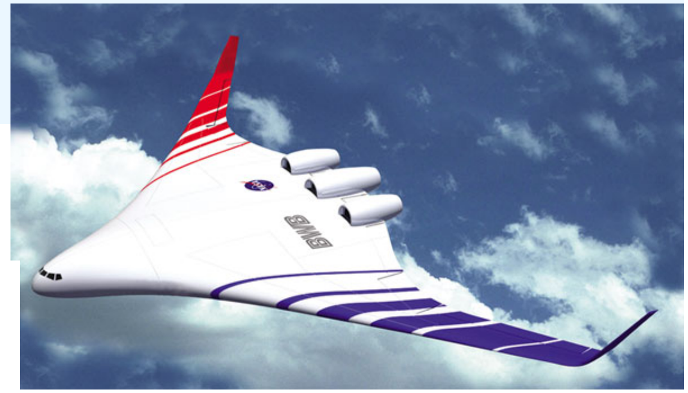
NASA Emissions Reduction and Alternative Fuels Research
UTIAS-MITACS 2nd International Workshop on Aviation and Climate Change



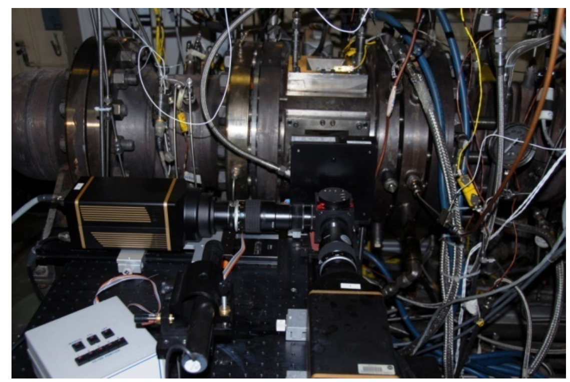
Dan Bulzan

Associate Principal Investigator, Subsonics Fixed Wing and Supersonic Projects

NASA Fundamental Aeronautics Program

May 27,28, 2010

Toronto, Canada



Objectives – Subsonics Fixed Wing

- Develop the necessary technologies to enable low emissions (gaseous and particulate) combustion systems to be developed for subsonic engine applications.
- Develop the fundamental technologies to assess the feasibility of alternative fuels in subsonic aircraft applications.
- Develop and validate physics-based models to enable quantitative emissions and performance predictions using Combustion CFD simulations.

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025)*** Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metroplex* concepts

*** Technology Readiness Level for key technologies = 4-6

** Additional gains may be possible through operational improvements

* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

SFW Approach

- *Conduct Discipline-based Foundational Research*
- *Investigate Advanced Multi-Discipline Based Concepts and Technologies*
- *Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes*
- *Enable Major Changes in Engine Cycle/Airframe Configurations*

Subsonics Fixed Wing
Combustion Discipline
Technical Approach

- NASA Research Announcement (NRA)
- Combustion Fundamental Research
  - Alternative Fuels
  - Fundamental Experiments
  - Physics-Based Model Development
- Combustion Technologies and Tool Development
  - Combustion CFD Code Development and Application
  - Low-emissions Combustion Concepts
- Multidisciplinary Analysis and Optimization

Supersonics
Technical Challenges

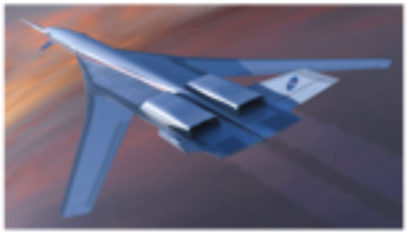
- Environmental impact of supersonic cruise emissions is greater due to higher flight altitudes which makes emissions reduction increasingly important.
- Accurate prediction tools to enable combustor designs that reduce emissions at supersonic cruise are needed as well as intelligent systems to minimize emissions.
- Combustor operating conditions at supersonic cruise are different than at subsonic cruise since inlet fuel and air temperatures are considerably increased.

Capability Metrics for Future Supersonic Aircraft NASA's Initial View

	N+1 Supersonic Business Class Aircraft (2015)	N+2 Small Supersonic Airliner (2020)	N+3 Efficient Multi-Mach Aircraft (Beyond 2030)
Environmental Goals			
Sonic Boom	65-70 PLdB	65-70 PldB	65-70 PLdB Low Boom flight 75-80 PldB Overwater flight
Airport Noise (cum below stage 4)	Meet with Margin	10 EPNdB	10-20 EPNdB
Cruise Emissions (Cruise NOx g/kg of fuel)	Equivalent to current Subsonic	< 10	< 5 & particulate and water vapor mitigation
Performance Goals			
Cruise Speed	Mach 1.6-1.8	Mach 1.6 -1.8	Mach 1.3 - 2.0
Range (n.mi.)	4000	4000	4000 - 5500
Payload (passengers)	6-20	35-70	100 - 200
Fuel Efficiency (pass-miles per lb of fuel)	1.0	3.0	3.5 – 4.5

N+1 "Conventional"

N+2 Small Supersonic Airliner



N+3 Efficient, Multi Mach Aircraft

Supersonics
Technical Approach

- NASA Research Announcement
- Emissions Prediction and Modeling
  - Physics-based model development for combustion CFD codes for improved supersonic cruise emissions predictions
- Diagnostics and Validation Experiments
  - Laser-based diagnostics development for quantitative major species and temperature measurements
  - CFD code validation experiments at supersonic cruise conditions
- Low Emission Concepts
  - Low NOx emission concept development
  - Active combustion control
- High Temperature Sensors
  - High temperature sensor development

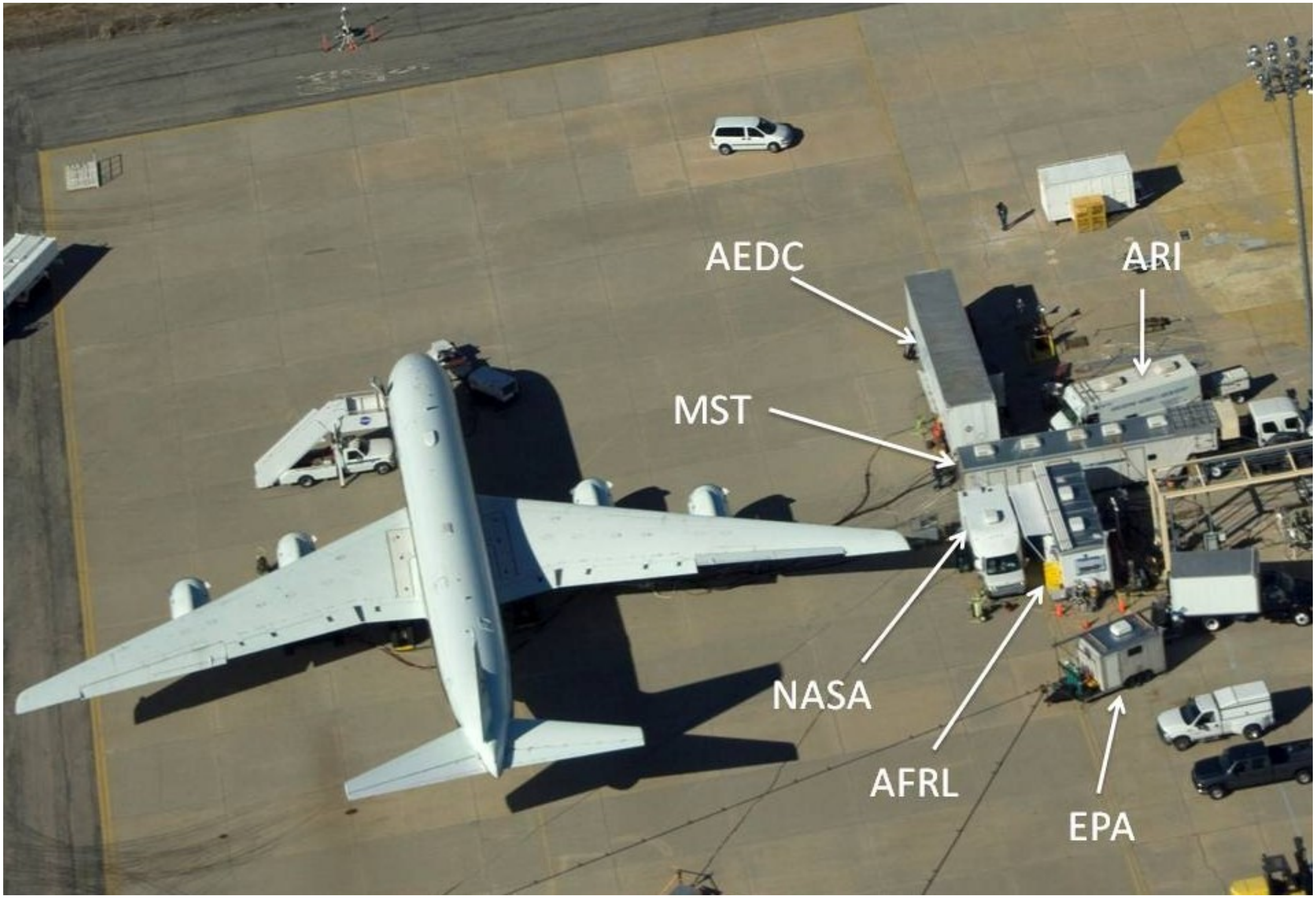
Alternative Aviation Fuel eXperiment (AAFEX) Objective

