NASA Aircraft Particle Emission Research: Highlights and Future Work

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Sponsoring Aeronautics Research Mission Directorate Programs

Atmospheric Effects of Aviation Project (AEAP)

Ultra-Efficient Engine Technology (UEET)

Fundamental Aeronautics Program, Fixed Wing Project (FW)

Objectives

AEAP: Assess climate and chemical impacts of aircraft emissions

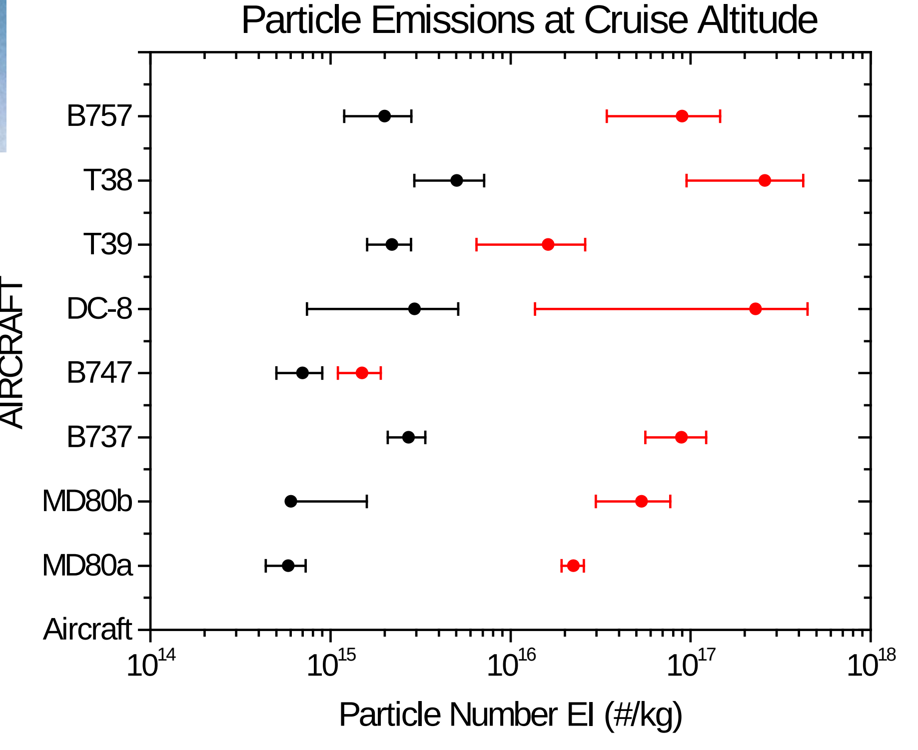
UEET: Characterize particles; assess environmental impacts

FW: Develop and validate tools for predicting emissions; evaluate performance of drop-in, alternative aviation fuels

AEAP SNIF Experiment: 1996

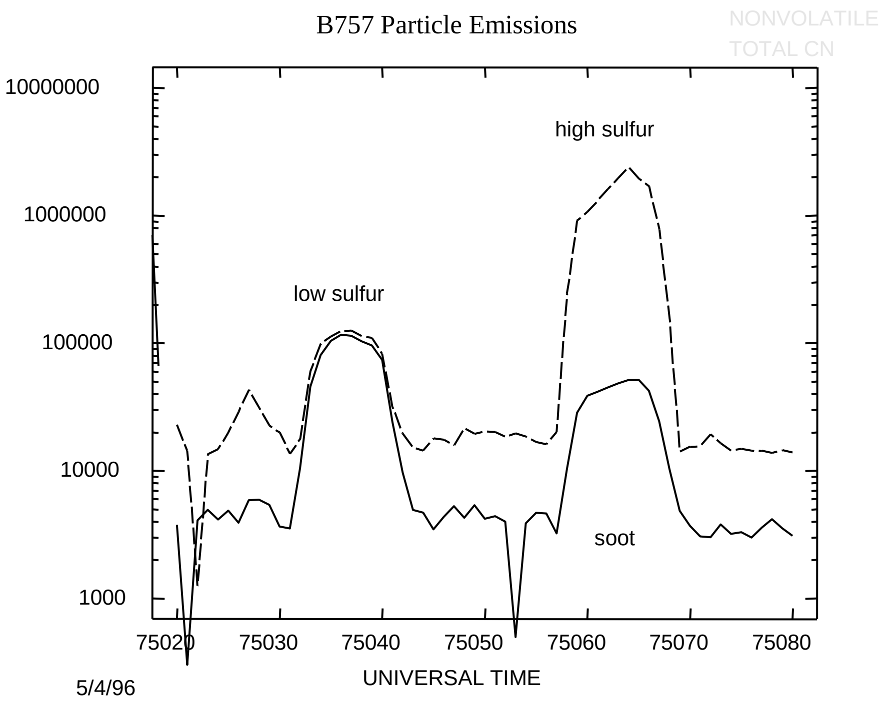
Flew Instrumented T-39 within flight corridors and behind NASA DC-8; measured particles, H2SO4 and wake vortex motion

Made detailed measurements behind > 8 commercial airliners; observed that volatile aerosols dominate particle concentrations within aged exhaust plumes of all aircraft



AEAP SUCCESS Experiment: 1996

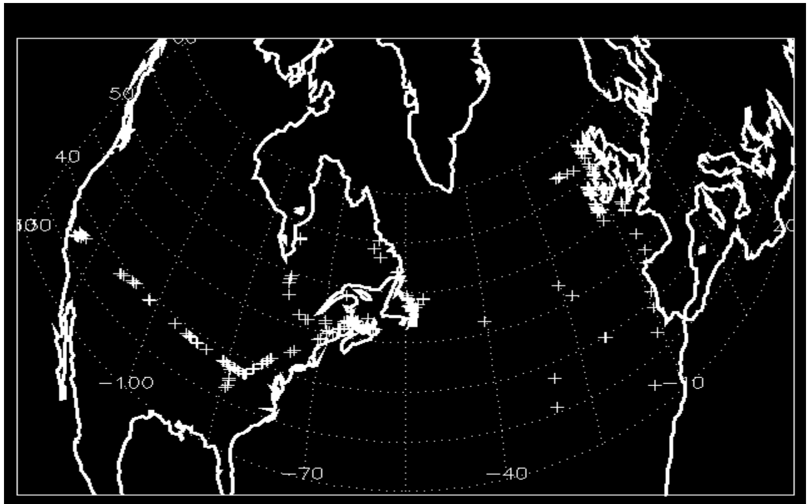
NASA LaRC B757 was flown with 70 ppmS fuel in left wing tank and 700 ppmS in right. Exhaust was sampled from T-39



