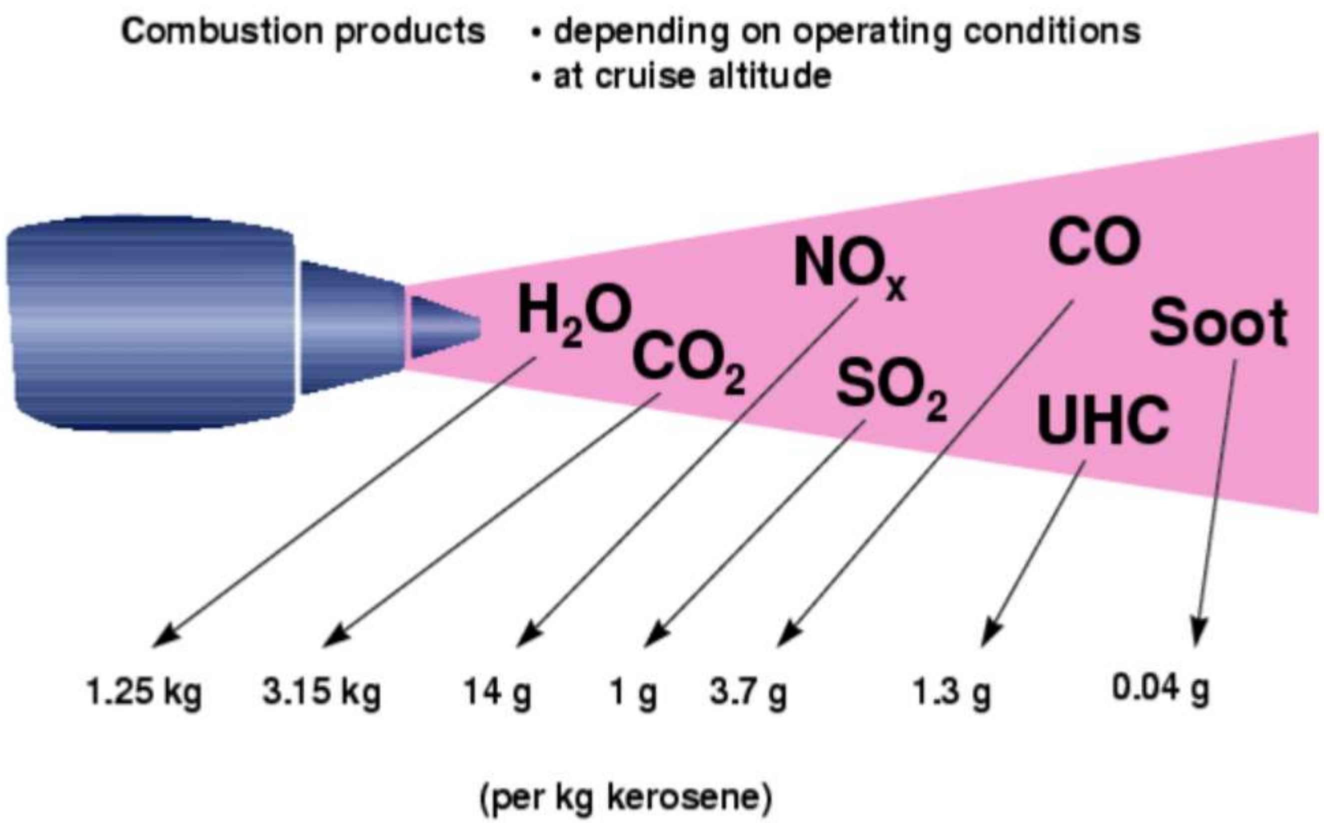
Emissions and non-CO_2 effects reductions by burning SAF

Patrick Le Clercq

German Aerospace Center (DLR), Institute of Combustion Technology

Department of Multiphase Flows and Alternative Fuels

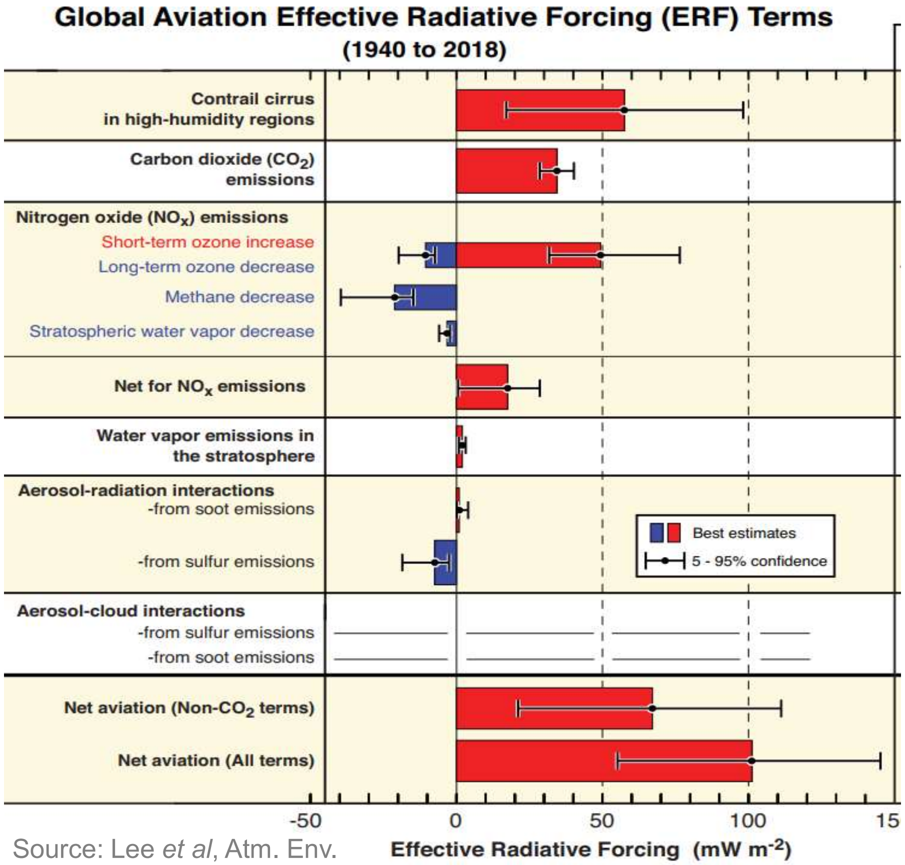
Air Traffic Emissions under Cruise Conditions



Combustion products
- depending on operating conditions
- at cruise altitude

(per kg kerosene)

Climate Neutral Aviation
Challenge: Reducing Emissions **AND** non-CO_2 Effects

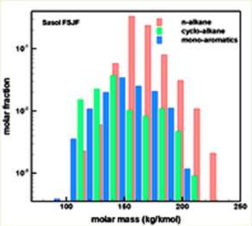


Source: Lee *et al*, Atm. Env. 2020.

