Research

Inter-comparisons of PM Emissions from CFM56 Engines Burning Bio-, FT and Conventional Fuels

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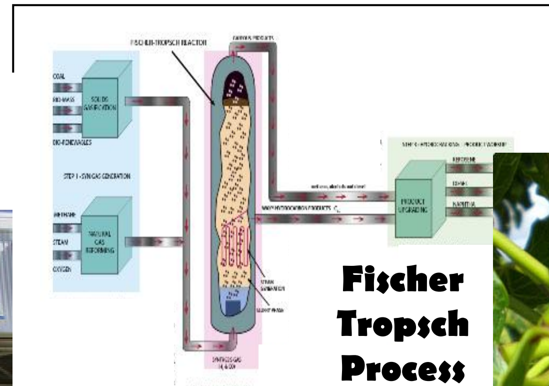
and Prem Lobo
Missouri University
of Science and Technology

Particles Meeting 16 March 2009

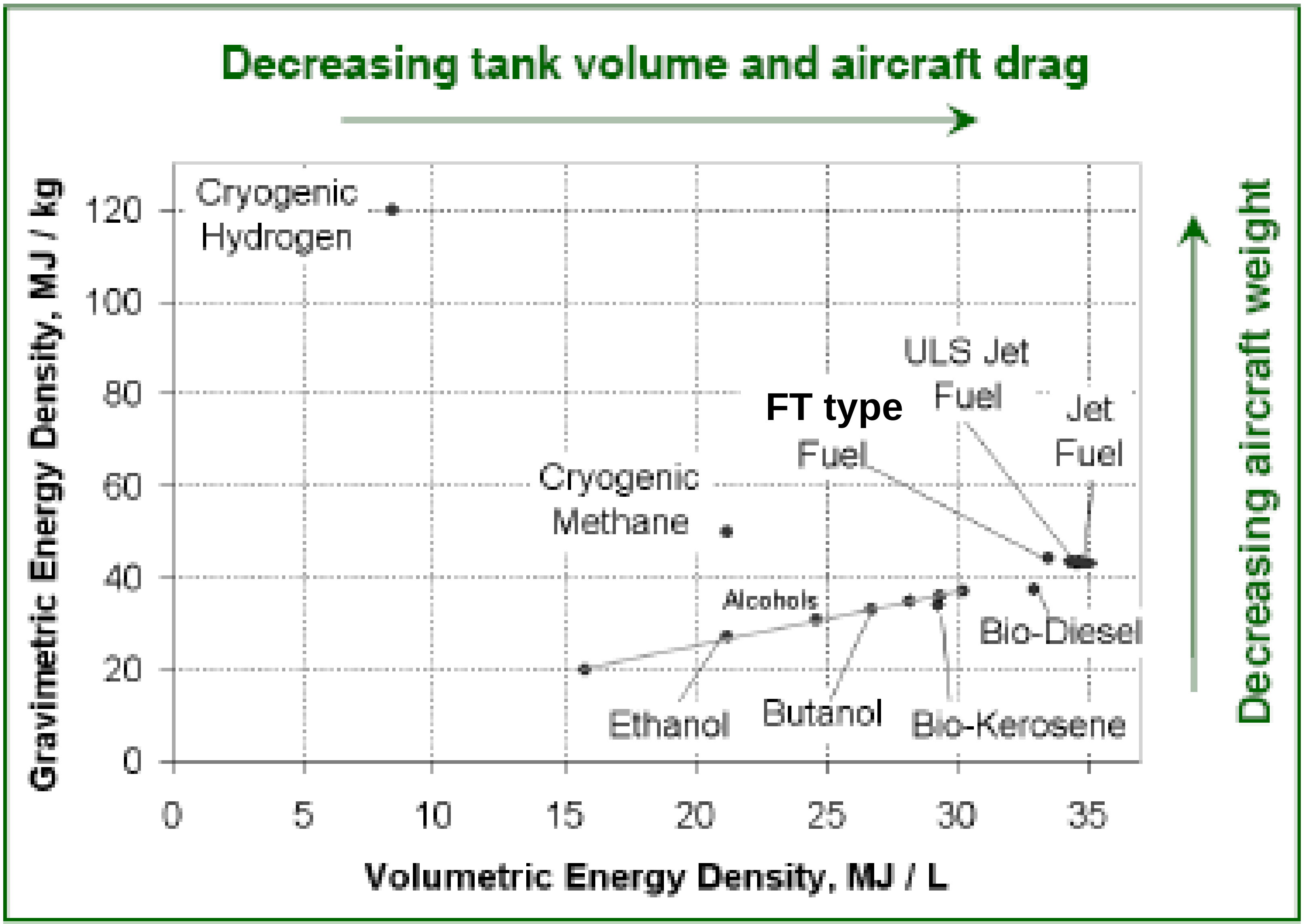
University Engineering Department, Cambridge U.K.

