Fuel Composition & Aircraft Emissions

Presented to: CAAFI Biennial General Meeting

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Office of Environment and Energy
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Date: December 4, 2018

FAA Efforts to Address Aircraft Emissions

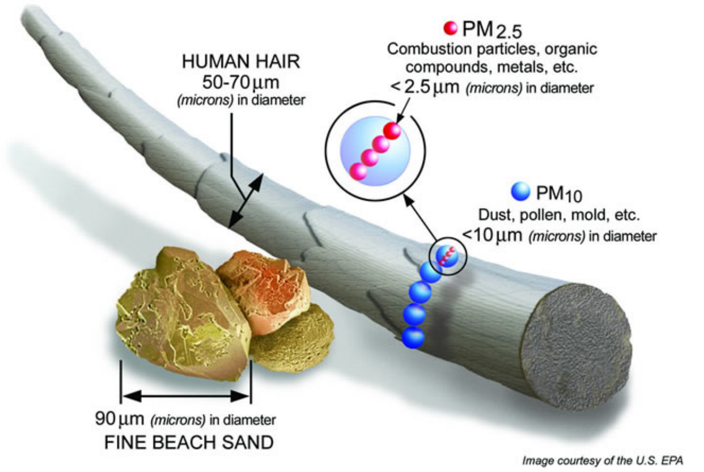
- **Understanding Impacts**
  - Particulate Matter (PM) measurements and modeling
  - Improving air quality and climate modeling capabilities
  - Evaluating current aircraft, commercial supersonic aircraft, unmanned aerial systems, and commercial space vehicles
- **Mitigation**
  - Engine standard (CAEP PM standard)
  - Policy measures (CORSIA)
  - Vehicle operations
  - Modifications to fuel composition
  - Alternative fuel sources
  - Airframe and engine technology
  - Aircraft architecture

Particulate Matter

- Epidemiological studies link long-term exposure to fine Particulate Matter ($PM_{2.5}$) to increased risk of premature mortality [Dockery et al. (1993); Pope et al. (2002); WHO (2008); Pope et al. (2009); USA EPA (2011)]

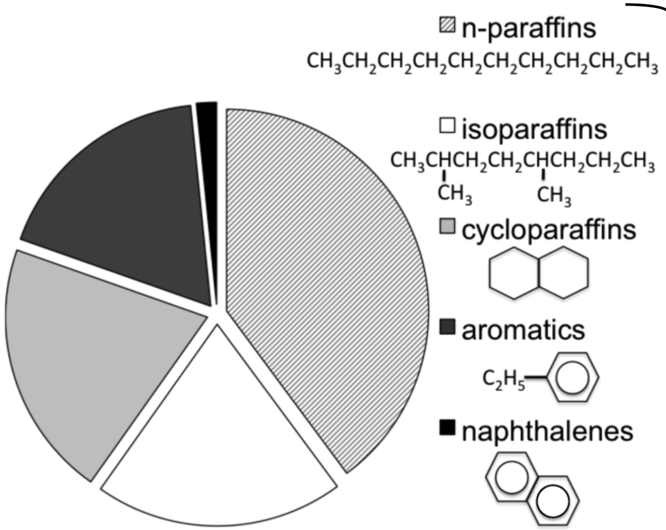
- Particulate Matter consists of particles and liquid droplets
  - Particulate Matter = PM_{10} = diameter ≤ 10 μm (enters lungs)
  - Fine Particulate Matter = $PM_{2.5}$ = diameter ≤ 2.5 μm (enters blood)
  - Ultrafine Particulate Matter = $PM_{0.1}$ = diameter ≤ 0.1 μm (could enter systems)

- PM from aircraft engines:
  - Soot (a.k.a., non-volatile PM, black carbo
  - Volatile organic compounds from engine sulfate and nitrates & atmospheric amm
  - Aircraft engine PM is sufficiently small to qualify as ultrafine particulate matter



http:/ / www3.epa.gov/ airquality/ particlepollution/ basic.html

Using Fuel Composition to Reduce Emissions

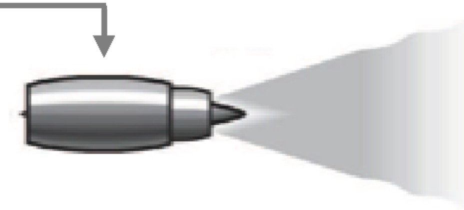


Weighted Mean Fuel Sulfur Content (PPM)		
	2006	2007
US East	446	321
US Gulf	858	800
US West	240	395
Nationwide	709	677

Fuel composition and engine design determine emissions

Fuel: $C_nH_m + S$

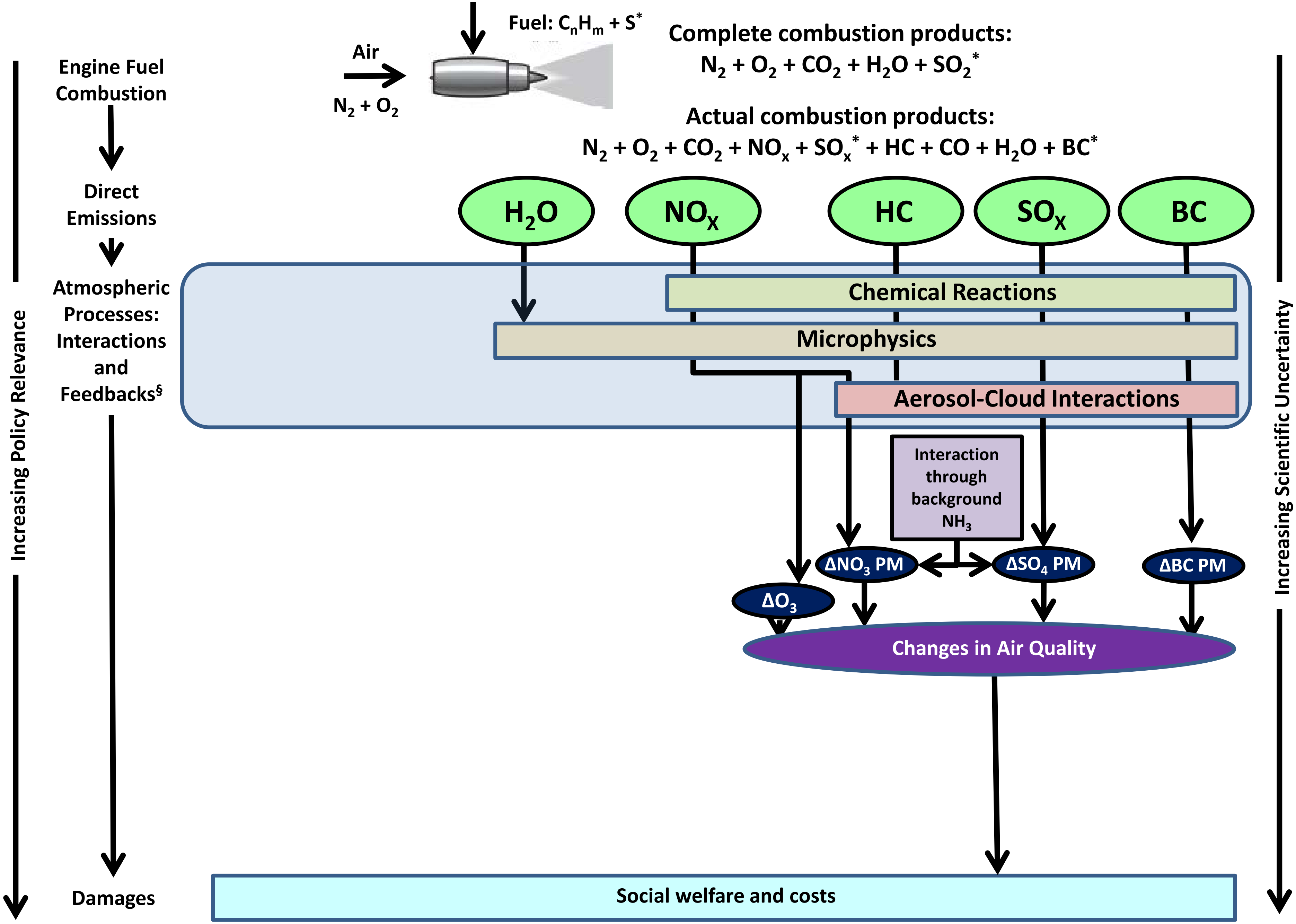
Air: $N_2 + O_2$



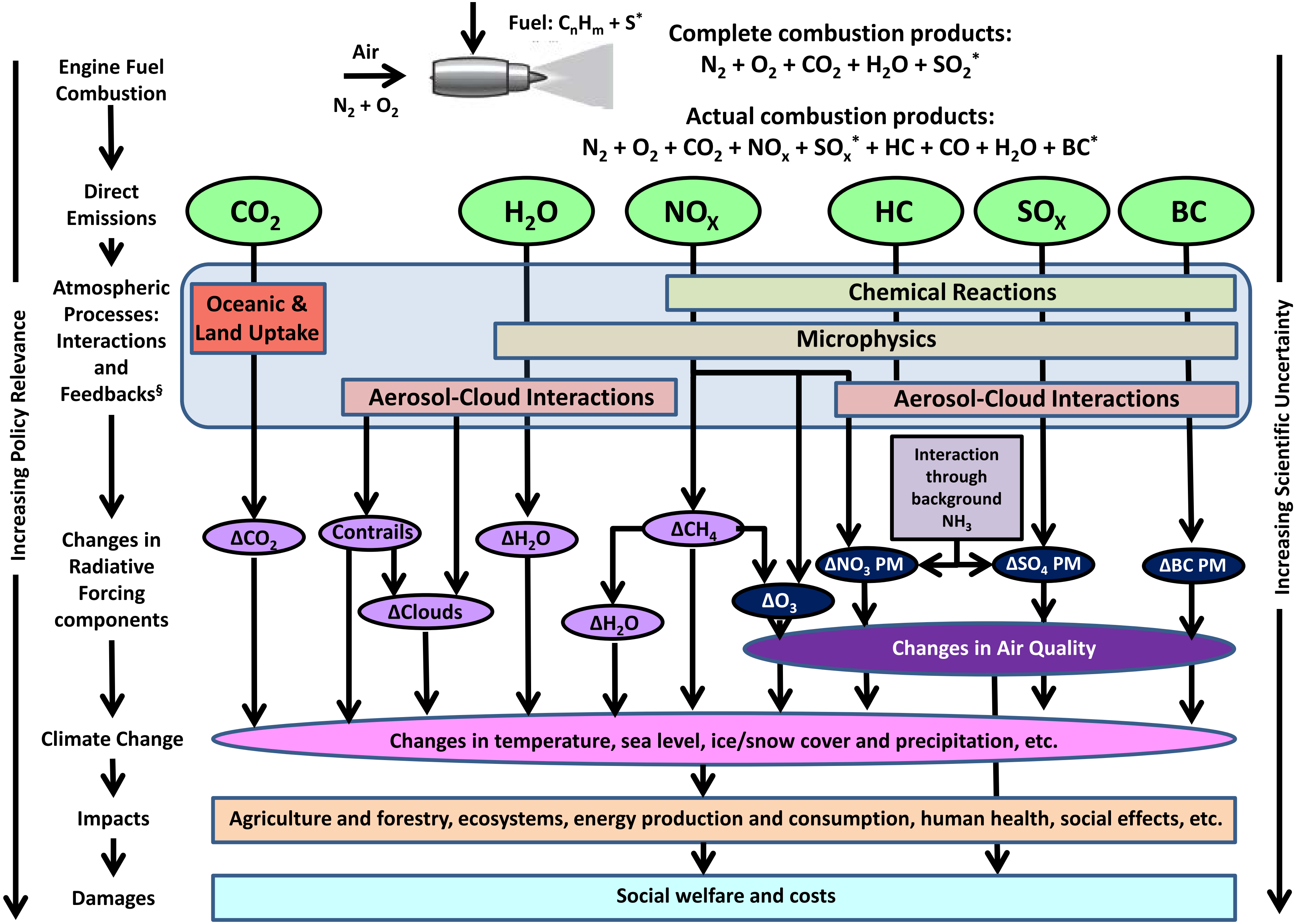
Tank-to-Wake Actual Combustion Emissions

$CO_2 + H_2O + NO_X + SO_X + soot + CO + HC + N_2 + O_2$

Conducting cost-benefit analyses to understand if the benefits of modifying fuel composition outweigh the economic costs (research effort at MIT under PARTNER/ASCENT)



§Account for radiative, chemical, microphysical and dynamical couplings along with dependence on changing climatic conditions and background atmosphere

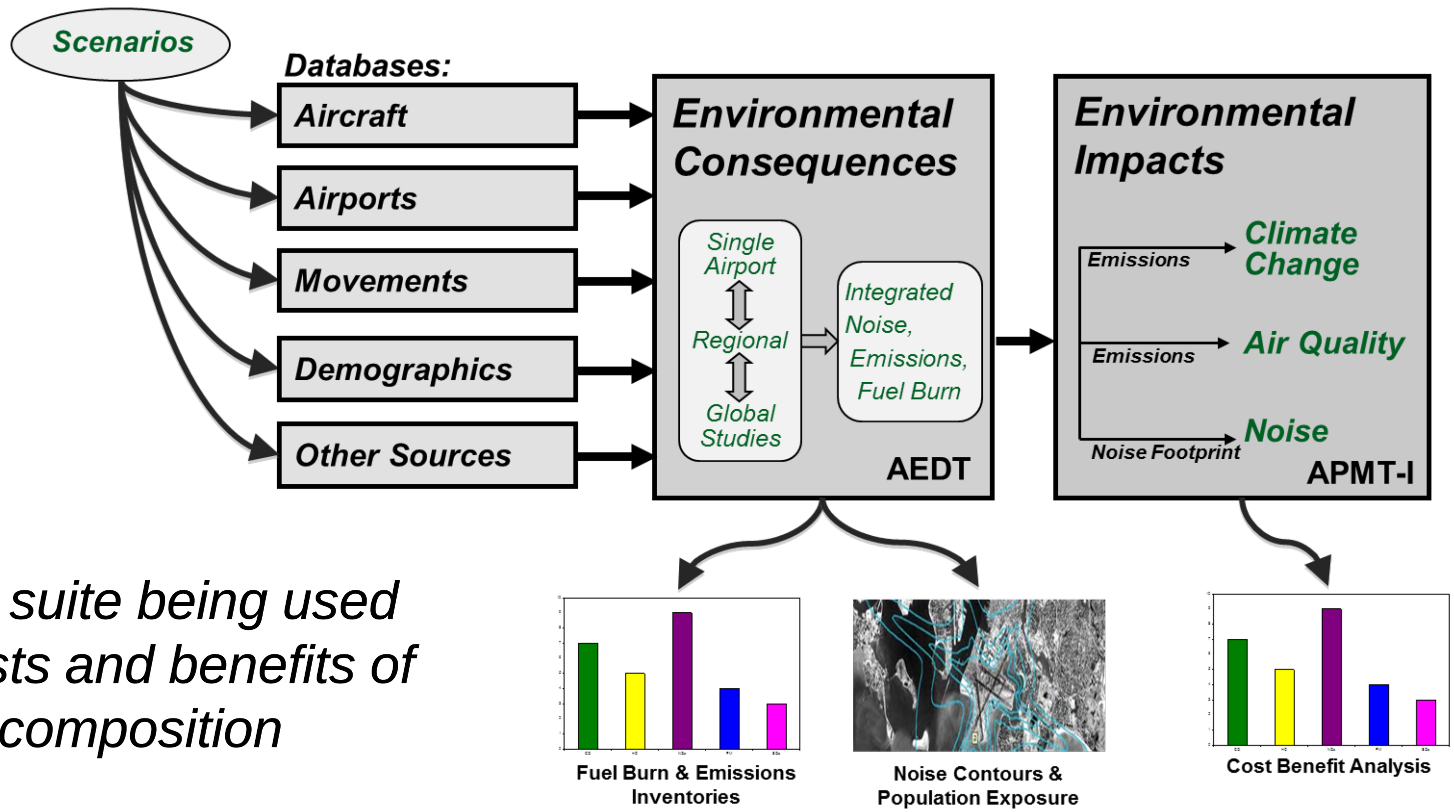


§Account for radiative, chemical, microphysical and dynamical couplings along with dependence on changing climatic conditions and background atmosphere

ASCENT COE Projects 20 and 21 and PARTNER Project 3 (2006 to present)

APMT-Impacts Cost Benefit Analysis Tools

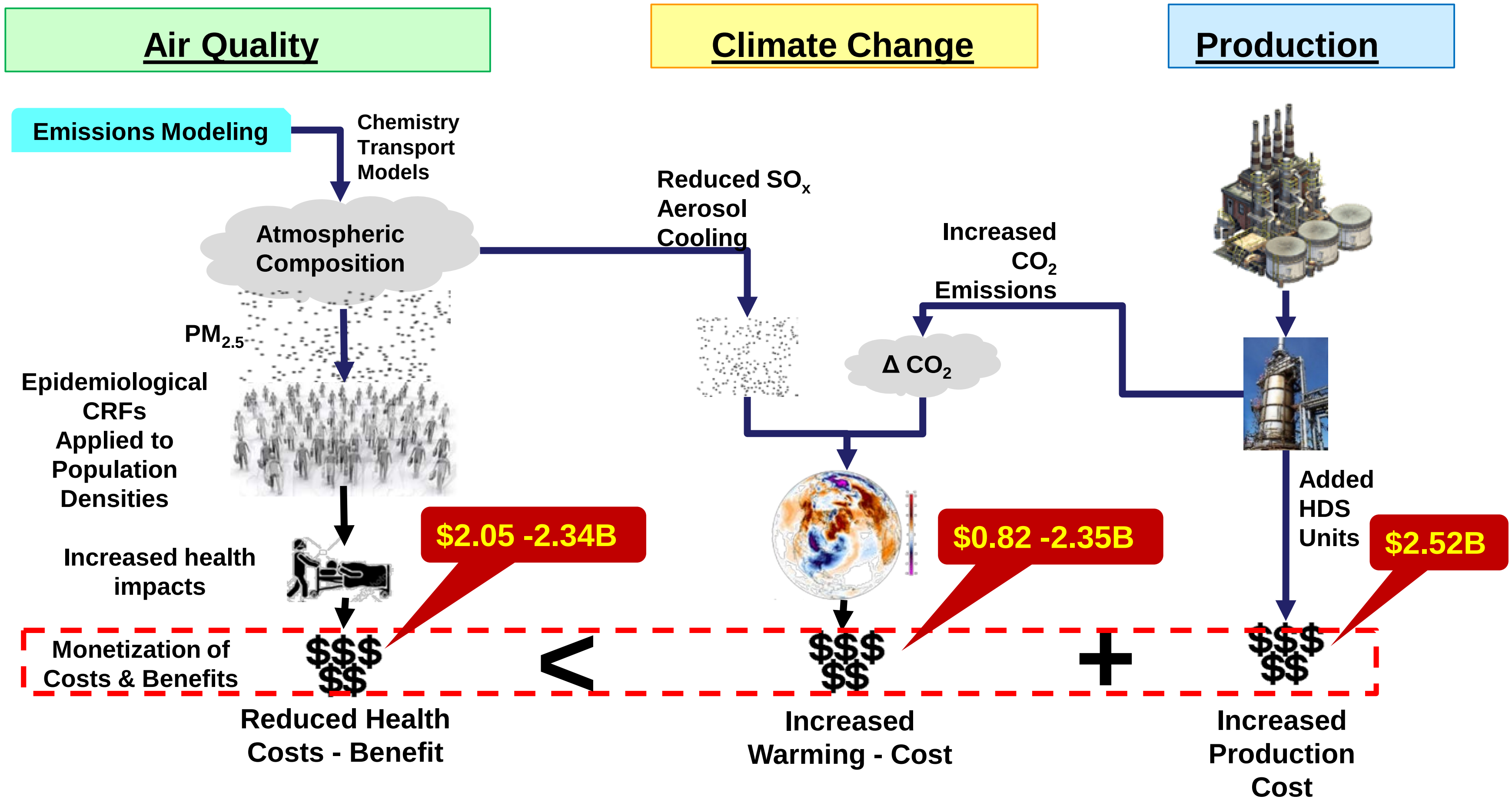
Changes in aviation technology could impact noise, global climate and air quality. Developed an aviation environmental tool suite to assess the impacts of noise and emissions to inform decision-makers.



