

A MICRO-TURBOJET TEST RIG TO ANALYZE THE IMPACT OF JET FUELS ON EMISSIONS AND PERFORMANCE

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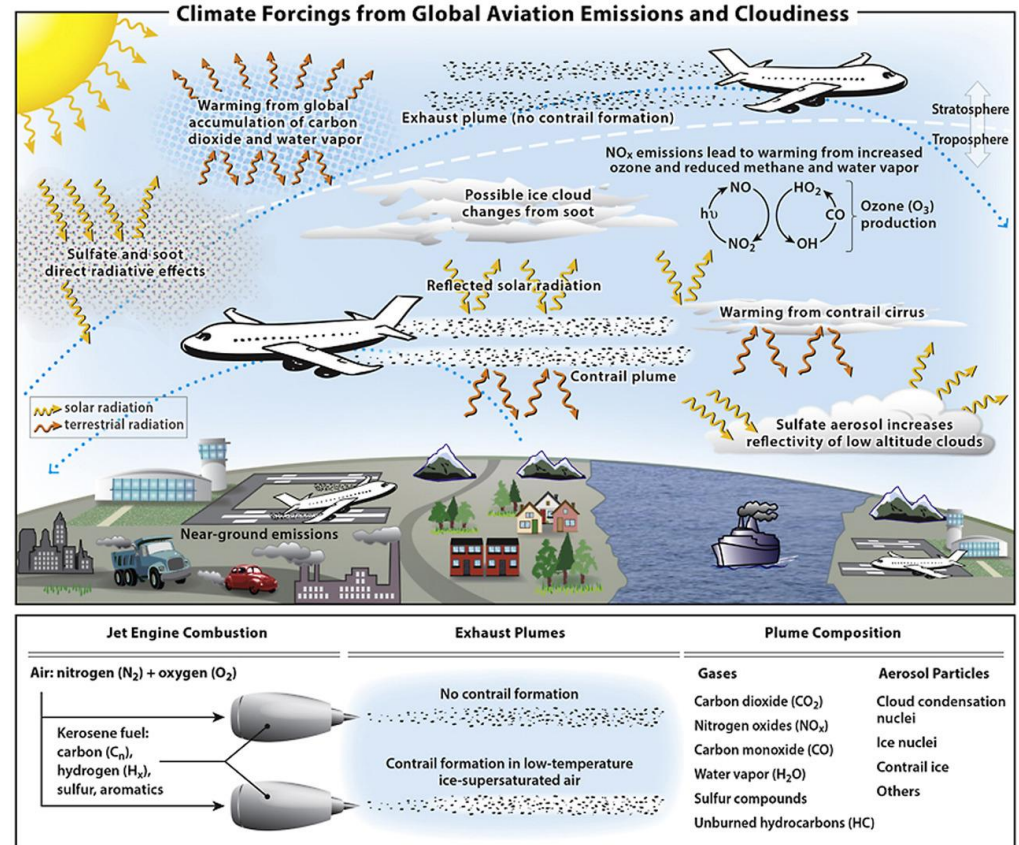
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1. Motivation
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Aviation's Climate Impact

- Aviation plays a pivotal role in modern society, but it contributes **3-5%** to global anthropogenic climate forcing [1,2].
- While CO₂ is a well-established climate forcer, **more than half** of aviation's total climate impact arises from non-CO₂ effects [1].
- These effects are mediated by relatively small magnitude of emissions from aircraft engines that contribute disproportionately to radiative forcing [3,4]
- Because multiple coupled processes contribute to net climate forcing, CO₂ alone is an incomplete proxy for aviation's total impact.



Schematic overview of the processes by which aviation emissions and increased cirrus cloudiness affect the climate system. Net positive RF (warming) contributions arise from CO₂, water vapor, NO_x, and soot emissions, and from contrail cirrus (consisting of linear contrails and the cirrus cloudiness arising from them). Negative RF (cooling) contributions arise from sulfate aerosol production [1].