Alternative Aviation Fuels

Continental Airlines uses biofuel on test flight Los Angeles Times



http://www.continental.com/web/en-US/content/company/globalcitizenship/environment.aspx


Decreasing tank volume and aircraft drag
Decreasing aircraft weight
Gravimetric Energy Density, MJ / kg
Volumetric Energy Density, MJ / L
0
20
40
60
80
100
120
0
5
10
15
20
25
30
35
Cryogenic Hydrogen
Cryogenic Methane
FT type Fuel
ULS Jet Fuel
Jet Fuel
Alcohols
Bio-Diesel
Ethanol
Butanol
Bio-Kerosene

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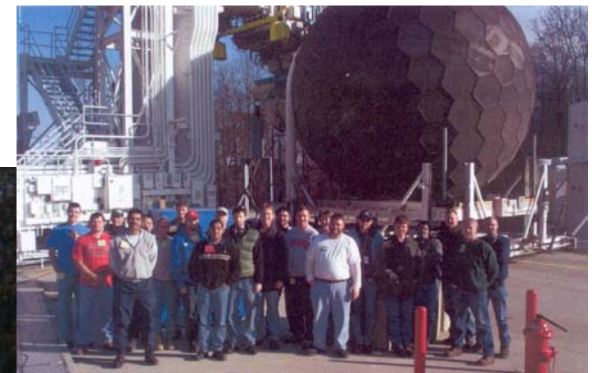
imagination at work

Virgin atlantic



Jet A, Jet A-1
FT fuel
Bio-fuel (FAME)
Blends

GE Test Facilities Ohio Dec 2007

Alternative Fuels Test Team

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CFM / GE (Engine Test)
Art Johnson (CFM ESD&I)
Bruce Mills (CFM)
Will Dodds (GE Combustion/Emissions)
Tim Held (GE Combustion - Fuels)
Dan Oehrle (CFM ESD&I)
Jerry Juenger (CFM ESD&I)
John Aicholtz (Advanced Tech)
Rick Keach (CFM ESD&I - Operability)
Dave Harris (Evaluation / Test)
Jim Girton (Test Engineering)
Jerome Friedel (CFM-Snecma)
Russ Arey (GE Test -Emissions)

Wright Patterson AFB (Emissions, Fuels)
Tim Edwards
Edwin Corporan

FAA (Biofuels Development)
Carl Ma

Boeing (Biofuels Development)
David Daggett
Steve Baughcum

Aerodyne Research, Inc. (Emissions)
Rick Miake-Lye

Missouri U. of Science & Tech (Emissions)
Phil Whitefield
Prem Lobo

Fuel blends tested and Data Types Acquired

Fuel ID	Alt. Fuel	Base-Fuel	Source	Tested Fuel	Amb Temp (F)
0	None	Jet A	GE	Jet A	28
1	None	Jet-A1	GE	Jet-A1	41
2	Ester	Jet-A1	Boeing	20% Ester / 80% Jet-A1	28
3	Ester	Jet-A1	Boeing	40% Ester / 60% Jet-A1	29
4	F-T	Jet-A1	Air Force,	50% F-T / 50% Jet-A1	31
5	F-T	None	Air Force,	100% F-T	31

PM emissions: Total conc, size distributions {Dp_j, $dN/dlogDp_j$}
Dgeom, DgeomM, Sigma, EIn, EIm Black carbon mass (MAAP)
Composition (AMS) Organic, Sulfate (Nitrate)
Size distribution of volatile component
**** No near field plume data

Gas emissions: CO, HCHO, Speciated HCs NO, NO_2, NO_x

Measured Fuel Properties

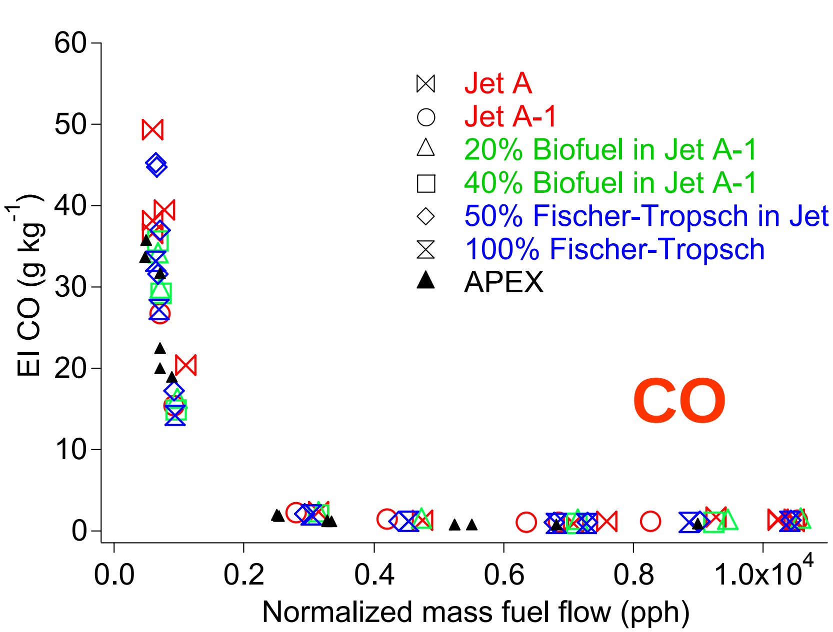
Fuel ID#	FUEL	Specic Gravity @ 15C	Heat of Combustion - LHV (kJ/kg) Btu/lb	Heat of Combustion - LHV (kJ/kg) Btu/lb	Kinematic Viscosity @ -20 deg C mm^2/s	Kinematic Viscosity @ -20 deg C mm^2/s	Kinematic Viscosity @ 100F	Lubricity-BOCLE wear scar (mm)	Thermal Stability Test @260C (tube/delta P)
		MEASURED FUEL PROPERTIES							
1	Jet-A1	0.797	43300 (18620)	(43523) 18715	4.2	4.27	1.31	N/A	1/0
2	20% Ester / 80% Jet-A1	0.808	42000 (18060)	(41600) 17888	5.1	4.74	1.41	0.51	1/0
3	40% Ester / 60% Jet-A1	0.825	40300 (17330)	(39633) 17042	n.a	5.62	1.55	0.53	1/0
4	50% F-T / 50% Jet-A1	0.776	43600 (18750)	(43737) 18807	4.7	4.4	1.33	0.57	1/0
5	100% F-T	0.755	44100 (18960)	(44126) 18974	4.7	4.65	1.36	0.56 (has CI/LI)	1/0
	Fuel Spec	0.78-0.82	42860 - 43500	42860 - 43500	2.5 - 6.5	2.5 - 6.5	N/A	<0.85 (fuel w/o CI/LI)	<3/<25
	Measurement Group	Air Force AFRL	Air Force AFRL	GE Aviation	Air Force AFRL	GE Aviation	GE Aviation	Air Force AFRL	Air Force AFRL