Analytical tool suite being used to quantify costs and benefits of changing fuel composition

PARTNER COE Project 27 (2007-2011)

Sulfur Removal Cost-Benefit Analysis



Naphthalene Removal Cost-Benefit Analysis

Naphthalene in jet fuel identified as disproportionate contributor to soot emissions

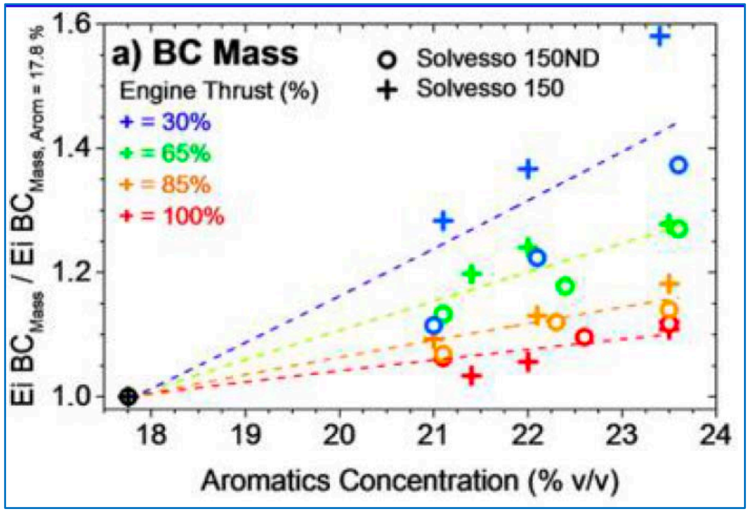
- Air Quality & Health Impact
- Climate Impact via Contrail Formation

Two means of fuel treatment considered

- Hydro-treatment (aromatics and sulfur)
- Extractive Distillation (aromatics alone)

Production costs (preliminary values)

- Societal economic cost: $0.06 to $0.09 per gal
- Market cost to refiner: $0.11 to $0.18 per gal



Key [1]

O :Jet A w/ Naphthalene-Depleted Aromatic Additive

+ :Jet A w/ Aromatic Additive

Monetized environmental impacts (preliminary values)

- Assumed 15% to 40% reduction in nvPM from change in fuel composition
- Air quality benefit (decreased impact): $0.00 to $0.04 per gal
- Climate cost (increased impact): $0.00 to $0.15 per gal (due to increased refining emissions, loss of sulfate aerosols, and assumption of no change in contrails)

Summary

- **Changes in fuel composition could reduce emissions**
  - Get reduced nvPM with reduced fuel aromatics – expect larger impact with reductions in naphthalenes and other more complicated aromatic compounds
  - Get reduced sulfates with reduced fuel sulfur content
- **Environmental impacts from reduced nvPM and sulfates**
  - Air quality benefit - less particulate matter pollution from aircraft operations
  - Climate impact is mixed – less radiative forcing from black carbon but increased radiative forcing from removal of sulfates and contrail impact is uncertain
- **Sulfur and Naphthalene Removal Cost-Benefit Analyses (CBA)**
  - Expect a net cost from reducing sulfur concentration in jet fuel to ULS levels
  - Might be a net cost with naphthalene removal using HDS and extractive distillation, but need to account for contrail impacts before being certain
- **Study Implications**
  - CBA studies are exploratory in nature - interested in knowing the relative merits of various means of reducing emissions from aircraft engines
  - Alternative jet fuels would provide air quality benefits relative to conventional fuel
  - Need to know more about contrail formation to get full story on climate impacts associated with changes in jet fuel composition

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AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP 02-80
Quantifying Emissions Reductions at Airports from the Use of Alternative Jet Fuels

CAAFI Biennial General Meeting 2018

Dr. Uven Chong, Booz | Allen | Hamilton

December 6, 2018

Booz | Allen | Hamilton

- ✓ Philip Soucacos
- ✓ Dr. Uven Chong
- ✓ Dr. Akshay Belle
- ✓ Clare Murphy
- ✓ Amandine Coudert

The Environmental Consulting Group LLC

- ✓ Sandy Webb

Missouri S&T

- ✓ Dr. Philip Whitefield
- ✓ Dr. Don Hagen

Csonka Aviation Consultancy, LLC

- ✓ Steve Csonka

ACRP Senior Program Officer: Joe Navarrete

Presentation Outline

Contents

- Project Background
- State of the Industry Report
- Quantification Methods
- Airport Dissemination

The objective of this research is to develop a method to help airport industry practitioners estimate potential emissions impacts by the use of ASTM-certified alternative jet fuels.

Key Research Products

- **State of the Industry Report:** A stand-alone report that includes a literature review and gap analysis of existing knowledge of emissions from SAJF.
- **Emissions Reductions Methodology:** A process that quantifies the emissions impacts that will allow airports to capture the air quality benefits from the use of SAJF.
- **Alternative Jet Fuel Emission Reduction Fact Sheet:** Quick slick-sheet that showcases the benefits of using alternative jet fuels at airports.
- **Case Studies and Alternative Jet Fuel Assessment Tool:** A tool under an Inputs-Calculations-Outputs model with scenario analysis and optimization routines.

1 **Emissions Quantification Plan and Review**

- Conduct Literature Review
- Develop Plan for Quantifying Emission Impacts

Completed

2 **E.Q. Methods Creation and Validation**

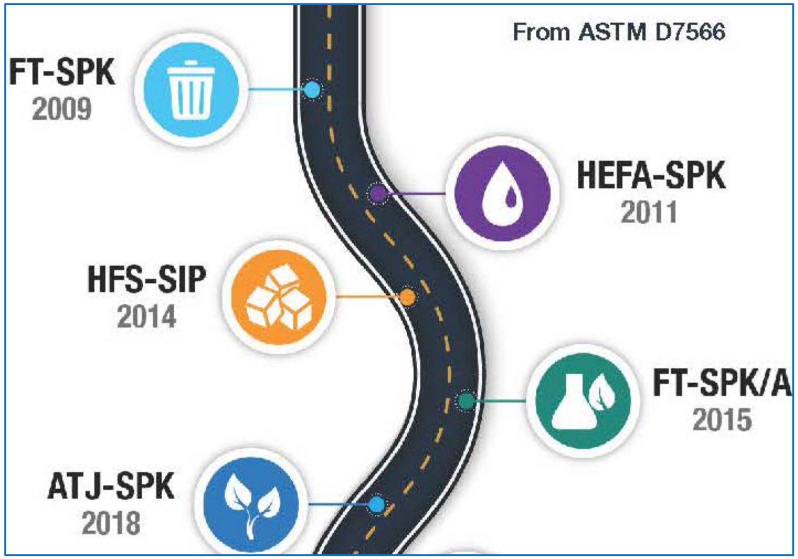
- Create Emissions Quantification Methodologies
- Conduct Independent Review
- Identify Case Studies

Completed

3 **Development of Tool and Final Deliverables**

- Develop Alternative Jet Fuel Assessment Tool
- Conduct Case Studies
- Create Fact Sheet & eLibrary
- Final Deliverables

Expected Publication
March – May 2019



Purpose

- Captured the current status of knowledge regarding emissions from the use of sustainable alternative jet fuels (SAJF).
- Collected, reviewed, and compiled data from reports of SAJF emissions tests sponsored by DOD, NASA, FAA, OEMs, fuel producers, university labs, and technical government briefings/reports.

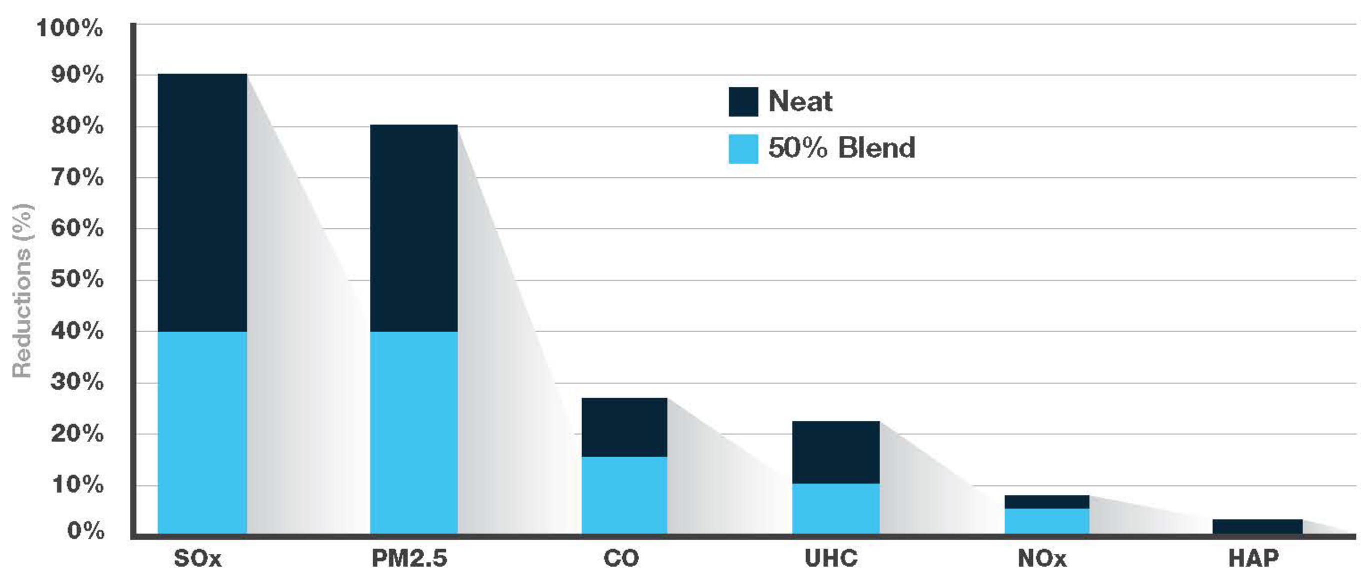
Document Hits	Search Criteria
35,136	Alternative jet fuel emissions
9,369	Alternative jet fuel emissions + criteria pollutants
73	Alternative jet fuel emissions + criteria pollutants + emission measurements
51	Reports with quantitative emissions analysis (used in this literature review)

Key Findings:

SAJF when blended with conventional jet fuel has:

- Significant reductions on SO_x and PM emissions
- Modest reductions on CO and UHC emissions
- Minimal reductions or no effect on NO_x emissions

REVIEWED BY THE ACRP PANEL PRIOR TO PUBLICATION



State of the Industry Report

Project Background	State of the Industry Report	Quantification Methods	Airport Dissemination

PUBLISHED

The State of the Industry Report is published on the ACRP 02-80 website. It can be downloaded from this link:

http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4238

Approach to Quantify Emissions

1 Critical Metrics

Identify critical metrics that define the positive or negative impact of burning SAJFs (e.g. engine type, operating condition, fuel composition, blend %, weather)

2 Pollutant Specific Impacts Spreadsheet

Generate a pollutant specific spreadsheet based on the metrics identified and quantify the observed impacts, typically represented by percent changes in the emission indices

3 Pollutant Specific Impacts Data Assessment

Assess the pollutant specific data to determine the extent to which a functional analysis per metric can be performed

4 Development of functional impact relationships

Develop functional impact relationships for those species identified, i.e. having sufficient data to support the functional analysis.

5 Functional Analysis

Fit suitable functions to the measured data using general linear least squares methodology

6 Interface Pollutant Impact Analysis to AEDT

Report the pollutant, fuel, and engine specific impact relationships to use with the Aviation Environmental Design Tool (AEDT)

Requirements

1. Create material for non-experts on a complex topic.
2. Provide background on SAJF
3. Present ACRP 02-80 results

Audience

Airport employees who are not necessarily environmental or air quality specialists or scientists.

FOCUS

- Present basic knowledge of the air quality issues related to SAJF.
- Identify potential benefits of using SAJF.
- Reference sources of information and tools to provide the audience with concrete and actionable next steps.

Alternative Jet Fuel Assessment Tool

Project Background | State of the Industry Report | Quantification Methods | **Airport Dissemination**

Content:

- Results of the emissions quantification methodology.
- Functionality for airports to evaluate the use of SAJF at their airport.

Status:

- A draft design has been built and discussed with Subject Matter Experts.
- The tool is currently being reviewed internally and will be submitted for Panel review within the month.

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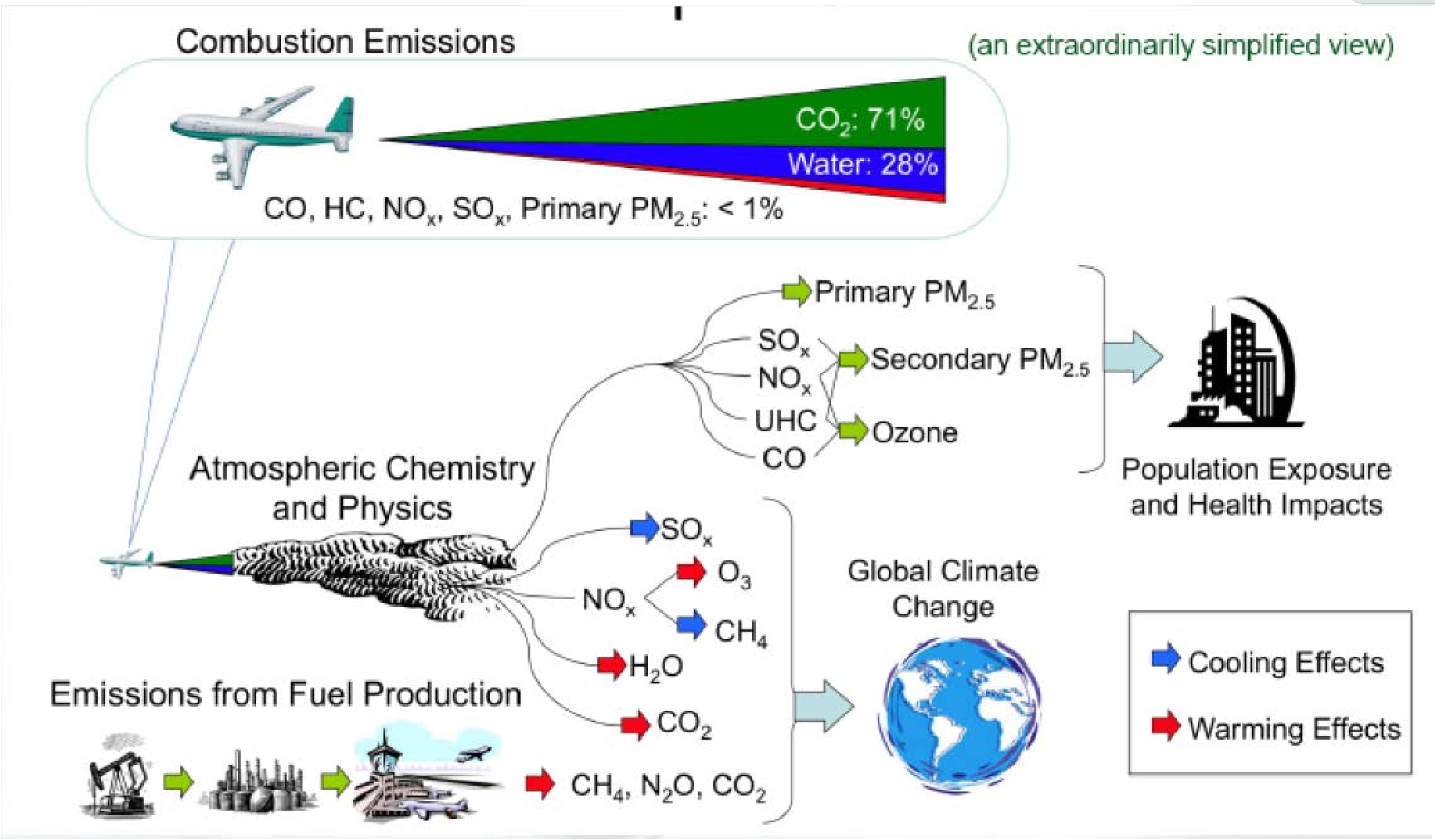
ECLIF - Emission and Climate Impact of Alternative Fuels
ND-MAX – NASA/DLR Multi-Disciplinary Experiment

CAAFI Biennial General Meeting

4-6 December 2018, Washington DC

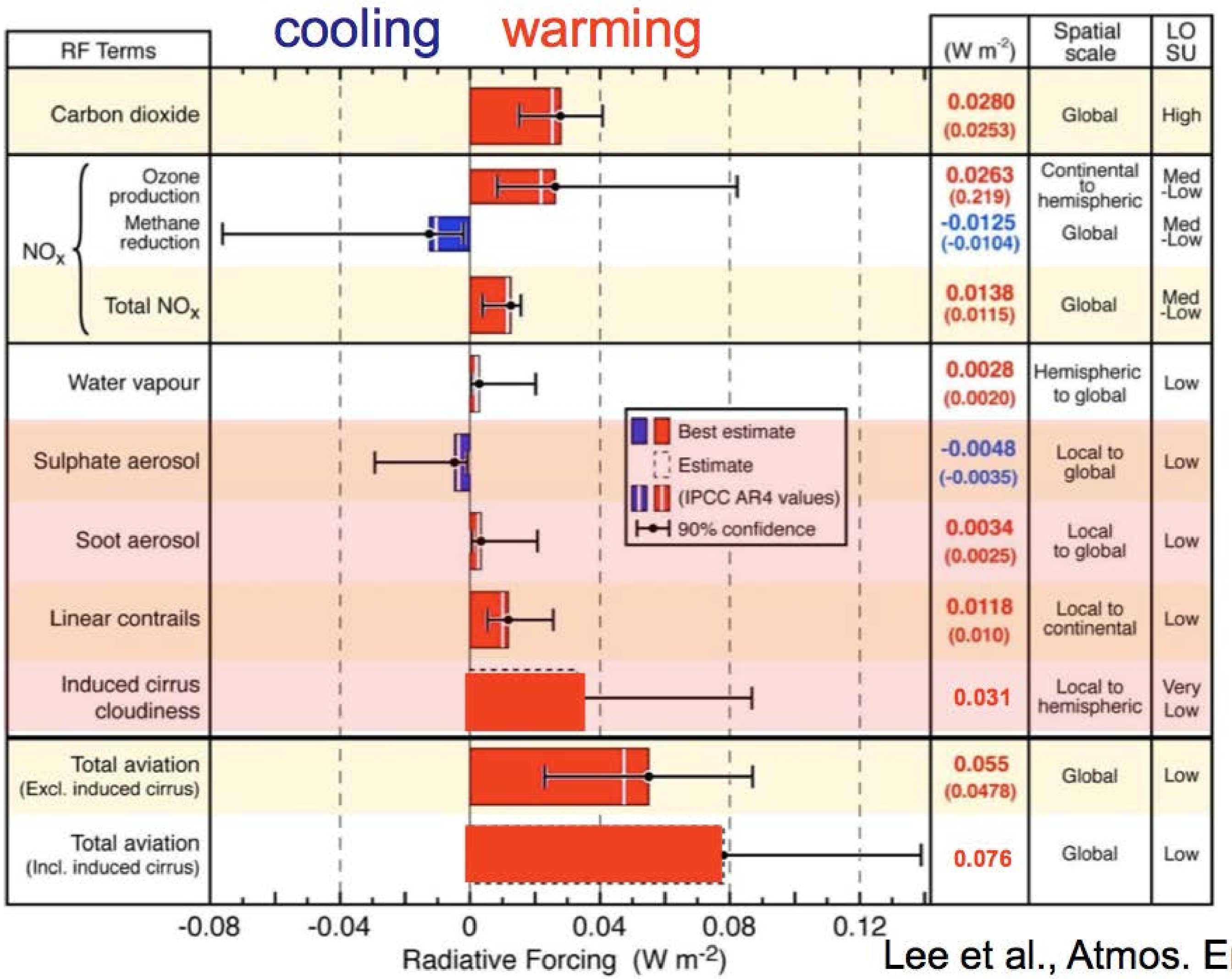
Presented by Patrick Le Clercq, DLR
Bruce Anderson, NASA

Aircraft Emissions Impact



Contrails and Climate Impact

Radiative Forcing Components from Aviation in 2005



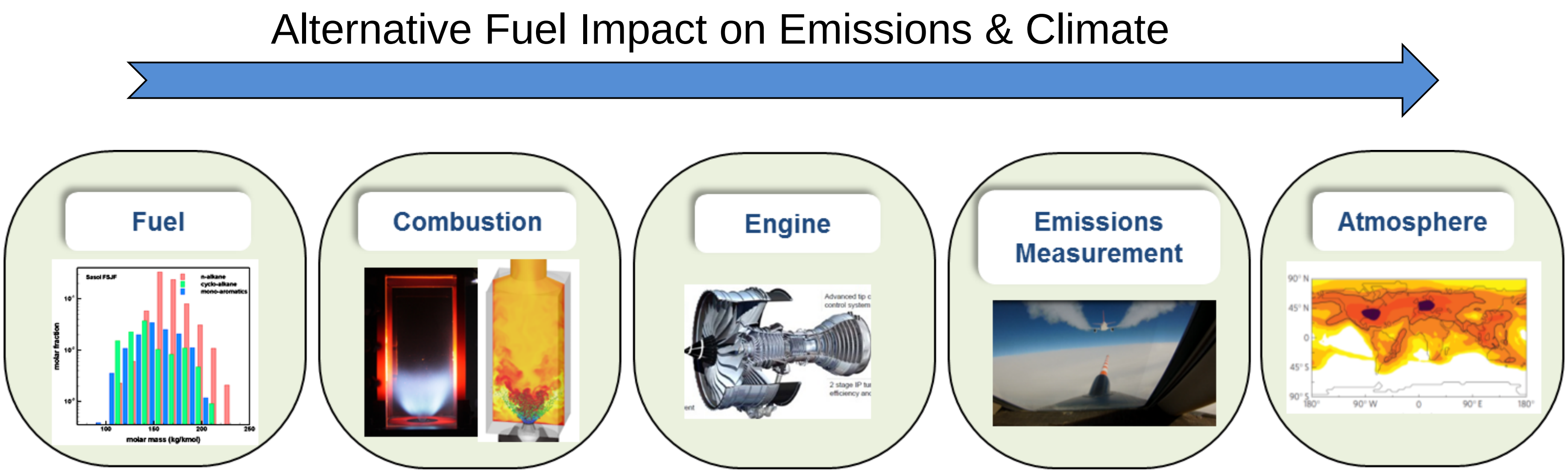
Lee et al., Atmos. Env., 2009

Total anthropogenic radiative forcing (RF) was 1.6 W/m^2

Aviation with 0.076 W/m^2 represented ~5%

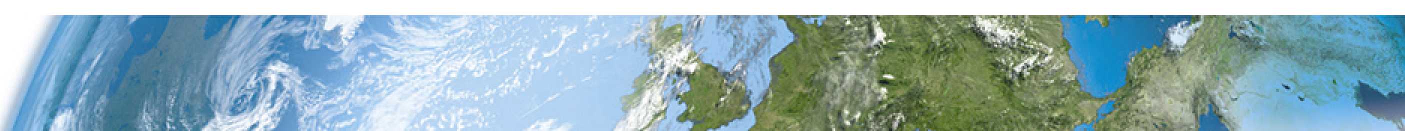
Recent models suggest that aviation induced cirrus cloudiness (0.031 W/m^2) is the largest RF contribution from aviation

ECLIF Objective and Overview



→ Investigate all the steps from fuel composition to in-situ measurements and climate models to understand

- How does fuel composition, fuel physical and chemical properties, fuel oxidation, and combustion system performance and emissions affect contrails and climate?
- Can alternative aviation fuels help mitigate the aviation induced radiative forcing and its forecasted increase?



