Fuel Composition & Aircraft Emissions

Presented to: CAAFI Biennial General Meeting
By: Dr. Jim Hileman
Chief Scientific & Technical Advisor for Environment and Energy
Office of Environment and Energy
Federal Aviation Administration
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 $\leq$ 10 $\mu$m (enters lungs)
  - Fine Particulate Matter = PM$_{2.5}$ = diameter $\leq$ 2.5 $\mu$m (enters blood)
  - Ultrafine Particulate Matter = PM$_{0.1}$ = diameter $\leq$ 0.1 $\mu$m (could enter systems)

- PM from aircraft engines:
  - Soot (a.k.a., non-volatile PM, black carbon)
  - Volatile organic compounds from engine sulfate and nitrates & atmospheric ammonia
  - 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

Fuel composition and engine design determine emissions

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

Fuel: $C_nH_m + S^*$

Complete combustion products:
$N_2 + O_2 + CO_2 + H_2O + SO_2^*$

Actual combustion products:
$N_2 + O_2 + CO_2 + NO_x + SO_x^* + HC + CO + H_2O + BC^*$

$\Delta NO_3 PM$ $\Delta SO_4 PM$ $\Delta BC PM$

$\Delta O_3$

Changes in Air Quality

$\triangle$. Account for radiative, chemical, microphysical and dynamical couplings along with dependence on changing climatic conditions and background atmosphere

Increasing Scientific Uncertainty

Engine Fuel Combustion

Direct Emissions

Atmospheric Processes: Interactions and Feedbacks

Direct Emissions

Increasing Policy Relevance

Social welfare and costs
Engine Fuel Combustion → Direct Emissions → Atmospheric Processes: Interactions and Feedbacks

Increasing Policy Relevance

Fuel: $C_nH_m + S^*$ → Complete combustion products: $N_2 + O_2 + CO_2 + H_2O + SO_2^*$

Actual combustion products: $N_2 + O_2 + CO_2 + NO_x + SO_x^* + HC + CO + H_2O + BC^*$

Oceanic & Land Uptake

Chemical Reactions

Microphysics

Aerosol-Cloud Interactions

Changes in Air Quality

Changes in temperature, sea level, ice/snow cover and precipitation, etc.

Agriculture and forestry, ecosystems, energy production and consumption, human health, social effects, etc.

Social welfare and costs

$^5$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

ASCENT Project 20 & Project 21 Info at: https://ascent.aero/project/
PARTNER COE Project 27 (2007-2011)

Sulfur Removal Cost-Benefit Analysis

**Air Quality**

- Emissions Modeling
  - Chemistry Transport Models
- Atmospheric Composition
  - PM$_{2.5}$
  - Epidemiological CRFs
  - Applied to Population Densities
- Increased health impacts

**Climate Change**

- Reduced SO$_x$ Aerosol Cooling
- Increased CO$_2$ Emissions

- $\Delta$ CO$_2$

**Production**

- Added HDS Units

- Monetization of Costs & Benefits
  - Reduced Health Costs - Benefit
  - $2.05 - 2.34B$

- Increased Warming - Cost
  - $0.82 - 2.35B$

- Increased Production Cost
  - $2.52B$

**Cost-Benefit Analysis**

- PARTNER Sulfur Cost Benefit Analysis Final Report
ASCENT COE Project 37 (2016 to present)

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

**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)

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Key [1]
- O : Jet A w/ Naphthalene-Depleted Aromatic Additive
- + : Jet A w/ Aromatic Additive

ASCENT Project 39 Naphthalene Cost Benefit Analysis Description
https://ascent.aero/project/naphthalene-removal-assessment/
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
Dr. Jim Hileman
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Office of Environment and Energy
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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
- Sandy Webb
- Dr. Philip Whitefield
- Dr. Don Hagen
- Steve Csonka

AIRC Senior Program Officer: Joe Navarrete
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.
Emissions Quantification Plan and Review
Conduct Literature Review
Develop Plan for Quantifying Emission Impacts
Completed

E.Q. Methods Creation and Validation
Create Emissions Quantification Methodologies
Conduct Independent Review
Identify Case Studies
Completed

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
Review of Existing Studies

Project Background

State of the Industry Report

Quantification Methods

Airport Dissemination

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.