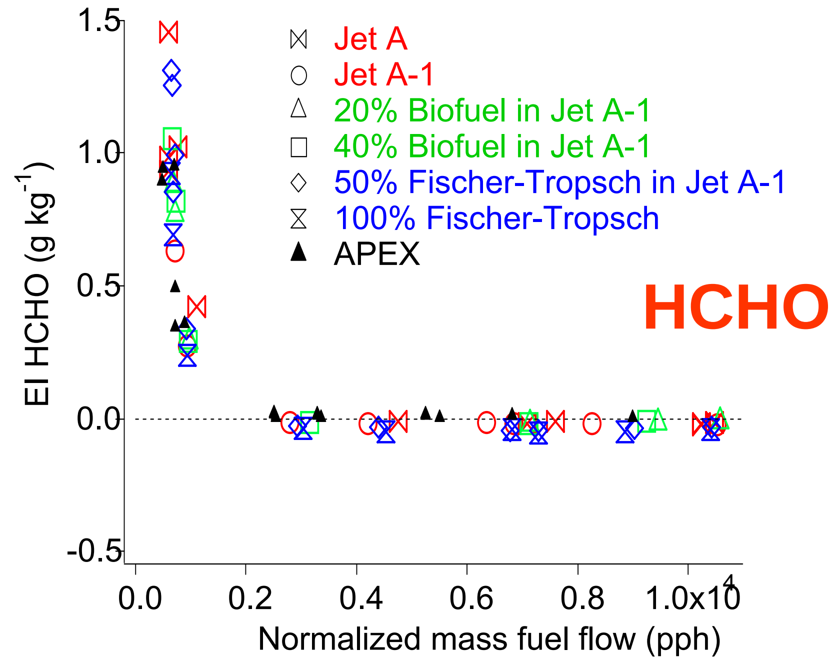
Fuel flow is a surrogate for engine power setting

Fuel flow has to be corrected to account for different heats of combustion

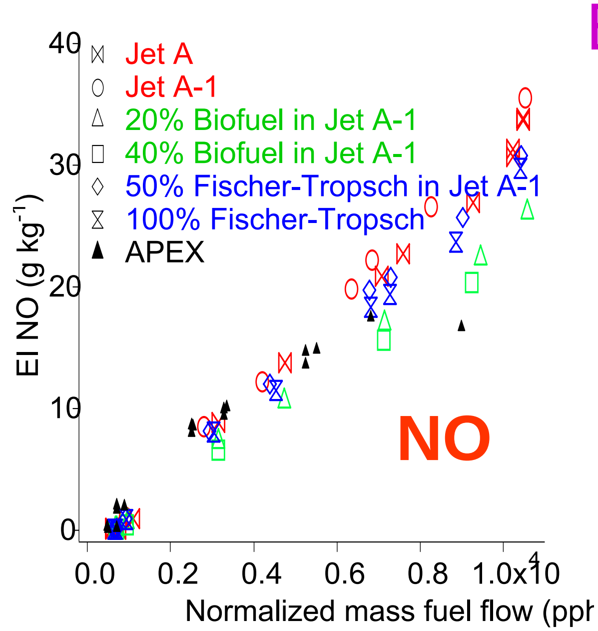
Ester fuels are not expected to see commercial aviation use, but were tested as they were readily available at the time of the engine test. Ongoing industry plans for use of bio-derived jet fuels include the hydrotreating/hydrocracking of plant and other bio-derived oils. Properties of such biojet fuels are expected to be similar to Fischer-Tropsch fuels.

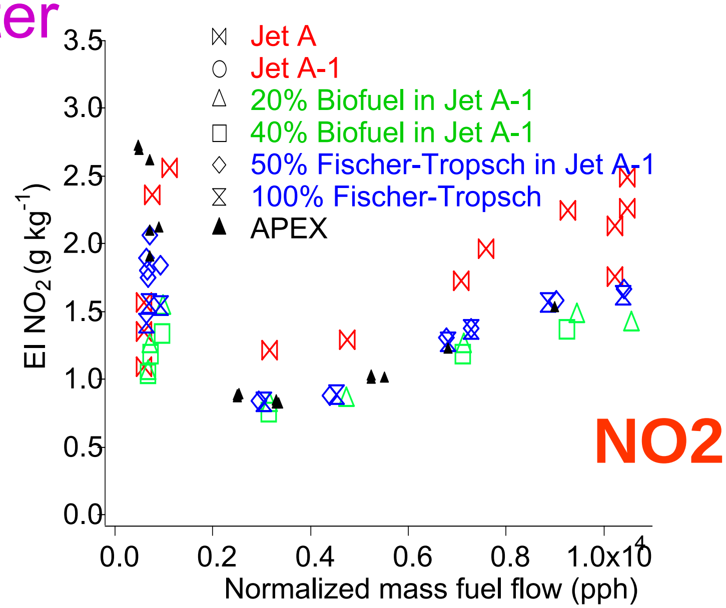
Emissions Representativeness cont.