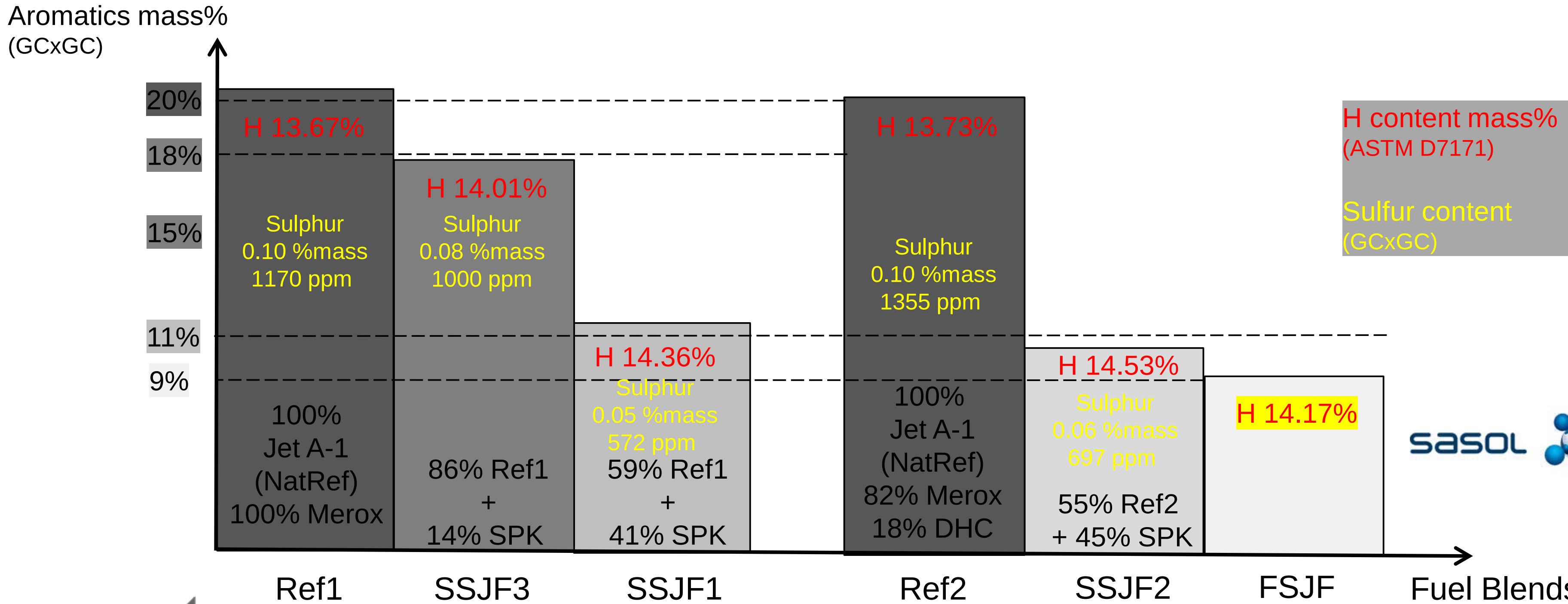
ECLIF – I Measurement Campaign
Scientific Objective & Fuel Strategy

Impact of aromatics content and aromatic molecular structure on soot emissions (ground and in-flight), ice crystals formation, and contrail properties

Fuel Strategy

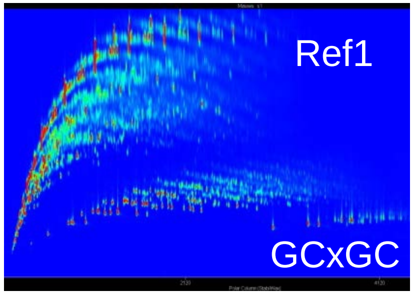
Impact of aromatics content on soot formation

Impact of aromatics **structure** on soot formation



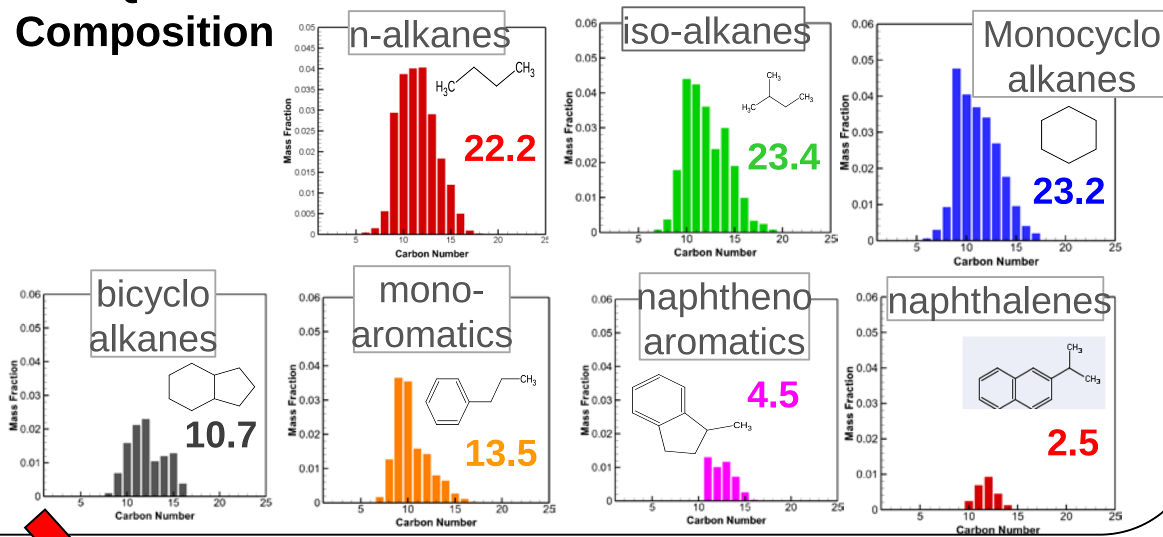
ECLIF Fuels – Modeling Physical & Chemical Properties

Jet Fuel Analytics
(SASOL)

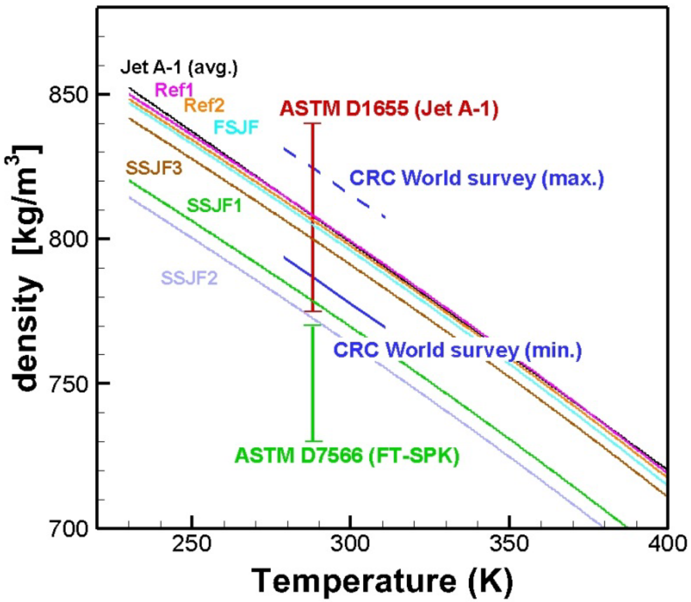


Complex mixture with hundreds of hydrocarbons

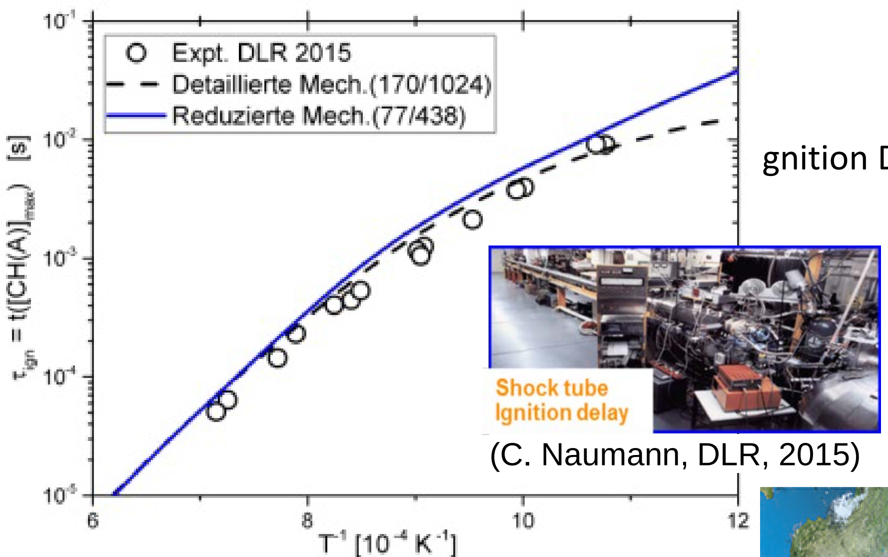
Jet Fuel Quantitative Composition



Physical Properties



Chemical Properties

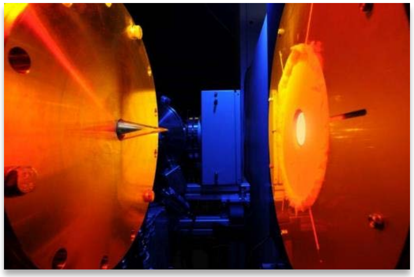


gnition Delay Time

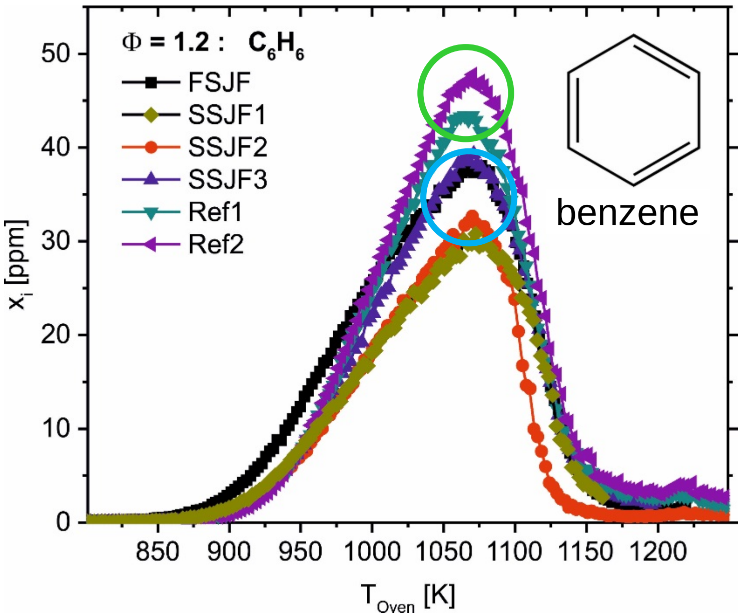
(C. Naumann, DLR, 2015)

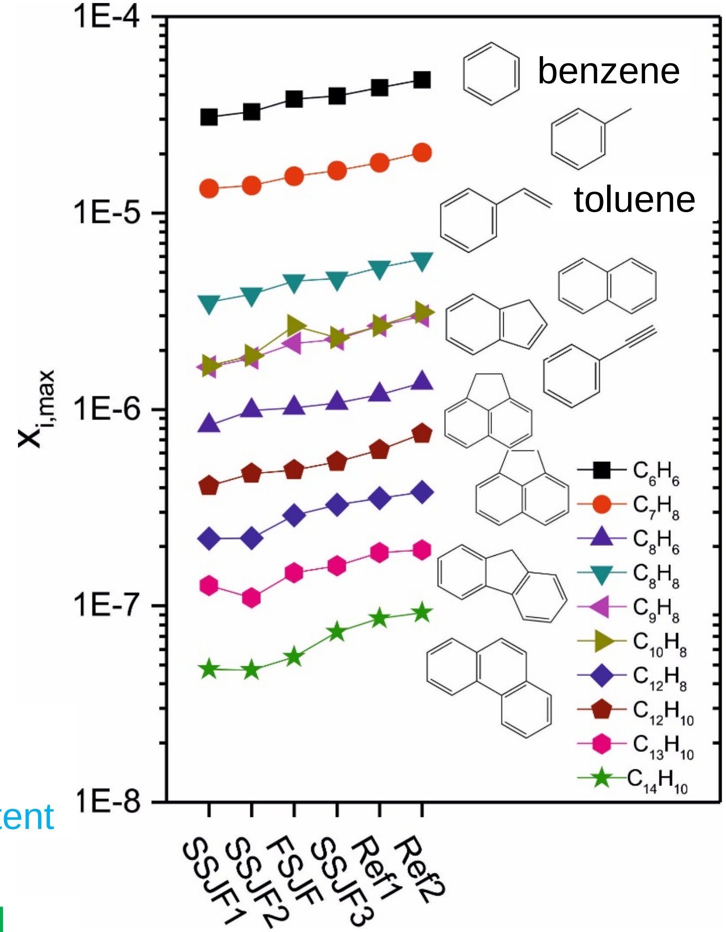
ECLIF – Combustion Properties

Soot precursors profiles in flow reactor



Flow reactor
Species profile
(P. Oßwald, DLR, 2016)



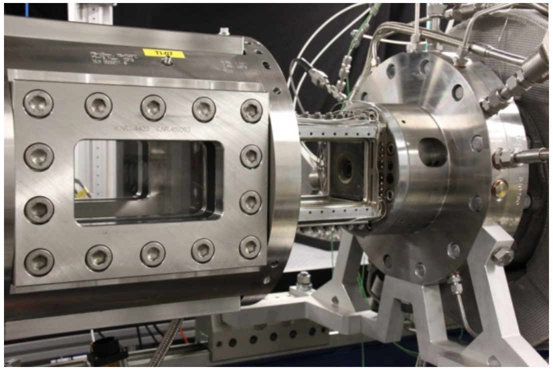


SSJF2: 11 m% aromatics & 14.65m% H
FSJF: 9 m% aromatics & 14.25m% H
→ C6H6 concentration scales with H content

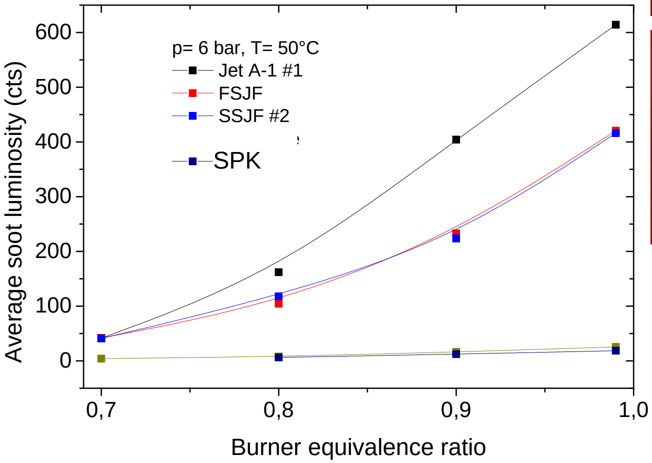
Ref2: 20.2 m% aromatics & 13.86 m% H
Ref1: 20.5 m% aromatics & 13.85 m% H
→ Impact of aromatics structure: Ref2 has 0.8m% more naphthalenes (di-aromatics)

ECLIF – Combustion Rig Test & CFD

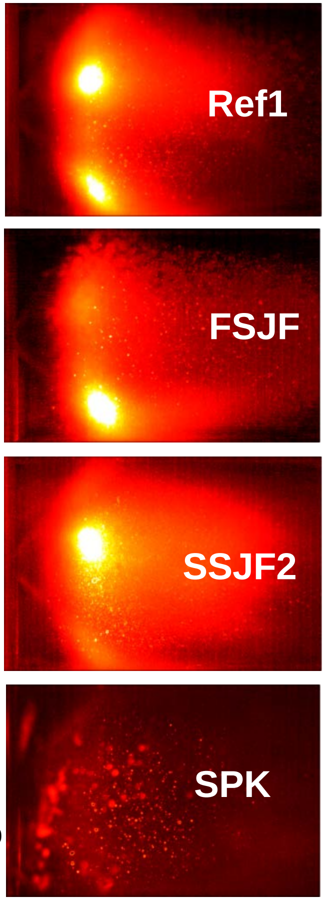
Soot emissions in high pressure single sector rig



Hi-POT
High Pressure single sector rig



Soot luminosity
p=6 bar, T_{air}=323 K, Φ=0.99



(T. Mosbach, DLR, 2016)

Qualitatively

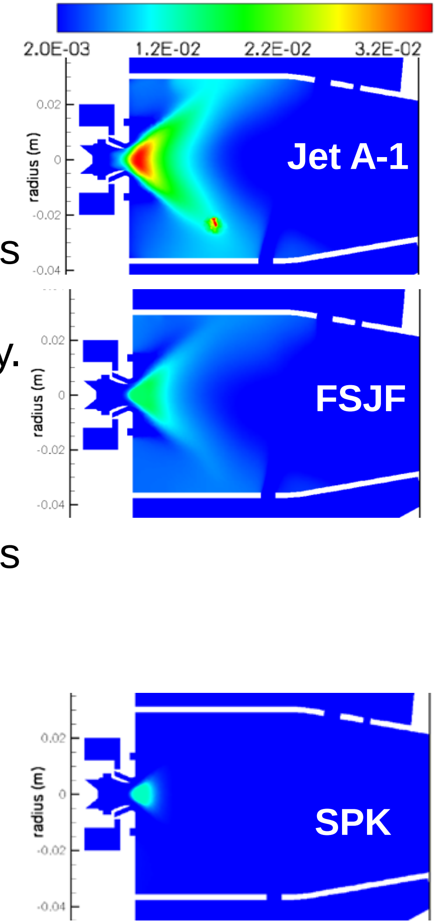
← Experiment:

The lower the aromatics content the lower the average soot luminosity.

Simulation: →

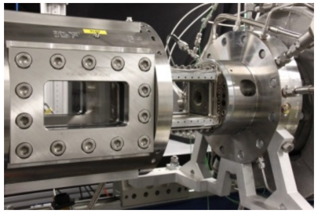
The lower the aromatics content the lower the soot precursor concentration.

