



THE UNIVERSITY  
OF BRITISH COLUMBIA



**NRC - CNRC**



# Jet Contrails from Aviation Lubricants and Fuels (JET-CALF)

## Preliminary Work – Performance & Gaseous Emission Measurement

Sid Sharma

Task 1 – Simone Saini, Anand Kumar, Steven Rogak.

Task 2 – Jan Goeing, Sid Sharma, Henna Lintusaari, Daniel Lieder, Cameron Varcoe, Peter Furmedge, Sung Hoon Park, Tim Sipkens, Patrick Kirchen, Steven Rogak

# Overview

1. Project Progress
2. Introduction to Engine
3. Methodology
4. Results & Upcoming work
5. Nishan Will discuss the PM Data

# Project Progress

Currently working on work package 2 (WP2) specifically 2.1 & 2.2.

Research questions in this update:

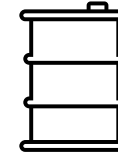
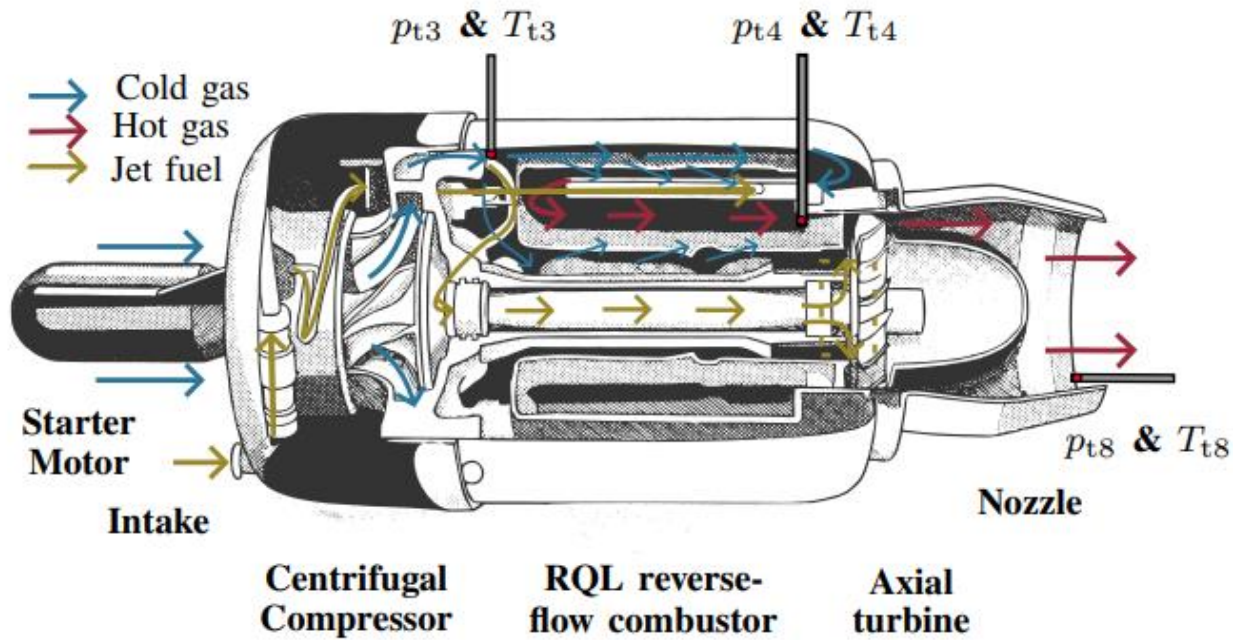
- How do different fuels affect engine performance?
- How do different fuels affect gaseous emissions?
- How do different fuels affect particulate emissions?
- How do the micro-turbojet results compare with full-scale engine trends?
- I will Focus on the 1st, 2nd, and the last research questions.

Nishan will focus on the third research question.

| #   | Tasks and <i>Milestones</i>                                                                        | Year 1 |   |   |   | Year 2 |   |   |   |
|-----|----------------------------------------------------------------------------------------------------|--------|---|---|---|--------|---|---|---|
| 0   | Partnership Meetings (all involved researchers attend)                                             | x      | x | x | x | x      | x | x | x |
| 1   | Develop CCN measurent using modified water CPC (led by PDF Kumar)                                  |        |   |   |   |        |   |   |   |
| 1.1 | Find suitable operating temperatures                                                               |        |   |   |   |        |   |   |   |
| 1.2 | Validate standard hygroscopic and hydrophobic particles                                            |        |   |   |   |        |   |   |   |
| 1.3 | Test method on fresh soot, stripped soot, coated soot                                              |        |   |   |   |        |   |   |   |
| 1.4 | <i>Manuscript 1 submitted to J. Aerosol Sci.</i>                                                   |        |   |   |   | x      |   |   |   |
| 2   | Commission and characterize microturbojet engine (led by PHD1 Sapkota)                             |        |   |   |   |        |   |   |   |
| 2.1 | Emissions tests with micro turbojet engine (gas& particulate)                                      |        |   |   |   |        |   |   |   |
| 2.2 | Review/compare emissions with data for full scale engines                                          |        |   |   |   |        |   |   |   |
| 2.3 | Select operating conditions and exhaust conditioning                                               |        |   |   |   |        |   |   |   |
| 2.4 | Characterize nvPM size, morphology, CCN potential                                                  |        |   |   |   |        |   |   |   |
| 2.5 | <i>Manuscript 2 submitted to Env. Sci. and Technol.</i>                                            |        |   |   |   |        |   | x |   |
| 3   | Chemical characterization (led by PhD2)                                                            |        |   |   |   |        |   |   |   |
| 3.1 | With partner, select and procure fuels and lubricants                                              |        |   |   |   |        |   |   |   |
| 3.2 | Trial gas phase measurements incl. PTR-TOF                                                         |        |   |   |   |        |   |   |   |
| 3.3 | Measurement campaign with filter samples and hi-res mass spect                                     |        |   |   |   |        |   |   |   |
| 3.4 | Data analysis                                                                                      |        |   |   |   |        |   |   |   |
| 3.5 | <i>Manuscript 3 submitted to Env. Sci. and Technol.</i>                                            |        |   |   |   |        |   |   | x |
| 4   | Synthesis: interaction of lubricating oil and solid particles on contrail-forming potential (team) |        |   |   |   |        |   |   |   |
| 4.1 | Evaluation of CCN/IN data for nvPM and oil for lab conditions                                      |        |   |   |   |        |   |   |   |
| 4.2 | Thermodynamic/kinetic modelling considering organic volatility                                     |        |   |   |   |        |   |   |   |
| 4.3 | Estimation of CCN/IN potential for flight conditions                                               |        |   |   |   |        |   |   |   |
| 4.4 | <i>Manuscript 4 submitted to Env. Sci. and Technol.</i>                                            |        |   |   |   |        |   |   | x |

# Introduction: The Micro-Turbojet Engine

## JetCat P200-SX Micro-Turbojet:



→ ~100 L of fuel required per fuel to collect data.