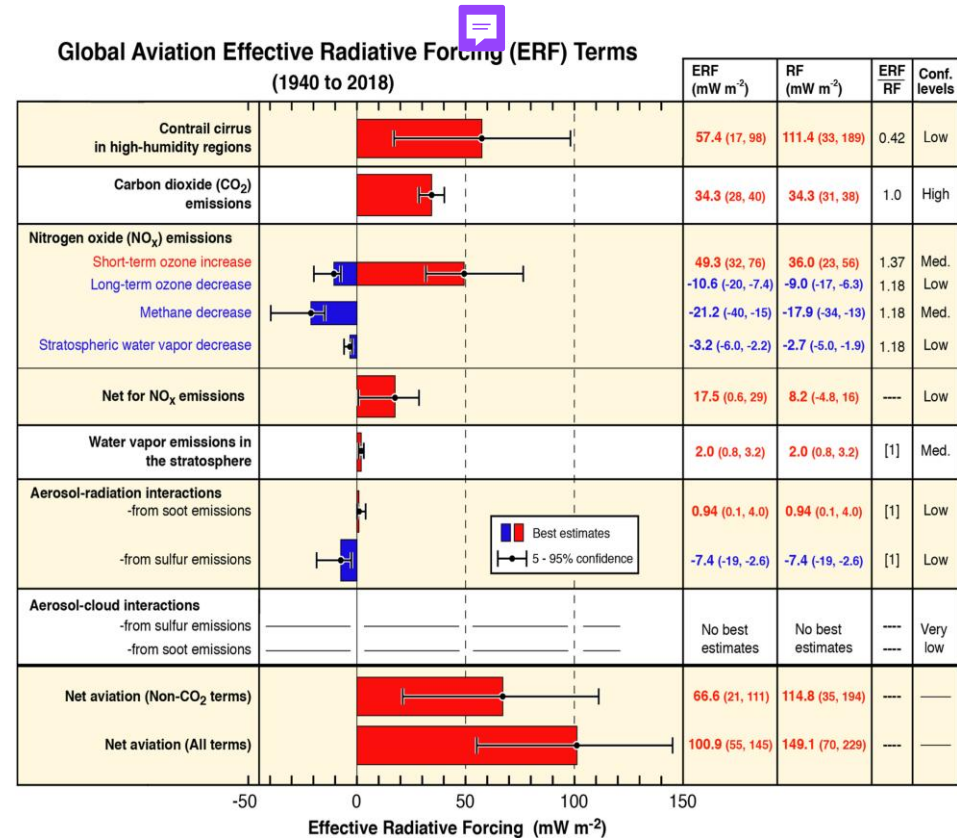
Non-CO₂ Forcing Mechanisms

Nitrogen Oxides (NO_x):

- Reactive nitrogen species drive near-field chemical transformations and interact with the atmosphere [5]
- Specifically, NO_x emissions alter ozone concentrations within the upper atmosphere, acting as an indirect greenhouse gas and altering regional air quality [6].

Particulate Matter & Contrails:

- Emitted soot and aerosols modify cloud microphysics, contributing to the formation of contrail-induced cirrus clouds [7].
- Soot particles can act as Ice Nucleating Particles (INPs), influencing the optical properties of clouds (albedo) which further amplifies radiative warming [3,7]



Best-estimates for climate forcing terms from global aviation from 1940 to 2018. The bars and whiskers show ERF best estimates and the 5–95% confidence intervals, respectively. Red bars indicate warming terms and blue bars indicate cooling terms [1].

Industry Shift & Regulatory Landscape



Net-Zero by 2050

The aviation sector has committed to ambitious net-zero targets, accelerating coordinated action across agencies, manufacturers, and airlines [8].



ICAO Regulations

Regulatory frameworks are responding. ICAO has introduced standards for non-volatile PM (CAEP 11) and Annex 16 specifies limits for key gaseous non-CO₂ species [8].



The Interest in SAFs

Sustainable Aviation Fuels (SAFs) are positioned as a practical near-term pathway to reduce climate impact without altering existing airframes.