Benzene concentration
p=6 bar, T_{air}=700 K, Φ=0.99

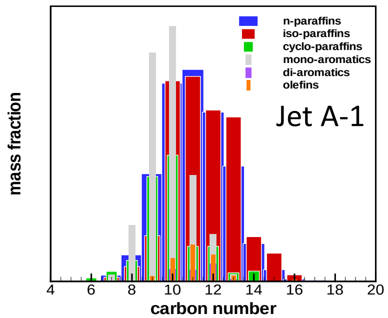


(P. Le Clercq, DLR, 2010)

Fuel Design

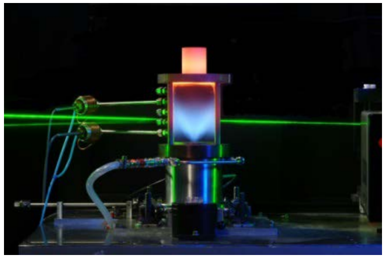


HP Rig



Composition

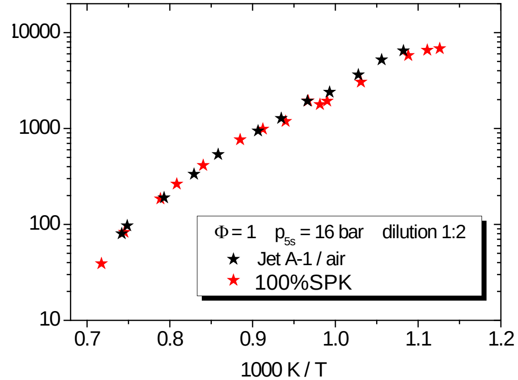
Generic Spray Burner



Data Base

Measurement

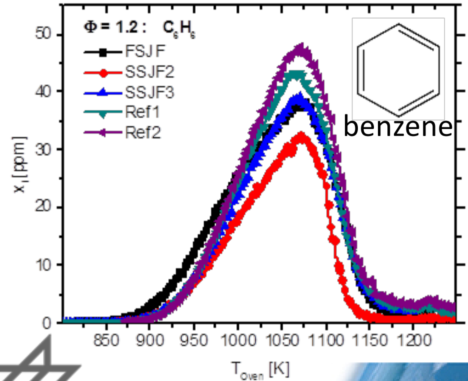
Ignition Delay Time



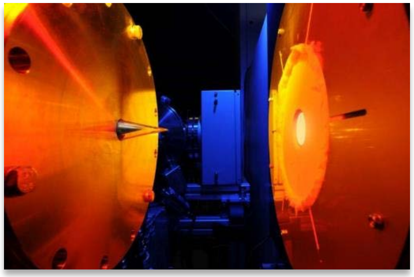
Diagnostics

Lab-scale Exp.

Species Profile



Plug Flow Reactor



DLR

ND-MAX/ECLIF – II Measurement Campaign

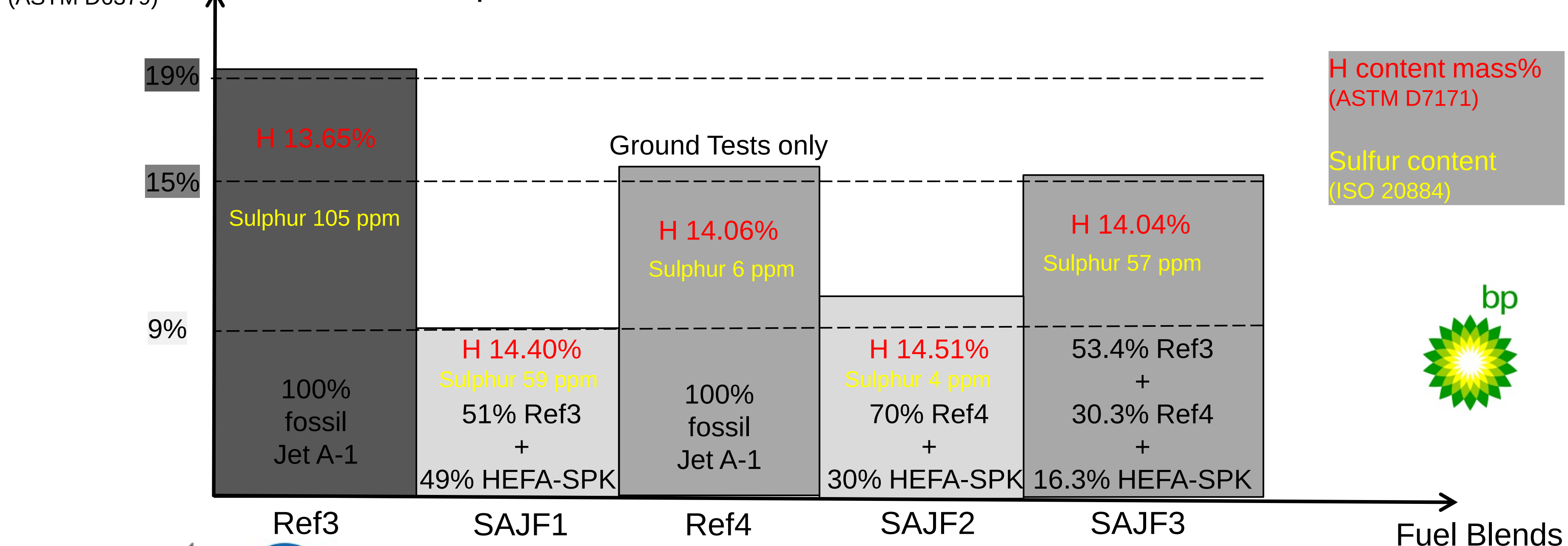
Scientific Objective & Fuel Strategy

Economically and industrially more feasible SAJF based on 30% HEFA (SAJF2) to achieve same 50% soot emissions reduction as a 50-50 blend (SAJF1).

Fuel Strategy

Impact of aromatics structure on soot emissions

SAJF1 slightly less aromatics w/r SAJF2,
very close H-content, 14.40%m/m and 14.51%m/m respectively.
SAJF1 has 0.59vol% naphthalenes, SAJF2 has an order of magnitude less naphthalenes: 0.042vol%.



ECLIF – I Measurement Campaign

Manching 21.09.2015 – 09.10.2015

Two Airfields & Two aircrafts

- WTD61 Airfield in Manching
  Base for Airbus A320-232 D-ATRA
  (Advanced Technology Research Aircraft)
  equipped with two IAE V2527-A5 engines.
  Fuel storage, tanking procedure,
  and ground measurements.
- DLR Airfield in Oberpfaffenhofen
  DLR Falcon 20E CMET as chaser + scientific team

Fuel Logistics

- 118 MT of fuel from Sasolburg, ZA to Manching, DE
- Customs in Hamburg, short-term storage in Munich and, delivery + TÜV certified storage in Manching
- 8 Iso-containers stored on the WTD61 apron#2
- Sampling, de-fueling and, fueling procedures after each flight
- Certificates of Analysis from Sasol for each blend, then cross-checked with WIWeB analysis (after flight samples)

ECLIF – II Measurement Campaign

Ramstein 15.01.2018 – 06.02.2018

One Airfield and two Aircrafts

- Ramstein Air Base, Germany
  DLR A320 ATRA parked on apron #5
  NASA DC-8 parked either in Hangar 5 or apron.
- Probe mounted on blast fence + 2 containers for instruments: DLR, NASA, NRC Canada, Missouri S&T, Aerodyne, Uni. Oslo to perform ground tests

Fuel Logistics

- 163 Tons (5 sorts), HEFA blend stock from California (Altair) and Jet A-1 from Germany (Gelsenkirchen & Schwedt) were used for the blending.
- 7 Iso-containers + 3 US Air Force Tank Trucks for fuel storage in Ramstein
- Sampling, de-fueling and, fueling
- Certificates of Analysis from Air BP for each fuel.

Advanced Air Transport Technologies

Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Alternative-fuel effects on aircraft emissions and contrails: Results from joint NASA-DLR missions

Bruce Anderson and Patrick Le Clercq

NASA-DLR Joint Atmospheric Measurement Campaigns

NASA ACCESS-II, Palmdale CA, Spring 2014

- NASA DC-8 burned Jet A and 50/50 Jet A Biofuel Blend
- Emissions sampled by NASA HU25, DLR Falcon 20 and NRC CT-133
- Ground emissions sampled by NASA

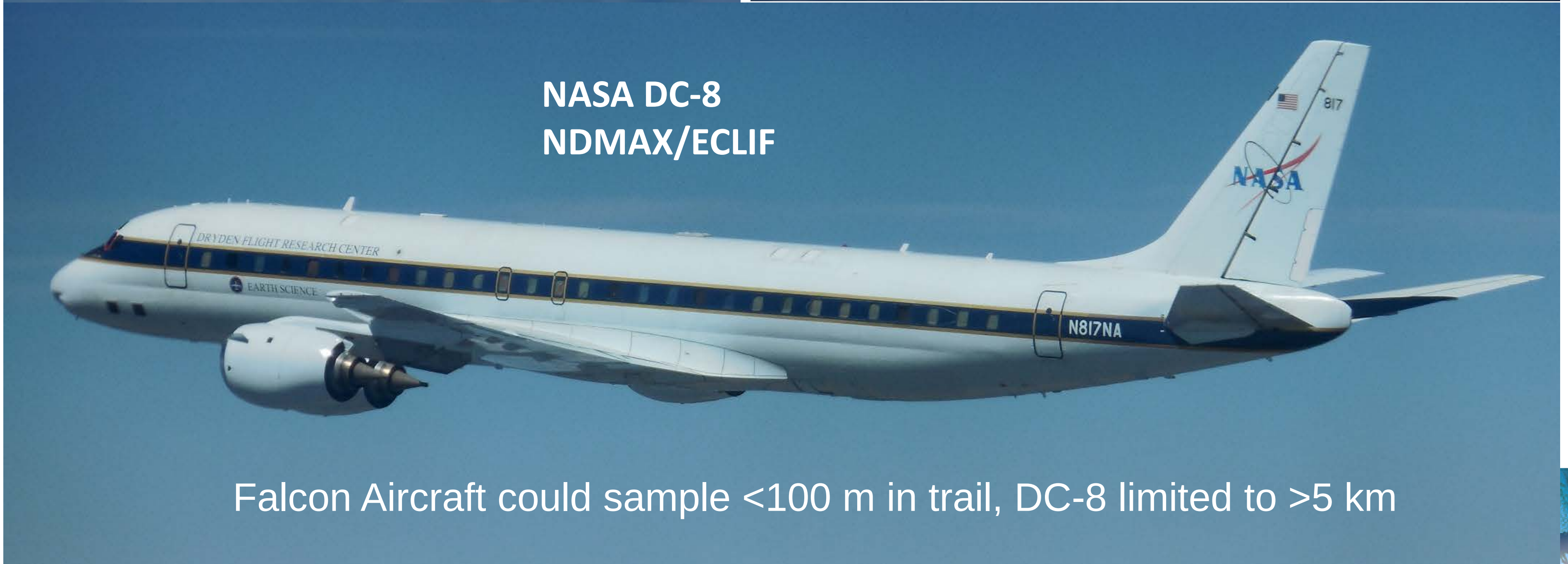
DLR ECLIF-1, Manching Germany, Fall 2015

- DLR A320 burned 2 Jet A reference fuels and 4 blended alt fuels
- Emissions/Contrails sampled by DLR Falcon 20
- Ground emissions sampled by NASA and DLR

NDMAX/ECLIF, Ramstein Germany, Winter 2018

- DLR/NASA Collaboration with Support from FAA and NRC-Canada
- DLR A320 burned Jet A and 3 blended alternative fuels
- Emissions/Contrails sampled by NASA DC-8
- Ground emissions sampled by DLR, FAA, NASA and NRC-Canada

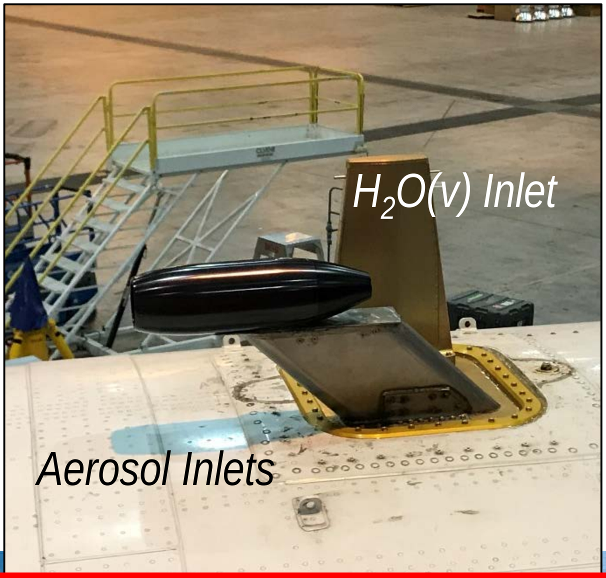
Sampling Platforms



Source Aircraft

ND-MAX/ECLIF DC-8 Instrument Probes and Inlets

Falcon Aircraft were similarly equipped during ACCESS-II and ECLIF-1



Measured aerosols, trace gases and cloud particles during each mission

Ground and Flight Measurements Similar

ACCESS-II, 2014

- **NASA**: Particle number, size, volatility and mass; CO2, NOx

ECLIF-1, 2015

- **NASA:** Particle number, size, volatility and mass; CO2, NOx
- **DLR**: Particle number, size; CO2, CO, NOx, SO2, THC
- **Oslo**: Hydrocarbons

NDMAX/ECLIF, 2018

- **NASA:** Particle number, size, volatility and mass; CO_2, NOx
- **DLR**: Particle number, size; CO_2, CO, NOx, SO_2, THC
- **Oslo**: Hydrocarbons
- **Missouri (FAA)**: Particle number, size, mass **(ICAO Method)**
- **Aerodyne**: Aerosol Composition
- **NRC-Canada**: Particle number, size, mass

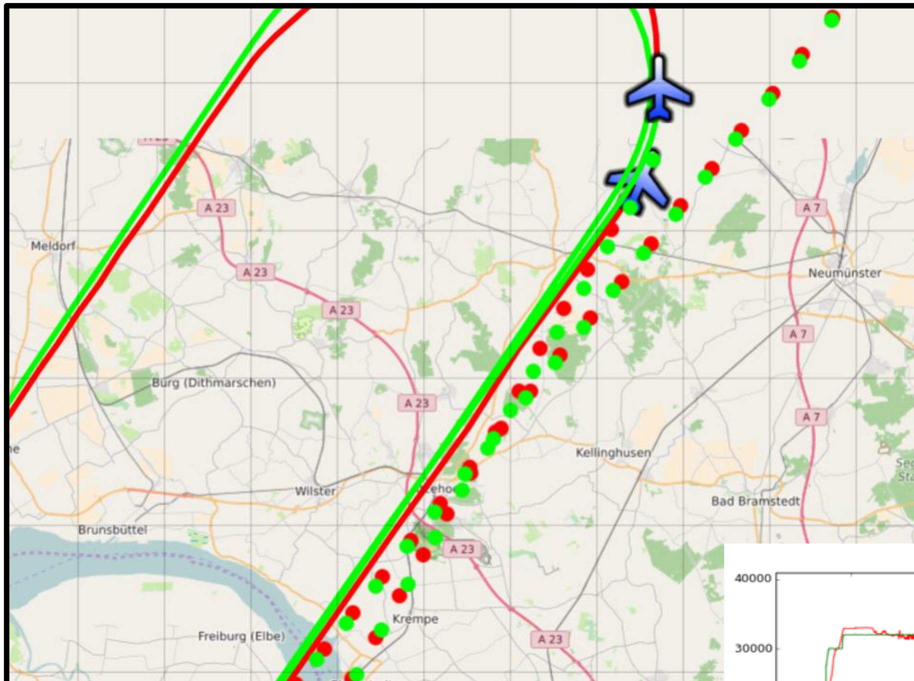
National Research Council Canada / Conseil national de recherches Canada

Missouri S&T

Aerodyne Research, Inc.

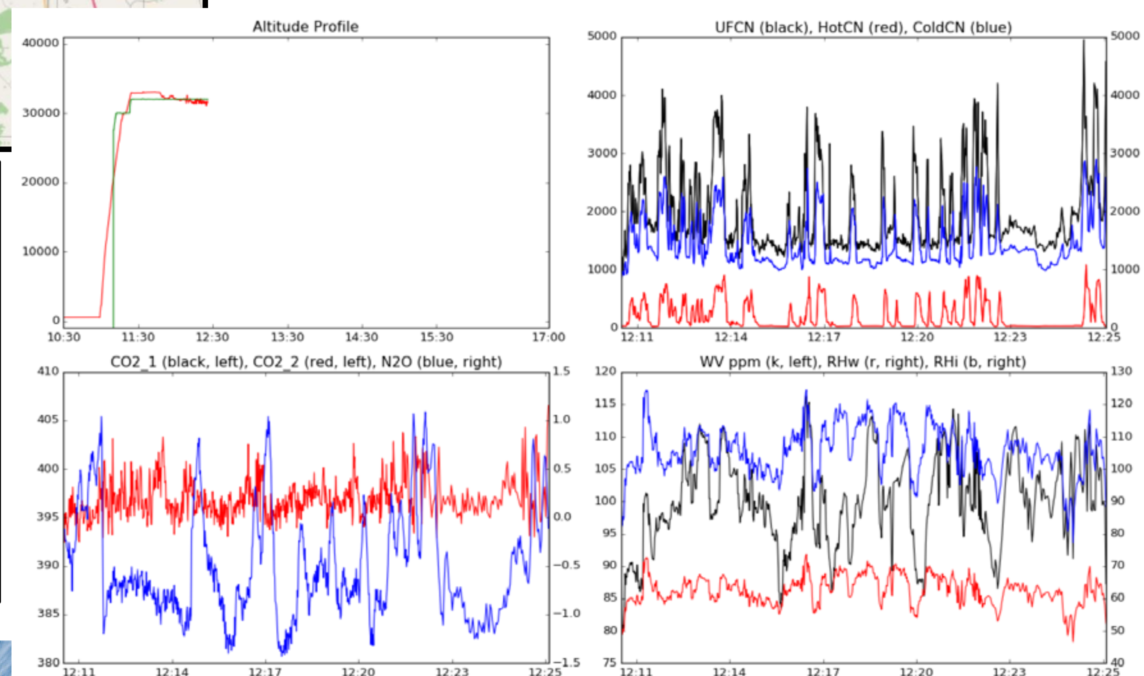
UiO : University of Oslo

Joint Flights Conducted in Restricted Air Space



- Pilots worked with Military ATC to coordinate use of airspace
- Typically flew race tracks at varying speeds and altitudes
- Viewed real-time data from particle instruments to detect crossings

- DC-8 received ADSB output from source aircraft to determine location
- Real time displays of wind-advected flight tracks aided in plume detection