Biofuel = Ester





Emissions Representativeness

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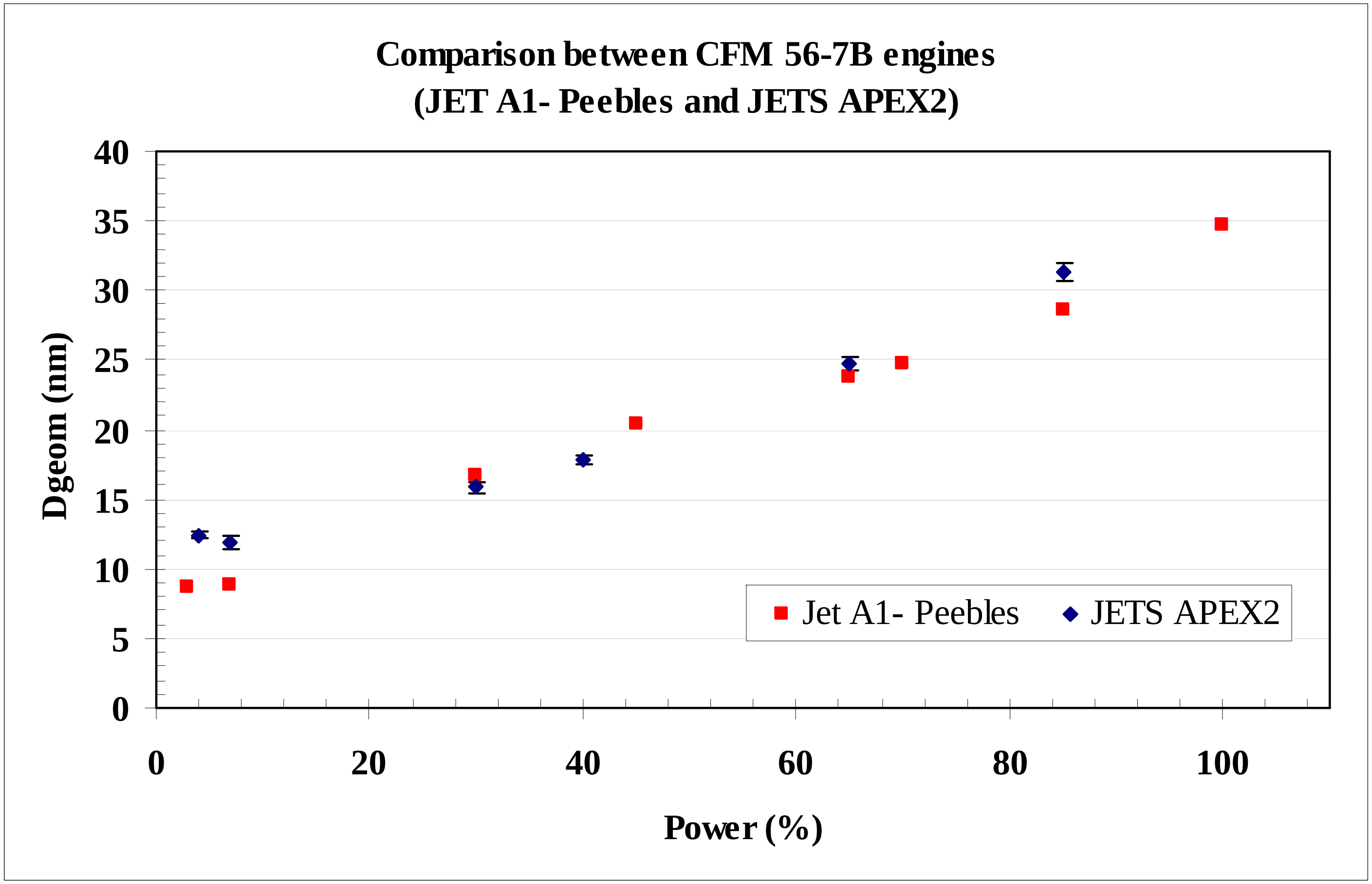
- Data from this test was compared to that from the same engine type investigated during the JETS APEX2 campaign