INTRODUCTION: AERO ENGINE EMISSIONS

Products of Complete Combustion (Greenhouse Gases):

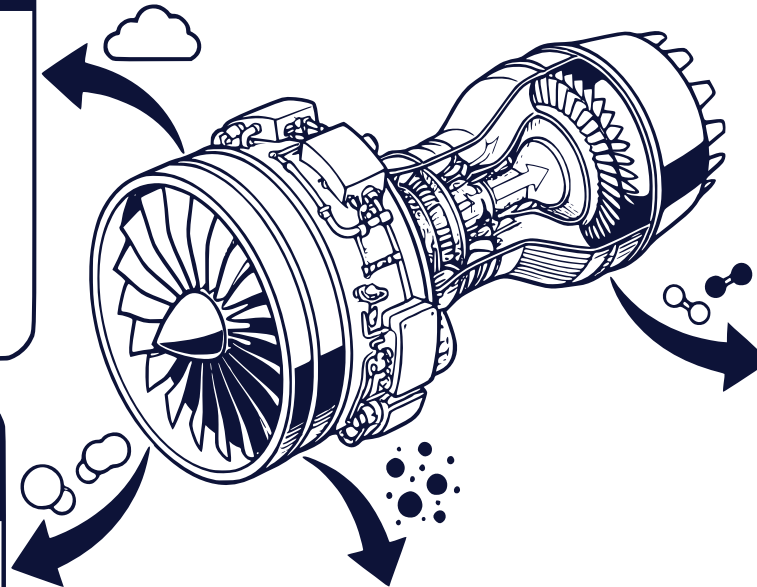


Carbon dioxide (CO_2) & Water vapor (H_2O): are the primary natural byproducts of hydrocarbon combustion. Both are GHGs. H_2O plays a critical role in contrail formation at high altitudes.

Products of Incomplete Combustion (Lower Power):



Carbon Monoxide (CO) & Unburned Hydrocarbons (UHC): Greatest concentrations predominantly generated during low-power operation (e.g., idle), where combustion efficiency is lowest.



High-Temperature Byproducts (Higher Power):



Oxides of Nitrogen (NO_x), (NO & NO_2): formed via the thermal reaction of atmospheric N_2 and O_2 at extremely high temps ($>1800 \text{ K}$, Thermal (Zel'dovich) mechanism), during high-power settings like take-off and climb.

Particulate Matter (PM) & Impurities:



nvPM



vPM

Non-volatile PM (nvPM): Ultrafine black carbon (soot) particles formed in fuel-rich regions of the combustor.
Volatile PM (vPM): Formed when gaseous precursors (like volatile organic compounds) cool and condense after exiting the engine.

Aero engine emissions (depend on flight phase, fuel composition, engine architecture):

INTRODUCTION: AERO EMISSIONS REGULATIONS

How do international bodies regulate these emissions and the fuels that produce them?

The Regulatory Landscape:

- **Engine Certification (ICAO Annex 16):**
Standards for NO_x, nvPM, CO, and UHC are set by the CAEP (Committee on Aviation Environmental Protection) and enforced by national authorities like the FAA or EASA [8].
- **Fuel Certification (ASTM International):**
***ASTM D1655:** The standard for conventional Jet A/A-1 [36].
 - **ASTM D7566:** The critical specification for Sustainable Aviation Fuels (SAF), certifying them as "drop-in" ready [35].
- **Sustainability Oversight:** Organizations like the RSB (Roundtable on Sustainable Biomaterials) or ISCC certify the lifecycle carbon footprint of the fuels.

ASTM D1655 – 25a

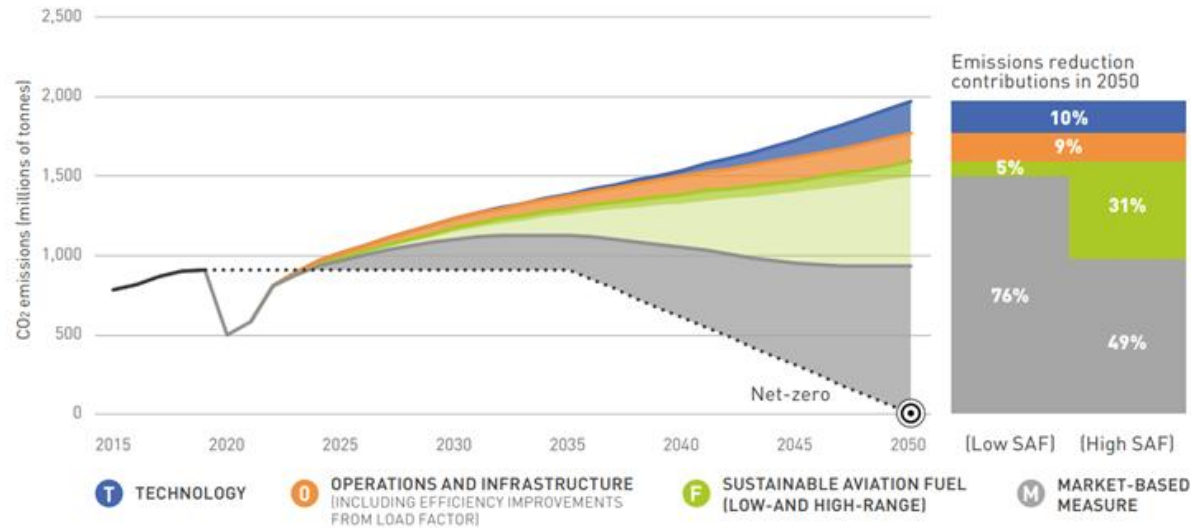
TABLE 1 Detailed Requirements of Aviation Turbine Fuels^A