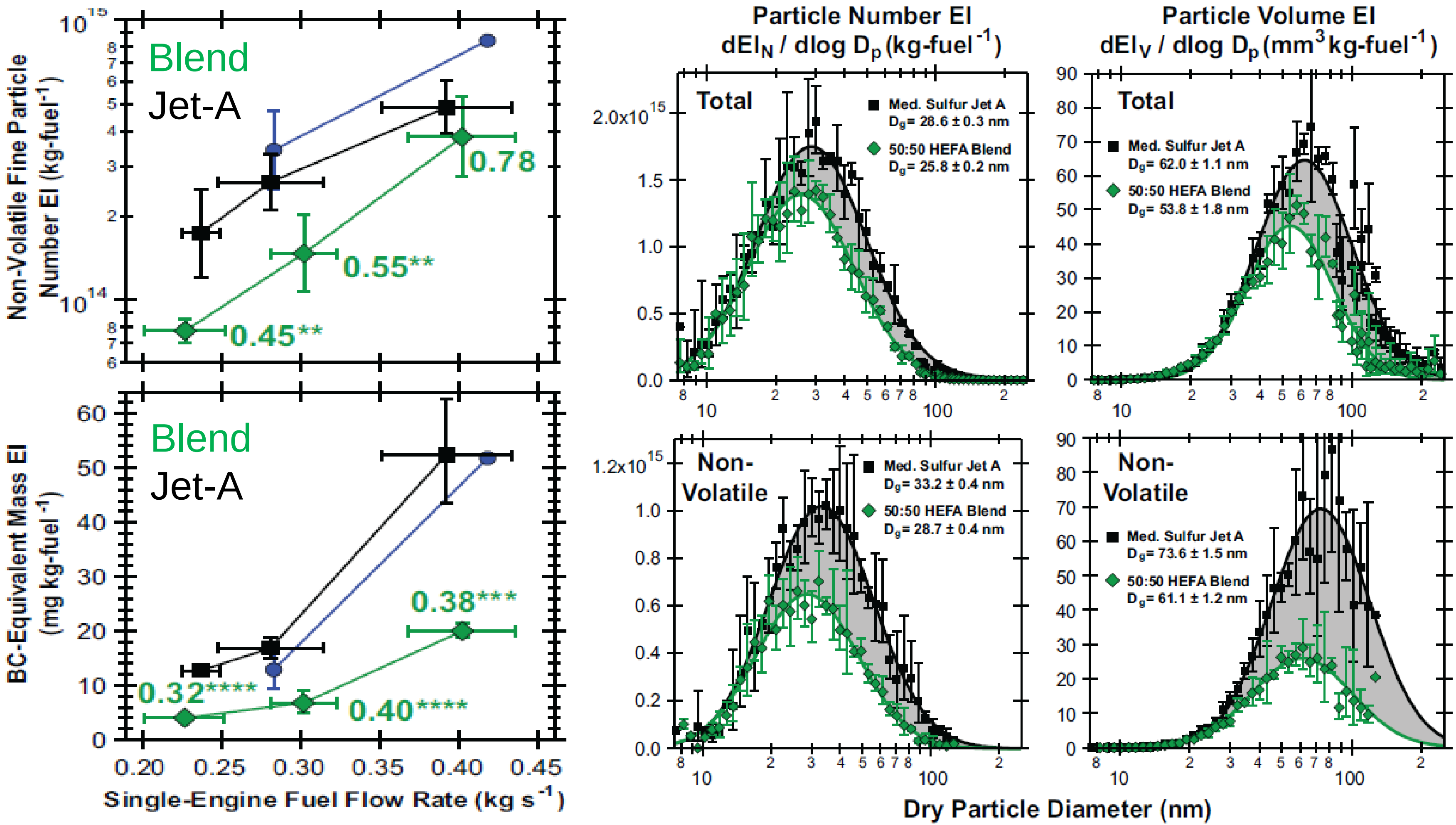
Combined Mission Accomplishments

ACCESS-II, 2014
- 8 flights, 25 hours
- Near-field emissions, very few contrail observations
- 1 ground test, 3-hour DC-8 runtime

ECLIF-1, 2015
- 9 flights, 35 hours
- Near-field emissions, good contrail observations
- 10 ground tests, 8-hour A320 runtime

NDMAX/ECLIF, 2018
- 7 flights, ~33 hours
- 1 Emission survey flight, 6 hrs
- Very good contrail observations
- 9 ground tests, 10-hour A320 runtime

ACCESS-II Observations Show that 50% Alt Fuel Blends Reduce nvPM emissions by 30 to 70% at Cruise

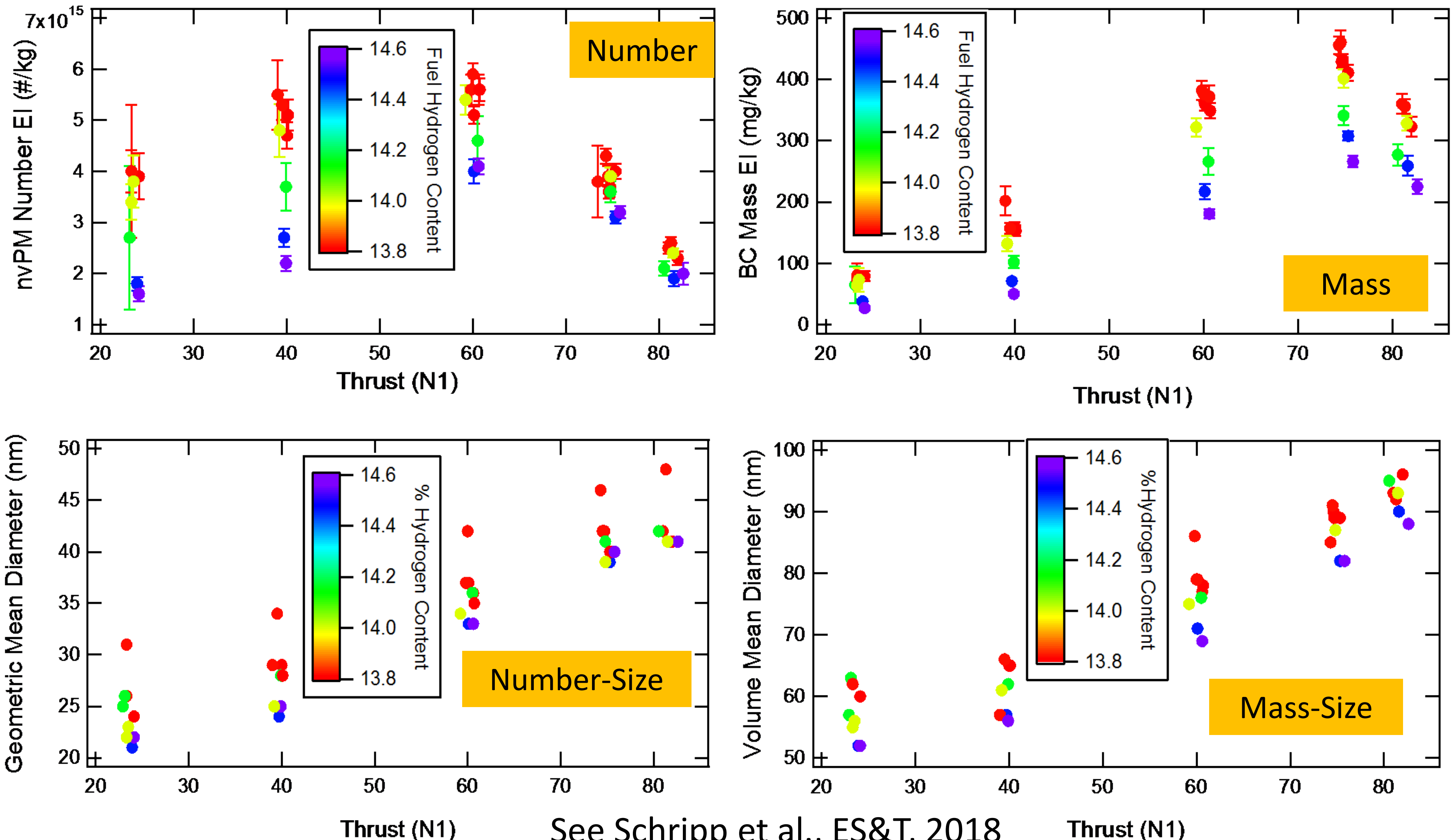


Moore et al., NATURE, 2017

DLR

ECLIF-1 Reveals nvPM Dependence on Fuel H Content

Number, mass and size decrease with increasing %Hydrogen Content



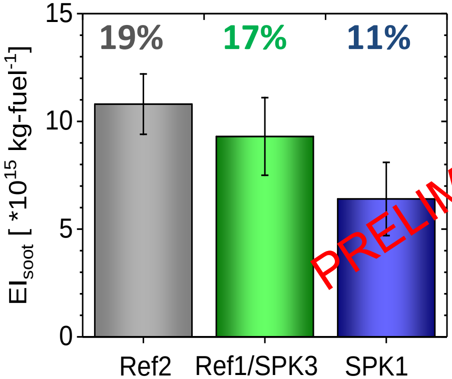
See Schripp et al., ES&T, 2018

DLR

ECLIF-1: Contrail Ice Concentrations also Proportional to Aromatics

- DLR-NASA flight experiment with Synthetic Paraffinic Kerosene (SPK) with low aromatic content (11%)
- Up to 50% reduction in particle/soot number/mass emissions for reduced aromatic content
- Similar reduction in contrail ice particle number
- **Reduced climate impact by alternative fuels**

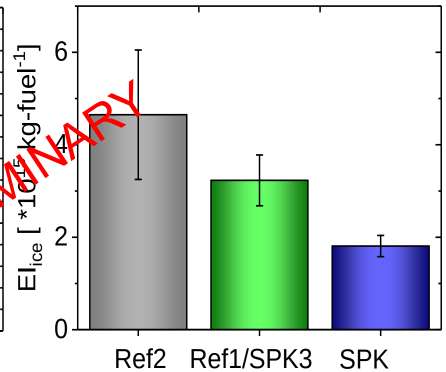
Ground measurements
Soot (aromatics)



Jet A-1 **Synth.** **SPK**

Schripp et al., 2018

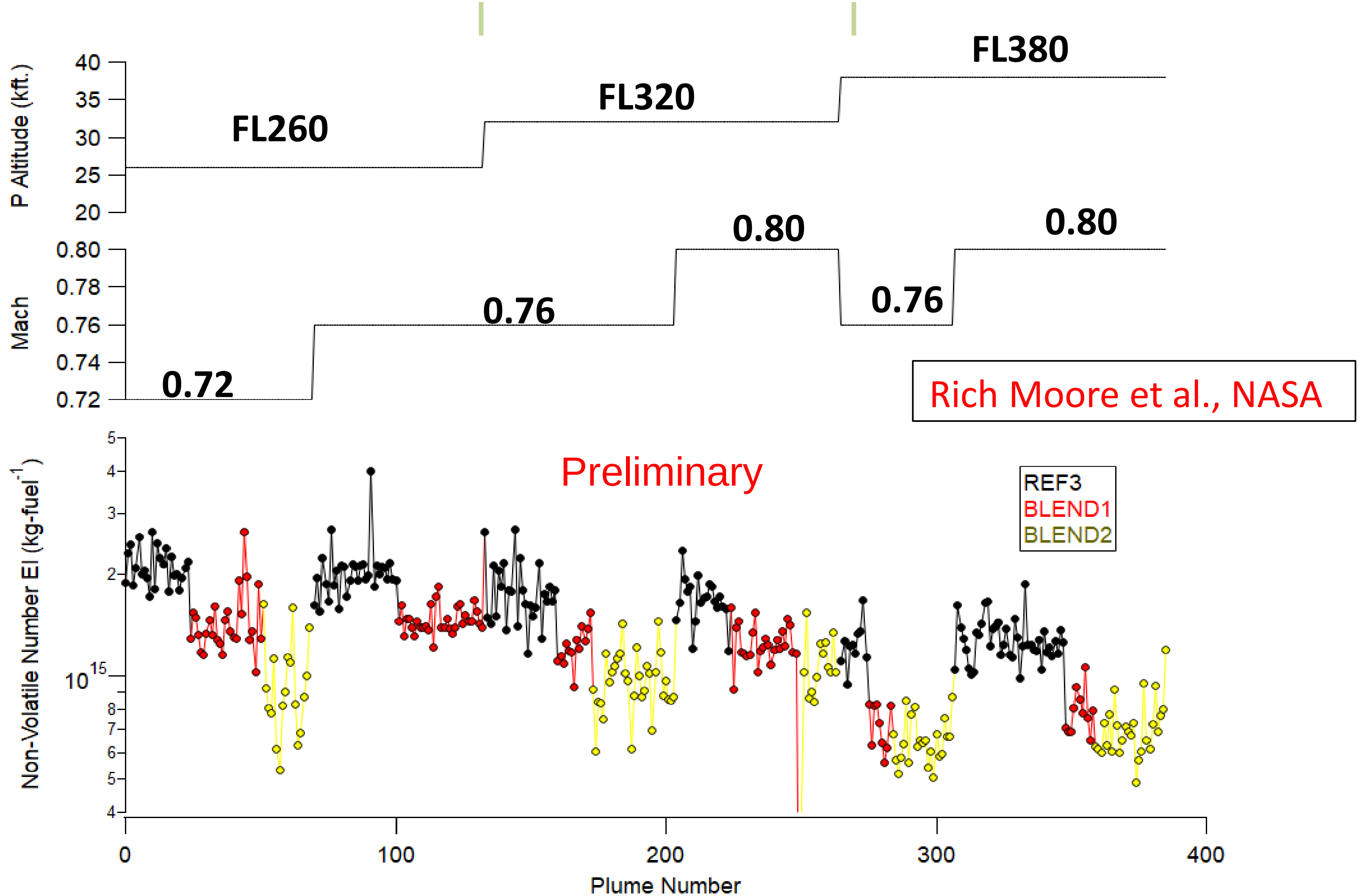
Flight measurements
Contrail ice



Jet A-1 **Synth.** **SPK**

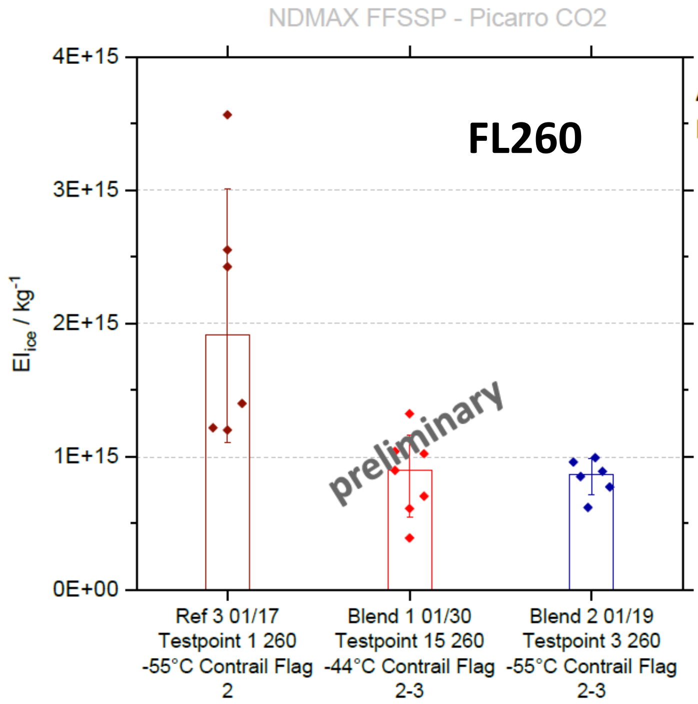
Voigt, Kleine et al., 2018

ND-MAX Further Demonstrates Alt Fuel nvPM Reductions at Cruise, Provides Data for Model Development



ND-MAX Apparent Contrail EIs Correlate with nvPM EIs

AEI ice - Ref 3, Blend 1 and Blend 2 Level 260 FFSSP

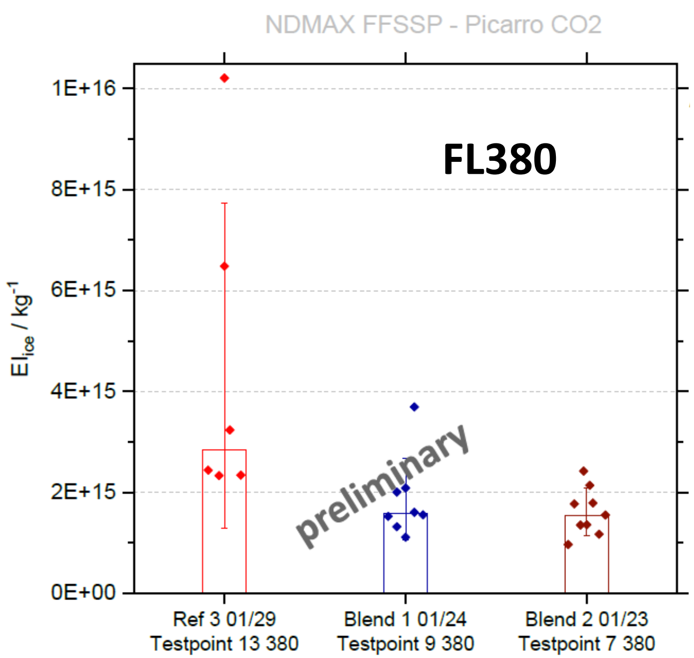


AEI ice derived using Moore et al., Nature, 2017

Results suggest that 100% of nvPM activate to form ice!

Data courtesy of Christiane Voigt et al., DLR

AEI ice - Ref 3, Blend 1 and Blend 2 Level 380 FFSSP



DLR

Summary of Results So Far

- Aircraft performance not affected by burning 50% Alt fuel blends—higher blend ratios would lower soot emissions
- No discernable difference in NOx and CO emissions between fuels
- 50% blends reduce soot number and mass emissions by ~30 to 80% on ground and at cruise
- Contrail ice concentrations proportional to soot emissions, which are proportional to fuel aromatics
- **Use of Sustainable Jet Fuels will Reduce Climate Impacts through both Reductions in CO_2 Emissions and Contrail Cloudiness**

Look for ECLIF and NDMAX Papers coming out in the next year

DLR


ECLIF-I
ECLIF

Thank You


ACCESS-II


ND-MAX/ECLIF-2
AIR MOBILITY COMMAND
ARMSTRONG FLIGHT RESEARCH CENTER
EARTH SCIENCE

GARDN Project CAAFCER, Civil Aviation Alternate Fuel Contrails & Emissions Research

Presented by : Fred Ghatala, Waterfall Group

Session: SAJF Benefits: Air Quality and Other Atmospheric Research

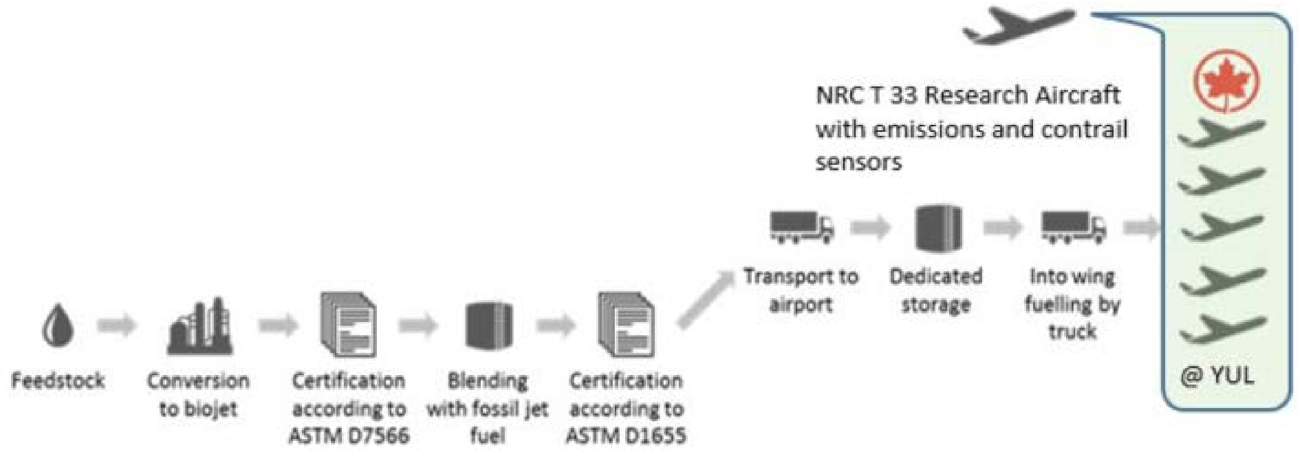
CAAFCER project team

- The CAAFCER project was a 2016 award from The Green Aviation Research and Development Network (GARDN), a non-profit organization funded by the Business-Led Network of Centres of Excellence (BL-NCE) of the Government of Canada and the Canadian aerospace industry. The research was conducted by a consortium, led by The Waterfall Group. Additional consortium members were the National Research Council Canada (NRC), Air Canada, SkyNRG, the University of Alberta and Boeing. DND QETE analysed fuel samples.
- All consortium members contributed In-kind support.

YUL – Civil Aviation Alternate Fuel Contrail and Emission Research (CAAFCER) - Blending Activity

Project Supply Chain Overview

- Research project led by the NRC to test the possible environmental benefits of biofuel use on contrails
- Neat Biofuel ASTM D7566 shipped from World Energy Refinery in Paramount CA
- Blending with fossil fuel at the highest possible blend ratio (43/57) and certify to ASTM D1655
- Transport to Airport and transfer to dedicated tanker.