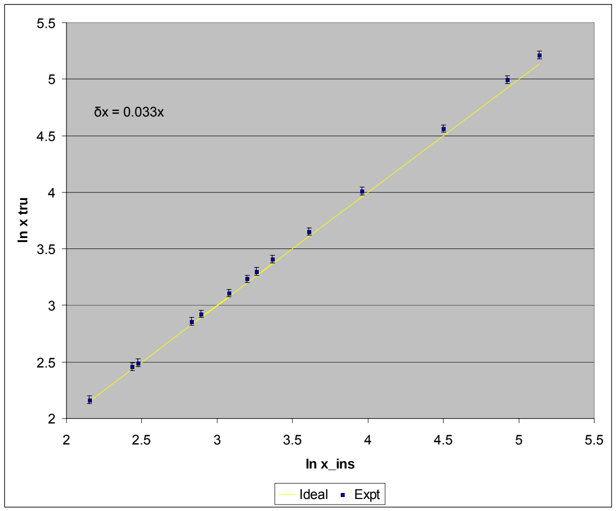


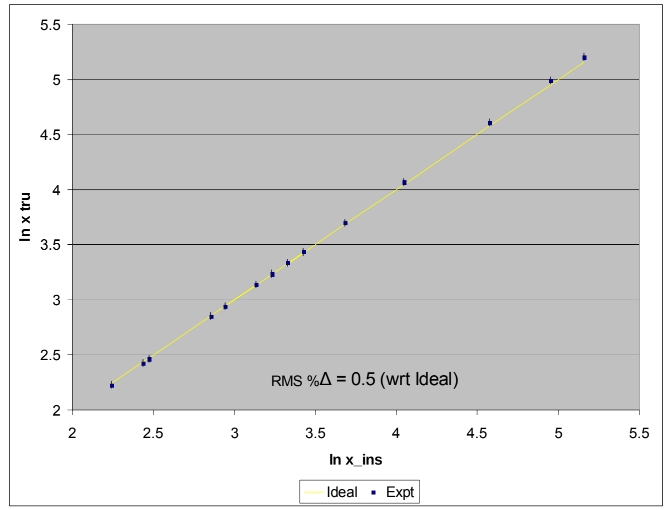
Summary

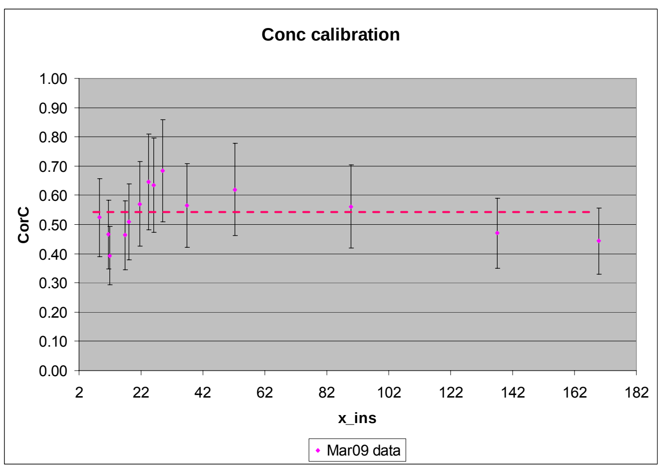
- Gaseous emissions performance:
  - very similar to APEX
  - Independent of fuel
  - Perhaps small changes in $NO/NO_2/NO_x$ for Ester
  - ***Exception***
  - speciated HCs distinct for alternative fuels: especially aromatic HC emissions