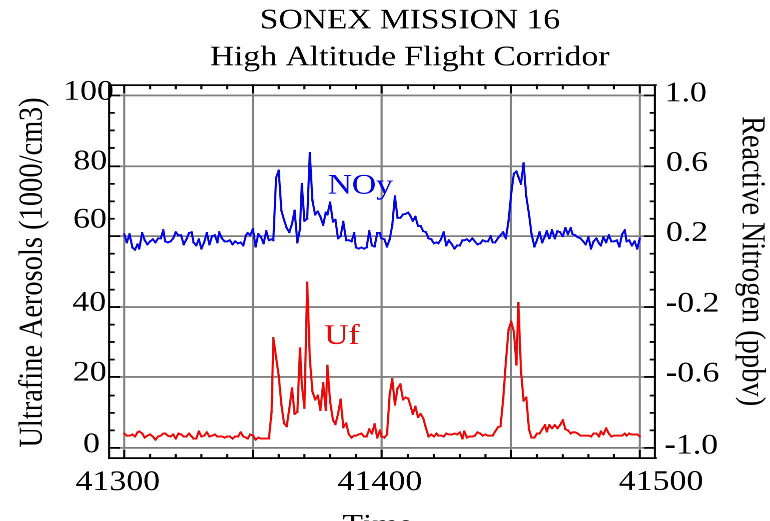
Particle concentrations were 10 to 20 times greater within the high S exhaust plume

AEAP/SONEX DC-8 Flight Campaign: 1997

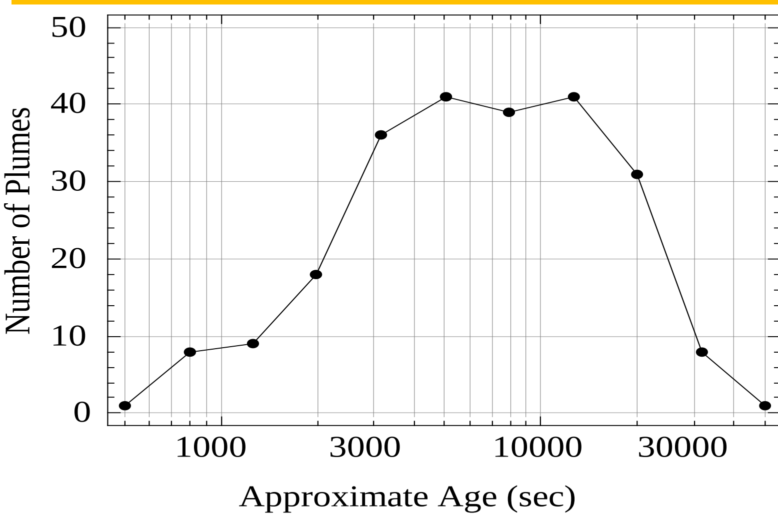
Based in Shannon and Bangor, project examined pollution in North Atlantic flight corridor



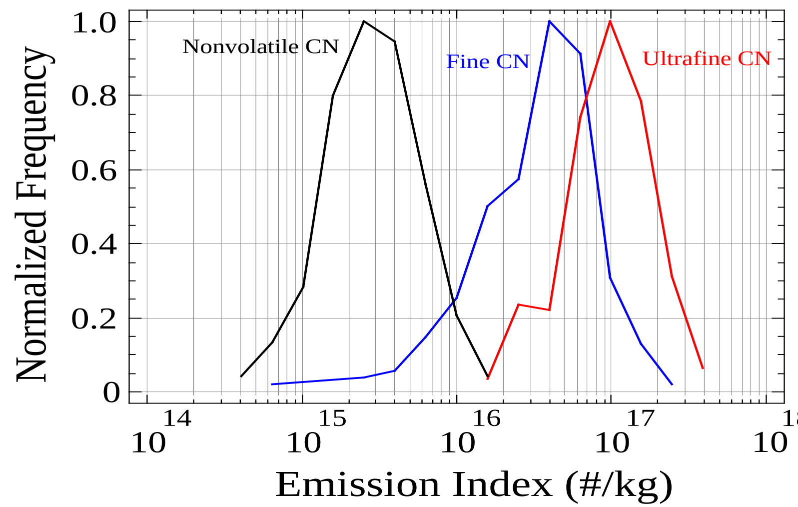
Aircraft plume crossings (+) at altitude