## Engine Specifications:

|                            |         |
|----------------------------|---------|
| Max RPM                    | 112,000 |
| Max Thrust (N)             | 230     |
| Pressure Ratio             | 4       |
| Mass Flow (kg/s)           | 0.45    |
| Fuel Flow @ Max RPM (kg/s) | 0.0096  |
| Nozzle Exit Area ( $m^2$ ) | 0.0028  |

- The engine utilizes **open-loop** lubrication system.

# Methodology: Experimental Setup Improvements

## Performance Measurements

Thermocouples, pressure transducers, a force transducer, speed sensor, and fuel flow metering were used to track engine operating condition.

## Undiluted Line (Jet Core)

Prandtl probe at nozzle exit.

ECOM measured raw  $\text{CO}_2$ , CO, and  $\text{NO}_x$ .

## Diluted Line

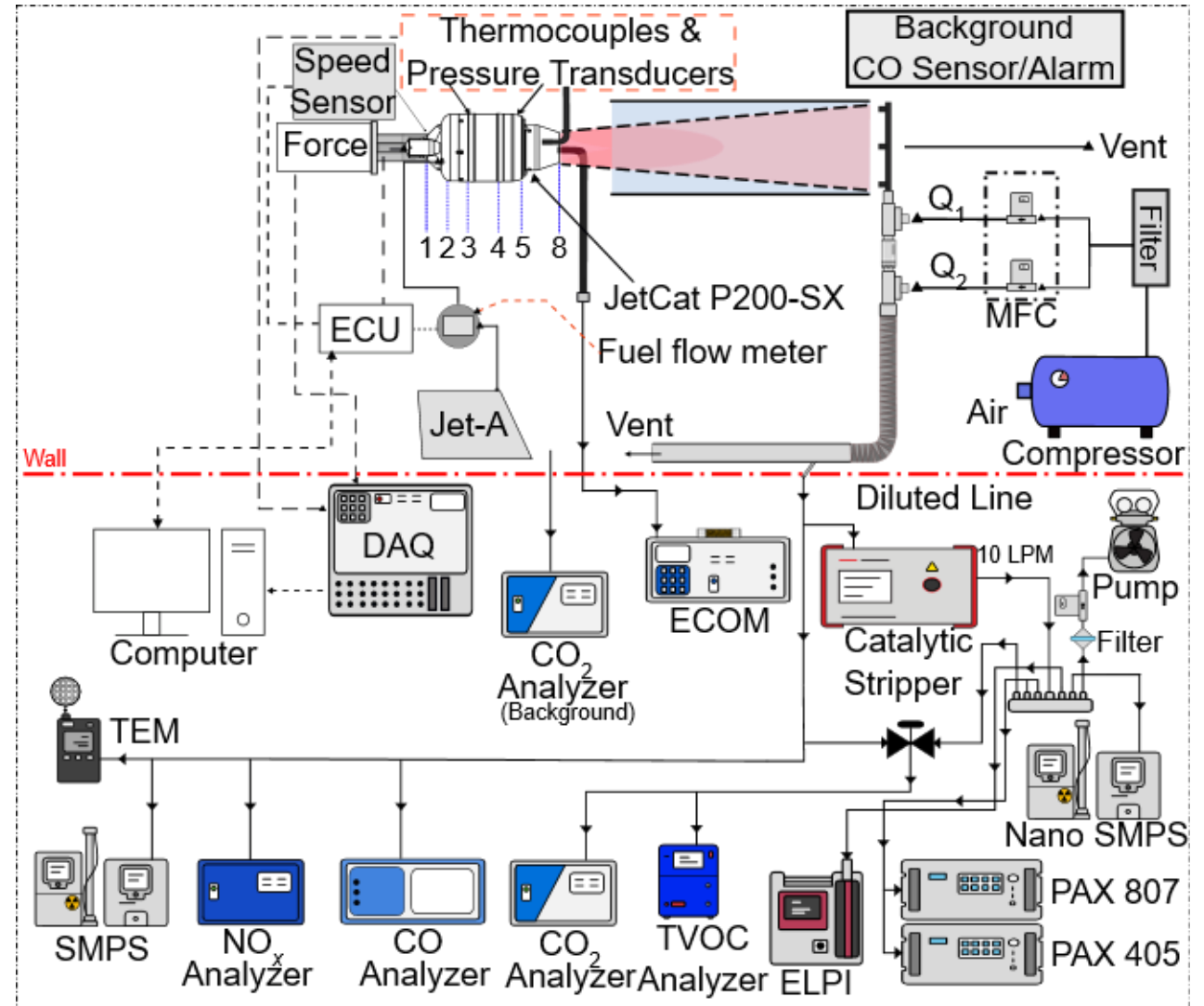
Multi-hole probe with 2-stage ejector dilution.

- **Gas-Phase Analysis**

- Dedicated  $\text{NO}_x$ , CO, and  $\text{CO}_2$  analyzers on the diluted line.