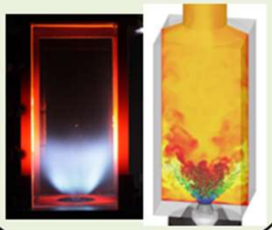
Outline

Sustainable Aviation Fuel (SAF) Impact on Emissions & Climate

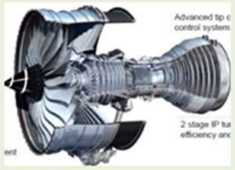
Fuel



Combustion

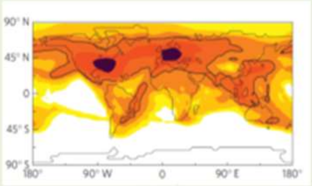


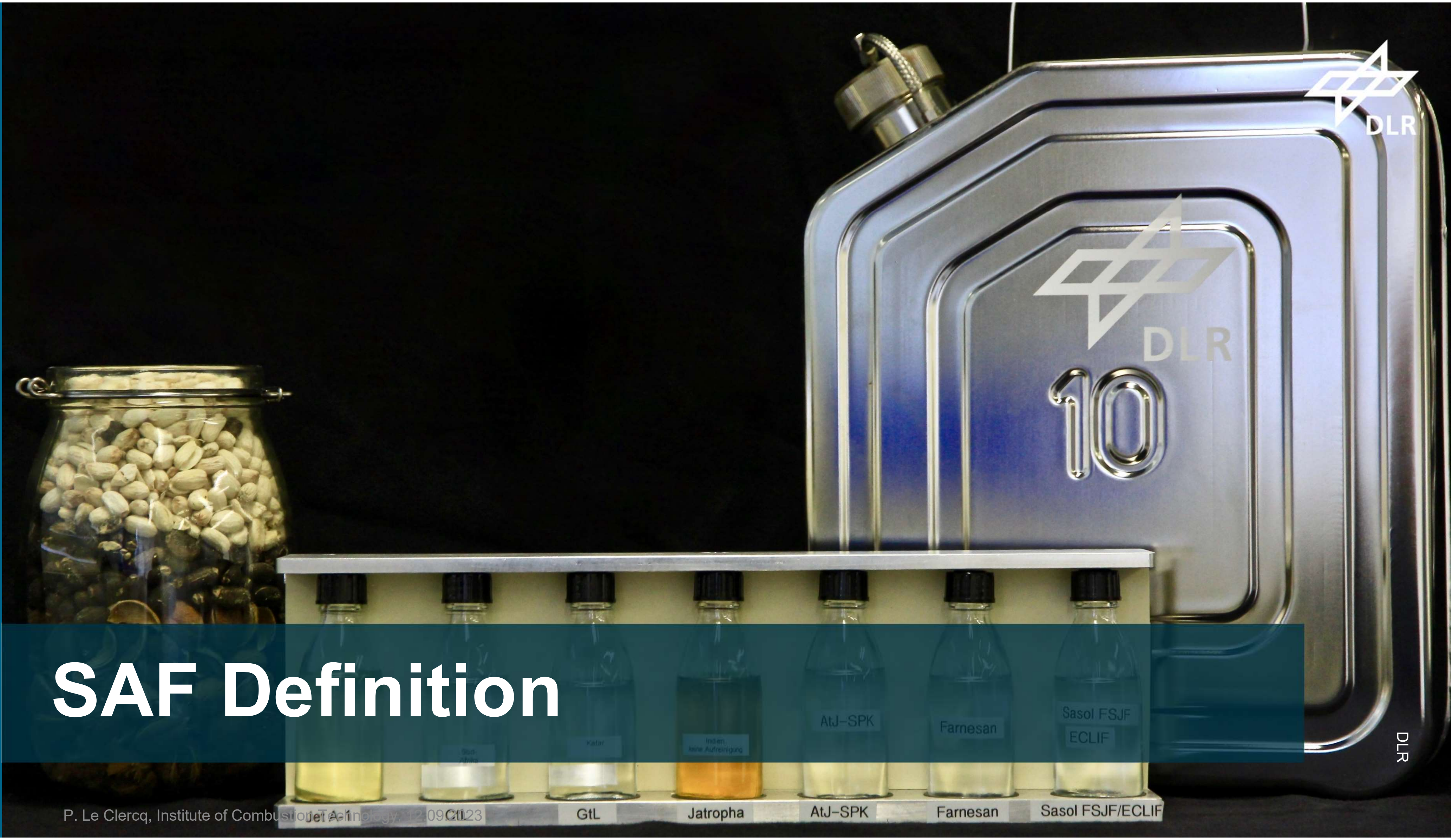
Engine



Emissions Measurement

Atmosphere

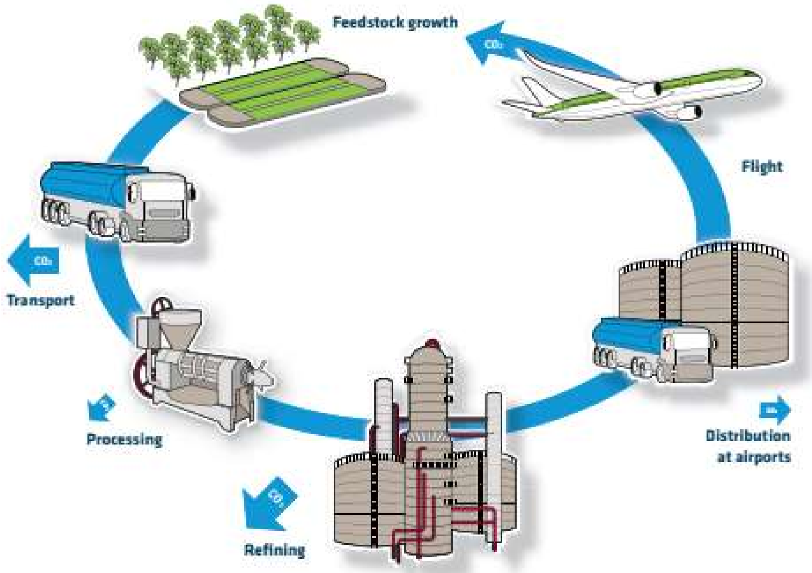




SAF Definition

Sustainable Aviation Fuel (SAF)

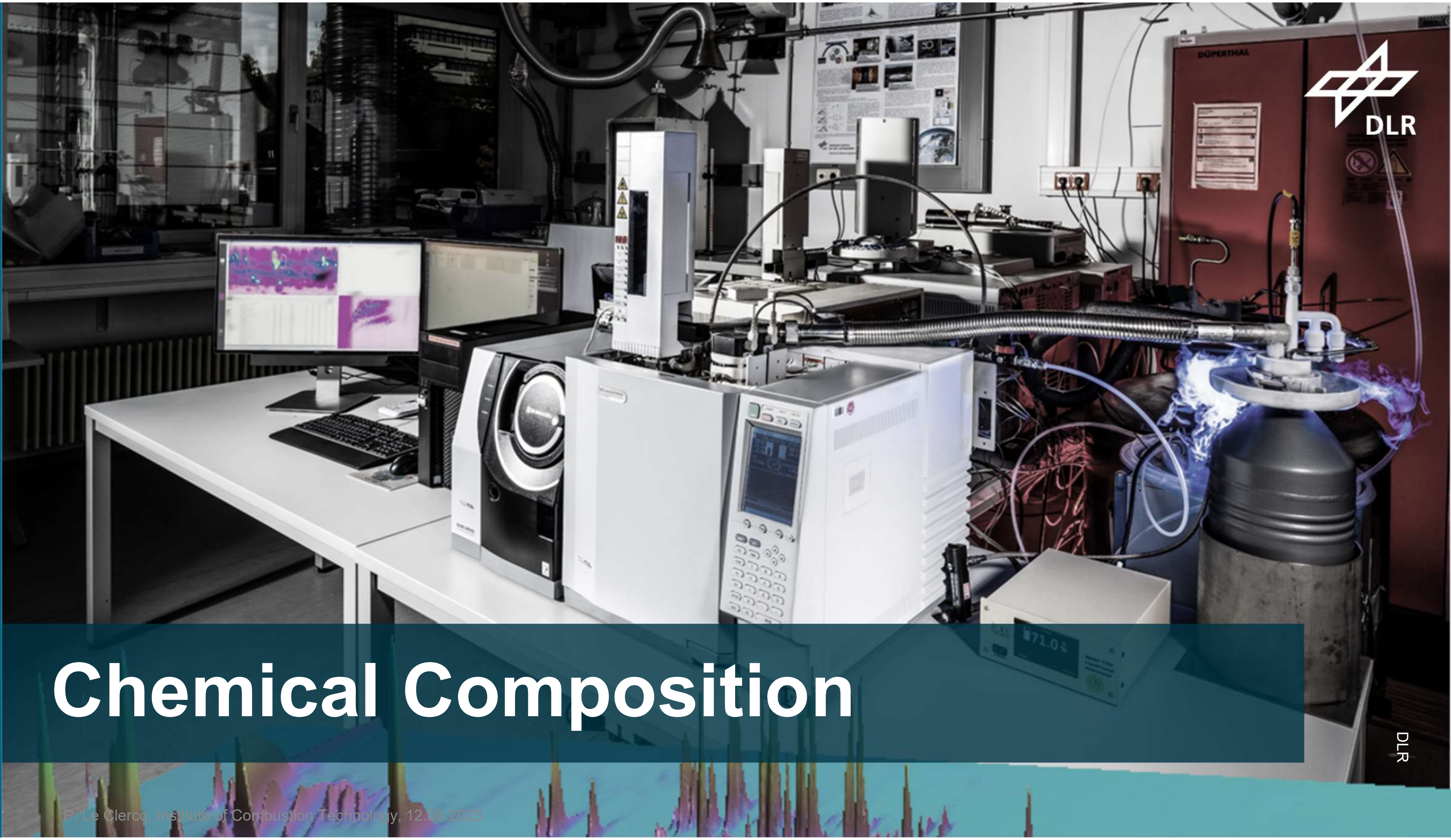
- SAF is a **synthetic renewable** or waste-derived aviation fuel that meets **sustainability criteria** as well as very stringent **technical criteria**.
- SAF production starts from various feedstocks:
    - oils from plants, algae, greases, fats; waste streams, alcohols, sugars, and hydrogen and captured CO_2.
- A sustainable feedstock is continually and repeatably resourced in a manner consistent with strong environmental, social, and economic (circular) criteria.
- The use of SAF lowers the lifecycle carbon footprint compared to conventional petroleum-based fuels



Carbon Lifecycle Diagram for SAF

Source: Beginner's Guide to Sustainable Aviation Fuel, ATAG.

Chemical Composition

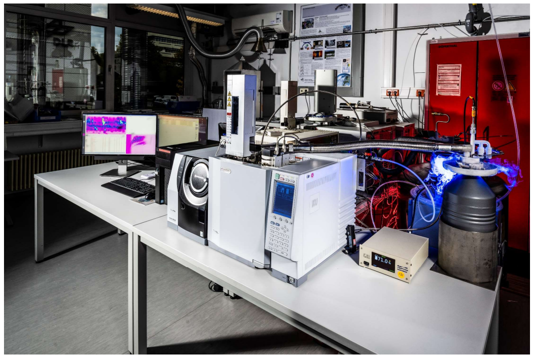


DLR

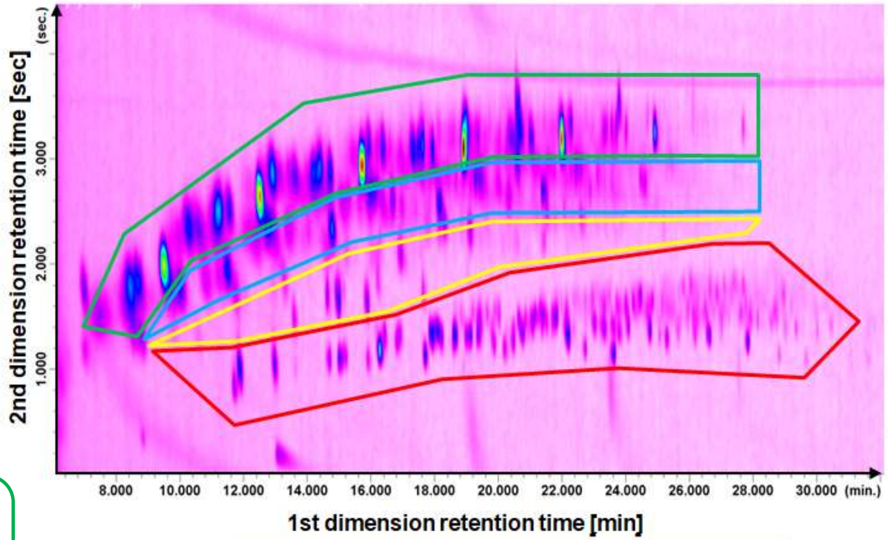
GC x GC coupled with mass spectroscopy (MS) and flame ionization detection (FID) for a quantitative and qualitative composition analysis