NOy and CN times series in crossing



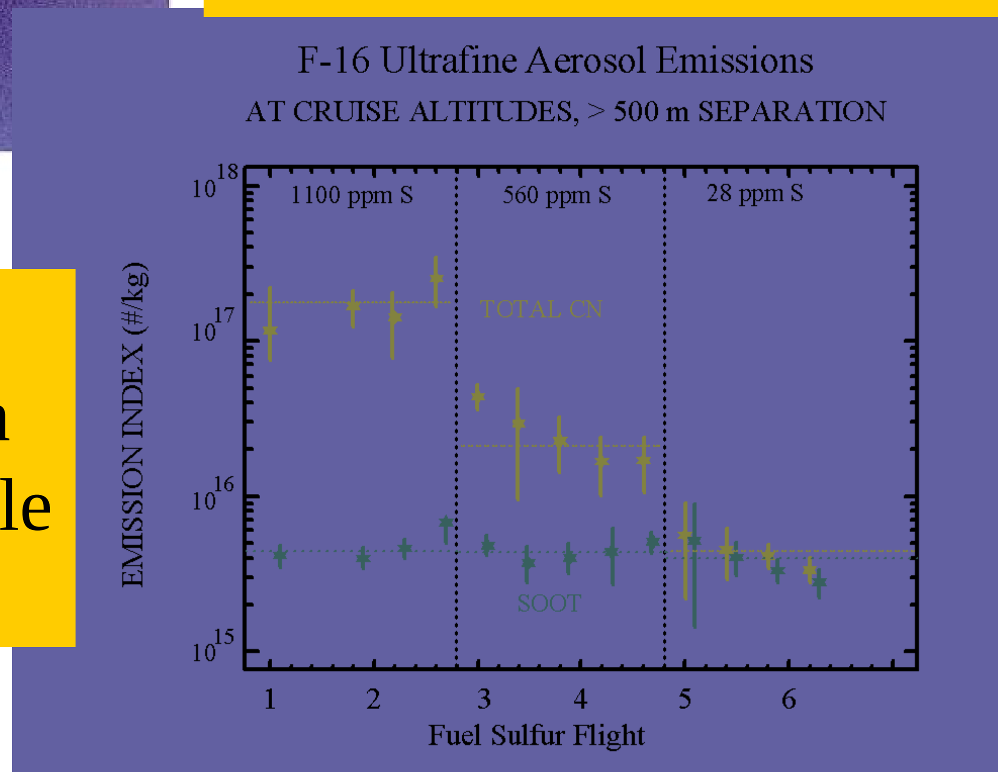
Ages estimated from NOy dilution



Histograms of CN number EIs for 223 plumes

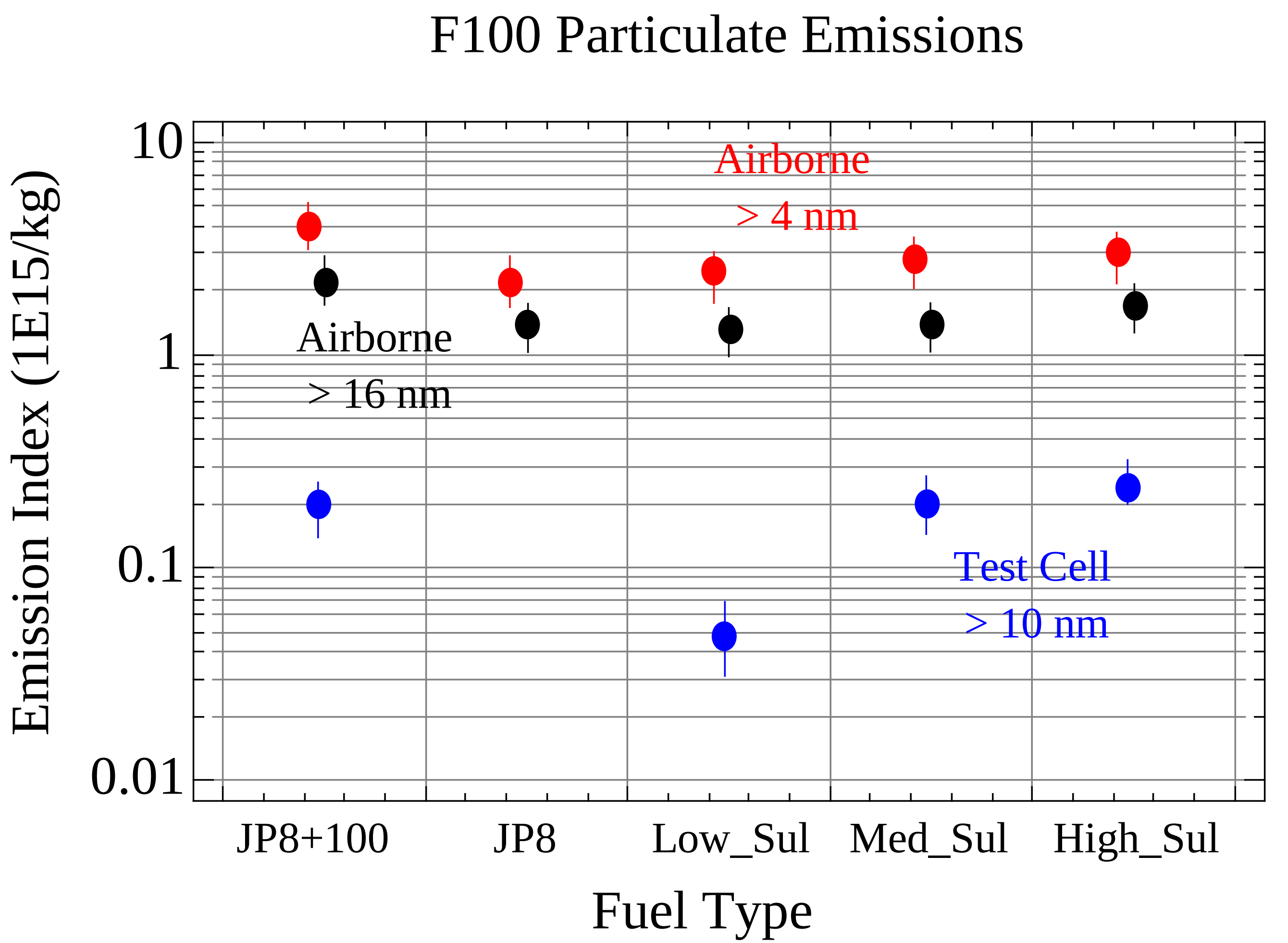
AEAP SNIF-III Experiment: 1997

Flew T-39 behind F16 aircraft from NJ and Vermont ANG; burned JP-8 with varying levels of Sulfur



Confirmed that sulfur plays significant role in regulating volatile particle emissions

SNIF-III/PSL F100 Comparison: 1997

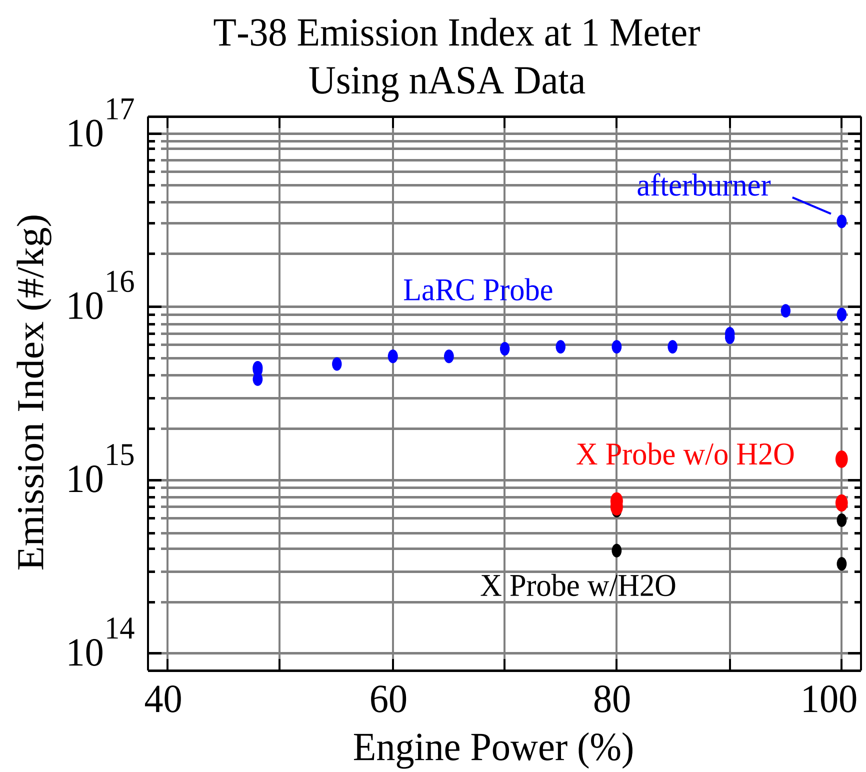


Same engines, same fuels—Vastly different results. Why?