1) Examine the effects of alternative fuels on engine performance and emissions
3) Investigate the factors that control volatile aerosol formation and growth in aging aircraft exhaust plumes
4) Establish aircraft APU emission characteristics and examine their dependence on fuel composition
7) Evaluate new instruments and sampling techniques
8) Inter-compare measurements from different groups to establish expected range of variation between test venues

Summary of AAFEX Experiment Plan

Location:	**NASA Dryden Aircraft Operation Facility**
Dates:	**January 20 – February 3, 2009**
Sponsors:	**NASA, Air Force, EPA, FAA**
Aircraft:	**DC-8 with CFM56-2 engines**
Fuels:	**1--Standard JP-8** **2-- Fischer-Tropsch Fuel from Natural Gas (FT1)** **3--50/50 JP-8/FT1 blend** **4-- Fischer-Tropsch fuel from Coal (FT2)** **5--50/50 JP-8/FT2 blend**
Runtime:	**~35 hours total**

AAFEX Test Site Arrangement



Boeing, GE, Pratt and Whitney, CMU, Harvard, MSU, UCSD, and UTRC also participated

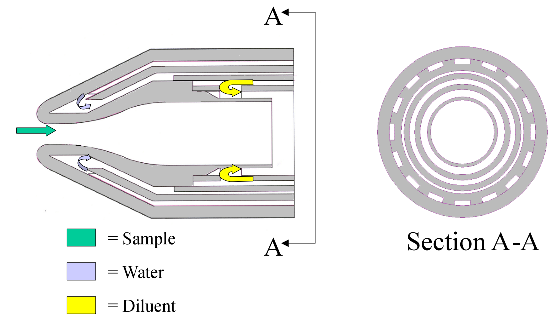
Primary Exhaust Measurements

- Certification species: CO_2, CO, THC, NOx and Smoke Number
- Hazardous Air Pollutants (HAPS): Acrolein, Benzene, etc.
- Green House Gases (CO2, CH4, H2O)
- Total Particle and Black Carbon Mass
- Particle Number Density and Size Distribution
- Single Particle Composition
- Bulk Aerosol Composition
- Black carbon morphology

Exhaust Sampled at Multiple Locations

Identical 1 and 30 m inlets behind left and right inboard engines

Complex Sampling Apparatus Used at 1-m



1-m rakes populated with gas, aerosol, pressure and temperature probes

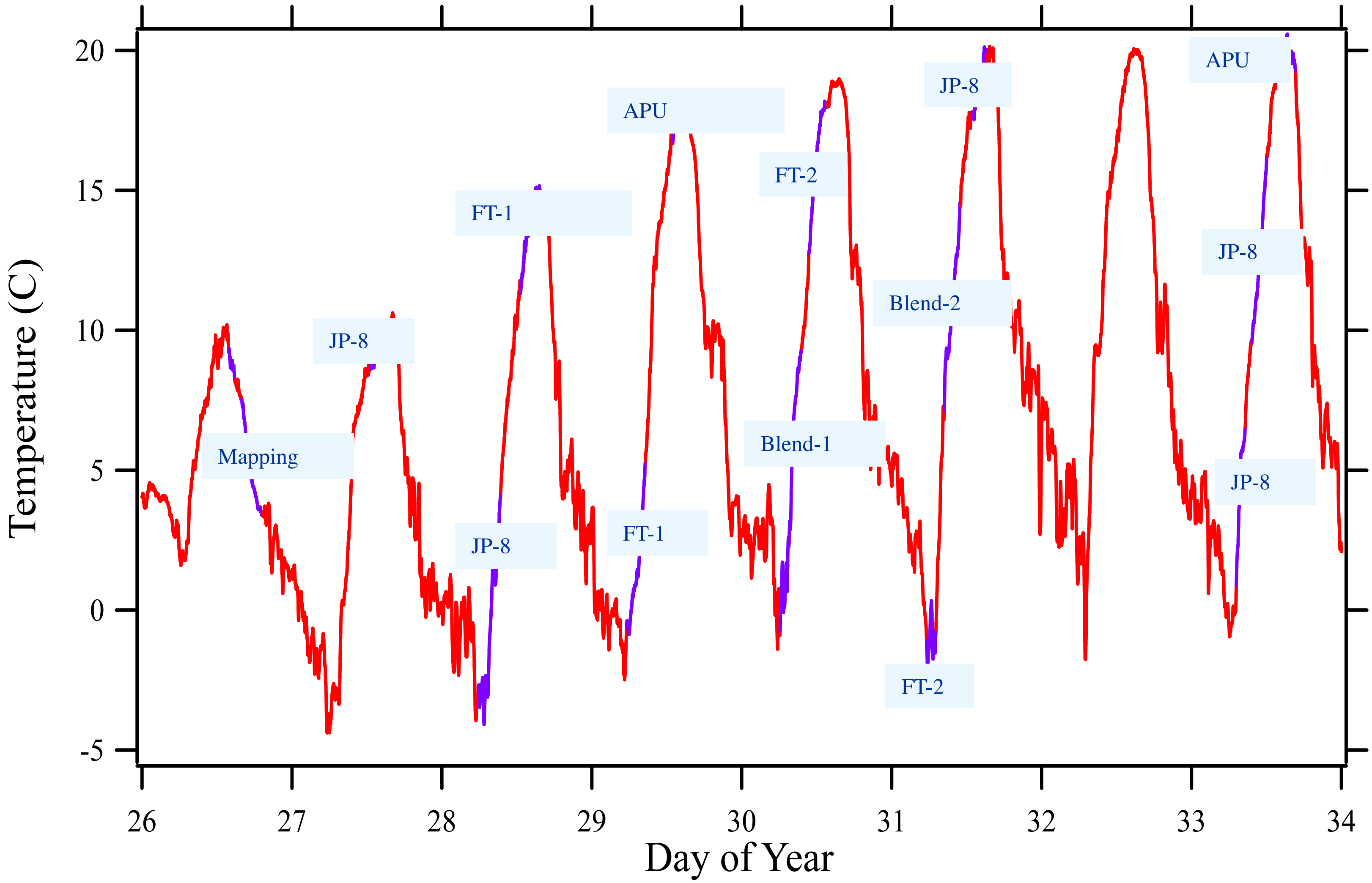
National Aeronautics and Space Administration

Plume Chemistry Studied with Van and 150m Trailer

Aerodyne van and downstream trailers equipped with sensitive particle and trace gas sensors

Van drove back and forth across exhaust plume at increasing distances as the aircraft was idling

Temperature Varied Widely During Tests



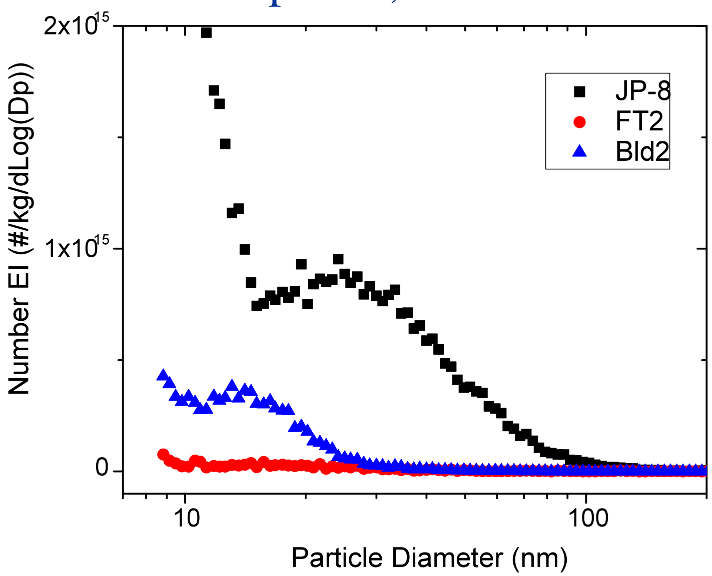
The experiment matrix included 13 engine and 3 APU test runs; burned >25,000 gallons of fuel in over 35 hours of testing.