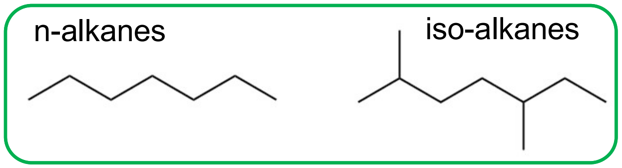
Fuel Sample

GC x GC



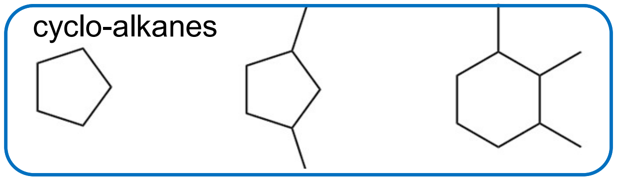
Analysis: Jet A-1 Chromatogramm



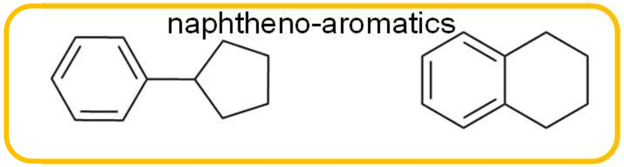


n-alkanes

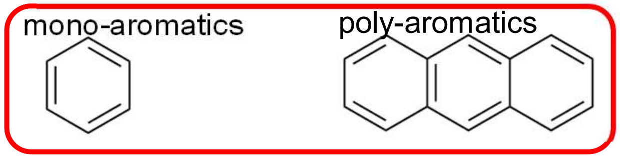
iso-alkanes



cyclo-alkanes



naphtheno-aromatics

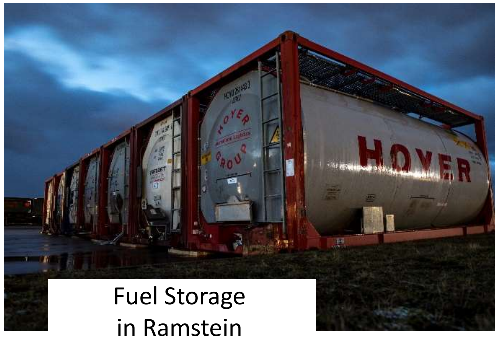


mono-aromatics

poly-aromatics

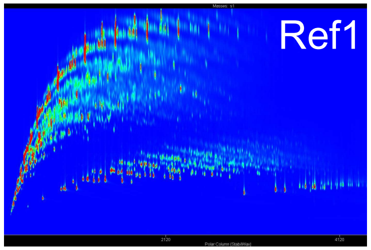
Hands-on Work: Fuel Composition, Blending and Fuel Delivery


Fuel Delivery in Manching (2015)


Fuel Storage in Ramstein Air Force Base (2018)

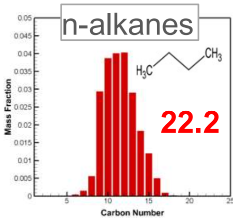

Fueling and sampling, Manching (2015)

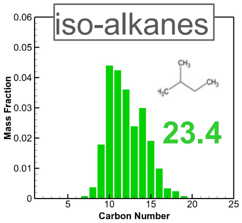
Analytics GC x GC

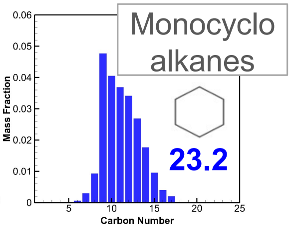


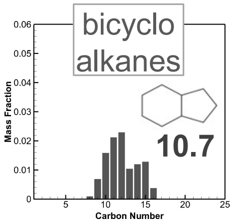
Aromatics: 20.5 %mass
Hydrogen: 13.64 %mass