AEAP Particle Measurement Workshop: 1999

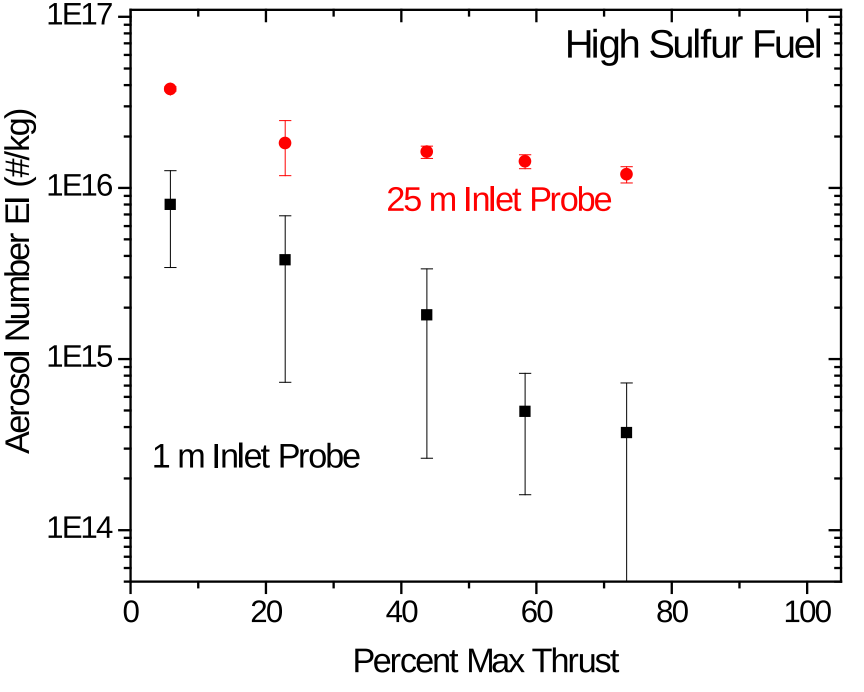
Lab Phase: Compared measurements from all groups involved in AEAP airborne and ground-based test venues; Instrument saturation a common problem

Field Phase: Compared inlet probes and sampling systems while sampling T-38: identified particle losses within inlet tips and sample lines as a huge, unaccounted for problem



AEAP/UEET EXCAVATE: 2002

NASA LaRC B757
Rolls Royce RB211-535E4
40,100 lbs thrust
Fuels: 810, 1050, 1820 ppmS
Inlets: 1, 10, 25, 35 m
Powers: 6,23,45,60,75%

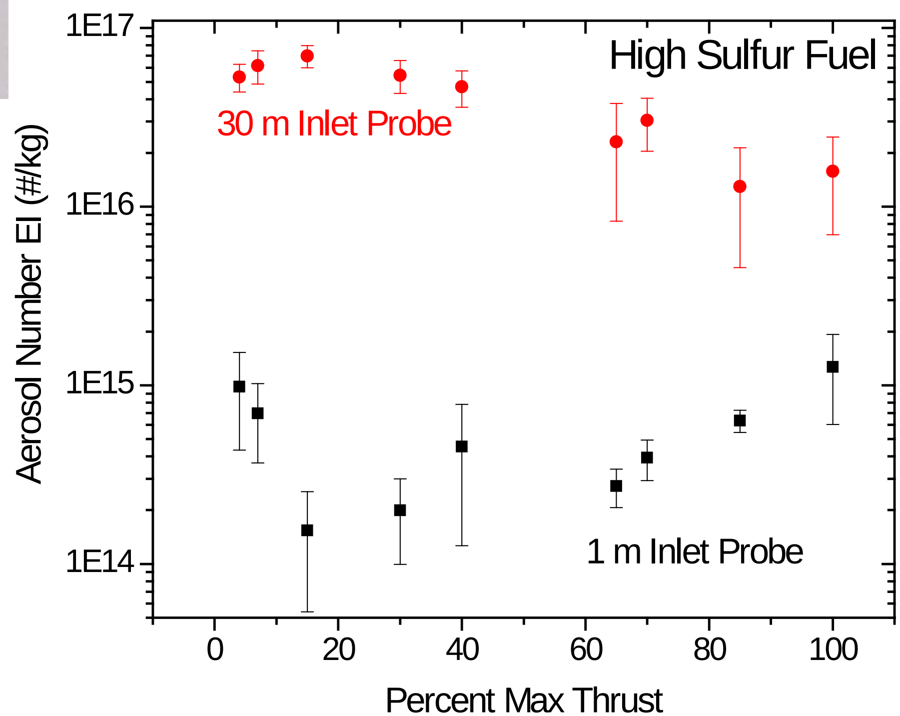


EXCAVATE observations of B757 particle mass, size and number emissions consistent with SUCCESS measurements at cruise altitudes

=> Careful ground measurements representative of airborne emissions

UEET APEX-1: 2004

Aircraft: NASA Dryden DC-8
Engine: CFM-56
Fuels: Hi, Lo S; Hi Aromatic
Inlets: 1, 10, 30 m
Powers: 4,7,30,45,65,85,100%
COMMUNITY INVOLVEMENT

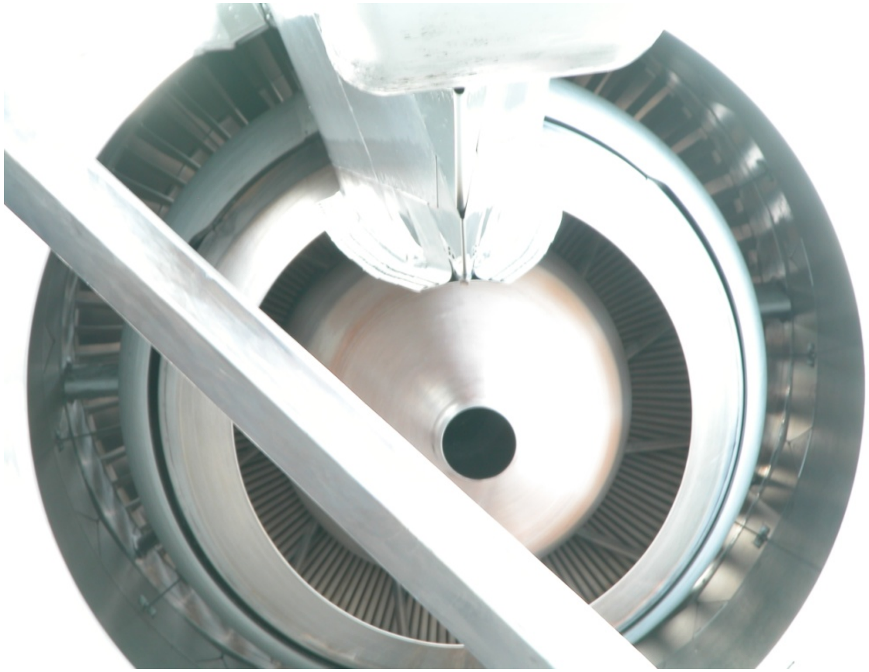


Results consistent with previous airborne and ground-based measurements; set the stage for systematic collection of data from a broader range of aircraft and engines with wide community support

UEET Engine Studies: 2005

JETS/APEX-2
Oakland CA; Aug '05
Four Southwest 737's with CFM-56-3-B1 or CFM56-7B24 Engines

APEX-3
Cleveland; November '05
9 Aircraft
CFM-56-3, CJ610, AE3007-A1E, PW4158, RB211-535E4 Engines