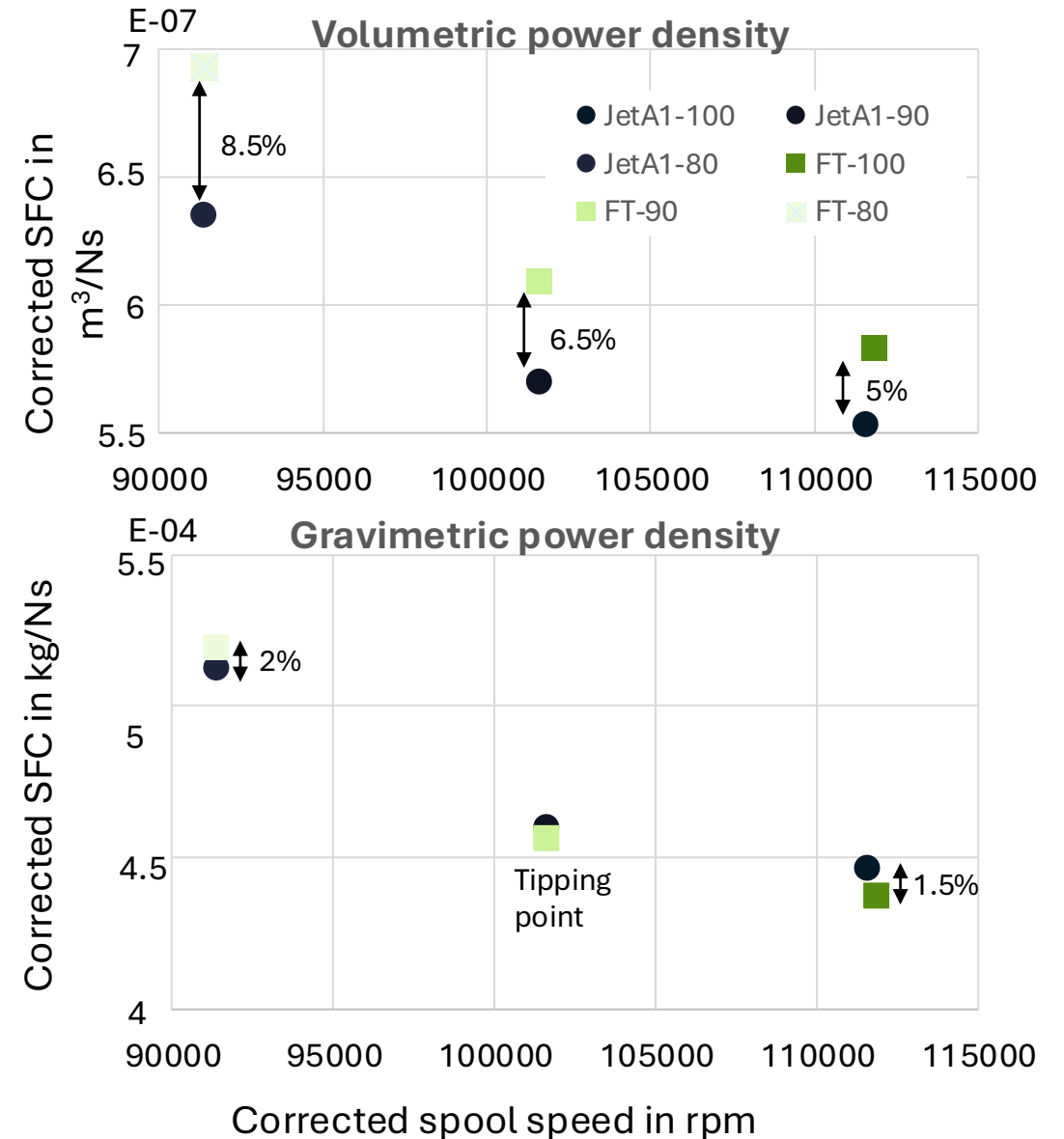
- **Particle Phase**

- Nishan will discuss particle instruments in more detail.

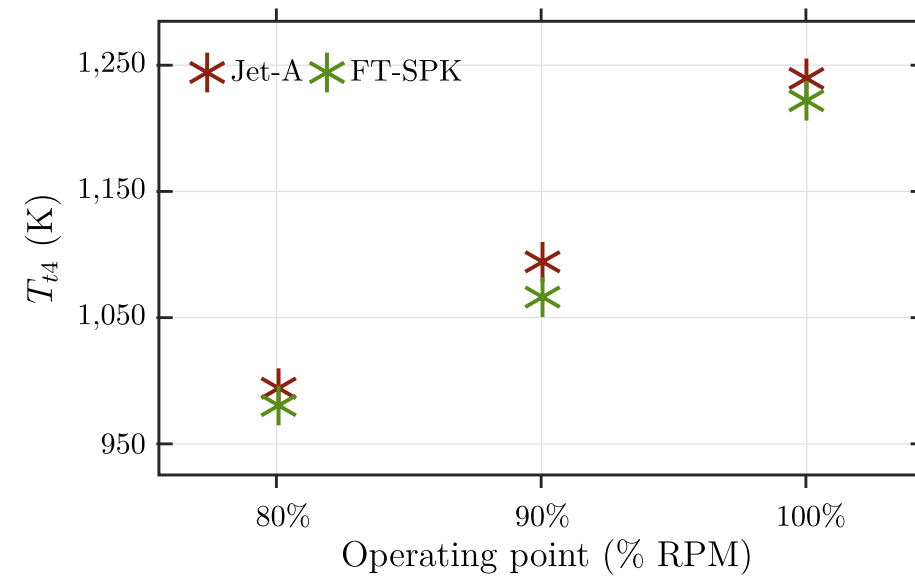
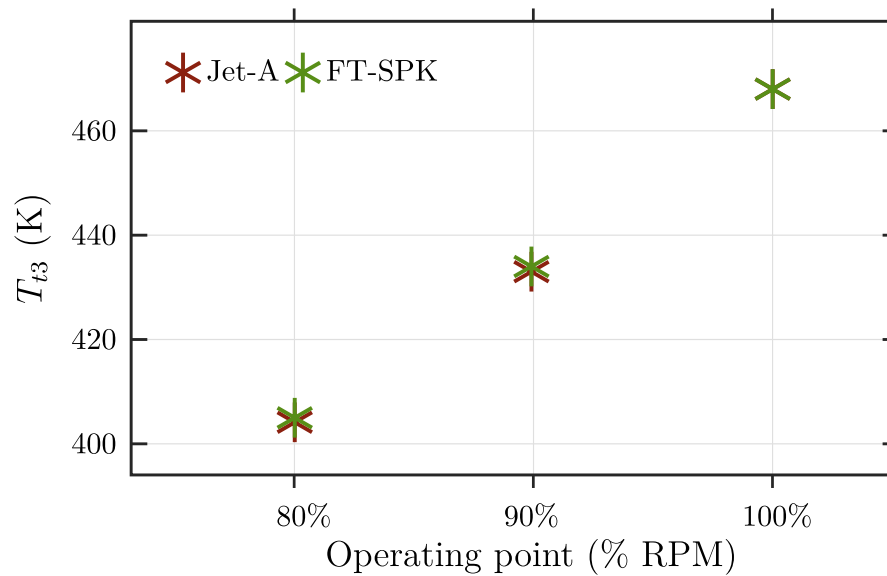
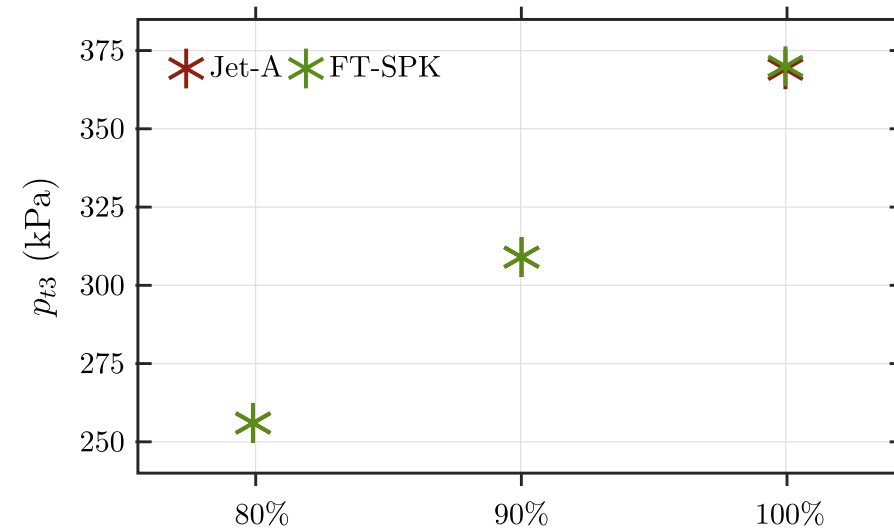
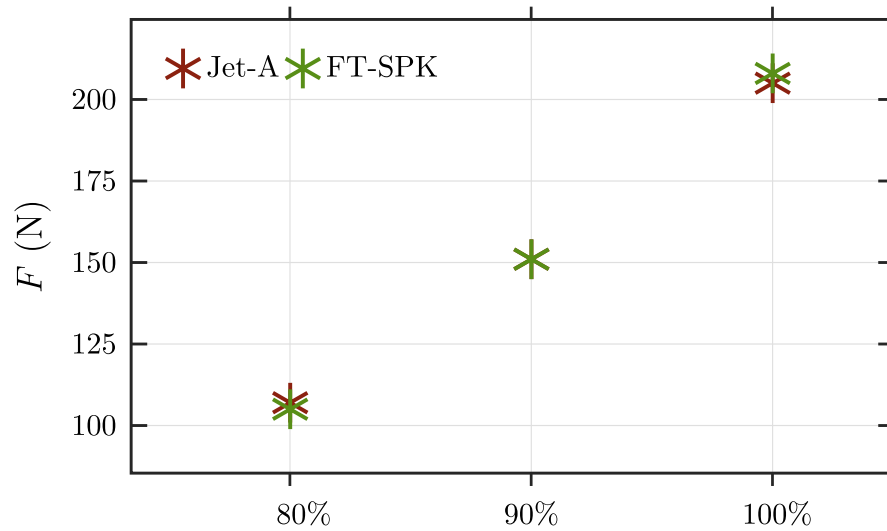