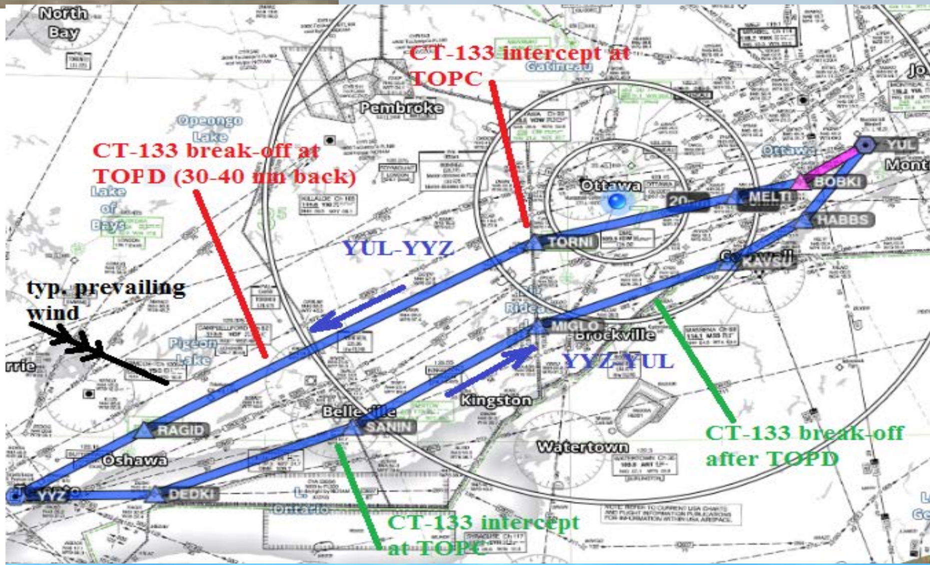


Challenges

- Transport to Montreal - Truck and Rail
- Availability of blending facilities
- Multiple certifications in order to get highest blend ratio
- Transfer to airport location and ability to segregate from regular fossil fuel.
- Operational knowledge and resources

CAAFCER

- Air Canada A320/321 on 43% HEFA blend, YUL->YYZ, plus
- Jet A1 A320/A321/B763 YYZ->YUL
  - Both measured back-back by NRC CT-133 research jet
- HEFA supplied by Alt-Air, LAX
- Blended by Air Canada and SkyNRG at Montreal
- Uni.Alberta, aerosol, nvPM analysis
- Boeing, technical advice & oversight
- DND QETE analysis of tank fuel samples



Contrails in the St Lawrence Seaway dynamic atmospheric jet-stream environment

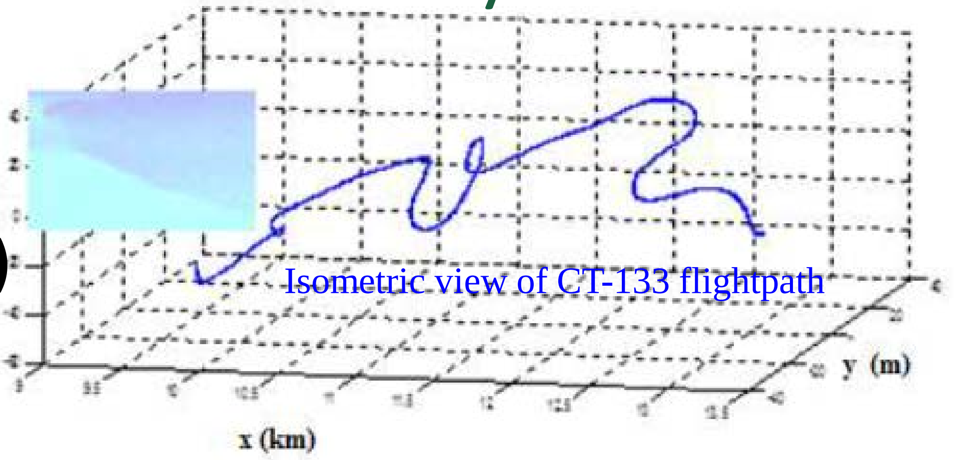
Contrails generated by aircraft can transform to various types of clouds depending on atmospheric conditions. All these type of clouds have climatic effects.

CAAFCER plume & contrail analysis

(1) NRC – Holistic (full cross-section, full-length) & autonomous (not reliant on an intermediate species such as CO_2)

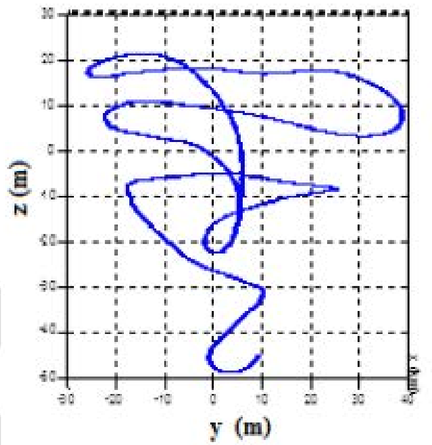
- *Horizontal & vertical transects*
    - *reconstruct cross-plane distribution of parameter state (primary usage, contrails)*
        - *for each species (ice, PM, nvPM)*

(2) Uni.Alberta – time domain, comparative PM to NOx concentration as an intermediate species (Boeing Fuel-flow Method)

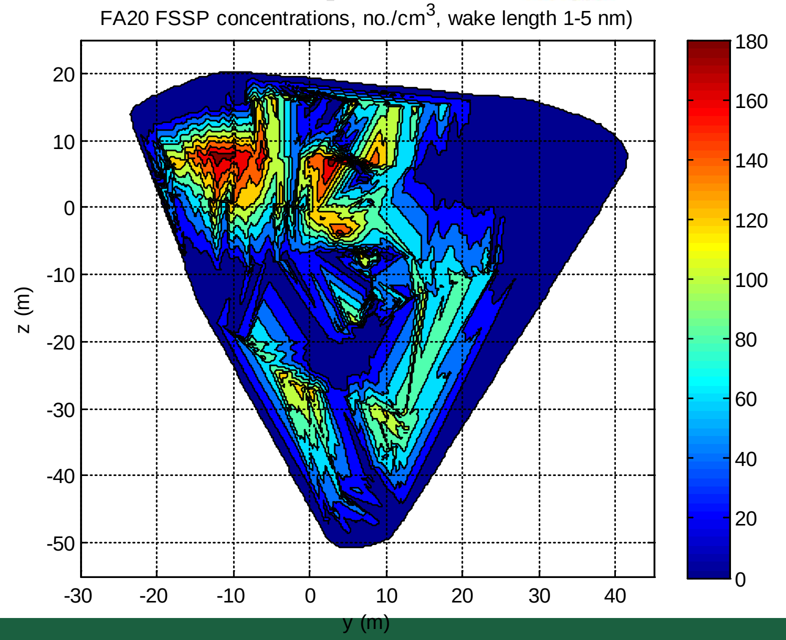


Isometric view of CT-133 flightpath

Endview of flightpath



Contour plot of contrail cross-sectional ice particle count/cc



CAAFCER & CAAFCEB – fuel properties

Table 1. List of fuel properties for Air Canada CAAFCER flights, Jet A1 from arriving aircraft fuel samples, 43% HEFA-blend from bowser fuel analysis, adjusted for residual tank Jet A1. Also shown for comparison are the NASA ACCESS II fuel properties for low-sulphur flights.

CAAFCER Flight date	25th April 2017		28th April 2017		3rd May 2017		4th May 2017 (1)		4th May 2017 (2)	
Property (% mass) [6]	JetA1	43% HEFA	JetA1	43% HEFA	JetA1	43% HEFA	JetA1	43% HEFA	JetA1	43% HEFA
Sulphur	0.07	0.052	0.08	0.052	0.04	0.052	0.07	0.052	0.03	0.052
Hydrogen	13.8	14.6	13.6	14.6	13.8	14.6	13.7	14.6	13.8	14.6

NASA ACCESS II	All low-sulphur flights	
	Jet A	50% HEFA
Sulphur	$22/10^4$	$11/10^4$
hydrogen	13.8	14.7

Table 2, CAAFSEB provisional fuel properties (references are included in brackets), from production batch testing.

Fuel	**Total hydrogen content (%m)**	**Sulphur content (%m)**	**Aromatics content (% vol)**
Jet A1	13.74 [4]	0.058 [4]	18.3
92% LT PNNL with 150 ND aromatics	15.33 [7]	0.000096 [7]	8
JP-5	13.7 [8]	0.02 [8]	18.3

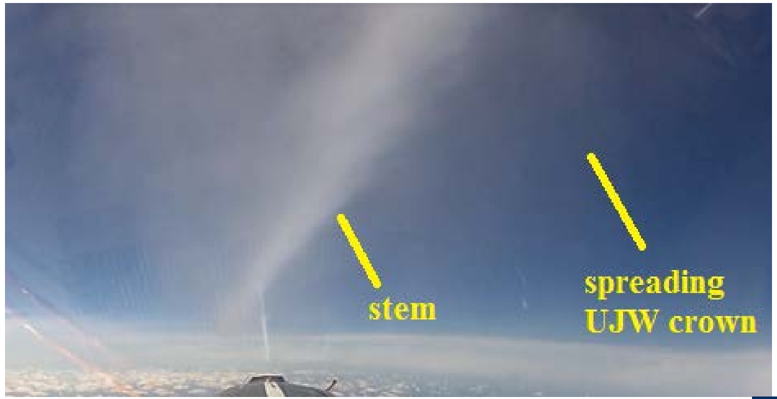
CAAFCER/CAAFCEB contrails

Transformation to cirrocumulus

Contrails

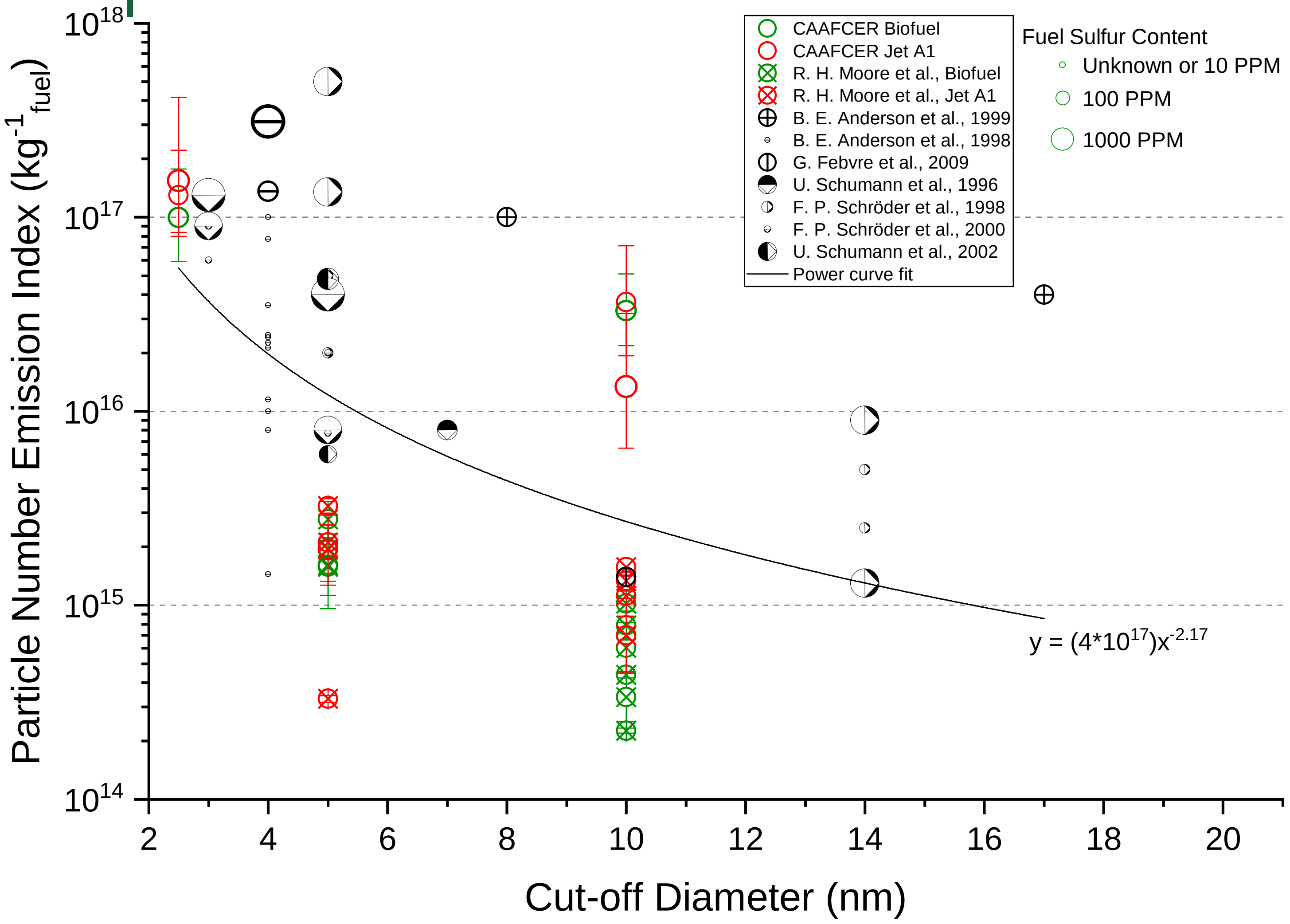
CAAFCER Air Canada A320 aircraft

Transformation to cirrostratus

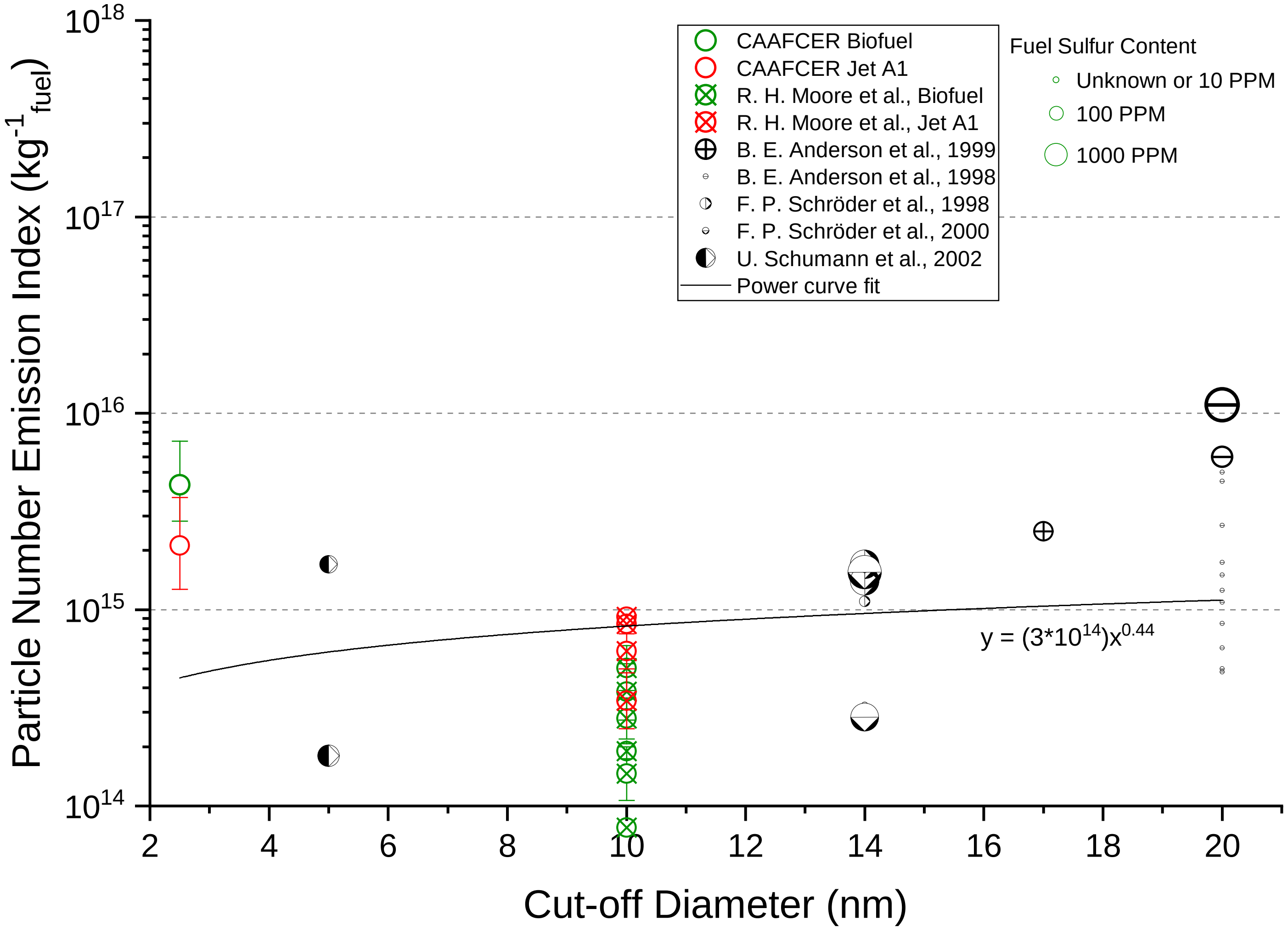


CAAFCEB, LT PNNL ATJ SPK (92%)

CAAFCER Total PM Comparison



CAAFCER Non-Volatile Particle Comparison



References (CAAFCER PM Comparisons)

R. H. Moore *et al.*, “Biofuel blending reduces particle emissions from aircraft engines at cruise conditions,” *Nature*, vol. 543, no. 7645, p. 411, Mar. 2017.

B. E. Anderson *et al.*, “An assessment of aircraft as a source of particles to the upper troposphere,” *Geophys. Res. Lett.*, vol. 26, no. 20, pp. 3069–3072, Oct. 1999.

B. E. Anderson, W. R. Cofer, D. R. Bagwell, J. W. Barrick, C. H. Hudgins, and K. E. Brunke, “Airborne observations of aircraft aerosol emissions I: Total nonvolatile particle emission indices,” *Geophys. Res. Lett.*, vol. 25, no. 10, pp. 1689–1692, May 1998.

G. Febvre *et al.*, “On optical and microphysical characteristics of contrails and cirrus,” *J. Geophys. Res. Atmospheres*, vol. 114, no. D2, Jan. 2009.

U. Schumann *et al.*, “In situ observations of particles in jet aircraft exhausts and contrails for different sulfur-containing fuels,” *J. Geophys. Res. Atmospheres*, vol. 101, no. D3, pp. 6853–6869, Mar. 1996.

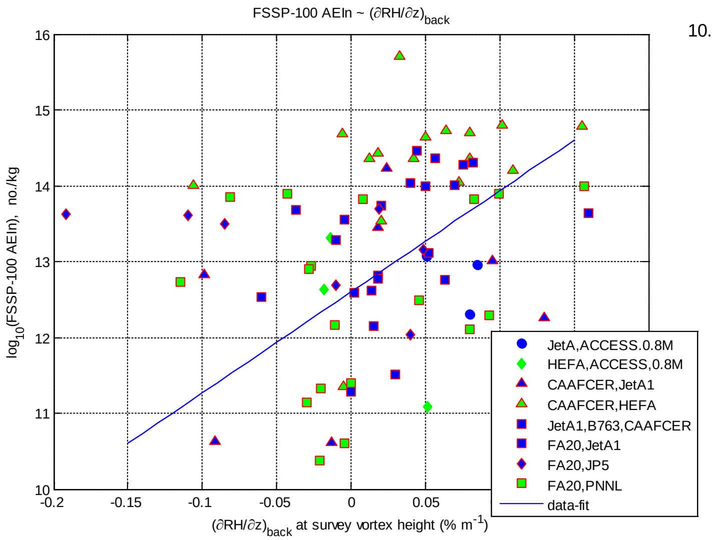
F. P. Schröder *et al.*, “Ultrafine aerosol particles in aircraft plumes: In situ observations,” *Geophys. Res. Lett.*, vol. 25, no. 15, pp. 2789–2792, Aug. 1998.

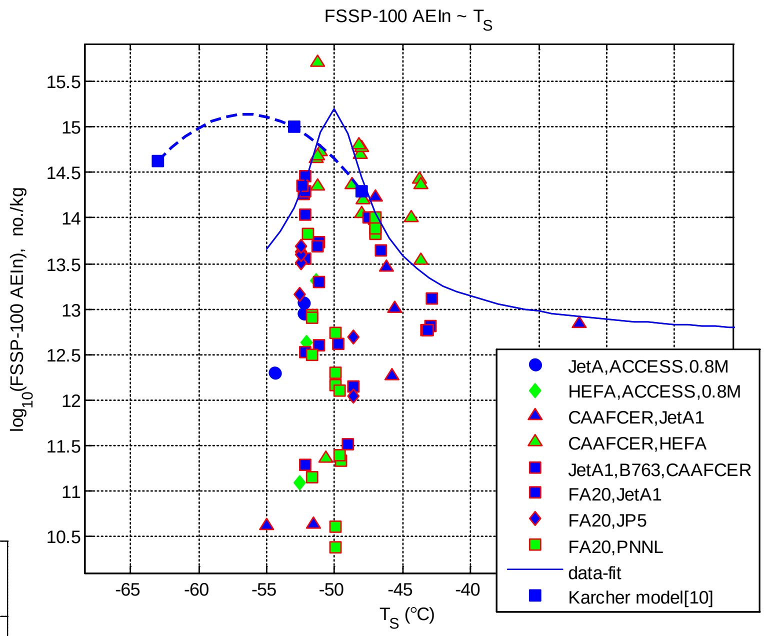
F. P. Schröder *et al.*, “In situ studies on volatile jet exhaust particle emissions: Impact of fuel sulfur content and environmental conditions on nuclei mode aerosols,” *J. Geophys. Res. Atmospheres*, vol. 105, no. D15, pp. 19941–19954, Aug. 2000.