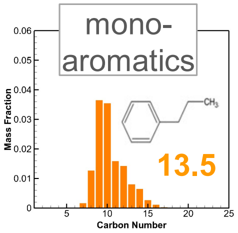
Discrete quantitative composition

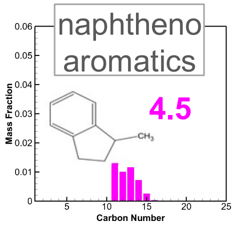


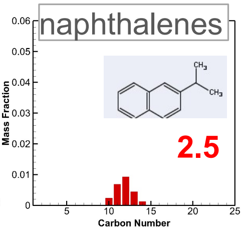


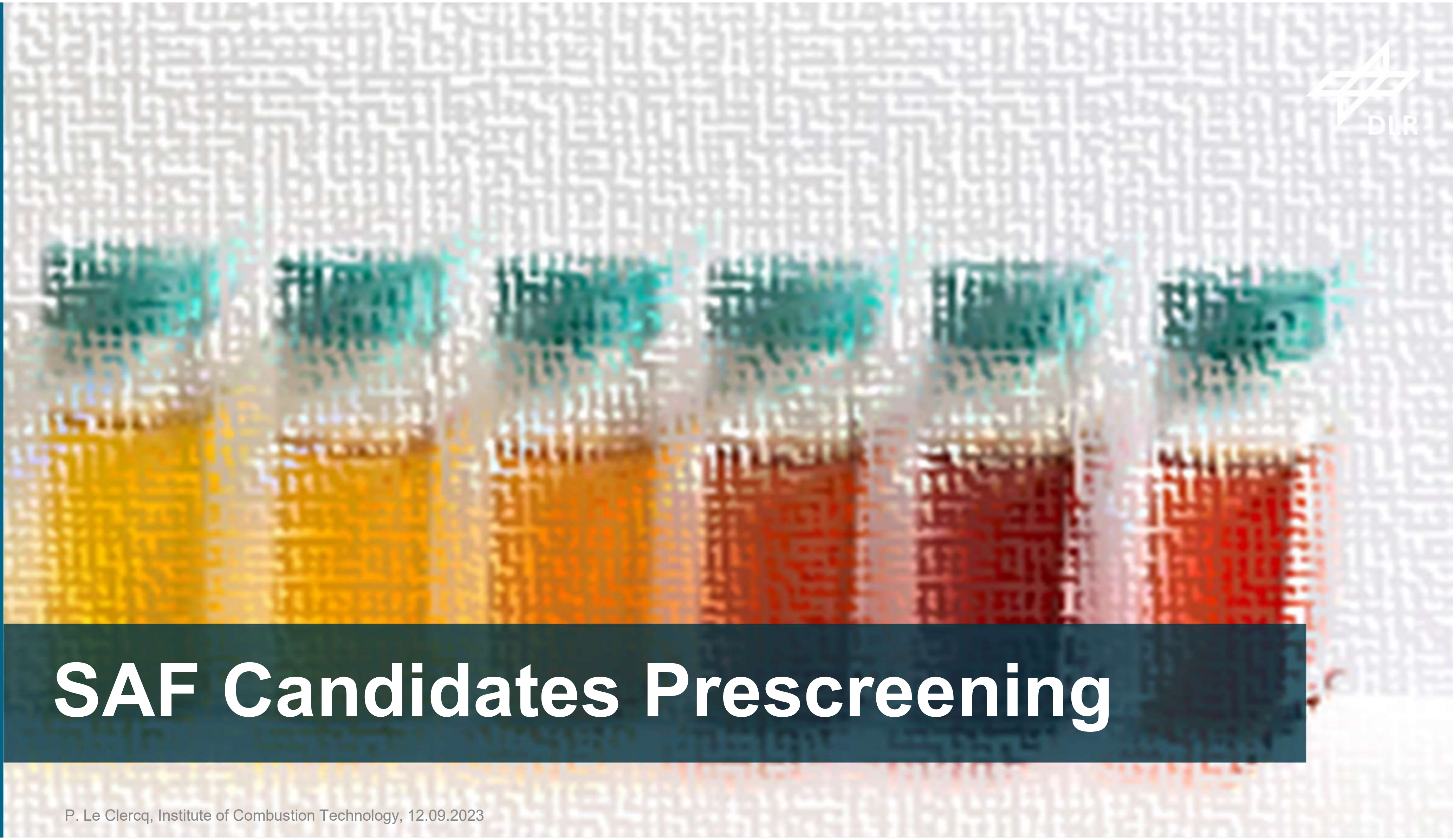






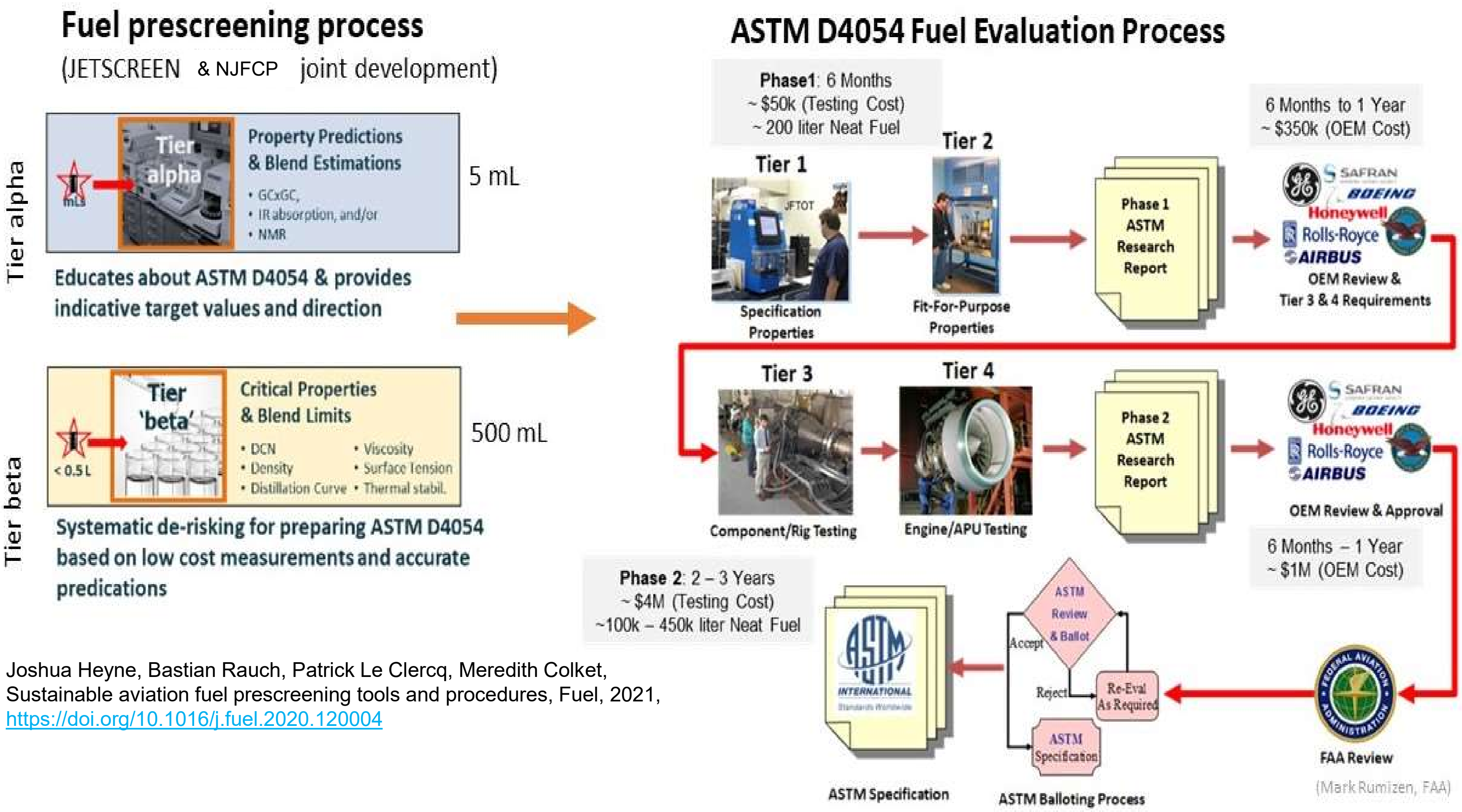






SAF Candidates Prescreening

SAF Candidates Prescreening and Approval Process



Fuel prescreening process

(JETSCREEN & NJFCP joint development)

Educates about ASTM D4054 & provides indicative target values and direction

Systematic de-risking for preparing ASTM D4054 based on low cost measurements and accurate predications

ASTM D4054 Fuel Evaluation Process

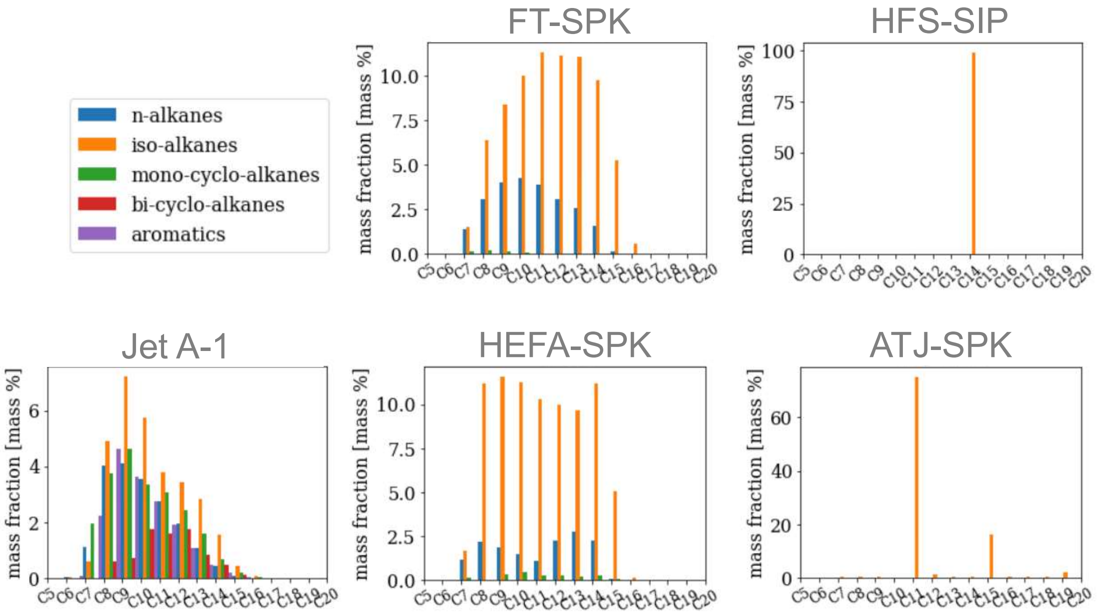
Joshua Heyne, Bastian Rauch, Patrick Le Clercq, Meredith Colket, Sustainable aviation fuel prescreening tools and procedures, Fuel, 2021, https://doi.org/10.1016/j.fuel.2020.120004

SAF Approval

From Challenges to Feasibility

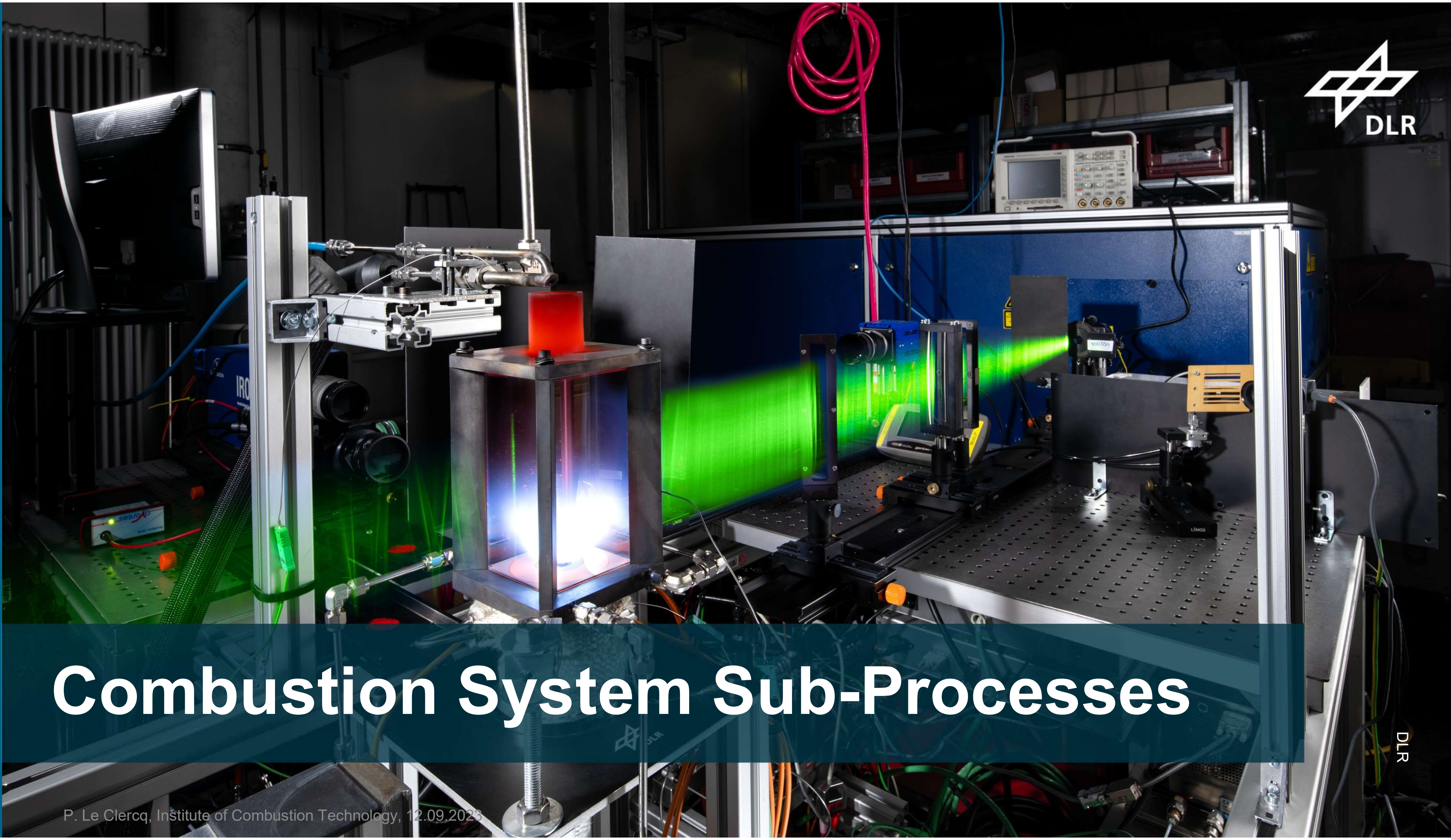
8 pathways included in the ASTM D7566 specifications for aviation fuel containing synthesized hydrocarbons:

- FT-SPK (2009)
- HEFA-SPK (2011)
- HFS-SIP (2014)
- FT-SPK/A (2015)
- ATJ-SPK [iso-butanol] (2016)
- ATJ-SPK [ethanol] (2018)
- CHJ (2020)
- HHC-SPK (2020)



Many more pathways are currently in the ASTM D4054 approval process.