FAP Particle Emission Foci: 2006-2008

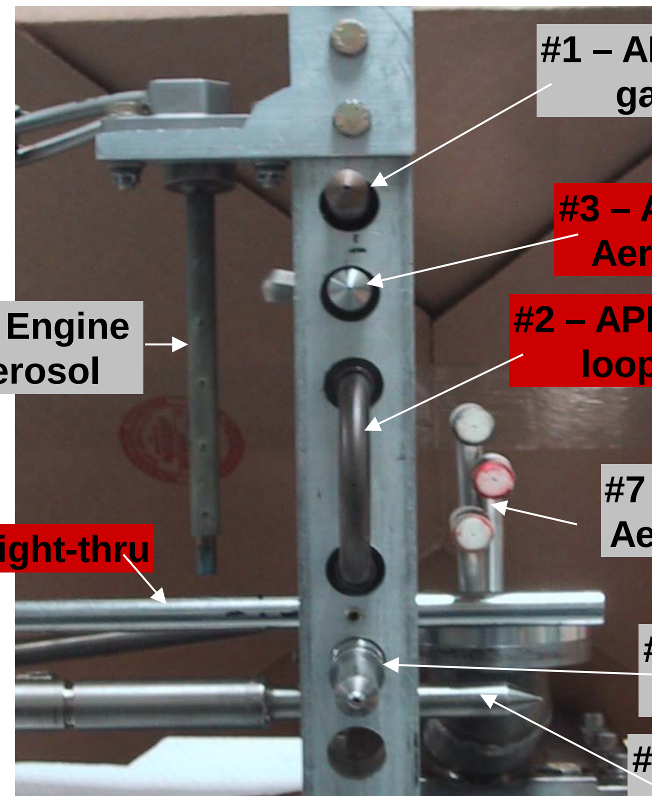
1. **Improve measurement techniques/develop standard approach**
   -validate line-loss model; use predictions to optimize sampling system
   -select and characterize best set of instruments
   -develop better techniques for sampling combustor emissions
   -develop approach for calibrating instruments and sampling systems

2. **Develop better understanding of soot emissions**
   -characterize morphology and microphysical properties of engine soot
   -investigate pressure, fuel atomization, fuel/air ratio effects in combustor
   -determine fuel matrix dependencies
   -verify that sector=>annular combustor=>engine
   -develop soot inception model; validate; incorporate into NCC

3. **Develop better understanding of volatile aerosol formation and growth**
   -identify volatile aerosol constituents (oil, unburned HC, sulfate, etc.)
   -investigate effects of fuel, ambient conditions, engine operation etc.
   -further develop and validate volatile aerosol model

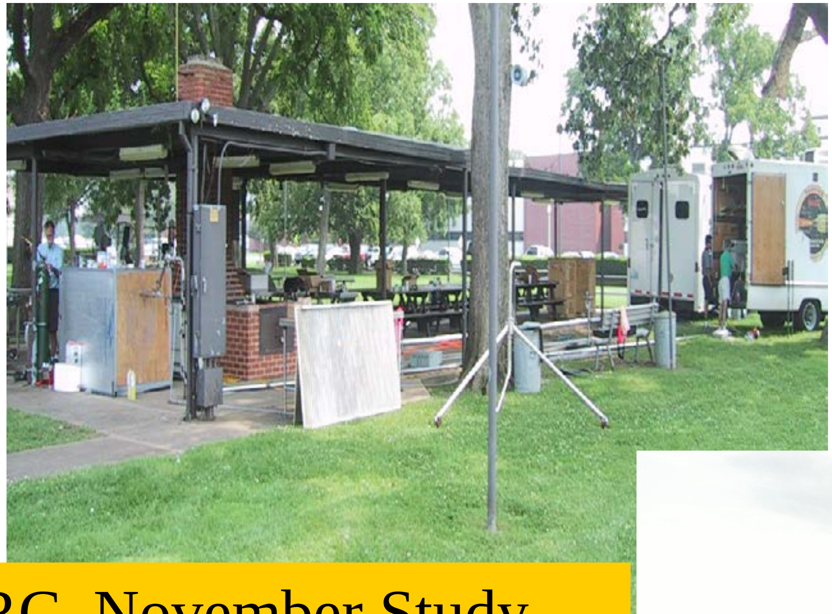
FAP Sampling System Characterization: 2006

Using "Start Cart" as an emission source, compared relative penetration efficiencies of a variety of sample inlet probes



Probes were mounted on cross bar suspended over engine exhaust. Examined probes from most recent experiments conducted by UTRC and NASA; Results still pending

FAP Sampling System Characterization: 2006



LaRC, July lab study
Using combustion source, measured transmission losses through sampling systems used in APEX and QL tests;
Compared sizing instruments

GRC, November Study
Measured particle transmission through inlet probes and sampling lines; intercompared more than a dozen particle instruments

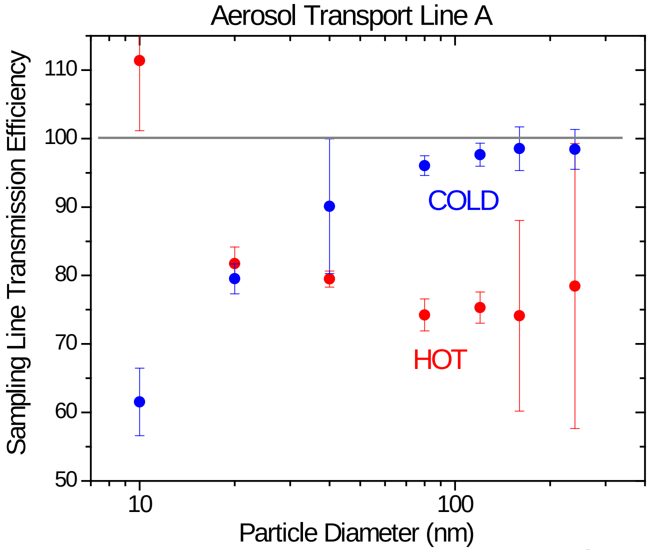
JSF Quick-look Tests: 2006

Sponsored by DOD and conducted at PW West Palm Beach Facility to evaluate emissions from new Joint-Strike Fighter Engines. Experiments examined procedures for sampling particles from high velocity, high temperature, exhaust plumes and led to improvements in inlet probes and sample transport systems

Tinker AFB Tests of F-100 Engine: 2007

Conducted at Tinker AFB in Oklahoma and sponsored by SERDP, the project used a tes-stand mounted F100 engine to test new methods of sampling aircraft engine exhaust.

Findings suggest that heated sampling lines produce additional losses, probably due to thermophoresis, not seen in lines operated at ambient temperature.