FT Fuels Caused Fuel Leaks

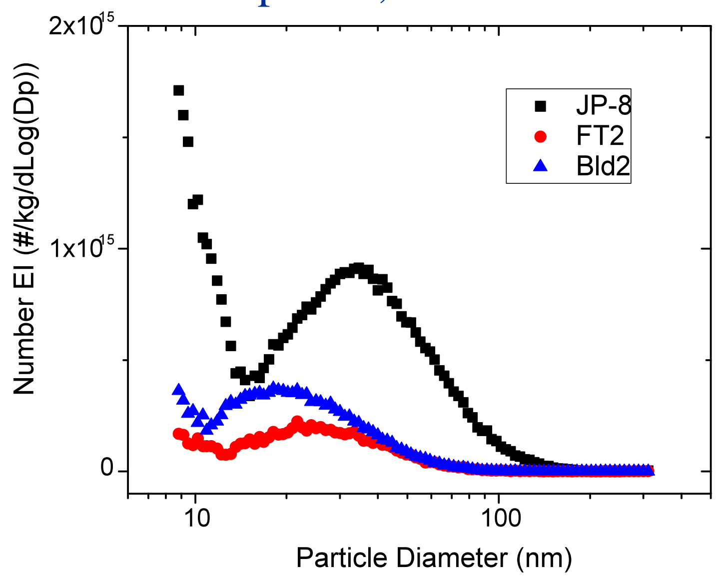
Leaks vanished as soon as aromatic-containing fuel introduced

FT Fuels Greatly Reduce Particle Emissions

30% power, 1 m inlet

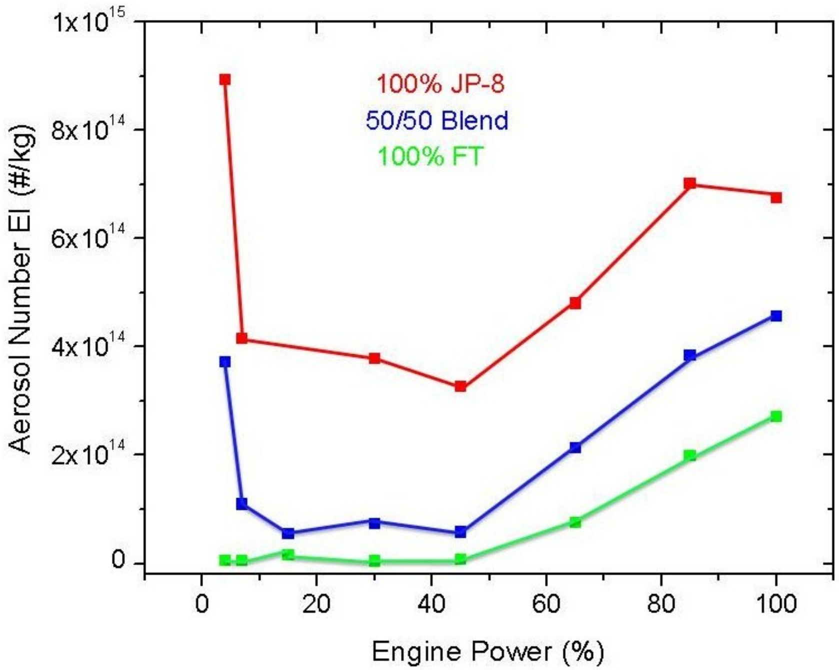


65% power, 1 m inlet



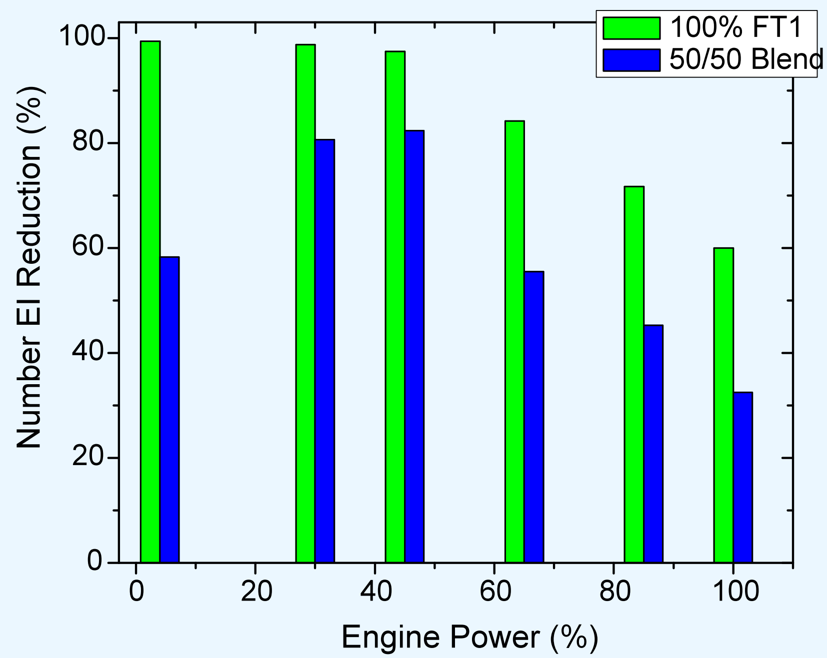
- Particle size highly dependent on fuel composition
- Particle concentrations only slightly above background in FT plume at low engine powers
- Lack of aromatics suppresses soot formation even at high power
- Lack of sulfur and aromatics reduces rates of volatile aerosol nucleation in sampling lines

Particle Numbers Densities Reduced by 60 to 95%



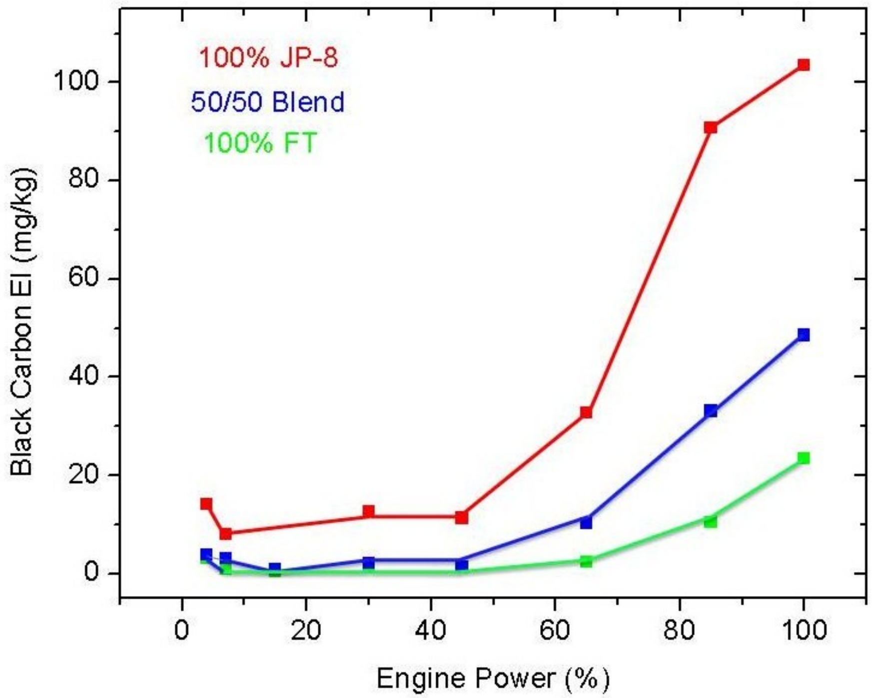
Nonvolatile Aerosols @ 1m
Differences in emissions greatest at idle, less at higher engine powers

Number emissions 98% lower at idle, 6d0% at takeoff power
Emission reduction disproportionate to fraction of FT fuel in blend