# Results: Back-to-Back Tests

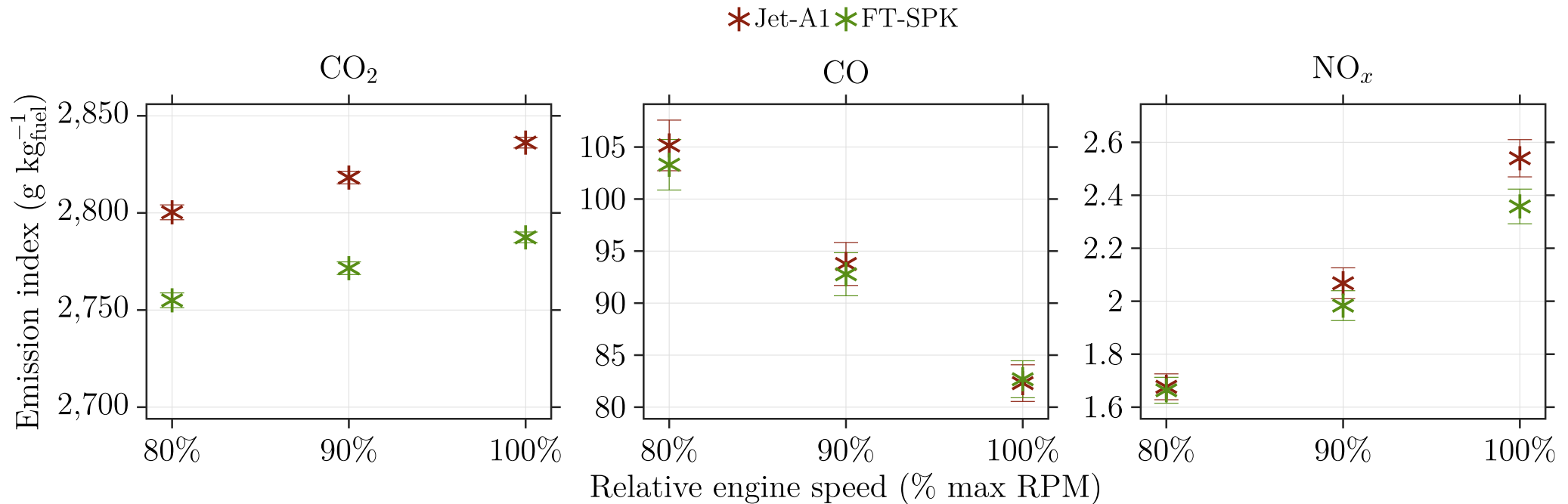
- Take-off consistent with literature for full-scale engines (validation required)
- Need for a baseline Jet A-1 as reference (**mean density of Jet-A1 and FT-SPK used**)
- Ready for SAF testing; FT is not part of this project



# Results: Back-to-Back Tests



# Results: Back-to-Back Tests



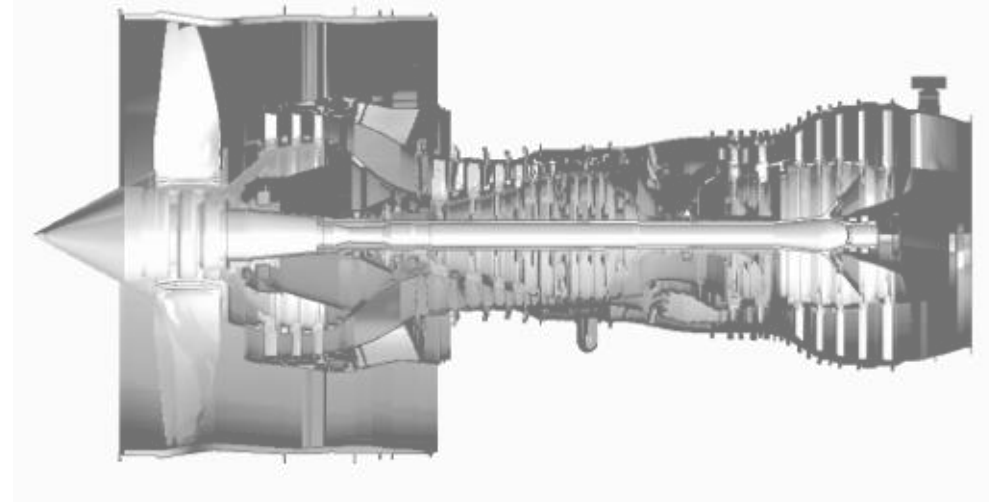
- FT-SPK produced lower emission indices than Jet A-1 for CO<sub>2</sub>, CO, and NO<sub>x</sub> at all tested engine speeds.
- CO<sub>2</sub> and NO<sub>x</sub> increased with increasing relative engine speed for both fuels, while CO decreased as engine speed increased.
- The gap between fuels remained fairly consistent across the speed range, indicating a repeatable emissions advantage for FT-SPK in the back-to-back tests.

# V2500 Turbo Fan Engine

- The V2500 provides the full-scale reference case for comparison with the micro-turbojet results.