U. Schumann *et al.*, “Influence of fuel sulfur on the composition of aircraft exhaust plumes: The experiments SULFUR 1–7,” *J. Geophys. Res. Atmospheres*, vol. 107, no. D15, p. AAC 2-1-AAC 2-27, Aug. 2002.

Contrail ice, variation with atmospheric conditions:

- Guiding functions (NOTE: each point is multivariate)
- RH_{ICE}
  - *erf* function ($^{2/3}$, DLR 90’s)
- T_S
  - *Strong* effect, ‘resonance’ function
- RH lapse rate, $\partial RH/\partial x$
  - linear





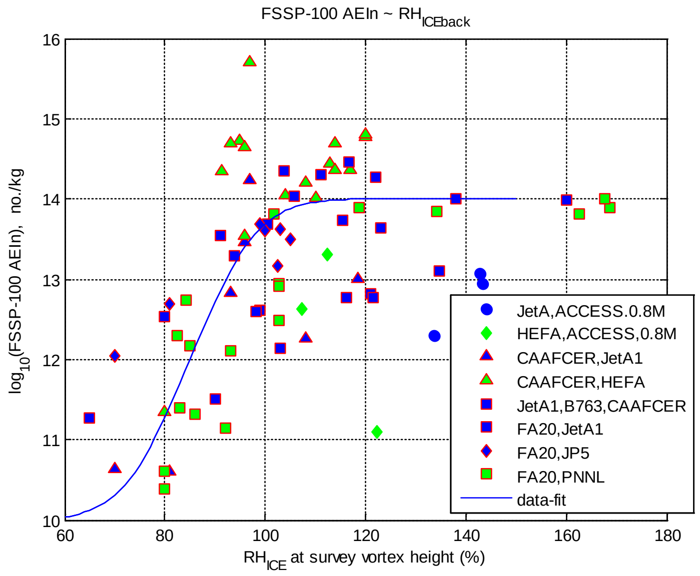


Figure 8: plots of contrail ice number AEIn against the atmospheric properties T_S, RH_{ICE}, $\partial RH/\partial z$, for NRC contrail data from NASA ACCESS II (low Sulphur Jet A and 50% HEFA, one aircraft the NASA DC-8), [ ], CAAFCER (Jet A1 and 43% HEFA-SPK, a number of aircraft) [ ], and CAAFCEB (Jet A1, A-3 JP-5 and 92% LT PNNL / 8% 150 ND, one aircraft, the NRCFA20). Shown as blue lines are assumed enveloping functional relations; in the T_S plot, the modelled ice particle generation data from Karcher [10] is included.

Contrail ice no. AEIn parameterisation with atmospheric conditions

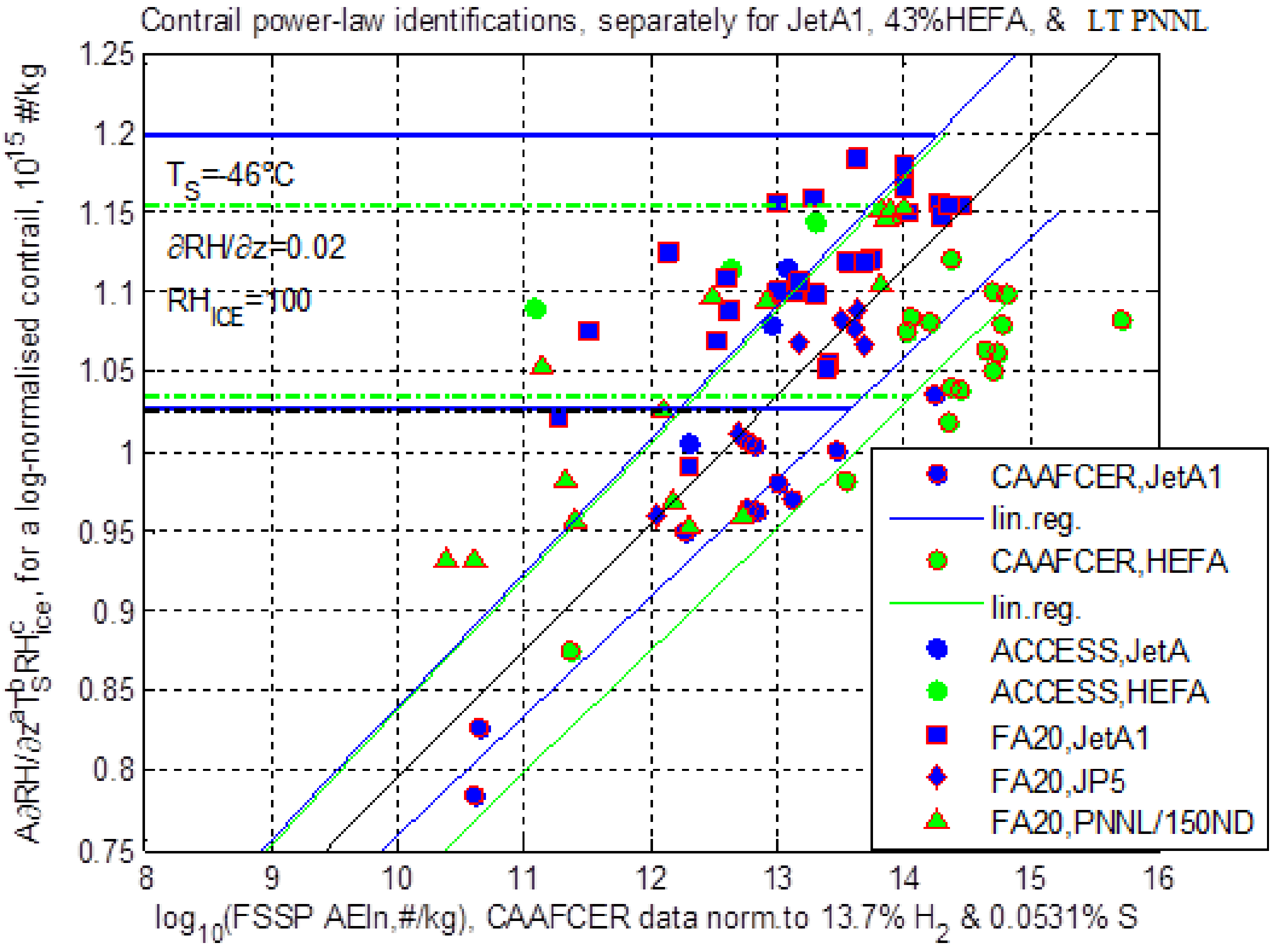


Figure 9: accounting for local variations in atmospheric state, for CAAFCER A320/321/B763 aircraft (AEIn adjusted to reference HC & SC, using the correlations identified earlier), CAAFCEB NRC FA20 aircraft (no HC or SC adjustments made); NRC data from NASA ACCESSII DC-8 is included for reference only, but was not included in atmospheric identification.

CAAFCER / CAAFCEB contrails conclusions

- Contrails measured for a range of fuels, JetA1, A-3 JP-5, 43% HEFA/JetA1 92% LT PNNL/150ND
- In CAAFCER, measurements done in context of revenue flights
  - Ice particle number associated with hydrogen content
  - Ice particle small dependency upon sulphur content
  - Introduced $AEI_{OPTICAL}$ extinction EI for optical effects
- Future:
  - Undertake holistic optical measurements, ECCC extinction probe
  - Radiation studies therefrom
    - Quantify RF effect upon GW – reduction thereof

Thank You

Technical Questions:

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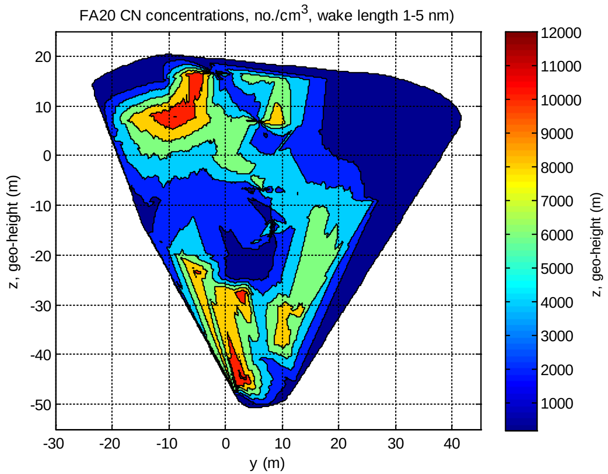
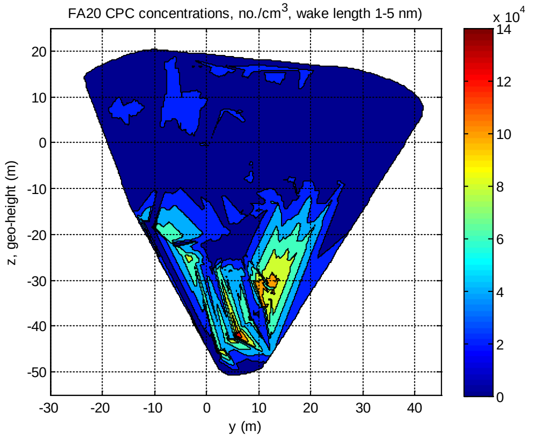
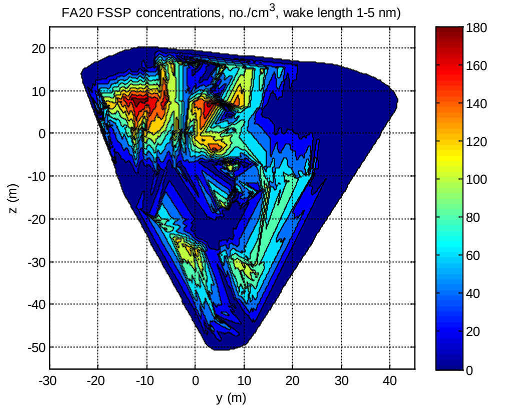
Tel: 613 990 4487

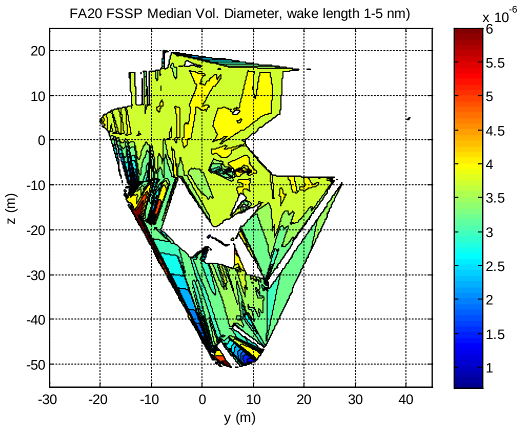
1920 Research Road, Bldg U-61, Uplands, Ottawa Airport, Ontario K1V 2B1
Government of Canada

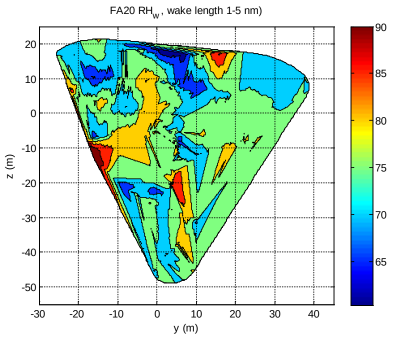
Contrail, PM, nvPM, optical X-sections (bottom right two figs.)

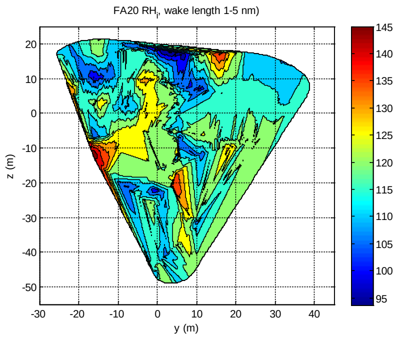


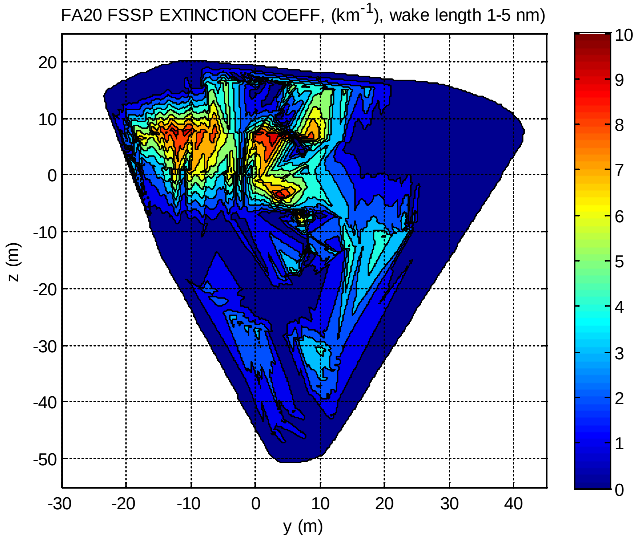


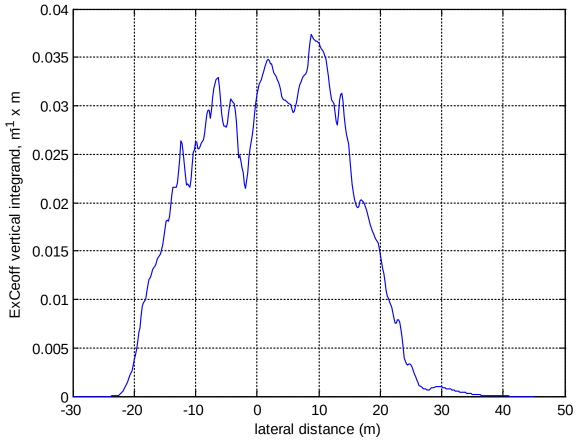








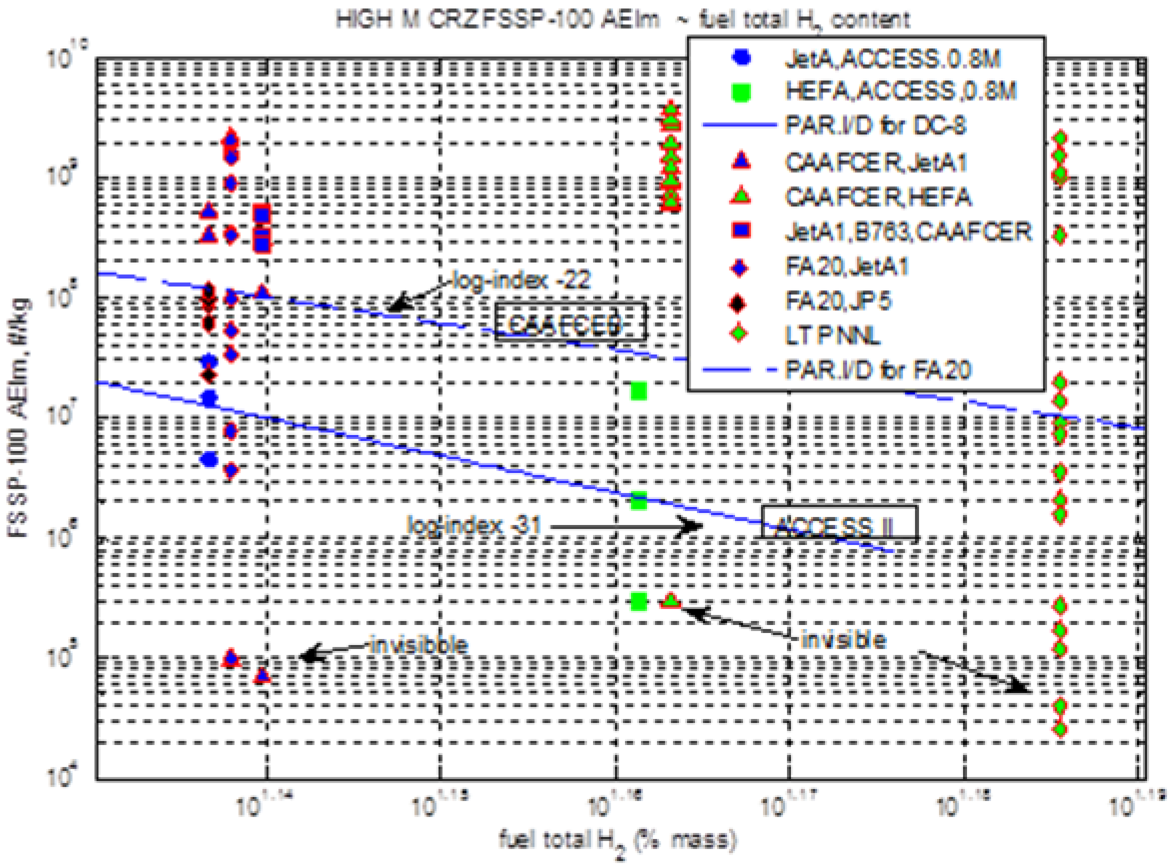


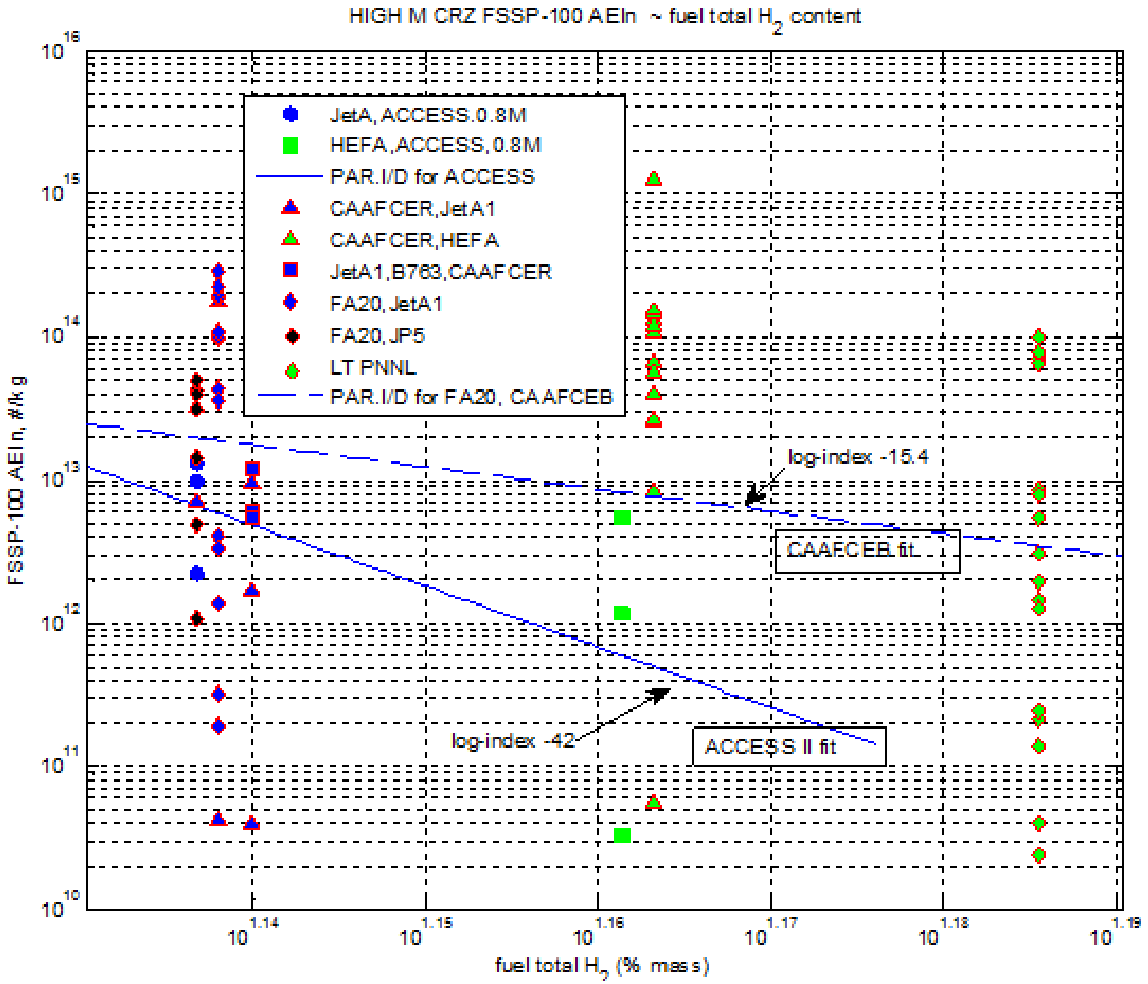


LT PNNL ATJ SPK: (*top row*) CN, CPCnv, FSSP no./cm3, ice particle MED (µm); (*bottom row*) RHw, RHice, extinction coefficient (km^{-1}), optical depth distribution across the contrail.