National Aeronautics and Space Administration

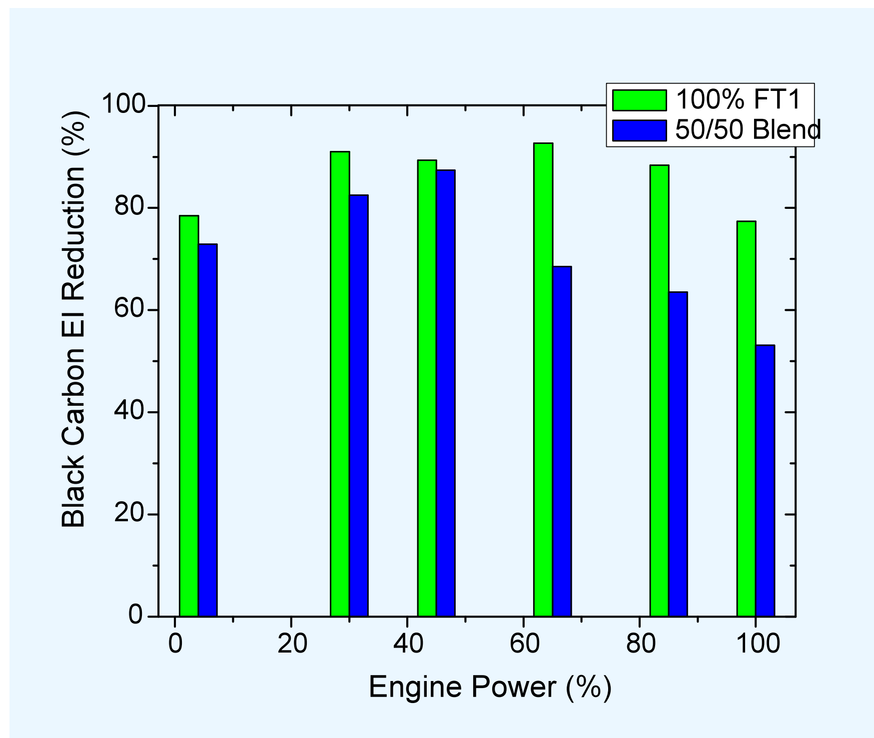
Particle Mass Emissions Reduced by 75 to 90%



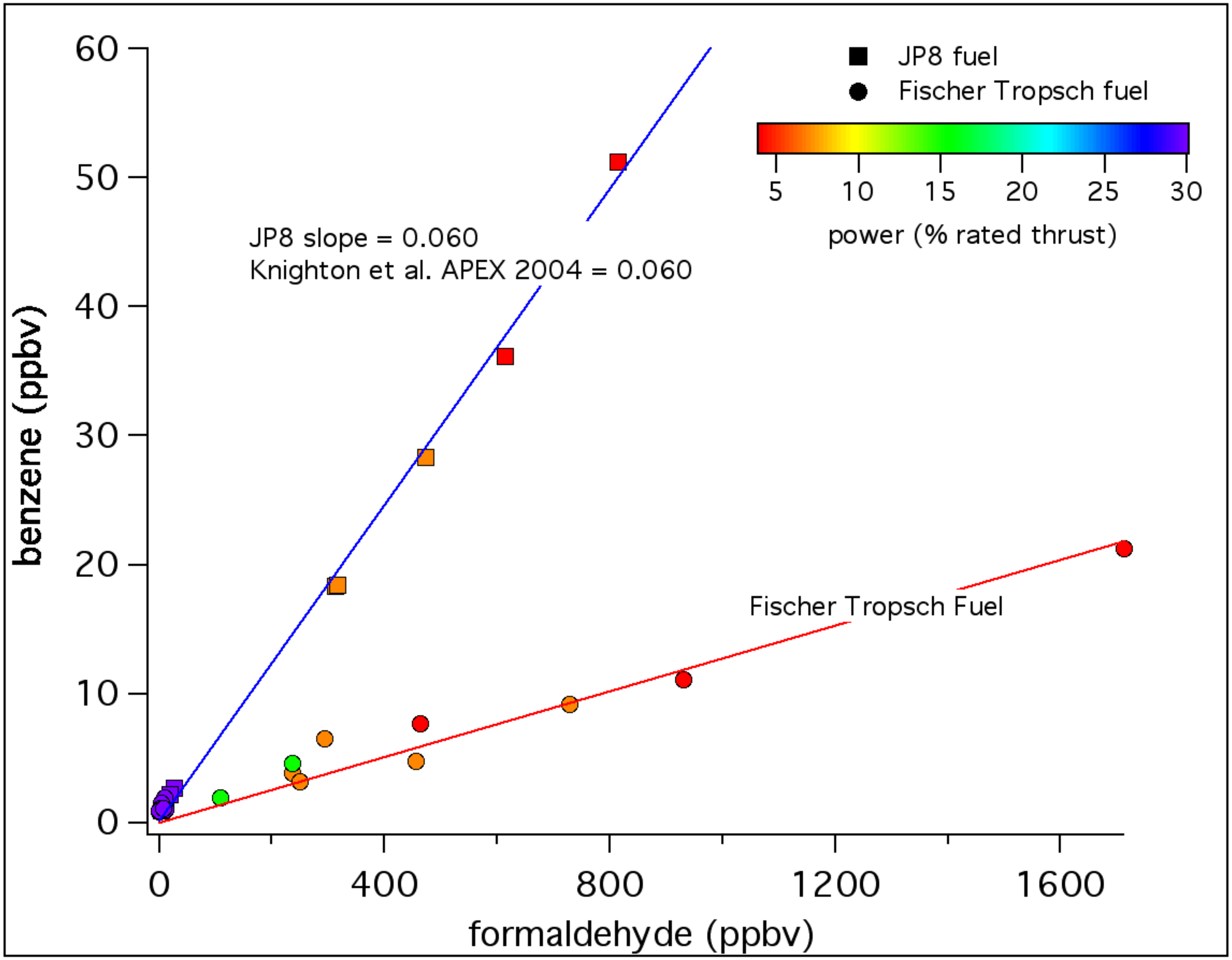
Nonvolatile Aerosols @ 1m
Differences in emissions greatest at idle, less at higher engine powers

Mass emissions 80% lower at idle, 50% at takeoff power

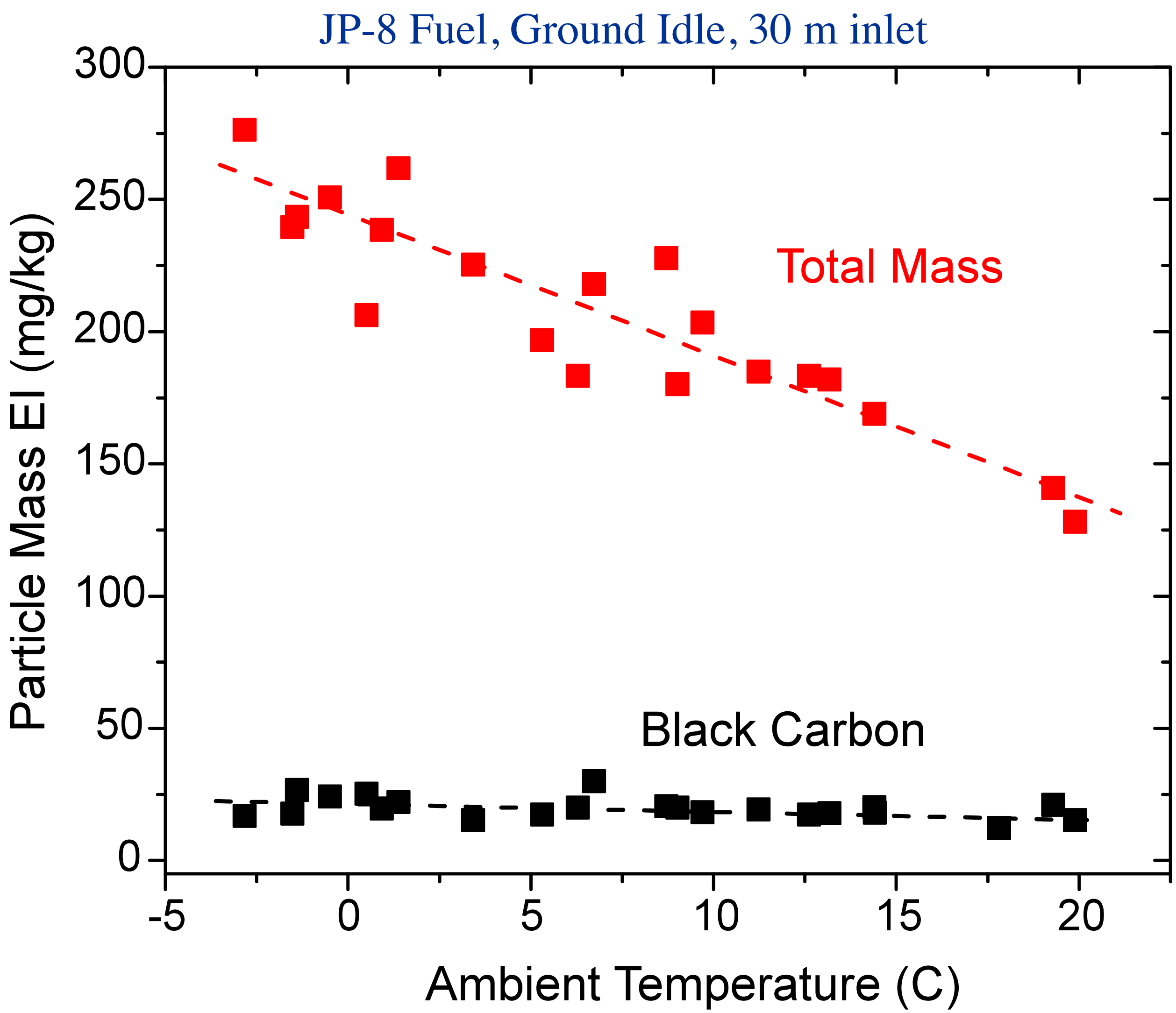
Blended fuel reduced mass emissions by >50% at all powers.