Fixed-Wing Environmental Foci: 2008-2015

1. **<u>Investigate the performance and emissions of alternative fuels</u>**
   -Characterize fuel thermodynamic and combustion properties in lab tests
   -Examine fuel impacts on soot formation in flame-tube experiments
   -Examine fuel effects on performance and emissions in on-wing studies
   -Examine fuel effects on APU emissions

2. **<u>Develop understanding of factors controling contrail ice formation</u>**
   Using SE-11 altitude simulation chamber:
   -Examine effects of soot size and concentration on ice nucleation
   -Investigate effects of sulfate and organic coatings on soot ice nucleation
   -Determine influence of background aerosols on contrail formation
   -Using APU soot generator, examine fuel effects on contrail formation

3. **<u>Determine how fuel properties effect contrails and cruise emissions</u>**
   Using instrumented aircraft:
   -obtain PM and ice measurements in exhaust aircraft burning standard and blended alternative fuels
   -Evaluate the role of fuel sulfur and soot concentrations on ice properties

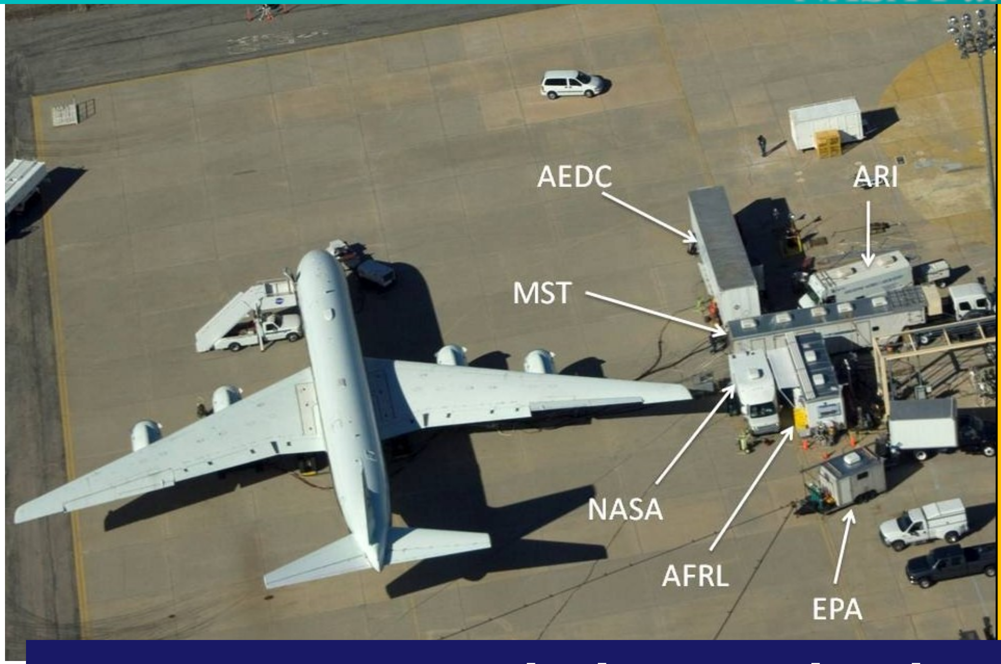
Ultra-High Bypass Engine Test: 2007-2008

Conducted at the Pratt and Whitney test facility in West Palm Beach, the test examined emissions from a high-bypass engine and included a number of runs using a blend of JP-8 and Fischer-Tropsch fuel.

PW308 Emissions Test: 2008

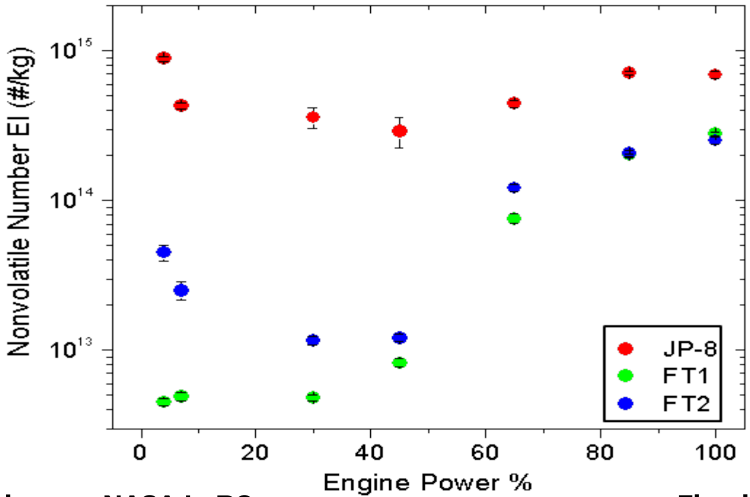
Conducted at the Pratt and Whitney test facility in West Palm Beach, the test examined emissions from a small turbofan engine and included a number of runs using a blend of JP-8 and Fischer-Tropsch fuel.

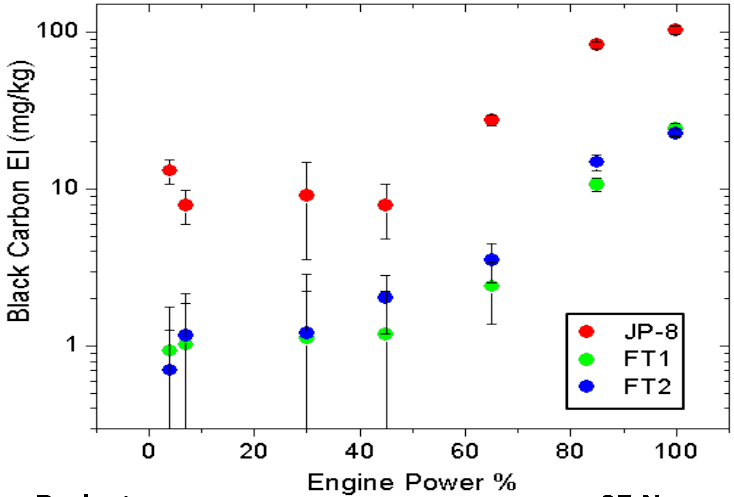
Alternative Aviation Fuel Experiment (AAFEX-1): 2009



Objectives
- Create gaseous and particulate emission profiles as a function of fuel-type and engine power;
- Investigate the factors that control volatile aerosol formation and growth
- Establish aircraft APU emission characteristics and examine their dependence on fuel composition
- Evaluate new instruments and sampling techniques

Huge PM Emissions Reductions Seen when Using Alt Fuels





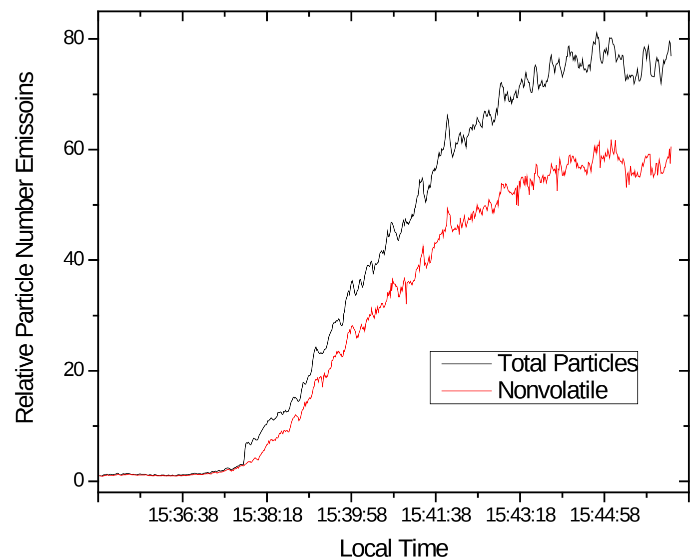
Alternative Aviation Fuel Experiment (AAFEX-2): 2011