Task forces to develop standard(s) for a) 100% Drop-In SAF (March 2021),
b) 100% SAF without aromatics (Mid 2022)

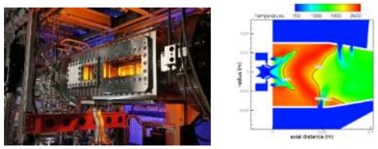


Combustion System Sub-Processes

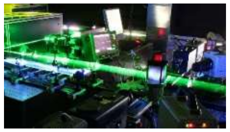
Validation Strategy for Fuel Sensitive Models

Capturing fuel sensitivity

Combustion chamber

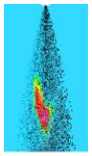


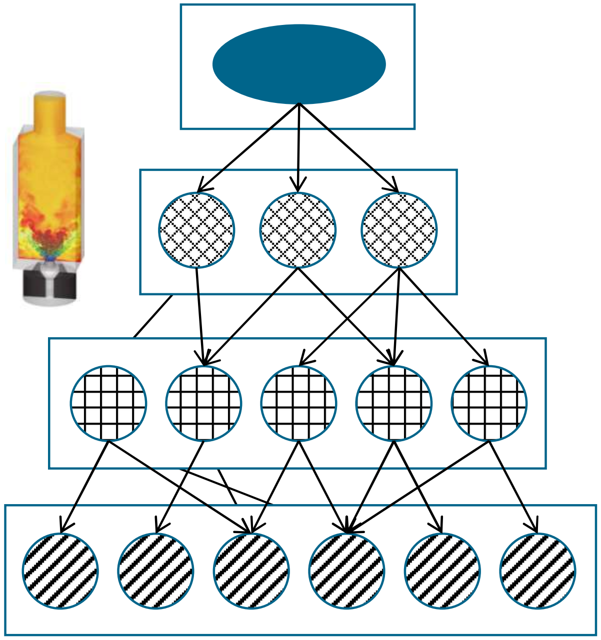
Standard Spray Burner
LBO, Flame position, Emissions



Reacting droplet chains

Spray ignition





System

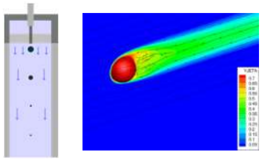
Subsystem

Benchmark Cases

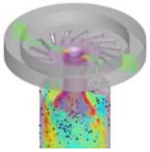
Unit Problems

New fuel

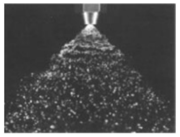
Single droplet evaporation



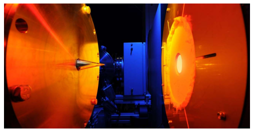
Turbulence-Particle interaction



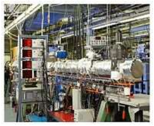
Atomization



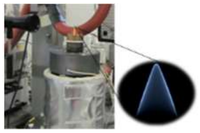
Flow reactor



Shock tube



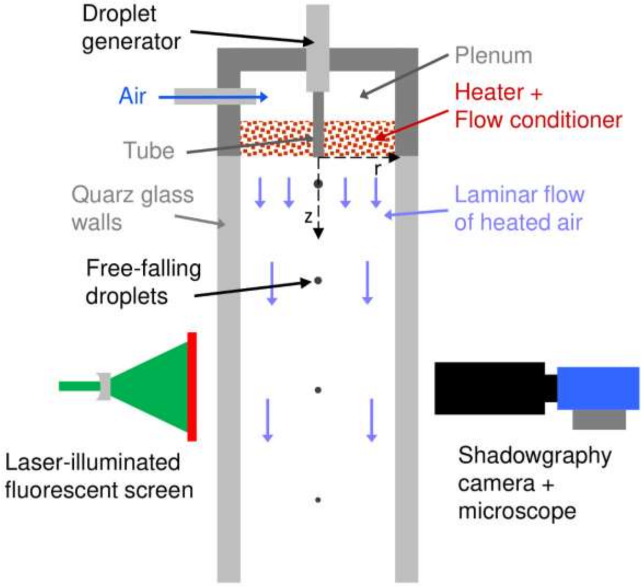
Lam. flame burner



Evaporation

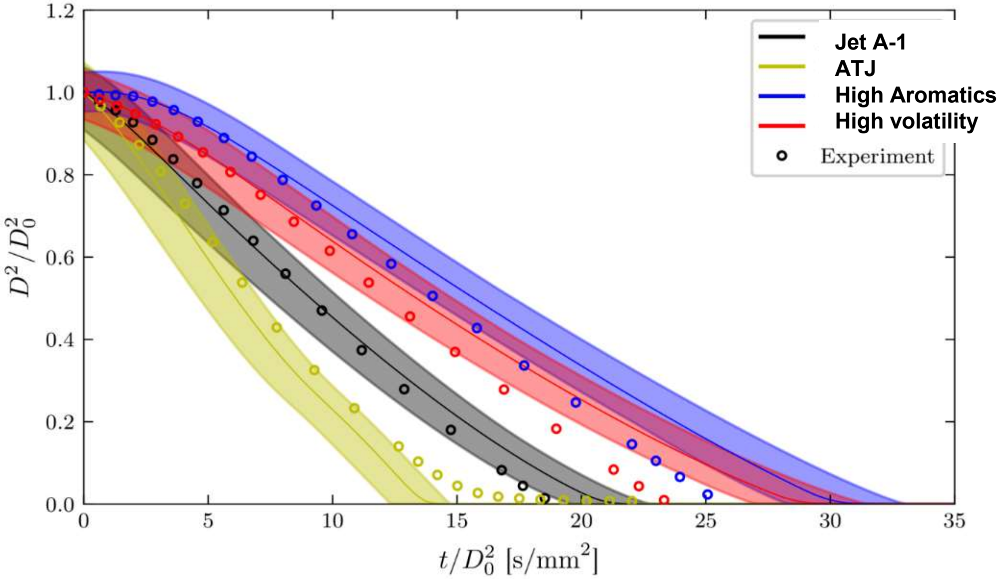
Unit Problem including UQ for Testing Fuel Sensitive Model

Single droplet evaporation experiment



M. Stöhr *et al.,* Proc. Combust. Inst. 38 (2021)
M. Stöhr *et al.,* Fuel 356 (2024)

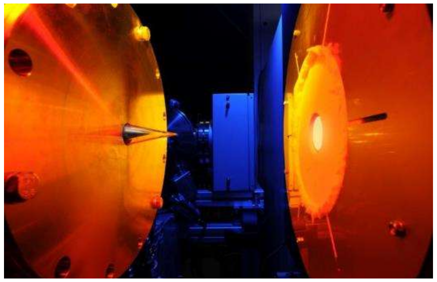
Single droplet evaporation rates: Exp. vs Comp.



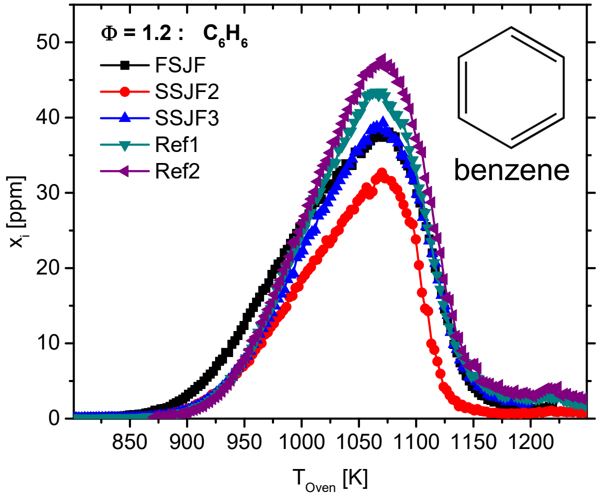
S. Ruoff *et al*, Atomization and Sprays "Special Issue: ILASS Europe 2020

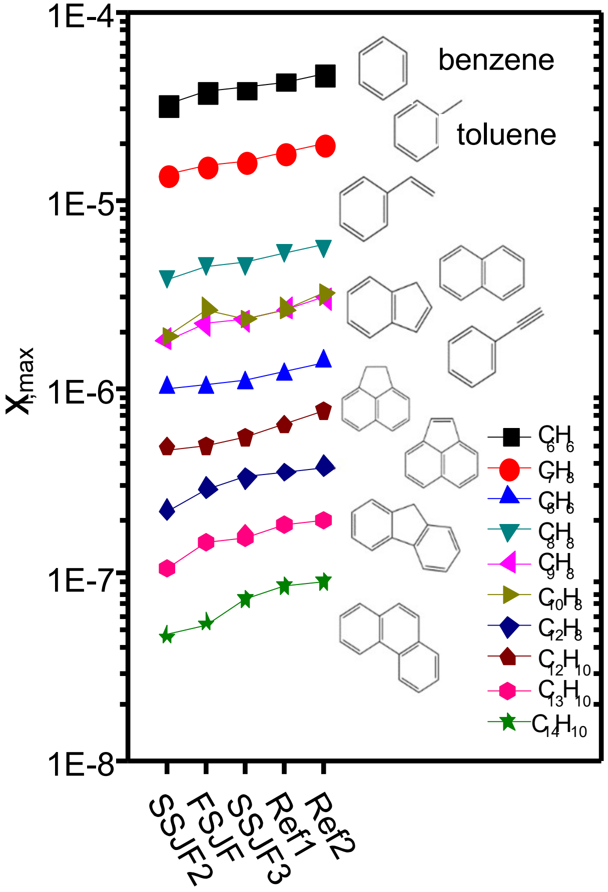
Fuels Impact on Soot Precursors Formation