Property	Jet A or Jet A-1		Reference	Test Methods ^B	Alternative	
COMPOSITION						
Acidity, total mg KOH/g	max	0.10	D3242/IP 354			
Aromatics						
(1) percent by volume, or	max	25	D1319 ^C		IP 156, ^C D8267, or D8305 ^D	
(2) percent by volume	max	26.5			D6379/IP 436	
Sulfur, mercaptan, ^E percent by mass	max	0.003	D3227/IP 342			
Sulfur, total percent by mass	max	0.30			D1266, D2622, D4294, D5453, or IP 336	
VOLATILITY						
Distillation temperature, °C:			D86 ^F		D2887 ^G or IP 406, ^G D7344, ^H I D7345, ^H IP 123 ^F	
10 % recovered, temperature	max	205				
50 % recovered, temperature		report				
90 % recovered, temperature		report				
Final boiling point, temperature	max	300				
Distillation residue, %	max	1.5				
Distillation loss, %	max	1.5				
Flash point, °C	min	38 ^I	D56		D93, ^K D3828, ^K D7094, ^K D7236, ^K IP 170, ^K IP 523, ^K or IP 534 ^K	
Density at 15 °C, kg/m ³		775 to 840			D1298 or IP 160 or D4052 or IP 365	
FLUIDITY ^L						
Freezing point, °C	max	−40 Jet A ^{M,N}	D2386/IP 16		D5972/IP 435, D7153/IP 529, or D7154 or IP 528	
		−47 Jet A-1 ^{M,N}				
Viscosity −20 °C, mm ² /s ^O	max	8.0	D445 or IP 71 Section 1		D7042 ^P or D7945	
COMBUSTION						
Net heat of combustion, MJ/kg	min	42.8 ^Q	D4809		D4529, D3338, ^Q or IP 12	
One of the following requirements shall be met:						
(1) Smoke point, mm, or	min	25.0	D1322/IP 598			
(2) Smoke point, mm, and	min	18.0	D1322/IP 598			
Naphthalenes, percent by volume	max	3.0	D1840		D8305 ^R	
CORROSION						
Copper strip, 2 h at 100 °C	max	No. 1	D130 or IP 154			
THERMAL STABILITY ^{L, S}						
(2.5 h at control temperature of 260 °C min)						
Filter pressure drop, mm Hg	max	25	D3241 ^T /IP 323 ^T			
Tube rating: One of the following requirements shall be met: ^U						
(1) Annex A1 VTR, VTR Color Code	Less than max	3 (no peacock or abnormal color deposits)				
(2) Annex A2 ITR, Annex A3 ETR, or Annex A4 MWETR, nm average over area of 2.5 mm ²		85				
CONTAMINANTS						
Existent gum, mg/100 mL	max	7	D381		IP 540	
Microseparator, ^V Rating			D3948			
Without electrical conductivity additive	min	85				
With electrical conductivity additive	min	70				
ADDITIVES						
Electrical conductivity, pS/m		See 6.2 w	D2624/IP 274			

ASTM D1655 – 25a: Detailed requirements of certified aviation fuels [36].

INTRODUCTION: SUSTAINABLE AVIATION FUELS

The Near-Term Solution: SAFs are the primary viable pathway to decarbonize aviation, offering "drop-in" replacements sourced from biogenic or waste feedstocks [8, 35].



Industry targets to achieve "net zero" CO₂ emission. [38].