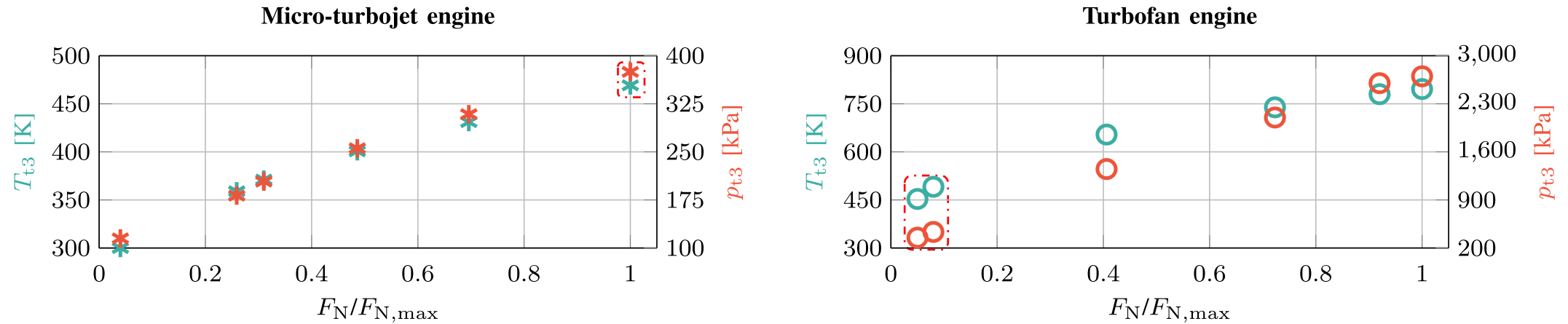


| IAE V2500 Turbofan Engine: |                        |       |           |               |
|----------------------------|------------------------|-------|-----------|---------------|
| Take-Off Thrust            | Weight                 | BPR   | Fan Power | Thermal Power |
| 110 kN<br>(25,000 lbf)     | 2,500 kg<br>(5,300 lb) | 5.6:1 | 20 MW     | 50 MW         |



[13] (Göing 2023)

# Results: Micro-Turbojet vs Turbofan (Jet-A1)



- Direct operating-point comparison between the JetCat and a full-scale V2500 turbofan is constrained by scale. However, a specific thermodynamic intersection exists:

| Engine                            | OPR               | $T_{t3}$     | $P_{t3}$       |
|-----------------------------------|-------------------|--------------|----------------|
| <b>Micro-Turbojet @ max OP</b>    | $\approx 4$       | <b>469 K</b> | <b>374 kPa</b> |
| Full size Turbofan @ idle OP [14] | $\approx 3.5 - 4$ | 453 K        | 351 kPa        |

**"Micro-Max / Macro-Idle":** This thermodynamic intersection establishes a physically valid anchor point for the performance. **Matching combustor inlet conditions creates a similar environment for combustion**, enabling valid comparisons. It allows us to approximate commercial turbofan idle conditions in a laboratory setting.

# Results: Micro-Turbojet vs Turbofan (Jet-A1)

$$EI_{CO} = \left( \frac{1000 M_{CO} \eta_{comb} Y_C}{M_C} \right) \frac{x_{CO}^{DL}}{x_{CO_2}^{DL} - x_{CO_2}^{bg} + x_{CO}^{DL}}, \quad (1)$$

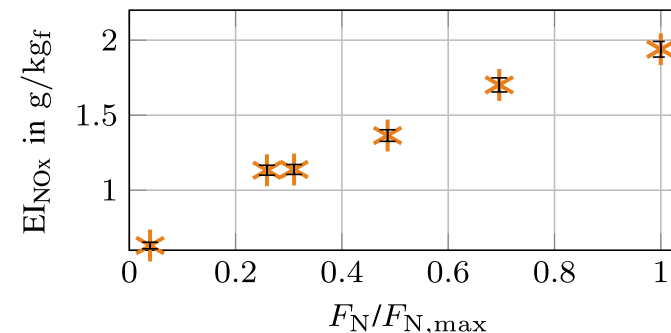
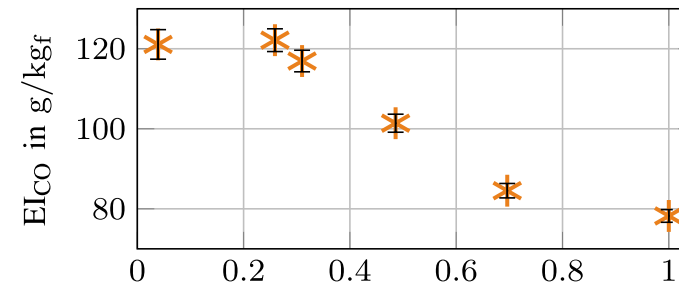
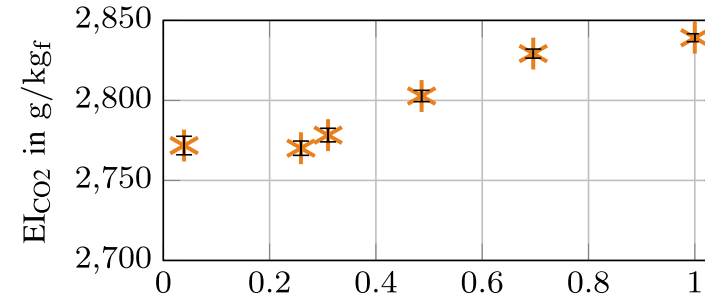
$$EI_{CO_2} = \left( \frac{1000 M_{CO_2} \eta_{comb} Y_C}{M_C} \right) \frac{x_{CO_2}^{DL} - x_{CO_2}^{bg}}{x_{CO_2}^{DL} - x_{CO_2}^{bg} + x_{CO}^{DL}}, \quad (2)$$

$$EI_{NO_x} = \left( \frac{1000 M_{NO_x} \eta_{comb} Y_C}{M_C} \right) \frac{x_{NO_x}^{DL}}{x_{CO_2}^{DL} - x_{CO_2}^{bg} + x_{CO}^{DL}}. \quad (3)$$

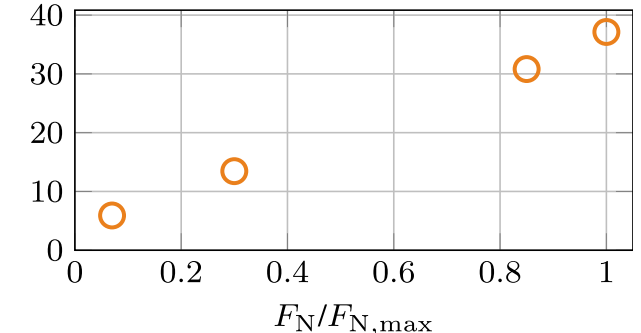
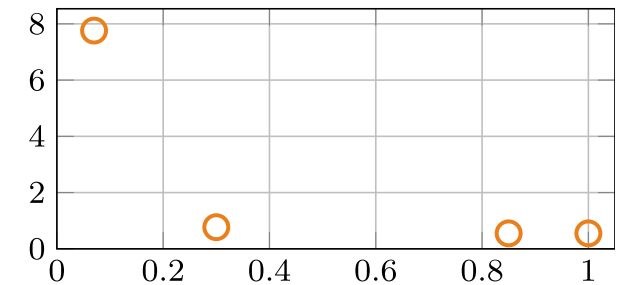
- **Qualitatively:** Preservation of directional trends confirms the facility's suitability for comparative fuel studies.

The ICAO emissions databank currently mandates reporting for CO and NO<sub>x</sub> but does not provide EI CO<sub>2</sub> or uncertainty ranges in its standard certification data, which is why those specific plots are blank for the full-scale engine [10].