Flow reactor



Species profile





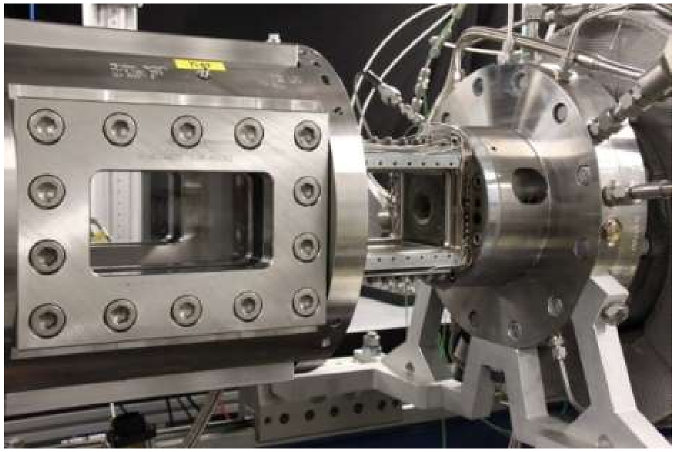
Molecular-beam mass spectrometry (MBMS)

P. Oßwald, J. Zinsmeister, M. Köhler, *et al* Fuel, 2021
https://doi.org/10.1016/j.fuel.2021.120735

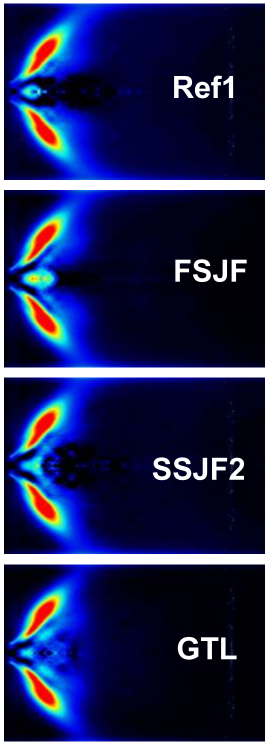
Fuels Impact on Combustor Performance and Emissions

Characteristic of the primary zone

Hi-POT
High Pressure single sector rig



OH* chemiluminescence
p=6 bar, T_{air}=323 K, Φ=0.99



T. Mosbach, DLR, 2016.

Qualitatively

← Experiment

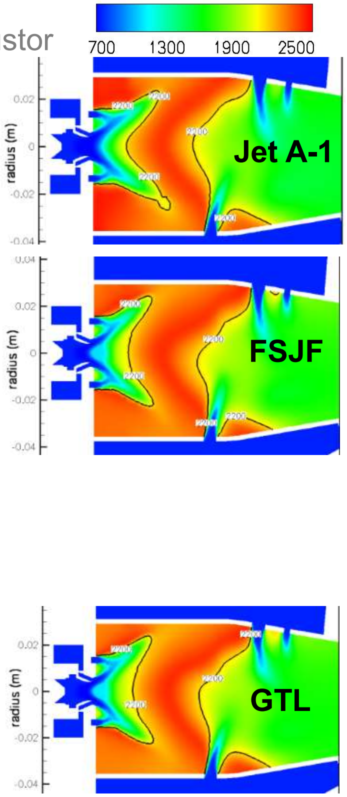
All jet fuels display quasi identical primary reaction zone position and volume integrated intensity.

Modeling →

Same conclusions based here on the temperature field.

Mod: E3E Combustor (VT-MAT)

Temperature field
p=6 bar, T_{air}=700 K

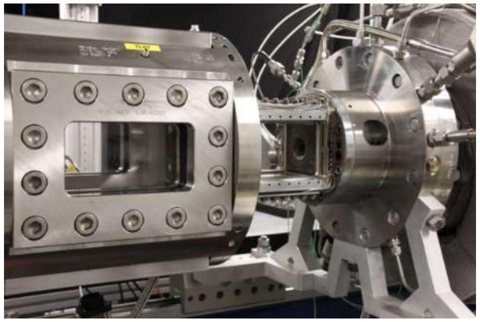


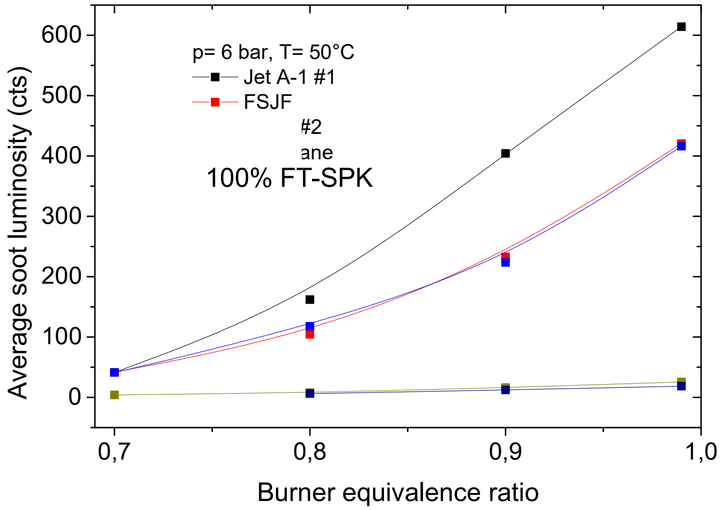
P. Le Clercq *et al*, DLR, AIAA, 2010.

Fuels Impact on Combustor Performance and Emissions

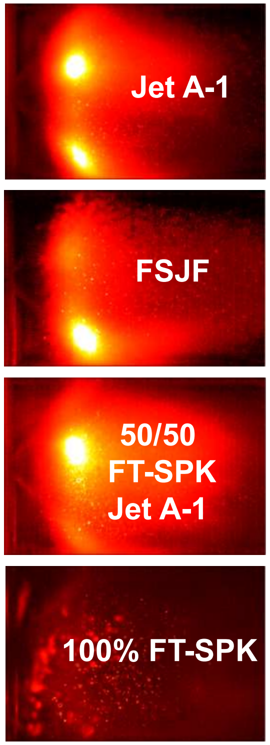
Characteristic of the primary zone

High Pressure single sector rig





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



Rig Test 2016

Source: T. Mosbach, DLR, 2016.

Qualitatively

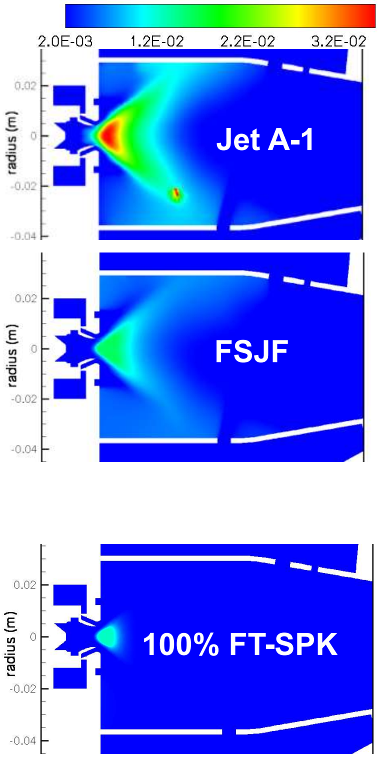
← Experiment:

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

Simulation: →

The lower the aromatics content the lower the soot precursor(e.g. benzene) concentration.

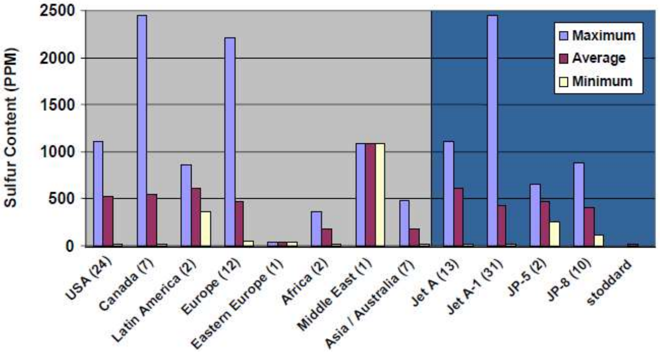
Benzene concentration
p=6 bar, T_{air}=700 K, Φ=0.99



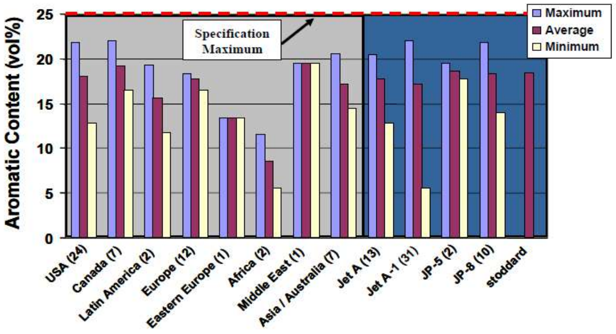
Prediction 2010

Source: P. Le Clercq *et al*, DLR, AIAA, 2010.