<table>
<thead>
<tr>
<th>Document Hits</th>
<th>Search Criteria</th>
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<tbody>
<tr>
<td>35,136</td>
<td>Alternative jet fuel emissions</td>
</tr>
<tr>
<td>9,369</td>
<td>Alternative jet fuel emissions + criteria pollutants</td>
</tr>
<tr>
<td>73</td>
<td>Alternative jet fuel emissions + criteria pollutants + emission measurements</td>
</tr>
<tr>
<td>51</td>
<td>Reports with quantitative emissions analysis (used in this literature review)</td>
</tr>
</tbody>
</table>
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
The State of the Industry Report is published on the ACRP 02-80 website. It can be downloaded from this link:

## Approach to Quantify Emissions

### 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).

### 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.

### Pollutant Specific Impacts Data Assessment
Assess the pollutant specific data to determine the extent to which a functional analysis per metric can be performed.

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

### Functional Analysis
Fit suitable functions to the measured data using general linear least squares methodology.

### Interface Pollutant Impact Analysis to AEDT
Report the pollutant, fuel, and engine specific impact relationships to use with the Aviation Environmental Design Tool (AEDT).
Project Background

- 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.

State of the Industry Report

Quantification Methods

Airport Dissemination

Requirements

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

Focus

Audience

Airport employees who are not necessarily environmental or air quality specialists or scientists.
Alternative Jet Fuel Assessment Tool

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.

Booz | Allen | Hamilton
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Philip Soucacos, soucacos_philip@bah.com
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

Knowledge for Tomorrow
Aircraft Emissions Impact

Combustion Emissions
- CO₂: 71%
- Water: 28%
- CO, HC, NOₓ, SOₓ, Primary PM₂.₅: < 1%

Atmospheric Chemistry and Physics
- SOₓ
- NOₓ
- O₃
- CH₄
- H₂O
- Global Climate Change
  - Cooling Effects
  - Warming Effects

Emissions from Fuel Production
- CH₄, N₂O, CO₂

Population Exposure and Health Impacts
Contrails and Climate Impact

contrails

contrail cirrus

contrail cirrus over northern Atlantic
Radiative Forcing Components from Aviation in 2005

Total anthropogenic radiative forcing (RF) was 1.6 W/m²
Aviation with 0.076 W/m² represented ~5%

Recent models suggest that aviation induced cirrus cloudiness (0.031 W/m²) is the largest RF contribution from aviation

Lee et al., Atmos. Env., 2009
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?
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

- n-alkanes: 22.2
- iso-alkanes: 23.4
- monocyclo alkanes: 23.2
- bicyclo alkanes: 10.7
- mono-aromatics: 13.5
- naphtheno aromatics: 4.5
- naphthalenes: 2.5

Physical Properties

Chemical Properties

Ignition Delay Time

(C. Naumann, DLR, 2015)
ECLIF – Combustion Properties

Soot precursors profiles in flow reactor

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

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

SSJF2: 11 m% aromatics & 14.65 m% H
FSJF: 9 m% aromatics & 14.25 m% 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 0.8 m% more naphthalenes (di-aromatics)
Soot emissions in high pressure single sector rig

Soot luminosity

$\Phi = 0.99$

$p = 6$ bar, $T_{\text{air}} = 323$ K, $\Phi = 0.99$

Qualitatively

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

Simulation: $\rightarrow$
The lower the aromatics content the lower the soot precursor concentration.

Benzene concentration

$p = 6$ bar, $T_{\text{air}} = 700$ K, $\Phi = 0.99$

(ECLIF – Combustion Rig Test & CFD (T. Mosbach, DLR, 2016))

(P. Le Clercq, DLR, 2010)
Fuel Design

Generic Spray Burner

HP Rig

Data Base

Measurement

Diagnostics

Lab-scale Exp.