Micro-turbojet engine



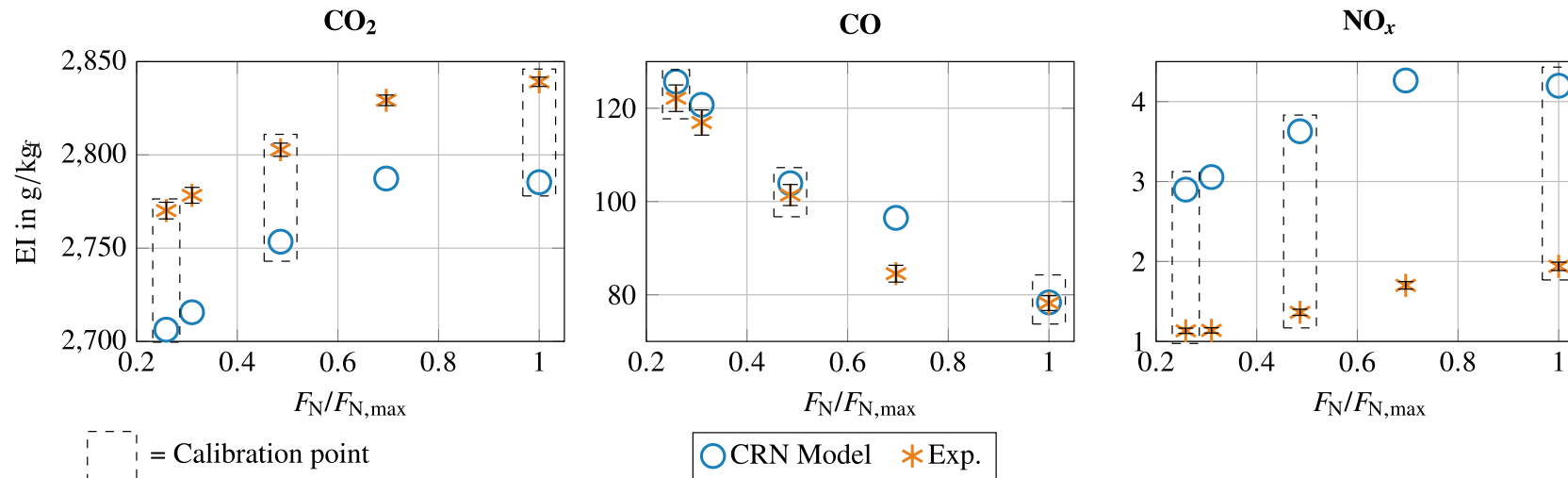
Turbofan engine



# Upcoming Work

**Summary: Matching combustor inlet conditions creates a similar environment for combustion, enabling valid comparisons.**

- While scale-dependent factors constrain direct quantitative extrapolation to full-scale engines, the micro-turbojet test rig successfully generates comparative data essential for identifying fuel-specific trends in a cost-effective environment.
- **“micro-max/macro-idle”** thermodynamic intersection enables calibration and validation of numerical scaling models.
- Experimental data will be used to calibrate and validate a chemical reactor network (CRN) model with TUBS [12].
- The goal of using such models is to extrapolate the fuel-specific micro-turbojet performance and emissions data to higher-load conditions in a full-scale engine.



# THANK YOU!

## In the next presentation Nishan will discuss PM emission measurement



THE UNIVERSITY  
OF BRITISH COLUMBIA

Sid Sharma



**NRC - CNRC**



# Appendix

# Introduction: Sustainable Aviation Fuels

**"Drop-In":** While marketed as "drop-in" replacements, SAFs are fundamentally different from one another. Depending on the feedstock and pathway, combustion characteristics can differ.

## **Key Chemical Differences:**

**Aromatic Content:** Often much lower in SAFs. This reduces soot/nvPM formation but causes critical issues with engine seals shrinking and leaking.

**Hydrogen-to-Carbon (H/C) Ratio:** Typically higher, which fundamentally alters the flame temperature and structure in the combustor.

**Lower Heating Value (LHV):** Differences in energy density directly impact fuel flow rates and overall engine performance.

**The Impact:** These chemical shifts dictate the emissions. Because SAFs are all different, we cannot assume any two SAFs will behave the same way in an engine.

# Back-to-back Testing

**Back-to-back testing:** Consecutively testing different fuels under identical ambient and operating conditions to strictly isolate fuel-property effects from engine effects.

**Why?**

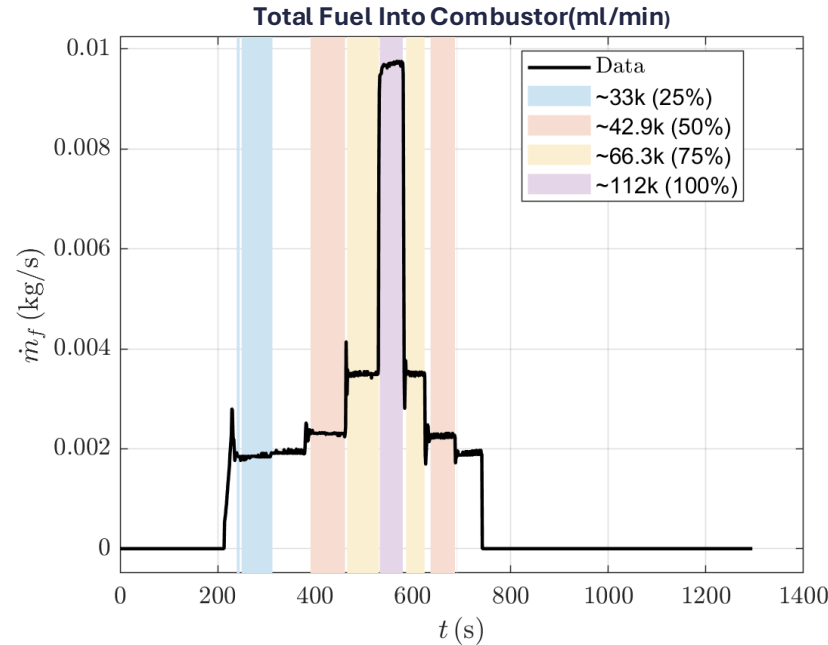
**Isolates the Variables:** Testing consecutively minimizes the impact of shifting environmental factors (temperature, humidity, atmospheric pressure) on combustion.

**Proves "Fuel is the Factor":** Ensures any observed shifts in emissions or performance are driven purely by fuel chemistry (e.g., aromatics, H/C ratio) and not by changes in engine operating conditions.

**Captures Relative Sensitivities:** Focuses on generating highly accurate differential data (e.g.,  $EI_{CO}$  between SAF and Jet A-1) rather than just absolute magnitudes.

**Enables Predictive Modeling:** Provides the tightly controlled, physically grounded datasets required to accurately calibrate numerical scaling tools, such as Chemical Reactor Network (CRN) models.