CAAFCER & CAAFCEB contrails

Contrail ice mass *(left)* /no. *(right)* variation with Total hydrogen content

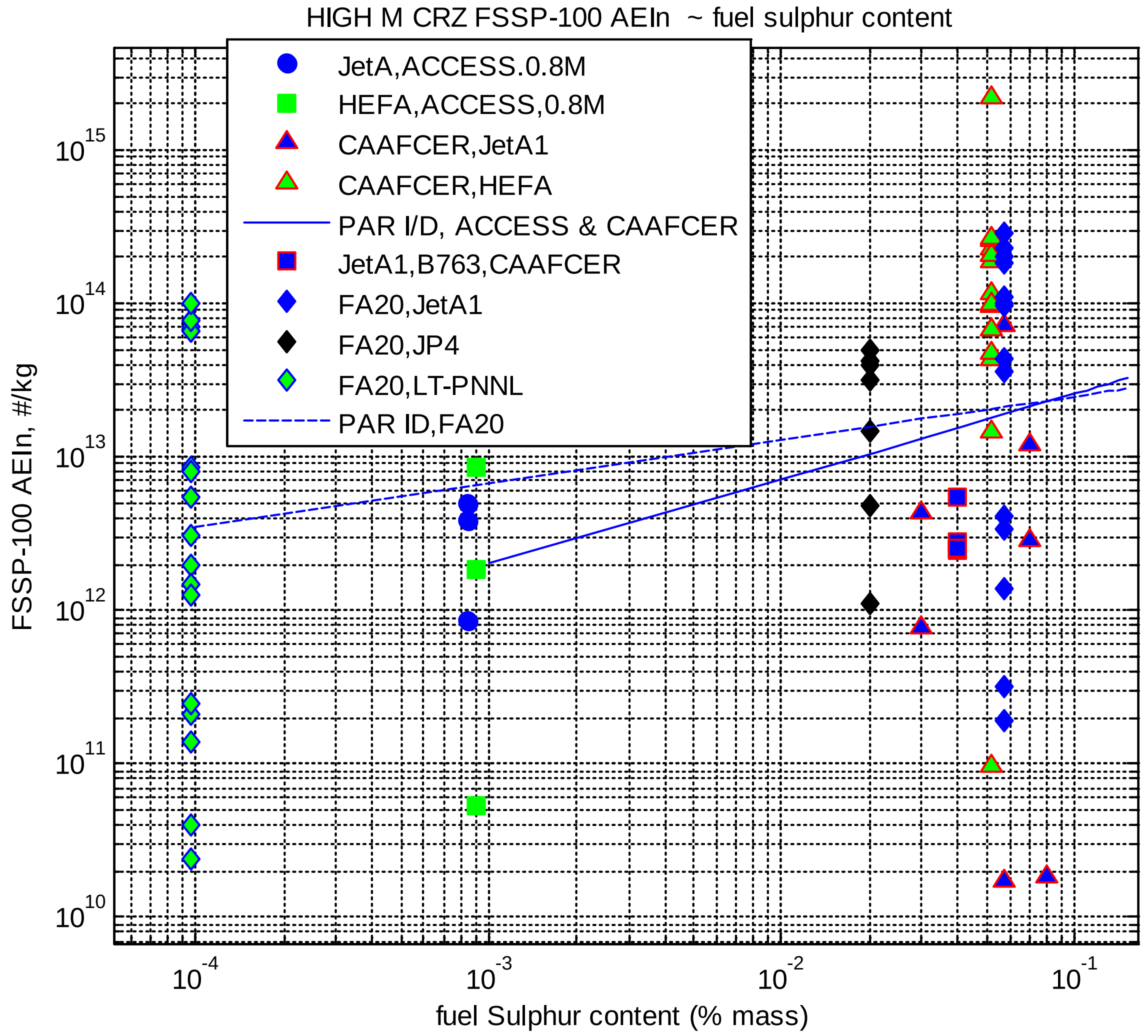




CAAFCER/CAAFCEB contrails & fuel sulphur content

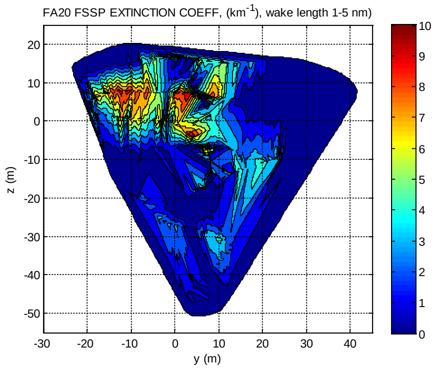
Contrail ice no. AEIn variation with Sulphur content

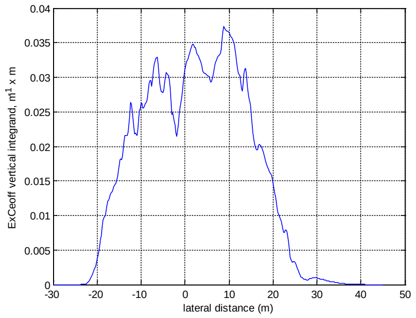
- Slight variation, $\propto S^{2/3}$, *c.f.* S^2 for PM (NASA, Aerodyne sulphur flight experiment)

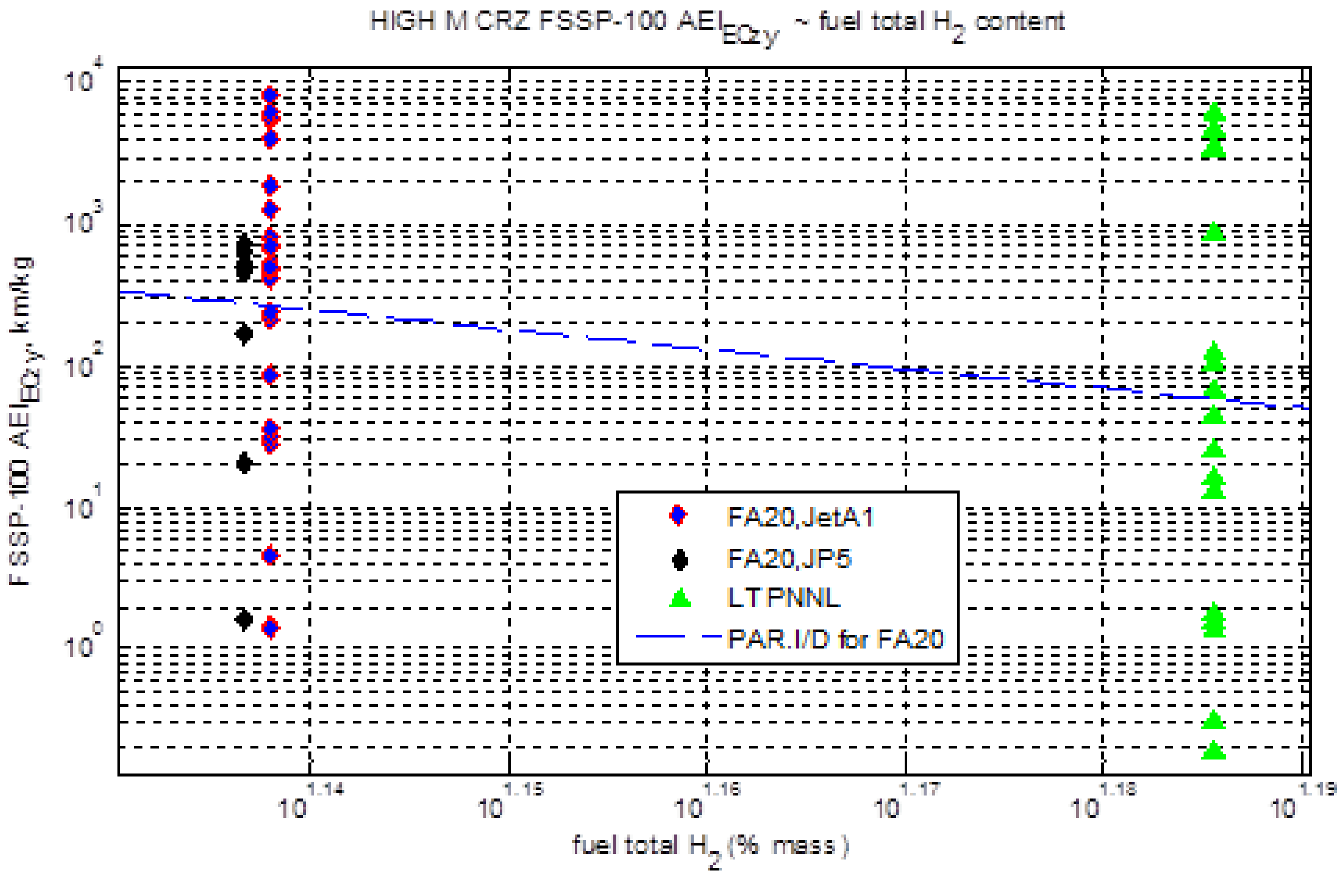


Contrail optical effects, $\iint ECdzdy$ per kg fuel

-- Variation with Total hydrogen content

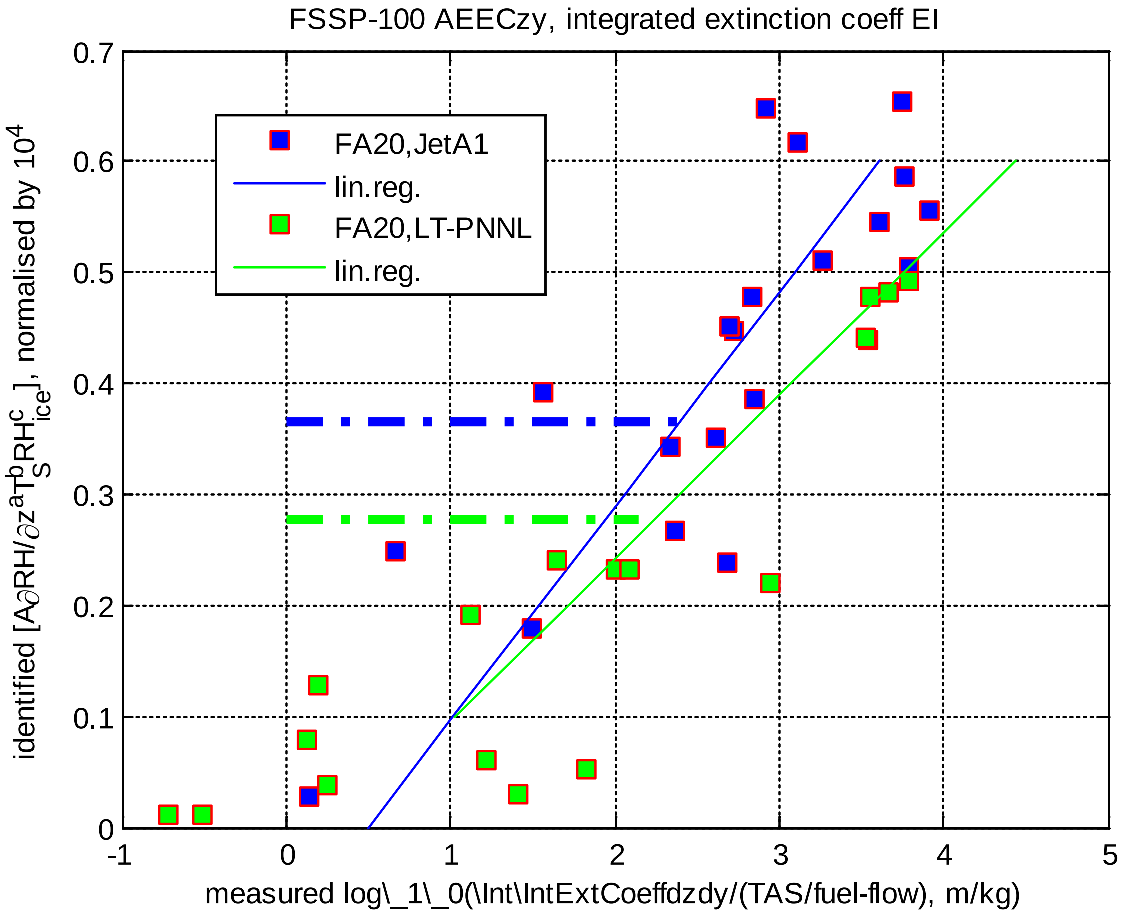






Contrail optical effects – atmospheric parameters

Figure 11 (*right*): plots of product-power-law identifications of contrail zenith optical apparent emission index AEI_{ECzy} for CAAFCEB Jet A1 (blue) and 92%LT PNNL SPK / 8%150 ND (green). Horizontal dashed lines are the corrected values for the two fuels, for T_S= -46°C, 100% RH_{ICE} and $\partial RH/\partial z$=0.02 %/m – a 50% reduction for LT PNNL.



CAAFCEB project

- The CAAFCEB project was a 2017 project, using the NRC Falcon to burn high-blend ATJ SPK, JP-5, JetA1
- Funded by ECCC (Transport office, Gatineau),TC and NRC Canada.

Air Canada CAAFCER operations

- ***For departing jet:*** HEFA-blend bowser, airside for refueling at YUL
  - Operational go-ahead, evening before (contrailing conditions sought)
  - AC flight at the gate overnight, in the early AM hours
    - Drained of fuel/Refueled with HEFA blend fuel load
    - Fuel sample taken from wing, for aromatics, H_2, napth., etc. tests
  - Dispatched into commercial service on-time
  - Standard flight profile
    - NRC T-33 intercepts at TOPC
      - 1-2,000 feet difference in height
      - might request $\pm$1-2,000 feet height change for contrailing conditions to prevail
      - at 5nm back, clearance to the AC height
        - Contrail & emissions survey

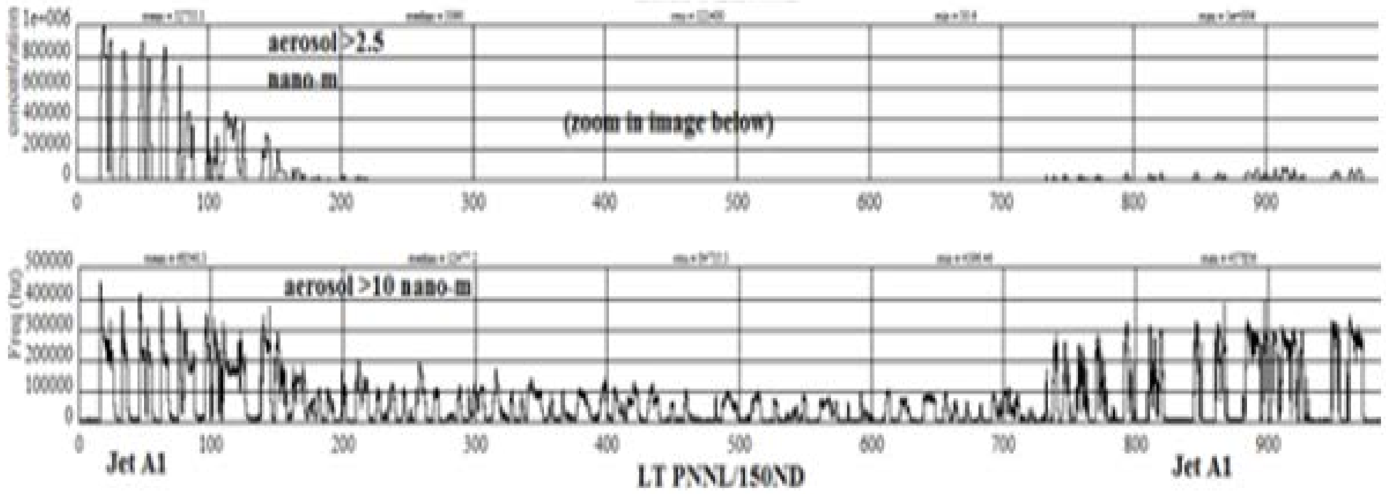
CAAFCEB PM emissions (holistic method)

Particulate matter (PM & nvPM, in high altitude M0.8 cruise (constancy of altitude, engine operating condition, fuel between flights):

- JetA1
  - 7.5% ultrafines (CPC, >2.5 nano-m) were non-volatile (nv), with 3x PM between 2.5-10 nano-m – such as sulphates.
- A-3 JP-5
  - nvPM higher than JetA1 (largely, soot)
  - 12% of CPC were nv (higher % than JetA1 likely due to lower sulphur)
- 92% LT PNNL / 8% 150 ND
  - large reduction in PM (time-trace)
    - 80% reduction in nv (soot)
    - 91% reduction in ultrafines
    - Less volatiles (nvPM was 19%)

CAAFCEB mean values of EIn for aerosols, ultra-fines, non-volatiles

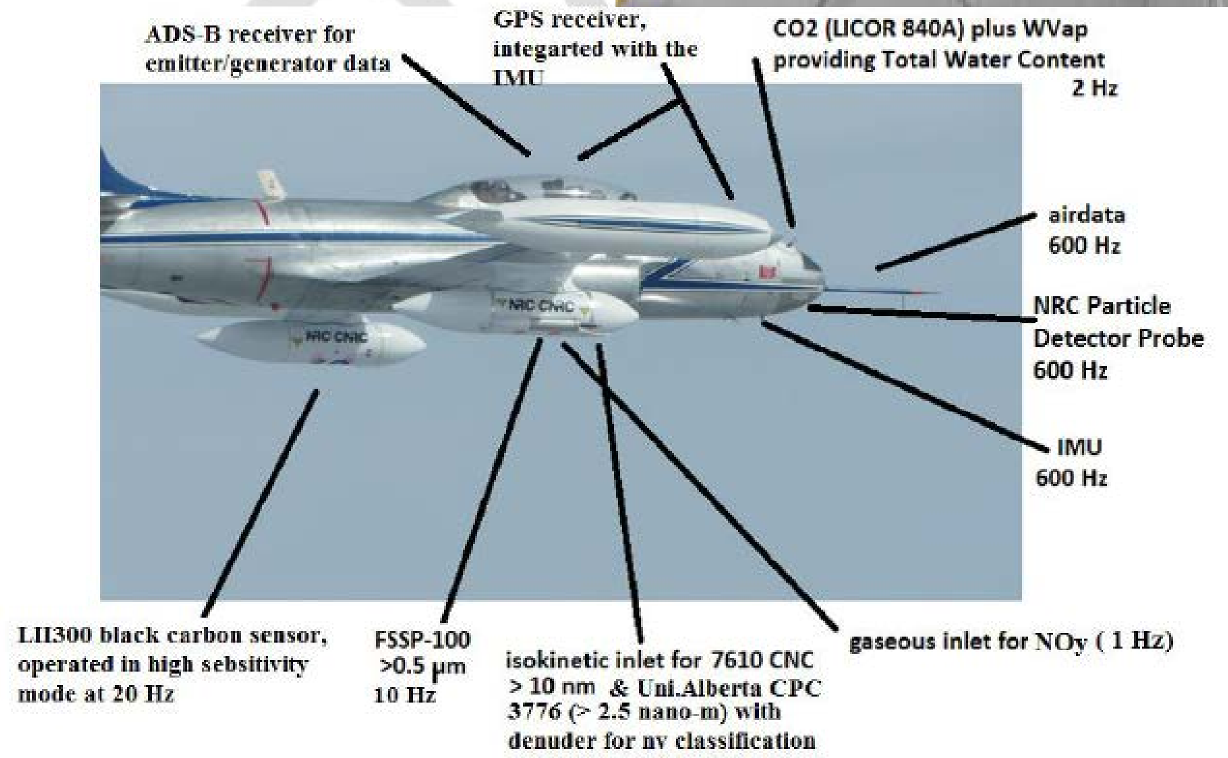
Fuel	Mean values of EIn for			For each fuel:
	CN	CPC	CPCnv	CPCnv/CPC
JetA1	1.1286e+16	4.6236e+16	3.4705e+15	0.0751
JP5	1.3311e+16	5.6662e+16	6.8873e+15	0.1216
LT PNNL	1.9884e+15	4.1636e+15	6.7268e+14	0.1616
Ratio LT PNNL to JetA1	0.1762	0.0901	0.1938	



CAAFCEB

Project CAAFCEB scope, aircraft:

- Aircraft
  - NRC Falcon 20 jet (GE CF700 engines)
  - NRC CT-133 measuring emissions & contrails
    - Position & winds, 600 Hz
    - PM – CN 7610, CPC 3776, denuder
    - NOx analyser (42I @ 1 Hz, NO)
    - LII300 BC mass
    - Licor 840A, H_20, CO_2,
    - Ice particles, FSSP-100



CAAFCER PM time-domain Boeing Fuel-flow Method EI derivation

Requires inflight engine data records availability – May 4a (CFM56-5B4/P Jet A1) and May4b (CFM56-5A1 Biofuel and Jet A1)