Composition

Jet A-1

Ignition Delay Time

Species Profile

Plug Flow Reactor

Species Profile

benzene

Species Profile

benzene

Plots:

- Ignition Delay Time
- Species Profile
- Composition

Other:

- HP Rig
- Generic Spray Burner
- Plug Flow Reactor

Symbols:

- $\Phi = 1$
- $p_{in} = 16$ bar
- Dilution 1:2
- Jet A-1 / air
- 100% SPK
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%.

**Aromatics vol% (ASTM D6379)**

- 19%
- 15%
- 9%

**H content mass% (ASTM D7171)**

- H 13.65%
- H 14.06%
- H 14.04%

**Sulfur content (ISO 20884)**

- Sulphur 105 ppm
- Sulphur 104 ppm
- Sulphur 57 ppm

**Fuel Blends**

- 100% fossil Jet A-1
- 70% Ref4 + 30% HEFA-SPK
- 53.4% Ref3 + 16.3% HEFA-SPK
Two Airfields & Two aircrafts

• WTD61 Airfield in Manching
• 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)
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.
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
Falcon Aircraft could sample <100 m in trail, DC-8 limited to >5 km
Source Aircraft

**DLR A320 ATRA**
- V2527-A5 engines
- 26,600 lbs thrust

**NASA DC-8-72**
- CFM56-2C1 engines
- 22,000 lbs thrust

**ECLIF-1, NDMAX/ECLIF**

**AAFEX-1, AAFEX-2, ACCESS-I, ACCESS-II**
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; CO2, NOx
- DLR: Particle number, size; CO2, CO, NOx, SO2, THC
- Oslo: Hydrocarbons
- Missouri (FAA): Particle number, size, mass (ICAO Method)
- Aerodyne: Aerosol Composition
- NRC-Canada: Particle number, size, mass
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
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
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

Schripp et al., 2018
Voigt, Kleine et al., 2018
ND-MAX Further Demonstrates Alt Fuel nvPM Reductions at Cruise, Provides Data for Model Development

Rich Moore et al., NASA

Preliminary
ND-MAX Apparent Contrail EIs Correlate with nvPM EIs

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

Data courtesy of Christiane Voigt et al., 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 CO₂ Emissions and Contrail Cloudiness

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

Thank You

ECLIF-I

ACCESS-II

ND-MAX/ECLIF-2
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
• 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

Panoramic sly-view at Ottawa, Ontario

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)
### 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.

<table>
<thead>
<tr>
<th>Flight date</th>
<th>25th April 2017</th>
<th>28th April 2017</th>
<th>3rd May 2017</th>
<th>4th May 2017 (1)</th>
<th>4th May 2017 (2)</th>
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</thead>
<tbody>
<tr>
<td>Sulphur</td>
<td>0.07</td>
<td>0.052</td>
<td>0.08</td>
<td>0.052</td>
<td>0.04</td>
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<td>Hydrogen</td>
<td>13.8</td>
<td>14.6</td>
<td>13.6</td>
<td>14.6</td>
<td>13.8</td>
</tr>
<tr>
<td><strong>NASA ACCESS II</strong></td>
<td>All low-sulphur flights</td>
<td>Jet A 50% HEFA</td>
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</tr>
<tr>
<td>Sulphur</td>
<td>22/10^4</td>
<td>11/10^4</td>
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<tr>
<td>Hydrogen</td>
<td>13.8</td>
<td>14.7</td>
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</table>

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

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Total hydrogen content (%m)</th>
<th>Sulphur content (%m)</th>
<th>Aromatics content (% vol)</th>
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<tr>
<td>92% LT PNNL with 150 ND aromatics</td>
<td>15.33 [7]</td>
<td>0.000096 [7]</td>
<td>8</td>
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<tr>
<td>JP-5</td>
<td>13.7 [8]</td>
<td>0.02 [8]</td>
<td>18.3</td>
</tr>
</tbody>
</table>
CAAFCER/CAAFCEB contrails