FT Fuels also Reduce HAPS Emissions



Much Learned about Temperature Dependence of Emissions

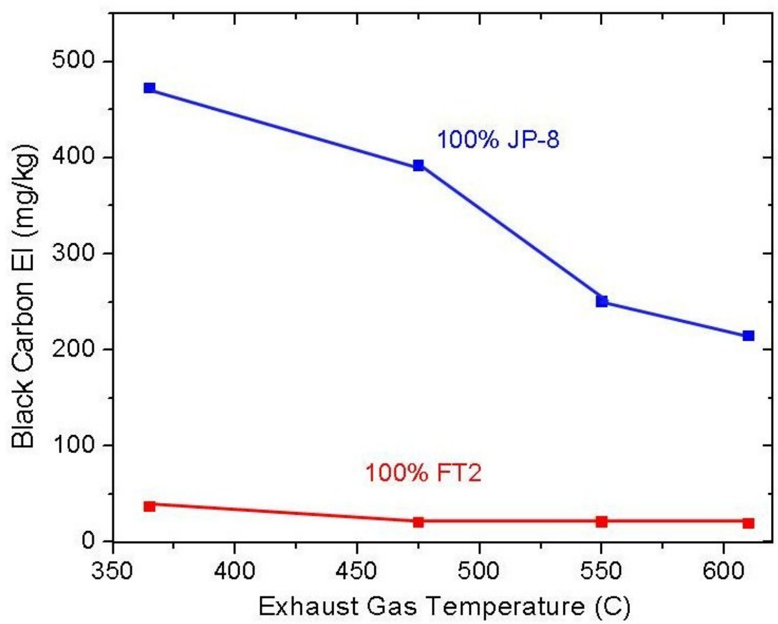


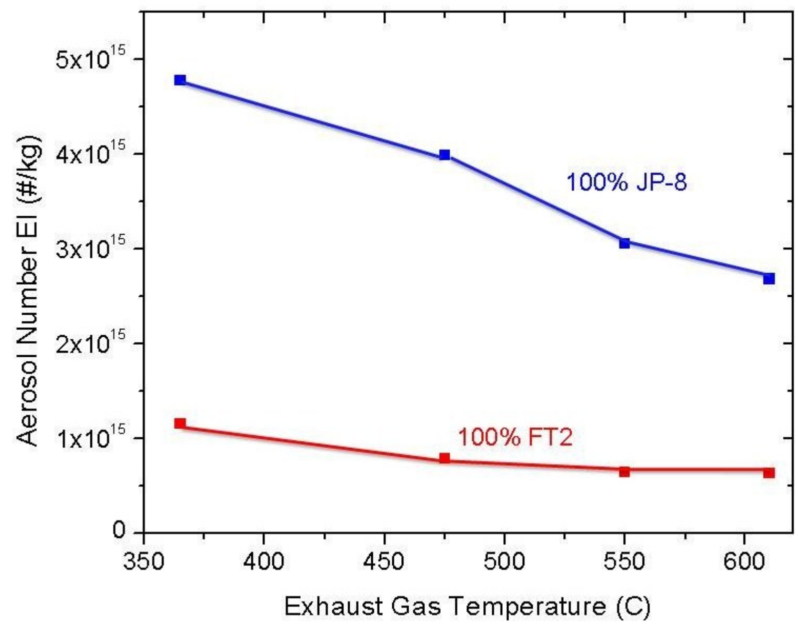
Data very important for developing and validating plume models

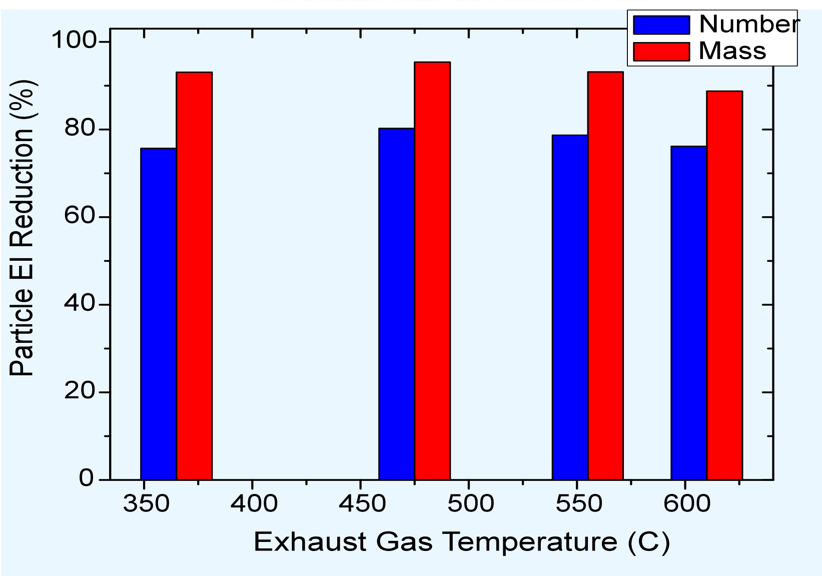
Aux Power Unit sampled while it burned JP8 and FT2