- **Regulatory Hurdles:** Aviation operates under strict safety margins. Aircraft cannot legally fly on a new fuel unless it has rigorous ASTM International certification (e.g., ASTM D7566) [35].
- **The Reality:** Many promising, highly sustainable SAF pathways are not yet certified for commercial use, meaning they cannot be deployed [37].

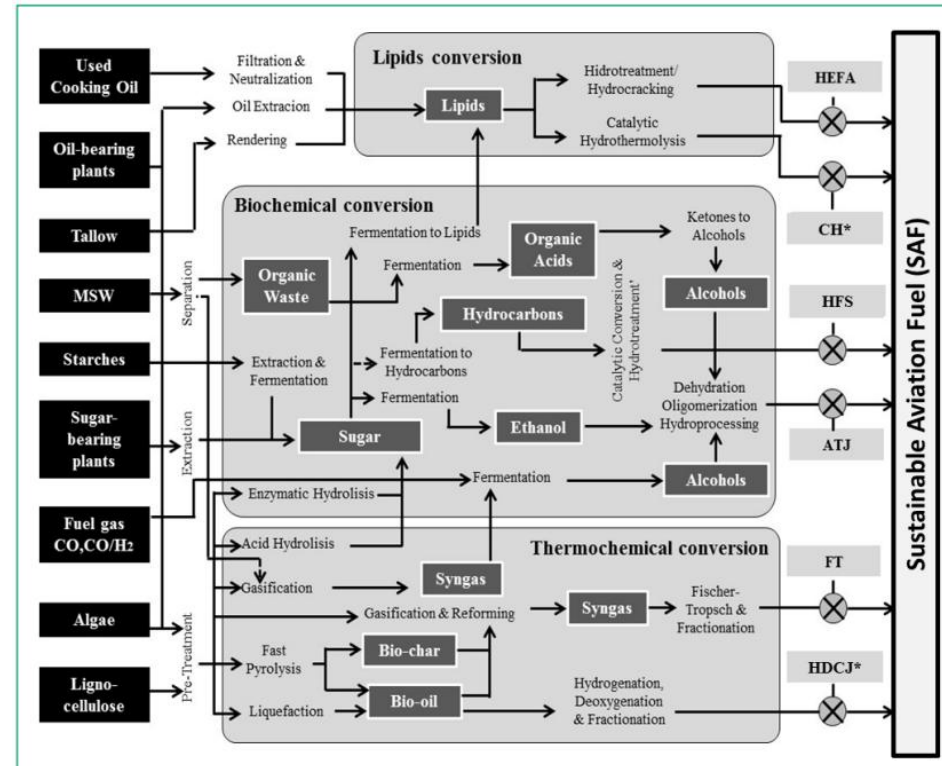
INTRODUCTION: SUSTAINABLE AVIATION FUELS

"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: 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.



*CH: Catalytic hydrothermolysis – not yet approved

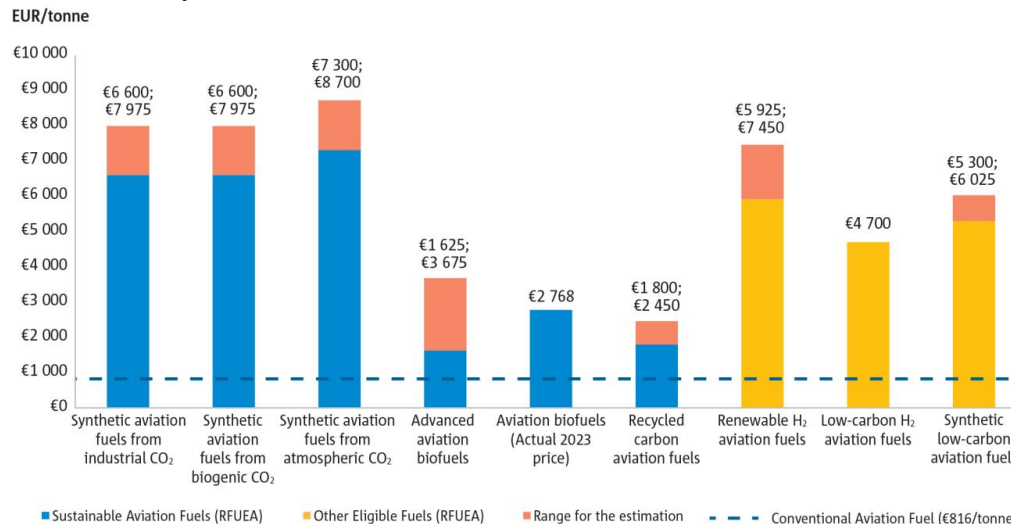
HDCJ: Hydrotreated depolymerized cellulosic to jet – not yet approved

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.** [37].