Contrails
CAAFCER Air Canada A320 aircraft

Transformation to cirrostratus

Transformation to cirrocumulus

CAAFCER, LT PNNL ATJ SPK (92%)
CAAFCER Total PM Comparison

![Graph showing particle number emission index versus cut-off diameter](image)

- **Fuel Sulfur Content**
  - Unknown or 10 PPM
  - 100 PPM
  - 1000 PPM

- **Power curve fit**
  - $y = (4 \times 10^{17})x^{-2.17}$

- **Data Sources**
  - R. H. Moore et al., Biofuel
  - R. H. Moore et al., Jet A1
  - B. E. Anderson et al., 1999
  - B. E. Anderson et al., 1998
  - G. Febvre et al., 2009
  - U. Schumann et al., 1996
  - F. P. Schröder et al., 1998
  - F. P. Schröder et al., 2000
  - U. Schumann et al., 2002
CAAFcer Non-Volatile Particle Comparison

![Graph showing particle number emission index vs. cut-off diameter](image)

- **Particle Number Emission Index (kg\(^{-1}\) fuel)**

- **Cut-off Diameter (nm)**

- **Fuel Sulfur Content**
  - Unknown or 10 PPM
  - 100 PPM
  - 1000 PPM

- **Power curve fit**: \( y = (3 \times 10^{14})x^{0.44} \)

- Sources:
  - R. H. Moore et al., *Biofuel*
  - R. H. Moore et al., *Jet A1*
  - B. E. Anderson et al., 1999
  - B. E. Anderson et al., 1998
  - F. P. Schröder et al., 1998
  - F. P. Schröder et al., 2000
  - U. Schumann et al., 2002

- CAAFCER Biofuel
- CAAFCER Jet A1

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*Note: The graph illustrates the relationship between cut-off diameter and particle number emission index, with a power curve fit that describes the data.*
References (CAAFCER PM Comparisons)


Contrail ice, variation with atmospheric conditions:

- Guiding functions (NOTE: each point is multivariate)
  - $\text{RH}_{\text{ICE}}$
    - erf function ($^{1/3}$, DLR 90’s)
  - $T_S$
    - Strong effect, ‘resonance’ function
  - RH lapse rate, $\partial \text{RH} / \partial x$
    - linear

Figure 8: plots of contrail ice number AEIn against the atmospheric properties $T_S$, $\text{RH}_{\text{ICE}}$, $\partial \text{RH} / \partial z$, 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), CAAFCER B 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.
• 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\textsubscript{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

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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, $\int\int ECdzdy$ 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 $\text{AEI}_{\text{ECzy}}$ 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 $T_s = -46^\circ\text{C}$, 100% RH$_{\text{ICE}}$ and $\partial\text{RH}/\partial z = 0.02 \%/\text{m}$ – 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, H₂, 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 ±1-2,000 feet height change for contrailing conditions to prevail
      - at 5nm back, clearance to the AC height
        - Contrail & emissions survey
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%)

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

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Mean values of EIn for</th>
<th>For each fuel:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CN</td>
<td>CPC</td>
</tr>
<tr>
<td>JetA1</td>
<td>1.1286e+16</td>
<td>4.6236e+16</td>
</tr>
<tr>
<td>JP5</td>
<td>1.3311e+16</td>
<td>5.6662e+16</td>
</tr>
<tr>
<td>LT PNNL</td>
<td>1.9884e+15</td>
<td>4.1636e+15</td>
</tr>
<tr>
<td>Ratio LT PNNL to JetA1</td>
<td>0.1762</td>
<td>0.0901</td>
</tr>
</tbody>
</table>
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, H₂O, CO₂,
    - Ice particles, FSSP-100
Requires inflight engine data records availability – May 4a (CFM56-5B4/P Jet A1) and May4b (CFM56-5A1 Biofuel and Jet A1)