APUs are small, low-bypass turbojet engines; emissions are not regulated

FT Fuel Greatly Reduces APU Particle Emissions



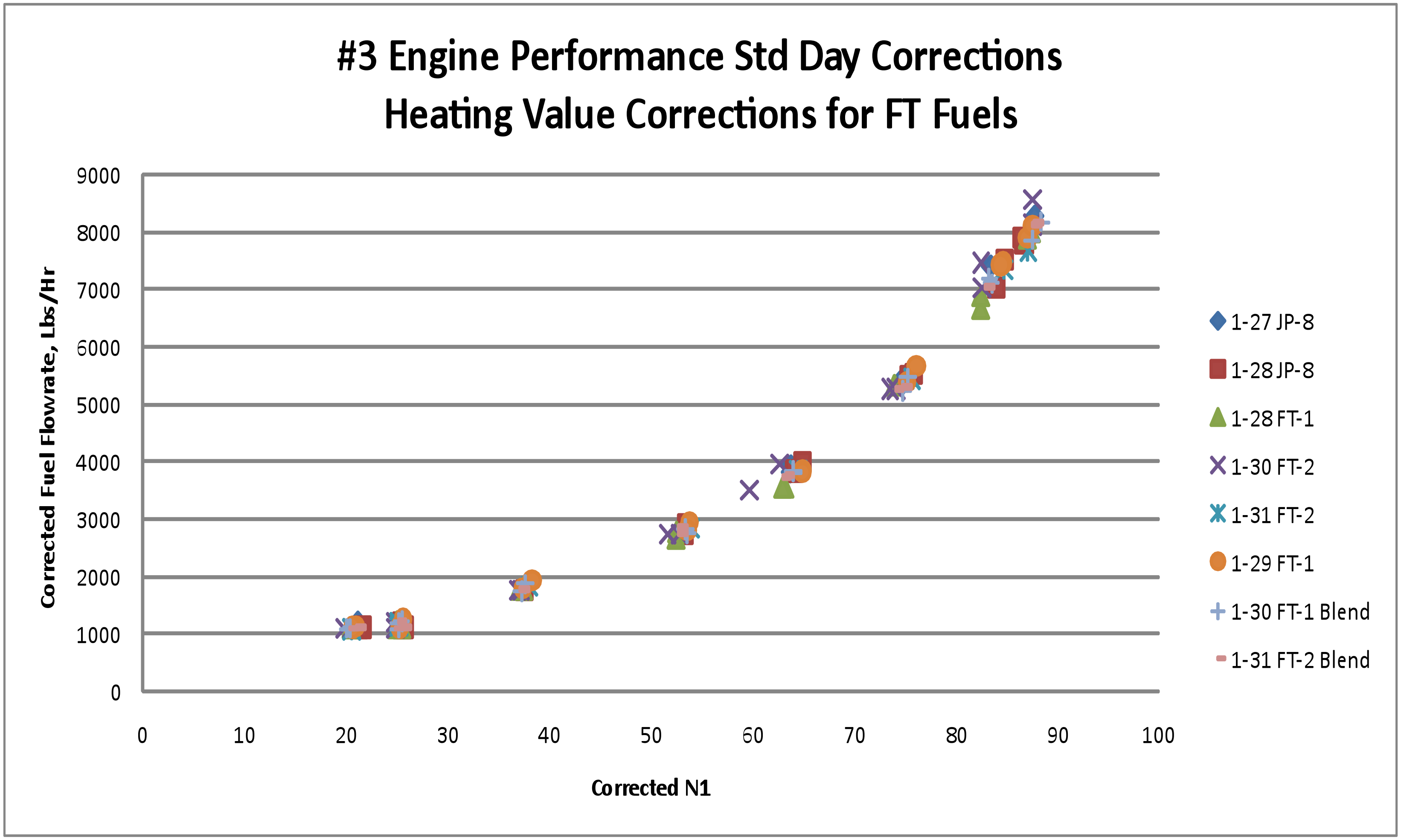




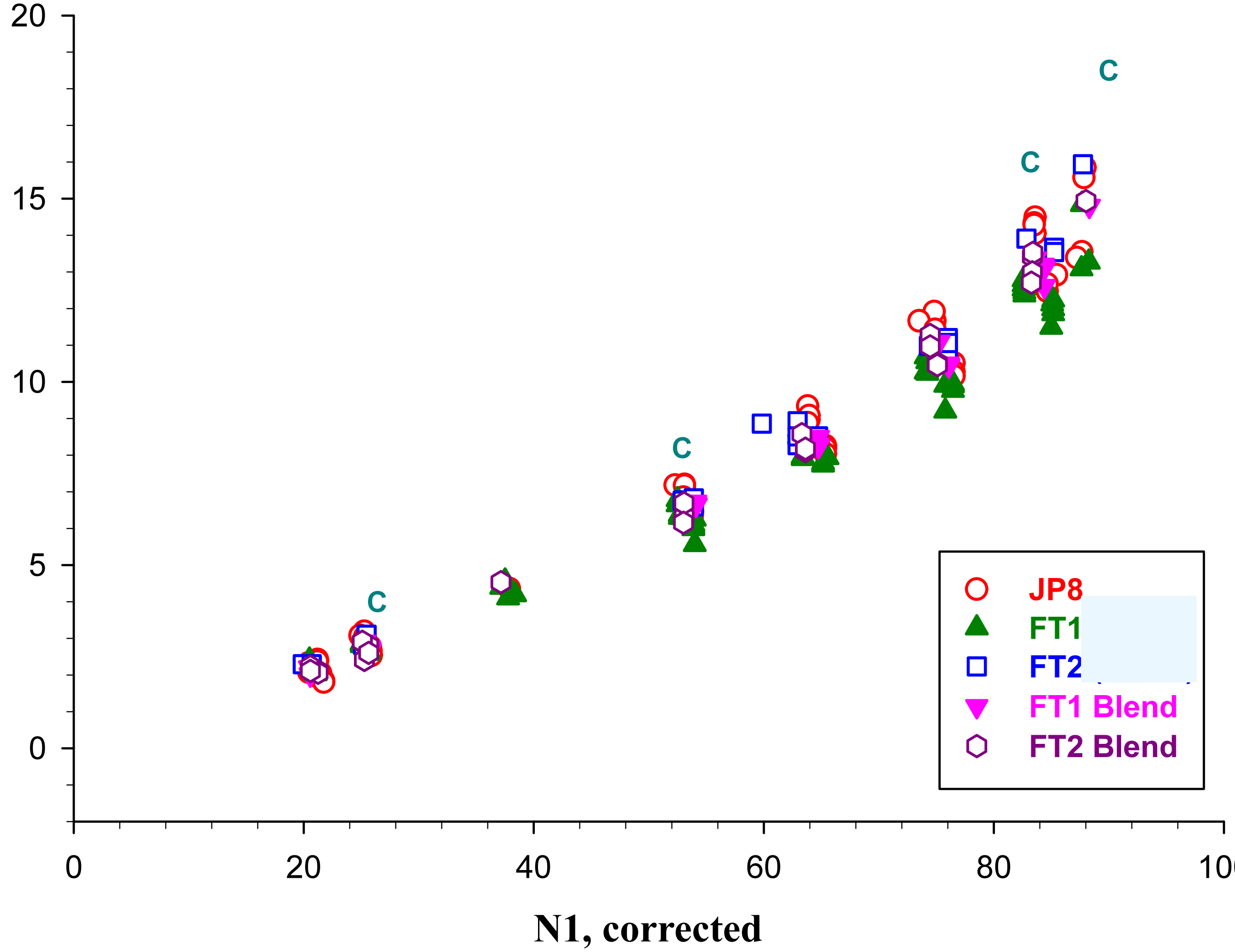
APU emits 25x more black carbon per kg fuel at idle than an aircraft engine

Mass emissions 90% lower when burning FT fuel

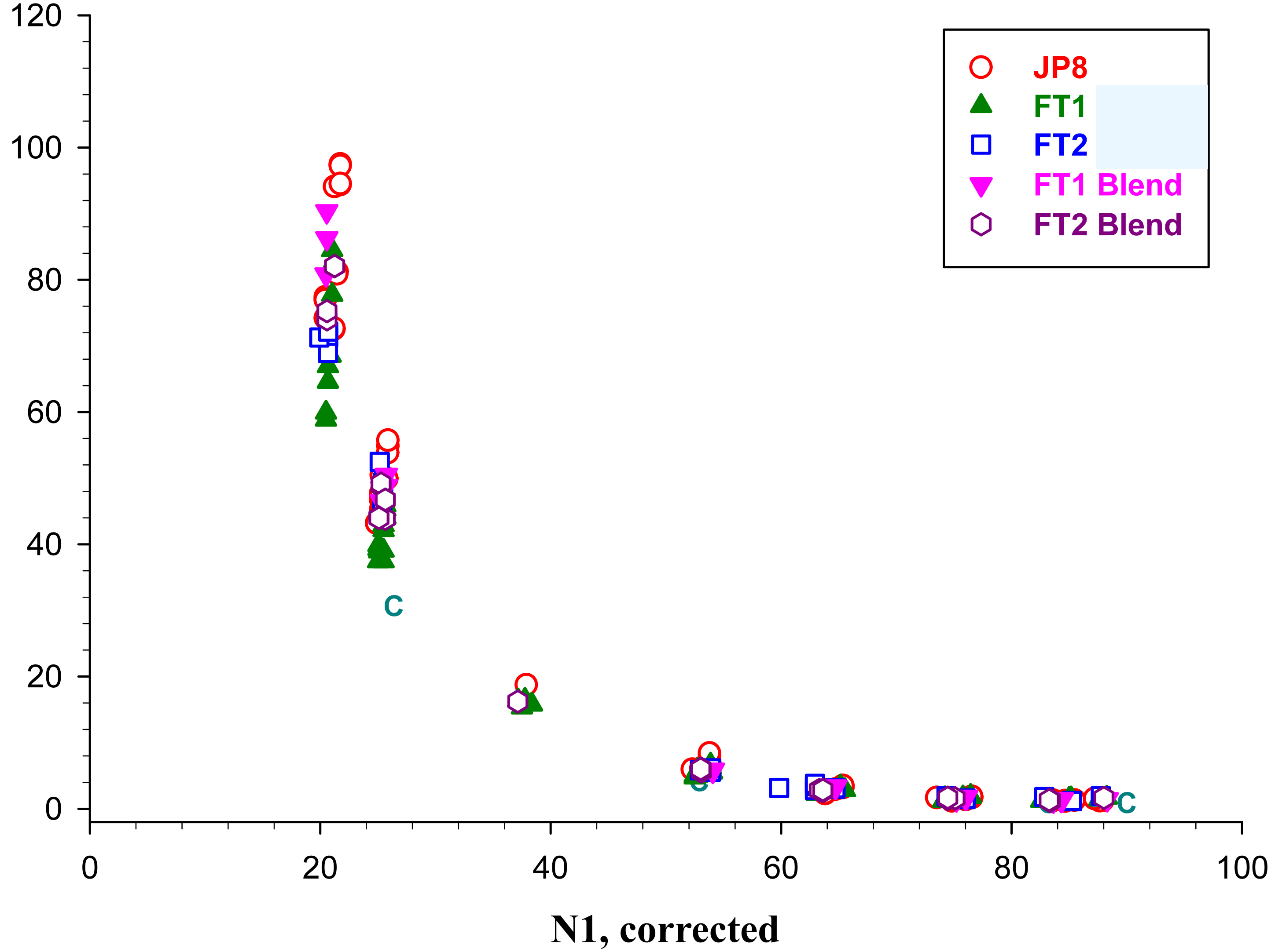
Engine #3 Corrected N1 vs Fuel Flow rate for all fuels – Heating Value correction