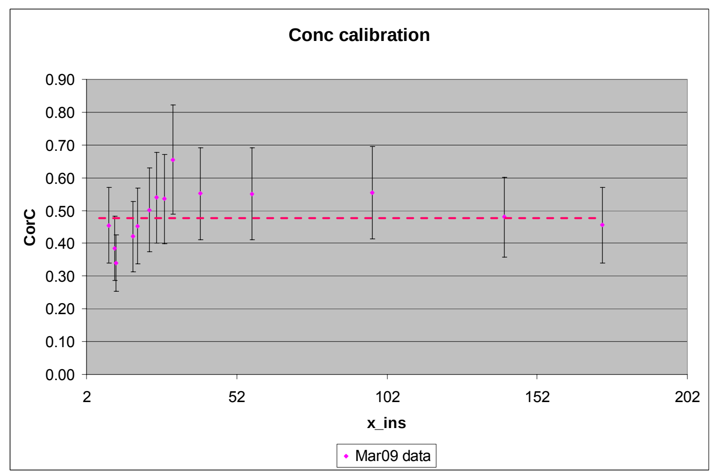
Particulate Emissions

Size and number calibrations for DMS 15 and 21

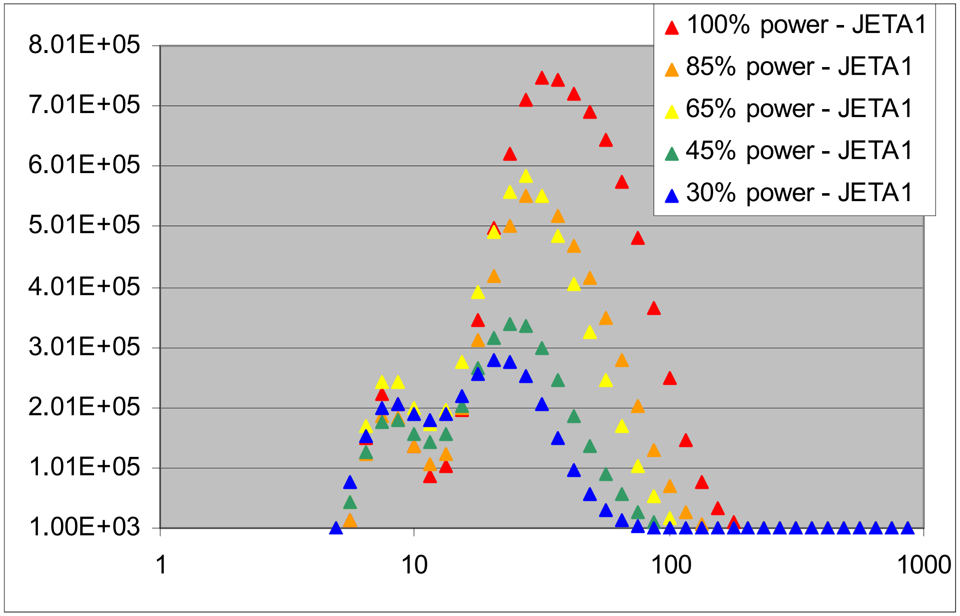


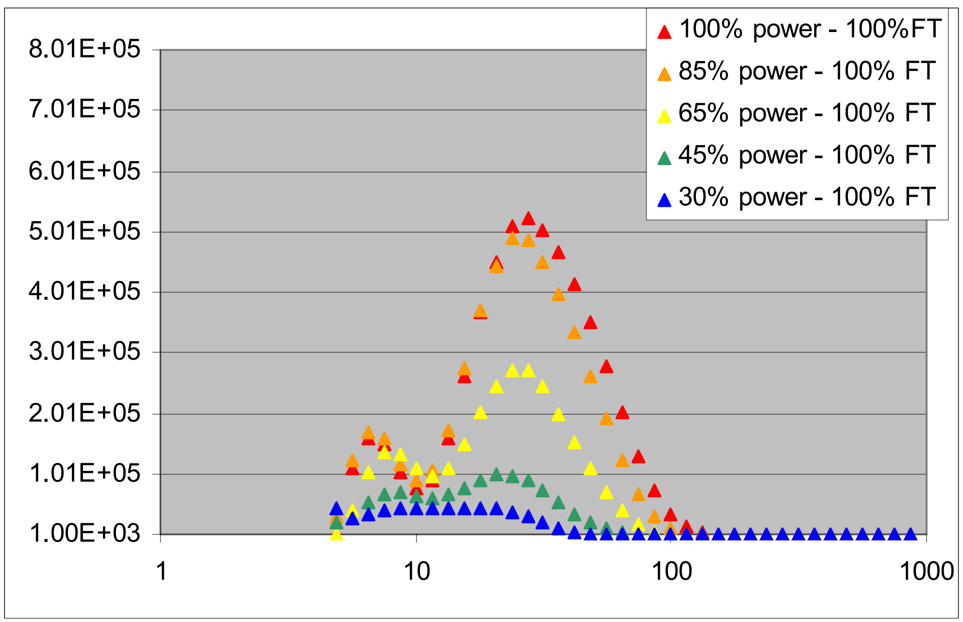




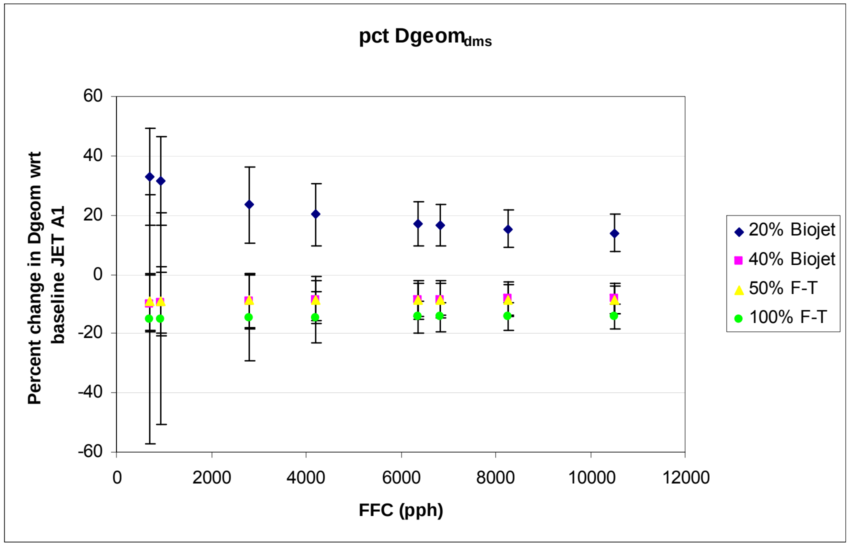


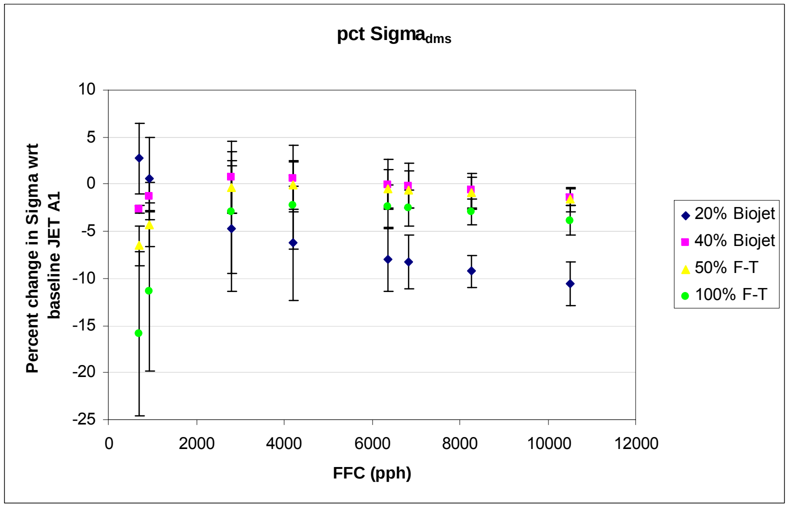
Total PM Emission Size Distributions for Jet A1 and 100% FT at 30, 45, 65, 85 & 100% Engine Power Settings