To characterize the emissions from fuels we need extensive data on how they burn. Gathering this emissions data using full-size commercial turbofans is a major bottleneck:

Regulatory constraints: Strict safety protocols make testing experimental, uncertified fuels on large commercial hardware incredibly restrictive.



Estimated prices and production costs in 2023 for ReFuelEU Aviation eligible fuels [39].

Fuel Intensive: Requires tens of thousands of gallons of experimental fuel, which is nearly impossible to produce for early-stage novel SAFs.

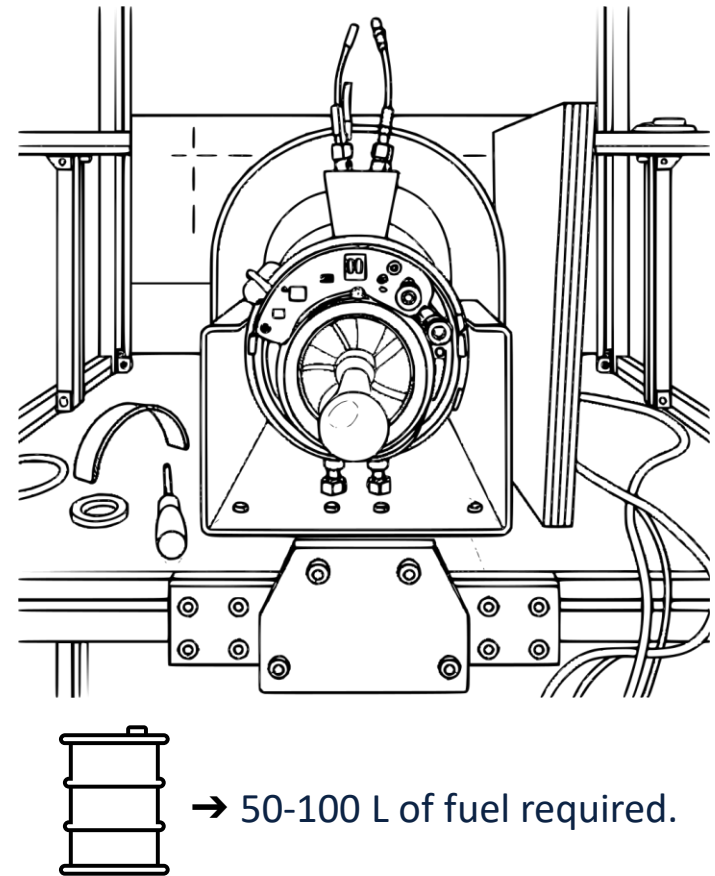
Prohibitively Expensive: These novel SAFs are orders of magnitude more expensive than Jet A-1 testing costs tens of thousands to hundreds of thousands of dollars per campaign for simply fuel costs, not accounting for the requisite hardware to burn and characterize these fuels.

INTRODUCTION: MICRO-TURBO JET TEST RIG

Relying solely on full-scale engine testing requires too much money, and too much fuel. We need a way to bypass this bottleneck.

The Alternative: Cost-effective, scaled-down laboratory facilities, such as an instrumented micro-turbojet test rig.

Benefit: Requires only modest fuel quantities → Ideal for testing and characterizing various SAFs.



→ 50-100 L of fuel required.

This capability facilitates the cost-effective acquisition of experimental data, enabling the exploration of operating-point and fuel-dependent sensitivities.

Primary Research Question: How can a laboratory-scale micro-turbojet test rig, configured for back-to-back testing of conventional and “drop-in” alternative jet fuels, be successfully commissioned to generate experimental data that serve as the foundation for predictive emissions models and regulatory impact assessments?