Objectives

- Evaluate alt fuel effects on engine performance and fuel-handling equipment
- Determine the effects of HRJ fuels on engine PM and gas phase emissions
- Investigate the role of sulfur in regulating volatile aerosol formation in engine exhaust plumes
- Examine exhaust plume chemical evolution
- Conduct tests to support SAE E-31 development of standard exhaust sampling methods

Summary of Findings

- Negligible effect of fuel type on engine performance, but some slight fuel system leakage with neat HRJ and F-T fuels
- Alt fuels greatly reduce black carbon number and mass emissions and volatile particle formation in exhaust plume
- High fuel sulfur promotes rapid volatile particle formation in exhaust, but downstream aerosol number EIs do not vary linearly with fuel sulfur content
- Sulfate aerosols create nucleation mode and coat soot particles to enhance solubility



SE-11 Altitude Chamber Experiments: 2010-present

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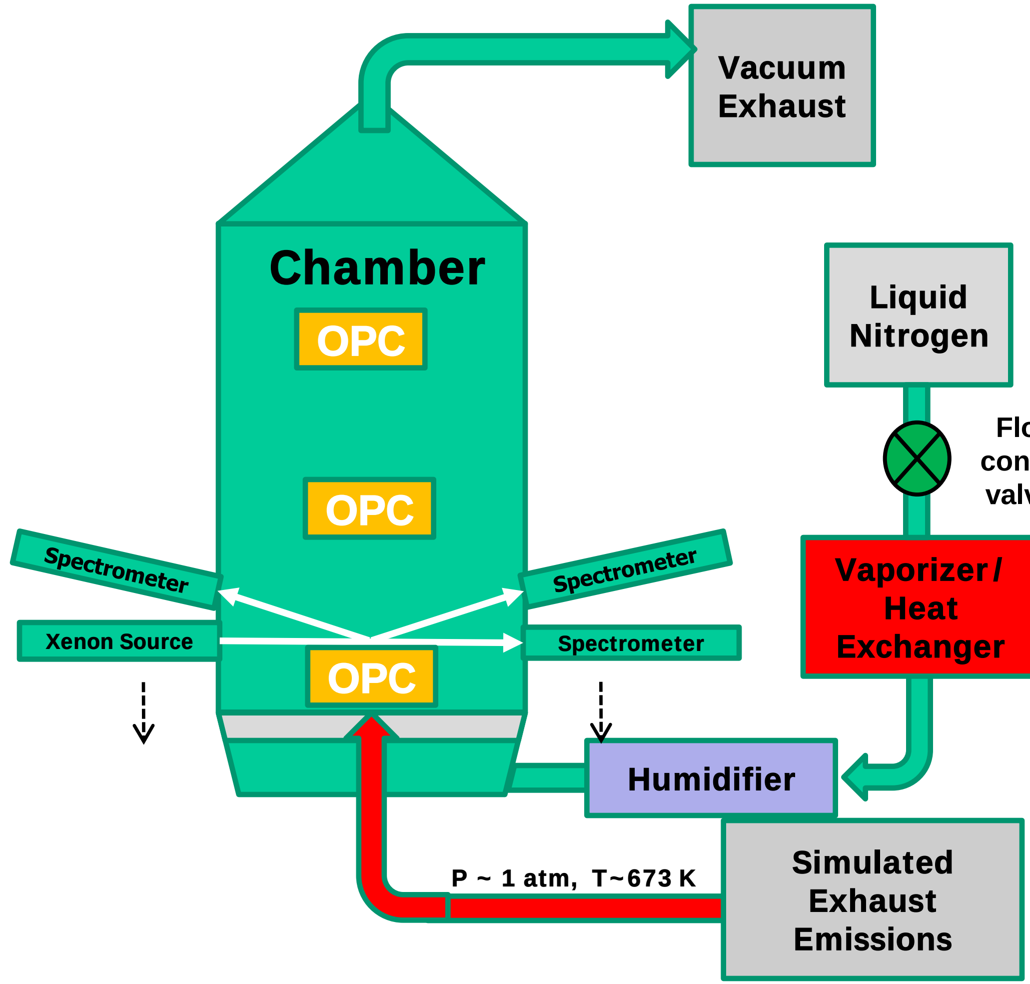
Tests examine the links between soot emissions/properties and ice formation



- Flow-through chamber can simulate conditions up to 50,000 ft
- Particles monitored using Optical Particle Counters and Light Scattering
- Can control soot size, number density, and sulfate and organic coatings

SE-11 Altitude Chamber Experiments: 2010-present

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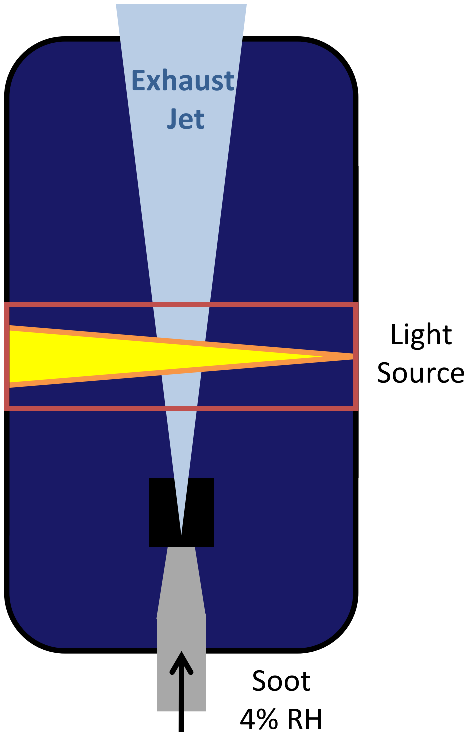
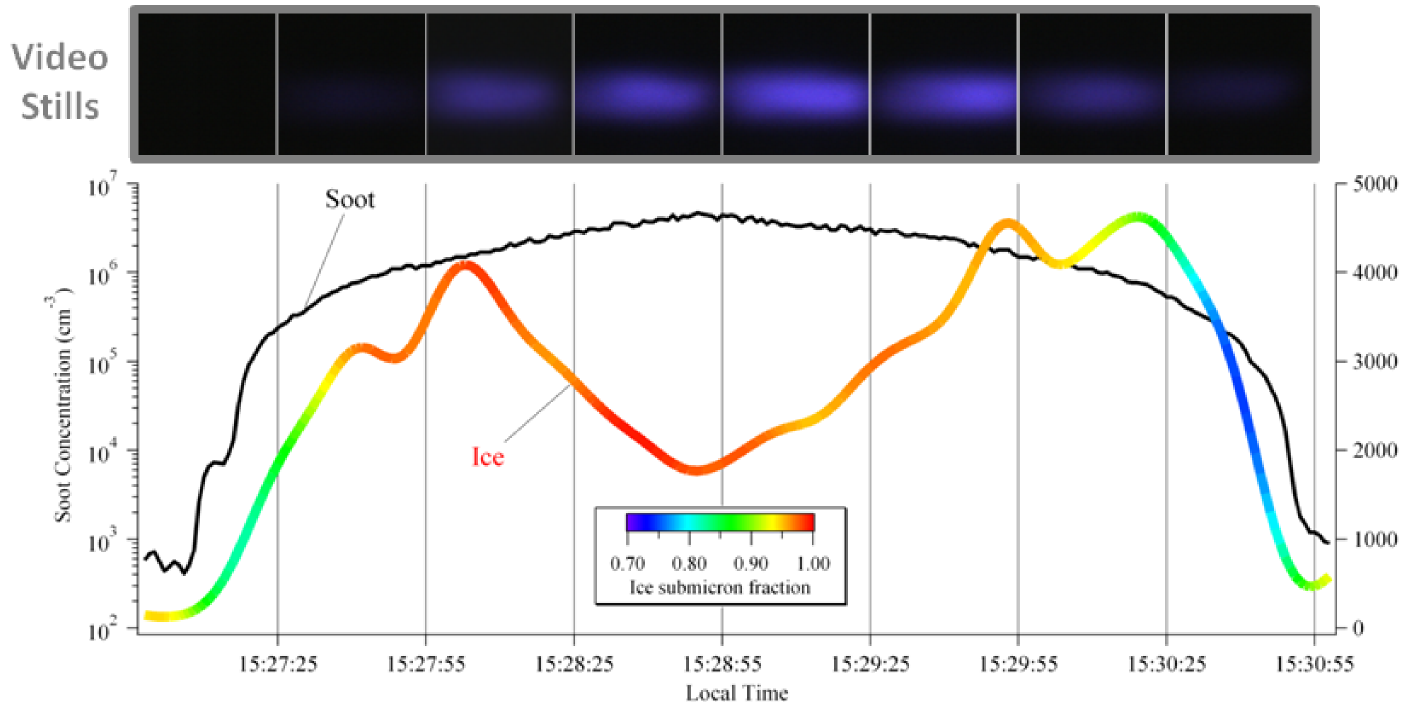
High PM Concentrations Required for Ice Formation