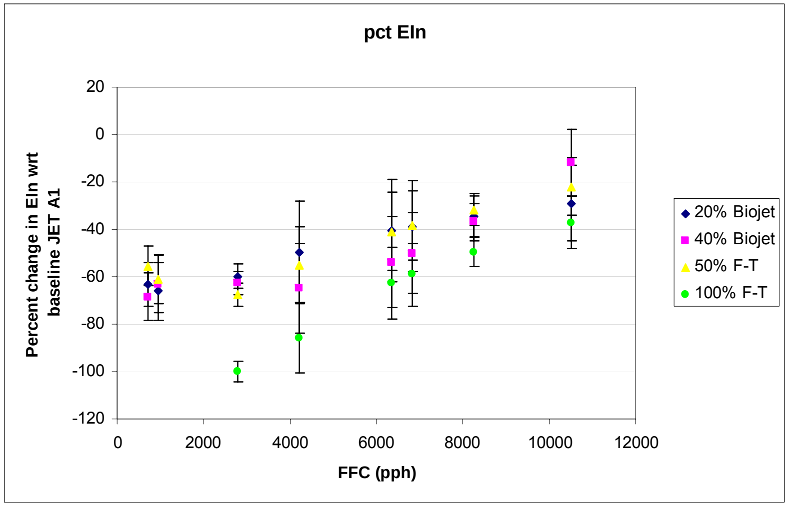


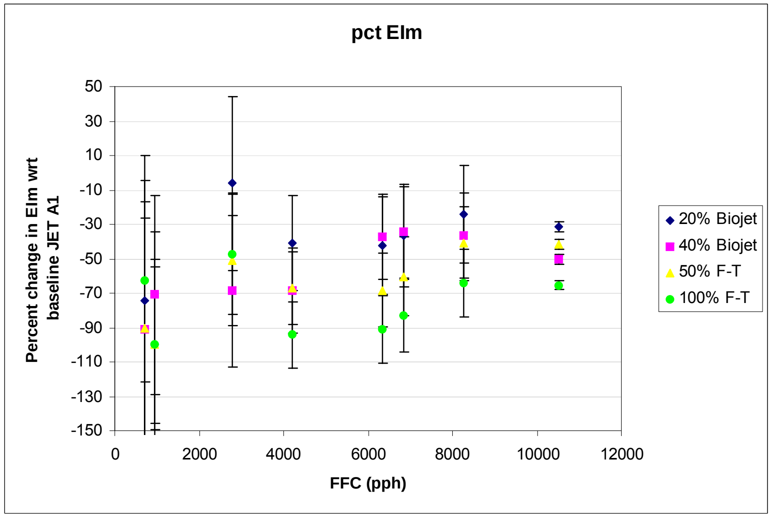


% Change in PM emission parameter vs fuel flow for all fuels and blends studied









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Composition (AMS) Organic, Sulfate (Nitrate)
Size distribution of volatile component

Gas emissions: CO, HCHO, Speciated HCs NO, NO_2, NO_x

Temperature Effect

- Measurements with Jet A1 were made at 41F; all other measurements ~ 30F
- Are the differences in observed emissions characteristics due to fuel change, temperature change or a combination of both?

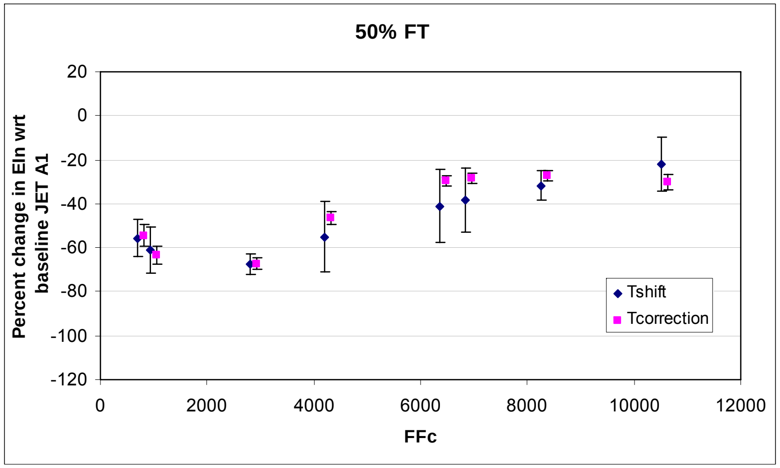
Impact estimation

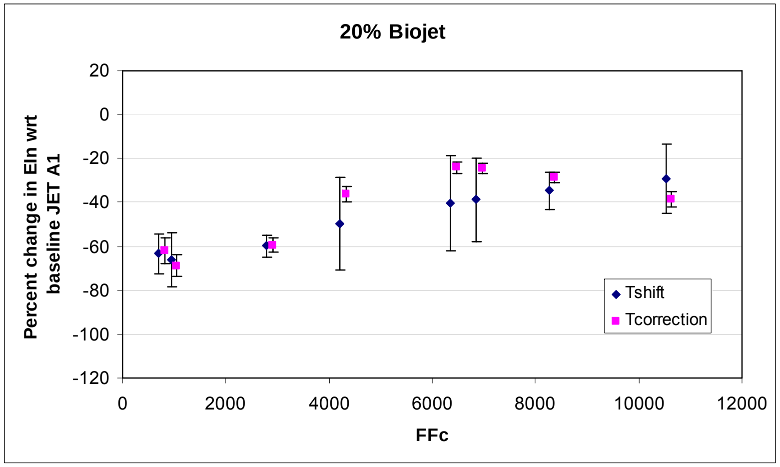
- Compare Jet A to Jet A1 measurements to estimate temperature effects on emissions

Methods employed to address estimated temperature effects

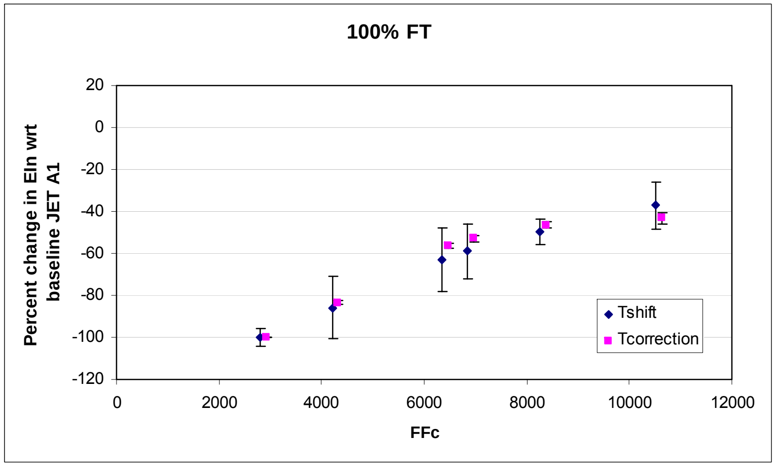
- Increase % change confidence levels to account for possible shift in reference Jet A1 emission characteristics due to temperature change
- Treat Tshift as a T-correction for the reference Jet A1 data and correct the Jet A1 reference data to the blend measurement temperature.