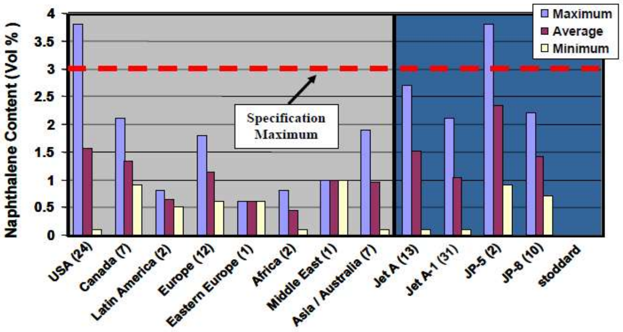
2006 CRC World Fuel Survey: Jet Fuel main characteristics



S content (% m/m)



Aromatics by FIA / ASTM D1319 (%v/v)



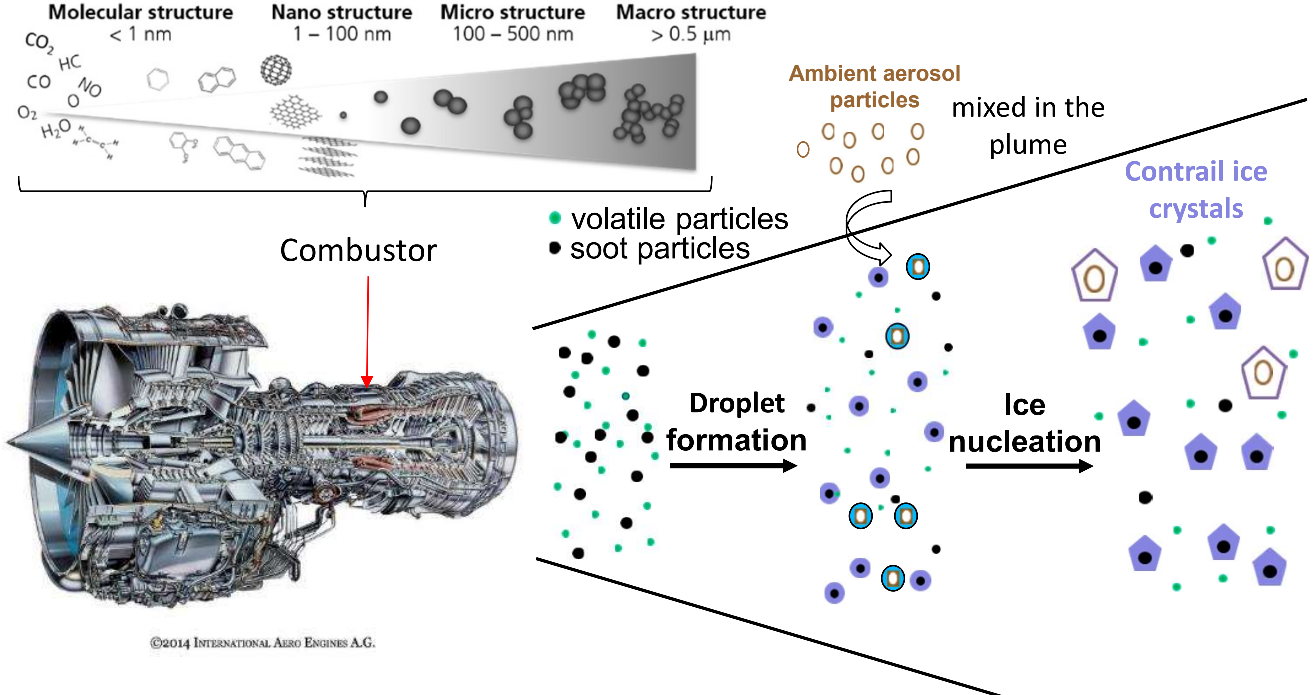
Naphthalenes by UV / ASTM D1840 (%v/v)

- **Sulfur: Average 400 ppm on Jet A-1,Max 2500 ppm** (in line with PQIS (Petroleum Quality Inspection, US Defense Logistic Agency, 2013) Survey)
- **Aromatics: average 17 - 18% v/v (Max 22%)**
  - **Minimum aromatics 12%** (in line with PQIS Survey)
- **Naphthalenes: average 1 to 1.5%,**
  - **Max: 3,5% on JP5, Max 2 to 2.5% on Jet A/A-1**

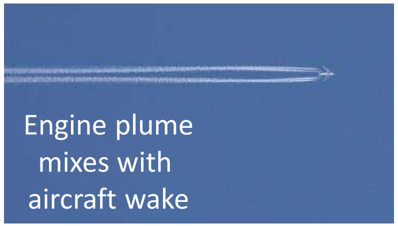
CRC Report No. 647, WORLD FUEL SAMPLING PROGRAM, June 2006, : https://crcao.org/crc-report-no-647/

Contrails and Climate Impact

Condensation Trail (Contrail)



Particles mainly act as condensation nuclei


Engine plume mixes with aircraft wake

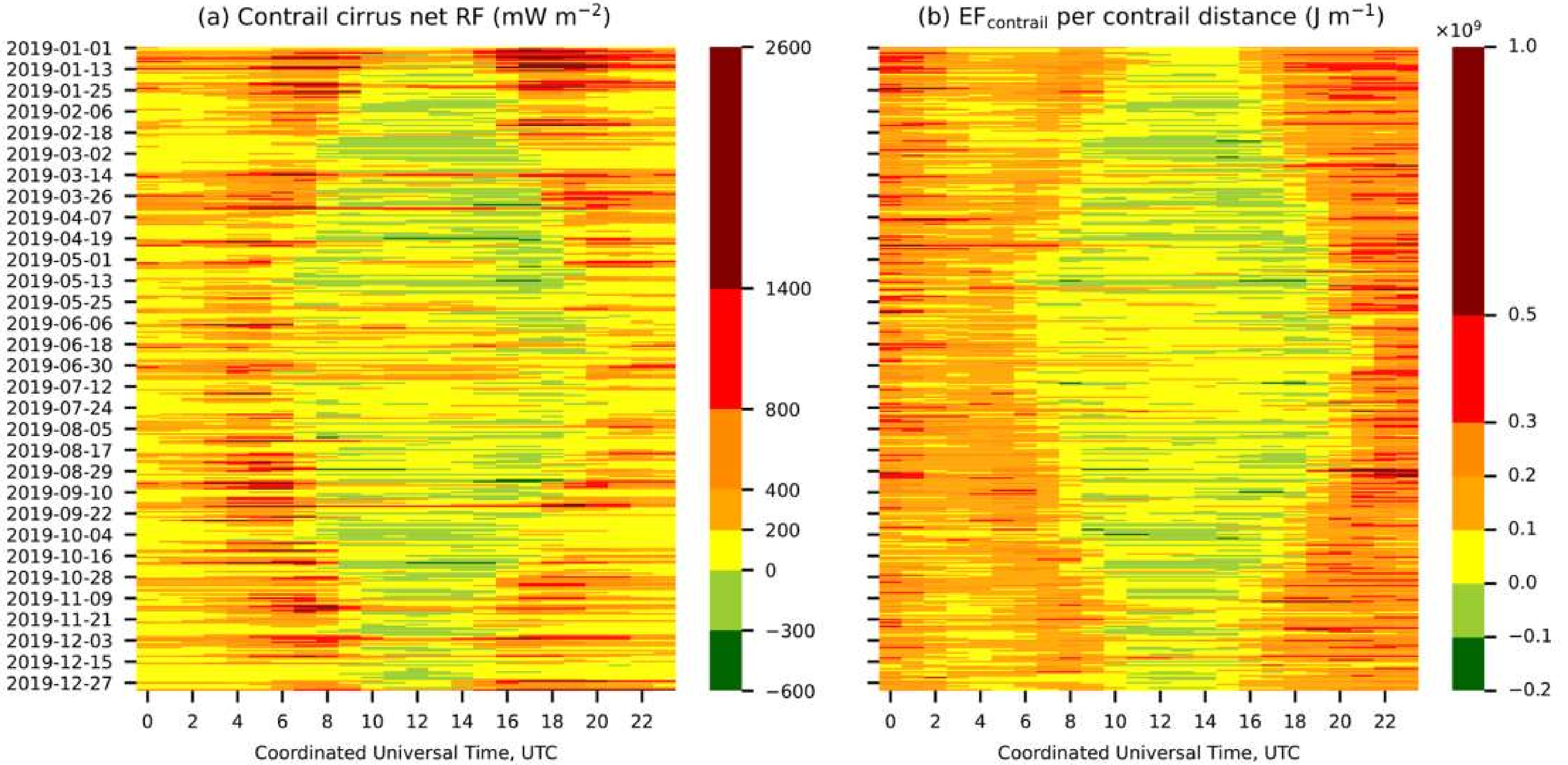
Contrail **formation** depends on engine conditions: T, P, water
ambient conditions: T, P, RH

Contrail **properties**
(number of ice crystal and cross section) depends on
engine emissions characteristics:
number of soot particles for soot-rich engine exhaust
aircraft size: weight, wingspan

Contrail **persistency** depends on ambient conditions: RH and supersaturation w/r ice

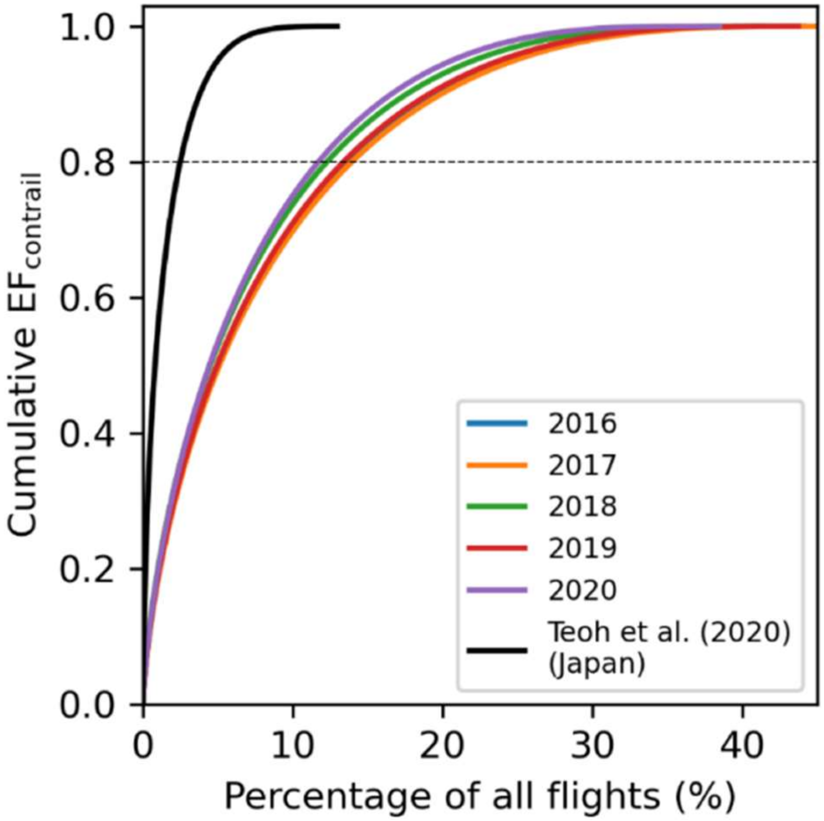
Aircraft Induced Cloudiness (AIC):
Persistent contrails leading to contrail-cirrus