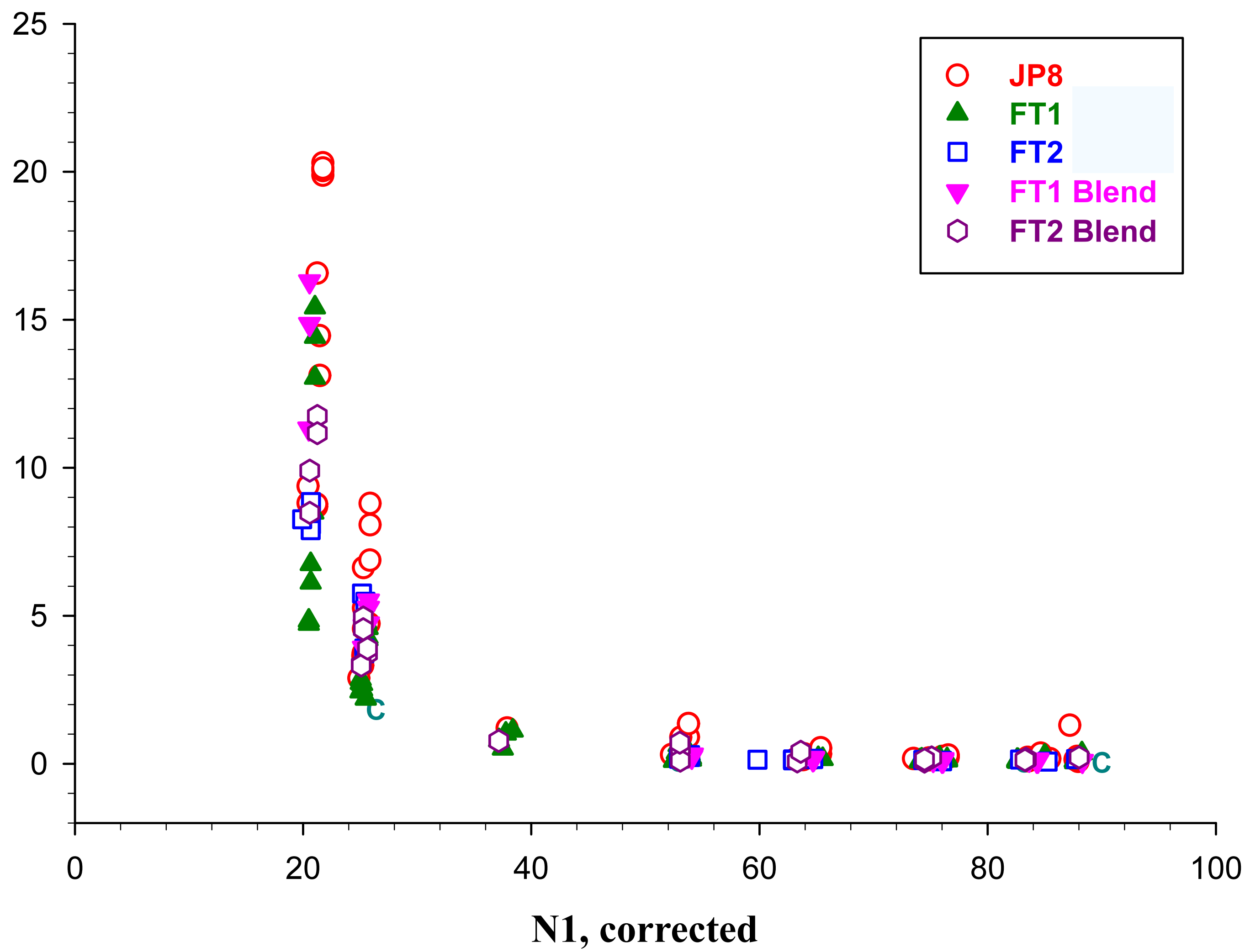
NOx Emissions



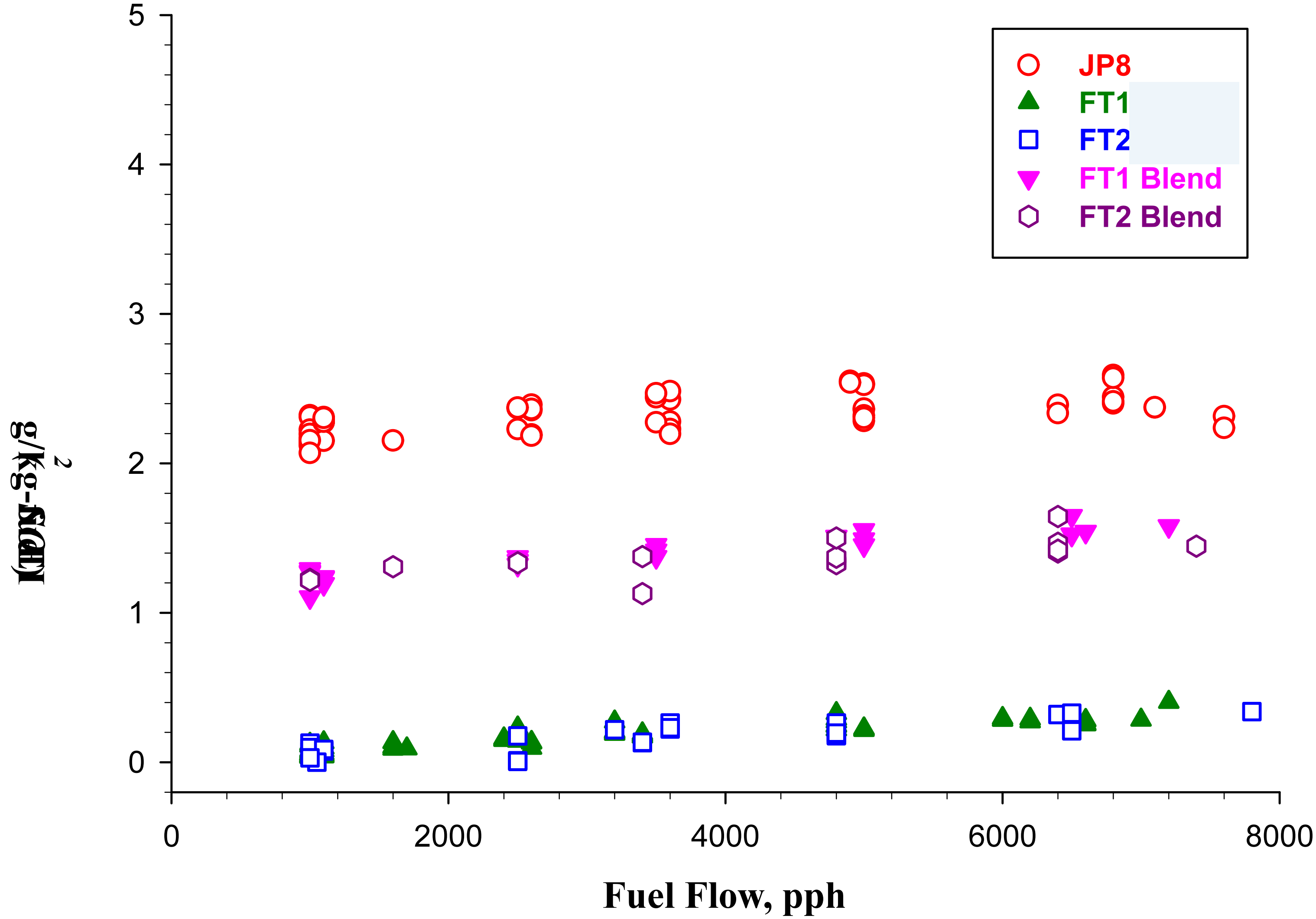
CO Emissions



HC Emissions

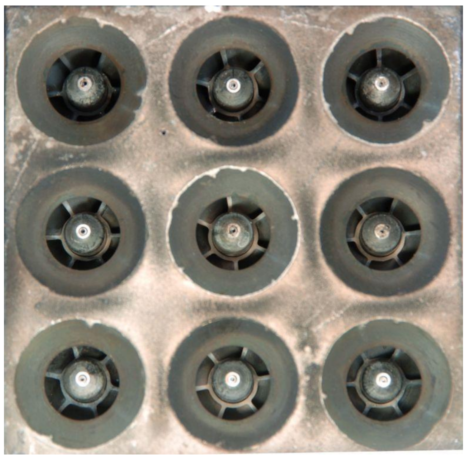


SO2 Emissions

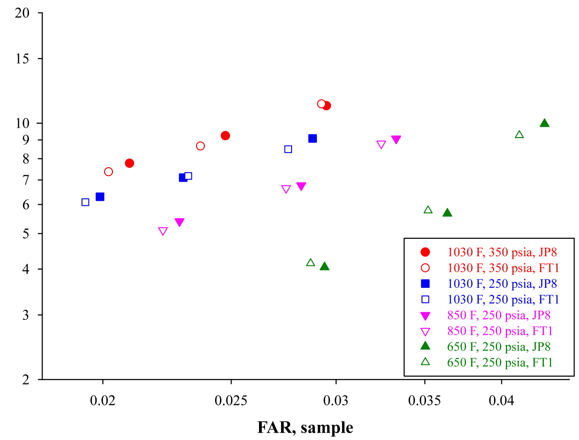


Alternative Fuel Testing using NASA 9-point LDI

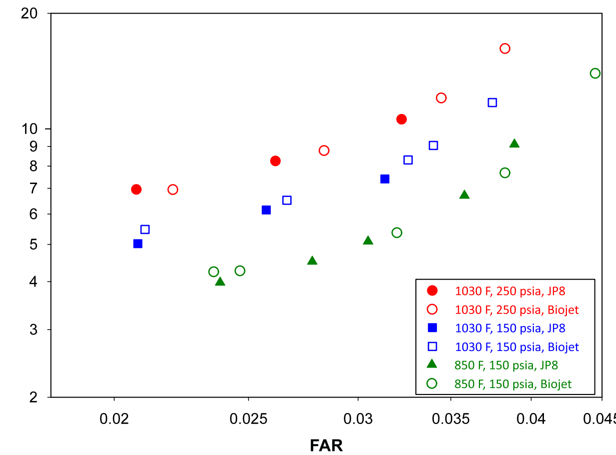
9-Point LDI



NOx Emissions

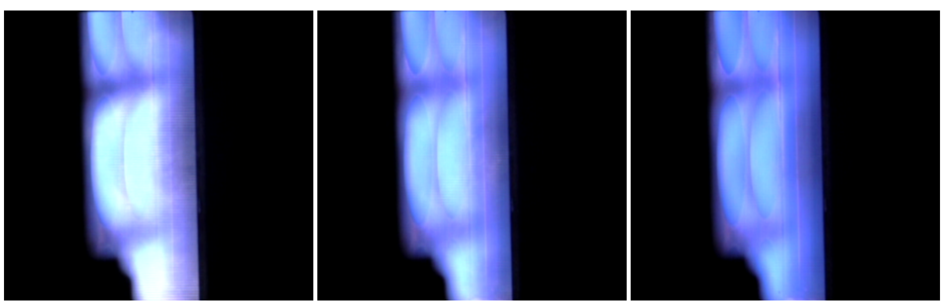


F-T Fuel

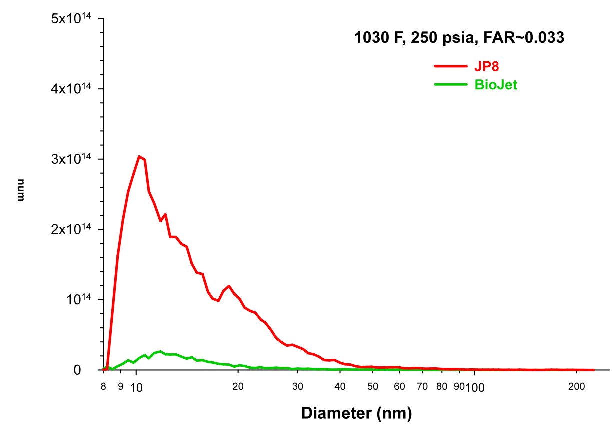


Biojet Fuel

Flame Images

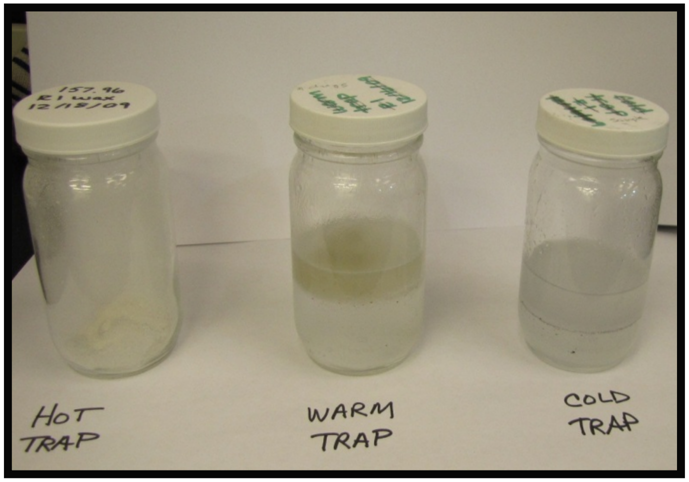


JP-8 F-T/JP-8 Blend F-T



Biojet Particle Emissions

Alternative Fuels Research Laboratory

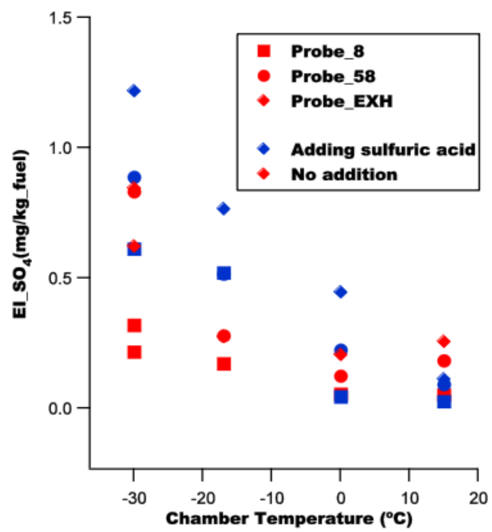


F-T Reactor Product Samples 12-18-09

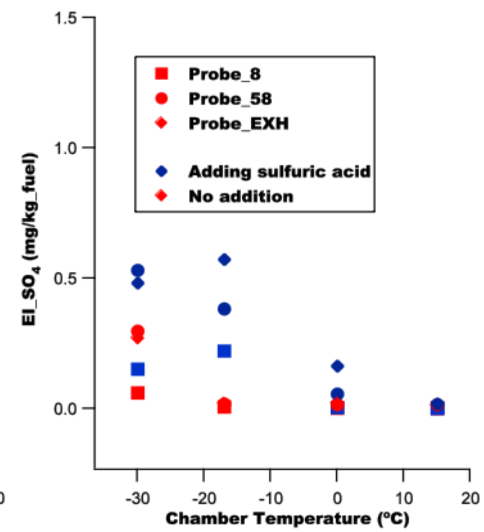
- **New Alternative Fuel Laboratory mechanical construction completed, finished functionality check-out, and secured safety permit for operation**
- **Initial campaign of Fischer-Tropsch synthesis reaction with a base-line cobalt catalyst completed in December, 2009**
  - **Collaboration with the University of Kentucky**
  - **Activated a cobalt catalyst with a novel preservation method developed at GRC**
  - **Operated Fischer-Tropsch reactor at base-line conditions for comparison with future catalyst development**
  - **Conducting product analysis to determine reactor yields and hydrocarbon conversions**

SE-11 Particle Altitude Simulation Laboratory Exhaust Plume Studies

Exhaust plume studies at sea level using JP-8 and F-T fuel conducted (NASA GRC, LaRC, Aerodyne) with sulfuric acid and anthracene added to exhaust to simulate fuels with various sulfur levels and engine oil in the exhaust