# Results: Jet-A



$$\dot{m}_f(t) = \rho_f \frac{\dot{V}_{f,comb}(t)}{60000}, \quad \text{with } \rho_f \approx 0.80\text{--}0.82 \text{ kg L}^{-1}$$

| Thrust % | Total fuel [mL/min] | Combustor fuel [mL/min] |
|----------|---------------------|-------------------------|
| 25       | 172                 | 150                     |
| 50       | 200                 | 177                     |
| 75       | 310                 | 270                     |
| 100      | 840                 | 750                     |

- Jan provided lookup data relating thrust command (%) to total fuel flow (mL/min)
- A fraction of this total flow actually reaches the combustor ( $\approx 87\text{--}89\%$ )
- By comparing combustor flow to total flow across all setpoints, an average ratio of  $\sim 0.88$  was established
- Converted volumetric flow (mL/min) to mass flow rate using fuel density ( $\approx 0.80\text{--}0.82 \text{ kg/L}$ )
- This provided the fuel mass flow into the combustor, which is critical for equivalence ratio calculations

# Results: Physics surrounding comparison

## Micro (JetCat)

- **Surface-to-volume:** High (significant wall quenching).
- Thus, **lower peak flame temperature:** Thermal NO<sub>x</sub> is exponentially dependent on temperature. We see **much lower EI NO<sub>x</sub>** for micro-turbojet which is consistent.
- Residence Time:  $\approx 2$  ms, this will limit CO oxidation.
- Max overall pressure ratio (OPR): 4

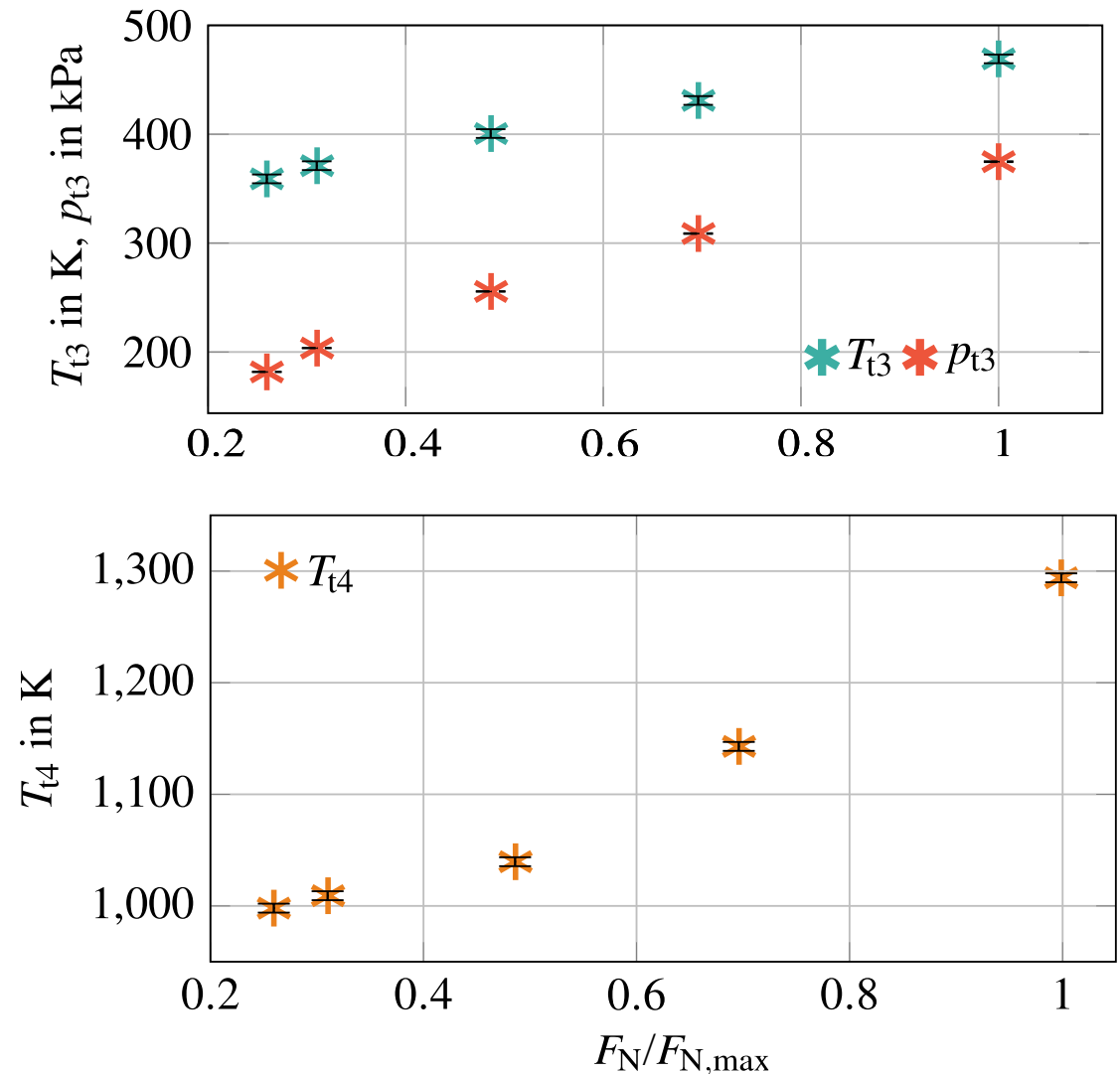
## Macro (V2500)

- **Surface-to-Volume:** Low (Adiabatic core).
- Peak flame temperature **closer to adiabatic** flame temperature, much higher thermal NO<sub>x</sub> production, illustrated in **significantly higher in EI NO<sub>x</sub>** for turbofan.
- Residence Time:  $> 6$  ms, assumed complete oxidation.
- Max overall pressure ratio (OPR):  $> 30$

**Direct operating-point-to-operating-point comparison across the thrust range is thermodynamically unjustified due to order-of-magnitude differences in scale. The sole meaningful correspondence exists at the operating envelope boundaries: “micro-max/macro-idle”.**

## Results: Jet-A

- Baseline testing began with Jet A1
- This allowed for improvements to be made to experimental setup.



# Results: Physics surrounding comparison

|                                   | OPR     | T <sub>t3</sub> | P <sub>t3</sub> |
|-----------------------------------|---------|-----------------|-----------------|
| Micro-Turbojet @ max OP           | ≈ 4     | 469 K           | 374 kPa         |
| Full size Turbofan @ idle OP [14] | ≈ 3.5-4 | 453 K           | 351 kPa         |

$$k = A \cdot P^n \cdot \exp\left(-\frac{E_a}{RT}\right)$$

$k$  (Reaction Rate Constant): The speed at which the chemical reaction (like soot nucleation) occurs.

$A$  (Pre-exponential Factor): A constant that represents the frequency of molecular collisions.

$P$  (Pressure): The local thermodynamic pressure (374 kPa).

$n$ : An empirical constant showing how sensitive the reaction is to pressure changes.

$E_a$  (Activation Energy): The minimum energy required to kickstart the chemical reaction.

$R$  (Universal Gas Constant): A standard physical constant (8.314 J/(mol·K)).

$T$  (Temperature): The local thermodynamic temperature (469 K).