<u>"Contrail" visible for CN > 1e6/cm3</u>



- Tests are being conducted with partial FAA sponsorship and in collaboration with Aerodyne, which is using the data to validate contrail model
- Tests explore particle size and solubility effects on ice formation
- New APU particle source will allow us to study alternative fuel-effects on contrails

Alternative-Fuel Effects on Contrails and Cruise Emissions (ACCESS-1): 2013

Accomplishments

- Field mission initiated February 19 in Palmdale, completed April 13, 2013
- Conducted 5 successful contrail sampling flights, with Falcon collecting measurements behind DC-8 as it burned both JP-8 and blended alternative fuels
- Completed 4-hour-long DC-8 ground study, collecting detailed aerosol and gas emissions data as the aircraft burned blended and JP-8 fuel at a range of power settings
- Completed ground-station fly-bys to verify instrument calibrations
- Conducted two-day study of aircraft emissions at LAX, collecting idle, takeoff and landing data from multiple airframe/engine combinations

Alternative-Fuel Effects on Contrails and Cruise Emissions (ACCESS-1): 2013

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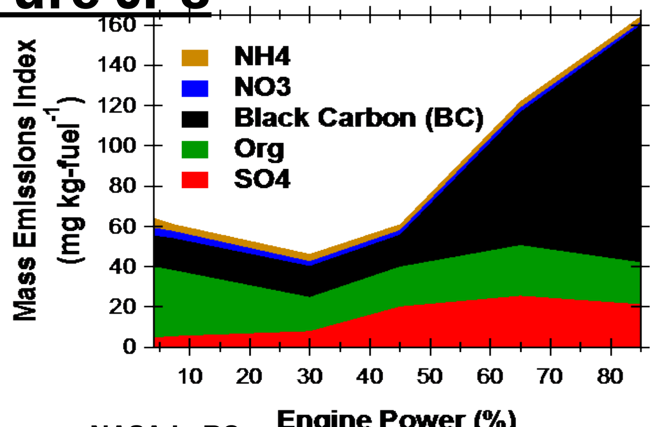
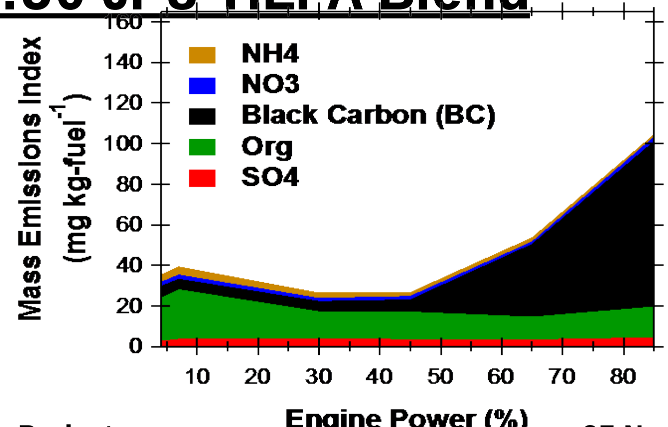
Significant Results

- Burning a 50:50 blend of HEFA and standard jet fuel JP-8 does not degrade gas-turbine engine performance on the ground or at cruise altitudes, hence blended fuel is a suitable, drop-in substitute for standard petroleum fuel
- Blended fuel does not reduce engine NOx or CO production, but does slightly decrease total hydrocarbon emissions at low engine powers
- Black carbon mass and number emissions are reduced 30 to 50% in both ground and cruise altitude operations when burning the alternative fuel blend compared to burning standard jet fuel.
- Total aerosol mass emissions are reduced by more than 50% at cruise altitudes due to large reductions in sulfate, organics, and black carbon

Pure JP8



50:50 JP8-HEFA Blend



ACCESS-II: May 2014

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ACCESS-II will engage international partners to examine fuel effects on cruise emissions and contrail properties

Future Research

- SE-11 APU fuel tests to:
  - ✓ Establish Black Carbon (BC) concentrations and characteristics as a function of fuel aromatic-hydrocarbon/hydrogen content
  - ✓ Investigate fuel sulfur oxidation and volatile particle formation
  - ✓ Examine the links between soot characteristics and cloud and ice nucleation potential

- Sample contrails in national airspace to:
  - ✓ Establish range of BC concentrations and characteristics in exhaust from a wide range of modern aircraft
  - ✓ Examine the links between BC properties and contrail ice concentrations and micro-physical characteristics
  - ✓ Investigate the evolution of exhaust PM and contrail ice over minutes to hours as plumes mix with background air

Future Research

- Sample taxi, approach and takeoff plumes at airports to:
  - ✓ Establish the range of PM number and mass emissions from next generation aircraft burning current fuels
  - ✓ Determine the composition and CCN potential of aged aircraft PM emissions
  - ✓ Further examine the links between fuel sulfur and volatile particle formation

- Conduct ground and airborne exhaust sampling experiments with modern aircraft burning alternative fuels to:
  - ✓ Establish detailed PM emission factors for next generation of aircraft engines
  - ✓ Examine effects of low PM emissions on contrail ice and radiation characteristics