JP-8



FT fuel

Sulfate emissions at various locations in the plume for the two fuels

National Aeronautics and Space Administration

BioFuels As An Alternative Fuel Source For Aviation

➔GreenLab Research Facility designed to optimize saltwater algal, halophytes and other biomass species for potential use as aviation biofuels. Contains seven unique ecosystems representing various soil/water salinities, several states of climatic adaptation total life cycle system laboratory and field trial data.

➔Over 800 GreenLab visitors in 2009 including three congressional visits , including State Department International Visitor Leadership Program (IVLP) delgation (2009).

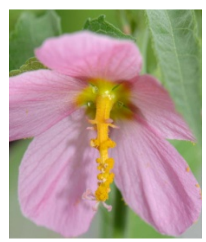
➔ Identified three optimal halophytes species (S. virginica, S. europea, S. bigelovii) out of 26 potential candidates worldwide using high throughput screening that do not use freshwater, arable land or compete with food crops.

➔Collaborations with Boeing, Evogene, DOE, Seambiotic The University of Arizona and The University of Delaware to optimize lipid extraction for saltwater algae ,halophytes and other oil-seed plants..

GreenLab Research Facility

Salicornia europea / Salicornia virginica

Seashore mallow in Delaware bay



Seashore mallow

Indoor biofuels lab

Salicornia bigelovii

Collaboration with the University of Delaware field study to demonstrate the feasibility of salinitizing *Kosteletzkya virginica* – Seashore mallow as an alternative biofuel biomass source.