Aviation Contrail Climate Effects



- Day : cooling, Night: warming & seasonal influences

Aviation Contrail Climate Effects (3)



Source: Teoh et al. "Aviation contrail climate effects in the North Atlantic from 2016-2021.“ Atmospheric Chemistry and Physics, (2022)

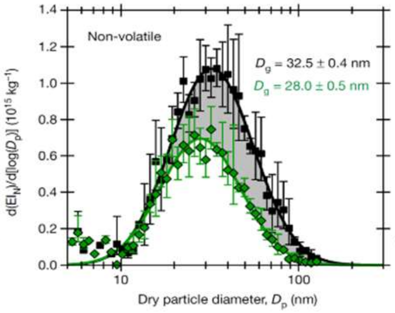
- Big Hits: 10% of flights cause 80% of climate impact

Measurement Campaigns

2014 ACCESS-II

NASA/DLR/NRC/FAA
Falcon/Falcon/DC8

50% SAF (HEFA) → ~50% reduction in soot emissions



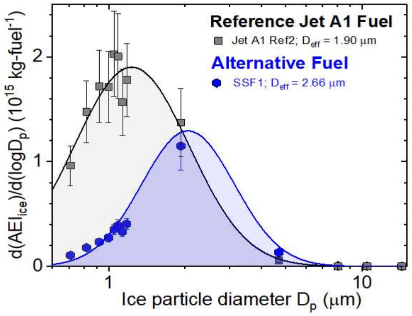
Moore *et al*, Nature, 2017

1. SAF (HEFA) reduces not only CO_2 but also nvPM emissions

2015 ECLIF-1

DLR/Sasol/NASA
Falcon/ATRA-A320

Systematic investigation → SAF optimization possible



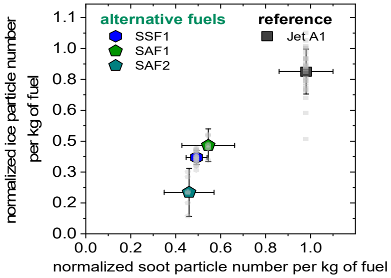
Voigt *et al*, Nature CEE, 2021

2. Aromatics & hydrogen content impact on nvPM and contrail formation

2018 ECLIF-2/ND-MAX

DLR/NASA/NRC/FAA
DC8/ATRA-A320

50% SAF (HEFA) → ~50% reduction in nvPM and of ice particles in contrails



Voigt *et al*, Nature CEE, 2021

3. Fuel Design

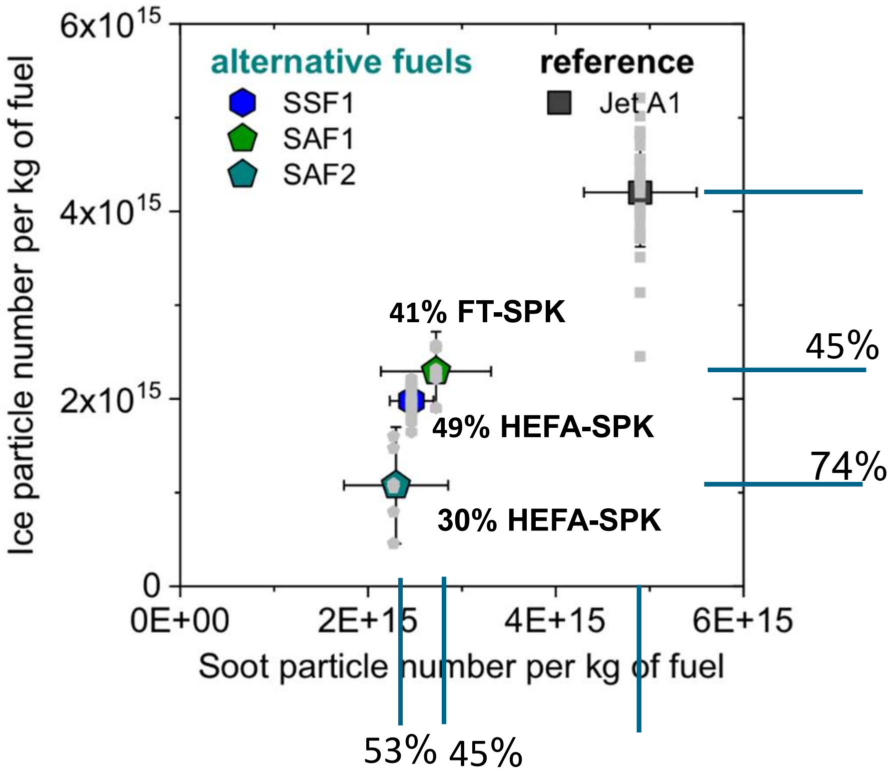
2021 ECLIF-3

DLR/AIRBUS/Rolls-Royce/Neste
Falcon/A350

World's first emissions measurements of 100% SAF (HEFA) behind large passenger aircraft

4. Demonstrate use and benefits of 100% SAF (SPK)

ECLIF I&II: Successful Fuel Design Application

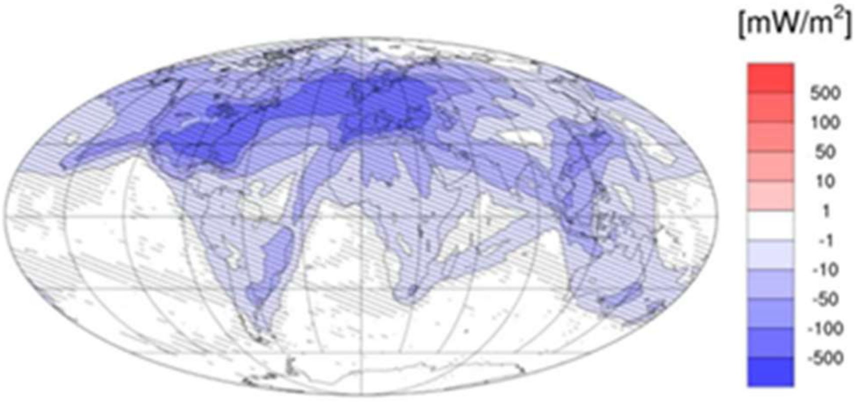


Voigt *et al*. (2021)
In Commun Earth Environ 2 (1). DOI: 10.1038/s43247-021-00174-y.

Fuel design to reduce CO_2 emissions & non-CO_2 effects:

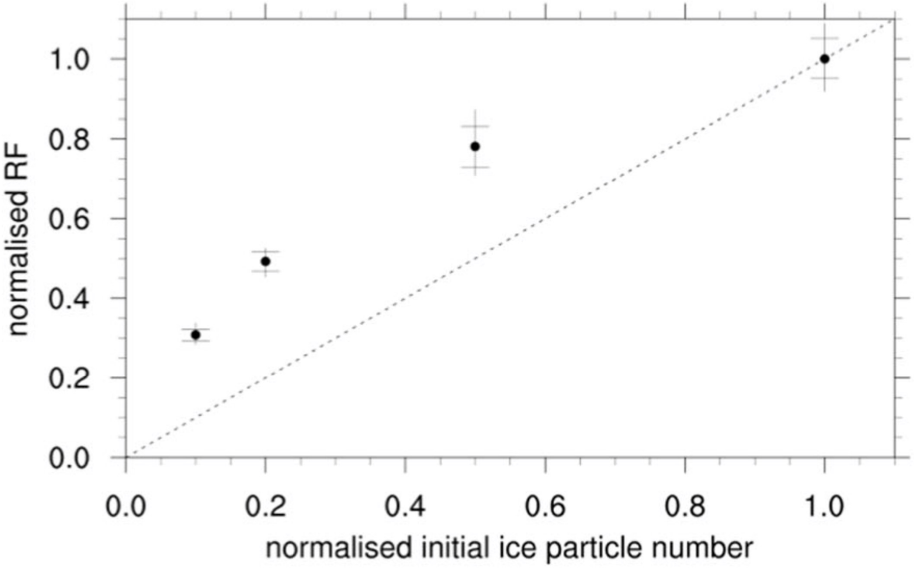
30% HEFA-SPK (SAF2), which is currently more realistic from a production capacity and economic perspective leads to greater reductions in soot emissions and ice crystal concentrations than the 49% HEFA-SPK (SAF1) blend.

Aviation Contrail Climate Effects



Relative change in contrail cirrus net radiative forcing due to a 80% reduced initial ice crystal number

Source: Burkhardt et al. npj Climate and Atmospheric Science (2018) 37



When reducing the initial ice crystal number by 80%, global contrail cirrus net radiative forcing is decreased by 50%.

Conclusion

- The use of sustainable aviation fuels (SAFs) is **technically feasible**. 8 pathways are approved for use in blends with fossil Jet A-1 up to 50%. Flying with SAFs can **reduce the CO_2 footprint by up to 80%** compared to fossil Jet A-1 potentially more in the future with PtL jet fuel and blending ratios going toward 100% (demonstrated!).
- Jet fuel's **composition**, and thus, **properties affect contrail formation**.
- Using high H-content (low aromatics) **SAFs reduces soot particle emissions** (by number), which yields lower apparent ice crystals concentration in young contrails, and in turn reduces the warming effect of contrail cirrus.
- SAF is a 'win-win-win' mitigation option for reducing the carbon footprint of aviation, **improving air quality** and reducing contrail cirrus impact on climate.

Thank You!

Credits: DLR/NASA/Friz

Imprint

Thema: Emissions and non-CO_2 effects reductions by burning SAF
Datum: 12.09.2023
Autor: Patrick Le Clercq
Institut: DLR Institute of Combustion Technology
Bildcredits: DLR, NASA