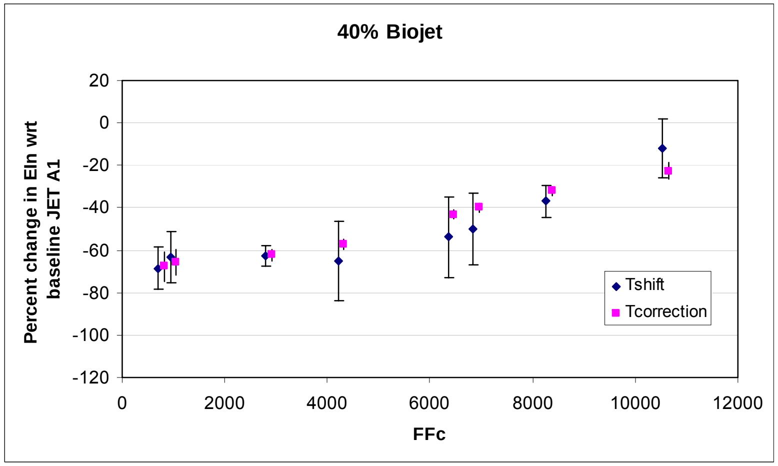
Temp. correction –v- Temp. shift





Biojet = Ester



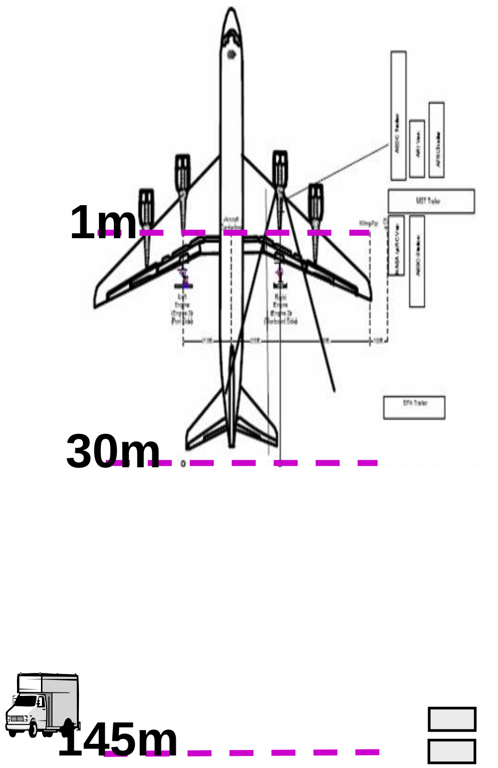


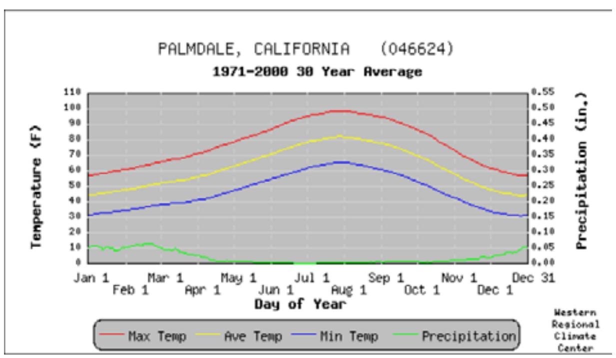
For ease of comparison, the data points for Tcorrection are offset from those of Tshift

Summary

- **There is a statistically significant reduction in the number and mass-based emission index with all fuel blends – e.g. an average between 50-60% for EIn.**
- **For all blends, the greatest percent reduction is observed at low fuel flow rates**
- **100% FT fuel yields the lowest emissions (consistent with previous studies – Corporan et al., 2007)**
- **Black carbon reduced**
- **Corresponding reductions in organic PM**
- **Background sulfate (& nitrate) contribute to emissions at idle, but sulfate contributions minimal at higher powers for engine exit plane, as expected**
- **Near-field plume data would shed more light on volatile PM emission amounts**
- Alt. fuels and their blends show promise as candidates for PM emission reduction particularly during low power operations thereby justifying continued study of these and other candidate fuels.

AAFEX –Alternative Aviation Fuels Emissions Experiment





AAFEX Plan

Summary of AAFEX Plan

Location: NASA DFRC/Palmdale Facility (near Skunkworks)

Time: Mid January 2009

Aircraft: DC-8, right inboard CFM-56 engine

Fuels (6):
*Standard Jet A
*FT (Natural Gas) + 50/50 Jet A blend
*FT (Coal) + 50/50 Jet A blend
*Biofuel + 50/50 Jet A blend

Runtime: ~5 hours per pure fuel, 2.5 hours per Blend
25 – 30 hours total

Duration: 5 days setup, 10 days testing

Daily Sched: 4 am – 2 pm (night/day tests for each pure fuel)

AAFEX Objectives

1) Examine the effects of alternative fuels on the performance (temperatures, pressures, thrust, etc.) and primary emissions (certification gases, HAPS, black carbon) of a representative commercial jet engine
2) Investigate the effects of engine power, fuel composition, and ambient conditions on volatile aerosol formation and growth in aging aircraft exhaust plumes
3) Establish aircraft APU emission characteristics and examine their dependence on fuel composition
4) Evaluate performance of new instruments
5) Compare particle number, size, and mass emission measurements made by separate groups to establish expected range of variation between test venues

AAFEX Approach

- Use government owned commercial aircraft in order to gather data set that is free of proprietary restrictions
- Conduct experiment at outdoor facility where exhaust can be sampled at multiple points downstream of the exit plane; simulate airport conditions
- Use standard procedures for sampling/measuring gas-phase emissions
- Work with engine manufacturer to replicate engine operating conditions sampled during ICAO certification tests (i.e., idle, takeoff, climb, and approach
- Conduct duplicate experiments in early morning and at mid-day to sample emissions across a broad range of ambient conditions

Acknowledgements

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The Emissions of Alternative Aviation Fuels project is managed by Carl Ma.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the FAA, NASA or Transport Canada.