At the “micro-max/macro-idle” intersection point, the combustor inlet air density, pressure, and temperature of the micro-turbojet and a full-scale turbofan are nearly identical. Combustion chemistry, specifically the formation of emissions that do not equilibrate in a gas turbine, depend entirely on how fast the chemical reactions are progressing (finite rate chemistry). For example, Nox, UHC, CO, Polycyclic Aromatic Hydrocarbons (soot pre-cursors) are driven local conditions and finite rate processes. This is also why a CRN model was used, finite rate chemistry is extremely important to modelling emissions accurately.

# References

- [1] Lee, D. S., D. W. Fahey, A. Skowron, M. R. Allen, U. Burkhardt, Q. Chen, S. J. Doherty, S. Freeman, P. M. Forster, J. Fuglestvedt, A. Gettelman, R. R. De León, L. L. Lim, M. T. Lund, R. J. Millar, B. Owen, J. E. Penner, G. Pitari, M. J. Prather, R. Sausen, and L. J. Wilcox. 2021. “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018.” *Atmos Environ*, 244. Elsevier Ltd. <https://doi.org/10.1016/J.ATMOENV.2020.117834>.
- [2] Gössling, S., and A. Humpe. 2020. “The global scale, distribution and growth of aviation: Implications for climate change,” *Global Environmental Change*, vol. 65, p. 102194.
- [3] Bickel, M., M. Ponater, L. Bock, U. Burkhardt, and S. Reineke. 2020. “Estimating the effective radiative forcing of contrail cirrus.” *J Clim*, 33 (5): 1991–2005. American Meteorological Society. <https://doi.org/10.1175/JCLI-D-19-0467.1>.
- [4] Teoh, R., U. Schumann, E. Gryspeerdt, M. Shapiro, J. Molloy, G. Koudis, C. Voigt, and M. E. J. Stettler. 2022. “Aviation contrail climate effects in the North Atlantic from 2016 to 2021.” *Atmos Chem Phys*, 22 (16): 10919–10935. Copernicus GmbH. <https://doi.org/10.5194/ACP-22-10919-2022>.
- [5] “Annex 16 to the convention on international civil aviation, volume ii — aircraft engine emissions,” 2017. Latest amendment as applicable.
- [6] Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. (2025). ASTM International. <https://doi.org/10.1520/D7566-25A>
- [7] Specification for Aviation Turbine Fuels. (2025). ASTM International. <https://doi.org/10.1520/D1655-25A>
- [8] “Annex 16 to the convention on international civil aviation, volume ii — aircraft engine emissions,” 2017. Latest amendment as applicable.
- [9] Göing, J., J. Hogrefe, S. Luck, and J. Friedrichs. 2021. “Validation of a Dynamic Simulation Approach for Transient Performance Using the Example of a Turbojet Engine,” in *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol. 151, pp. 559–568, Springer Science and Business Media Deutschland GmbH.
- [10] EASA. 2024. “ICAO Aircraft Engine Emissions Databank.”
- [11] Durdina, L., B. T. Brem, M. Elser, D. Schonenberger, F. Siegerist, and J. G. Anet. 2021. “Reduction of nonvolatile particulate matter emissions of a commercial turbofan engine at the ground level from the use of a sustainable aviation fuel blend,” *Environmental Science and Technology*, vol. 55, pp. 14576–14585.
- [12] Lieder, D., S. Sharma, P. Kirchen, S. Rogak, and J. Göing. 2026. “Development of a validated chemical reactor network model for non-CO<sub>2</sub> emissions in rql aircraft combustors.” Accepted.
- [13] Göing, J. 2023. Modellierung des nicht-linearen aerothermodynamischen Systemverhaltens von Flugantrieben. PhD thesis, Technische Universität Braunschweig.

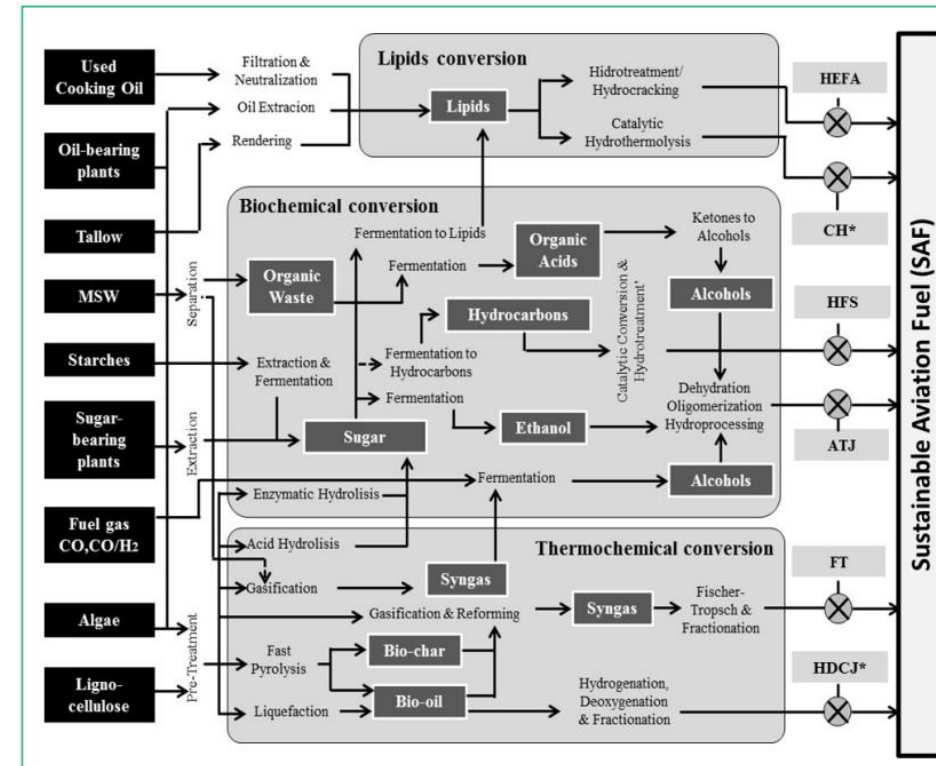
# Background: Sustainable Aviation Fuels

**"Drop-In":** While marketed as "drop-in" replacements, SAFs are different from conventional Jet Fuel (Jet A-1) & one another. Their chemistry is dependent on the feedstock and processing pathway.

## Key Chemical Differences:

- SAFs differ in Aromatic Content
- SAFs differ in Hydrogen-to-Carbon (H/C) Ratio
- SAFs differ in Volatility

**The Impact:** The chemical composition dictate the emissions. Because SAFs are all different, we cannot assume any two SAFs will behave the same way in an engine.



\*CH: Catalytic hydrothermolysis – not yet approved

HDCJ: Hydrotreated depolymerized cellulosic to jet – not yet approved

ICAO – Sustainable Aviation Fuels Guide: Different processing routes can be adopted to convert feedstocks into a liquid drop-in SAF. Several combinations of feedstocks and conversion processes have been proposed. **Only some of them have been certified to be used as a drop-in fuel.**