Objectives:

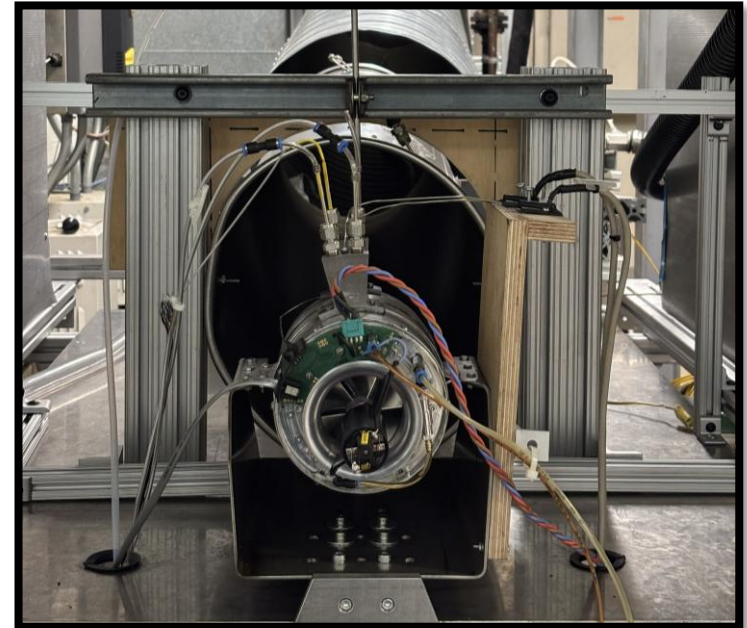
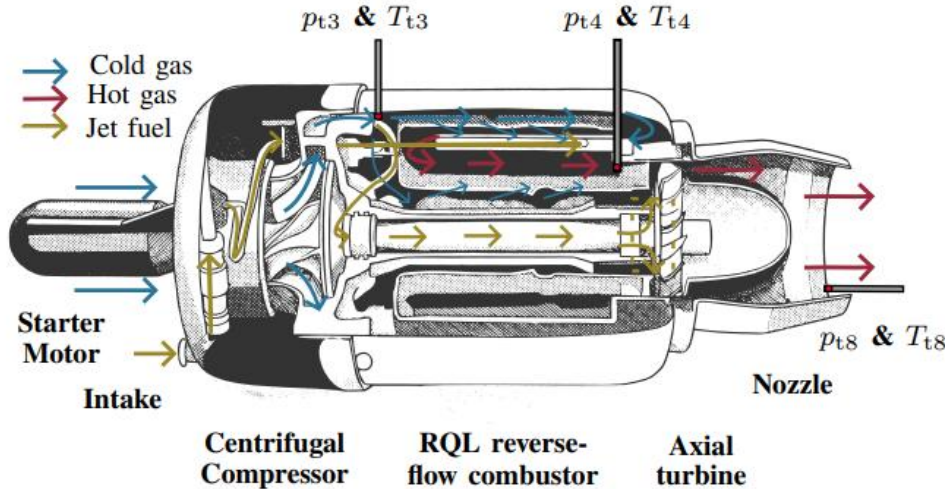
- **Commissioning:** Successfully configure a micro-turbojet test rig at CERC for back-to-back testing of conventional Jet A-1 and "drop-in" Sustainable Aviation Fuels (SAFs).
- **Data Generation:** Produce experimental data characterizing thermodynamic performance, gaseous emissions, and nvPM using **Jet A-1 fuel**.
- **Comparison:** Evaluate the thermodynamic and emissions relationship between the laboratory-scale micro-turbojet and full-scale commercial engines (e.g., V2500) to determine if, and under what conditions, the micro-turbojet data is representative of real-world operations.

Follow-Up Objectives: Predictive Modeling & Scaling

- **Model Validation:** Evaluate the predictive accuracy of a physics-based Chemical Reactor Network (CRN) model using the generated micro-turbojet emissions data.
- **Benchmarking:** Compare the scaled CRN model's predictions against industry-standard semi-empirical methods (e.g., Boeing Fuel Flow Method 2 / BFFM2) across an entire flight trajectory to demonstrate improved capture of fuel-specific sensitivities
- **Scale-Up / Model Transfer:** Recalibrate and transfer the validated CRN model from the micro-turbojet to a full-scale commercial turbofan engine (e.g., the IAE V2500-A1).

METHODOLOGY: THE MICRO-TURBOJET ENGINE

JetCat P200-SX Micro-Turbojet:

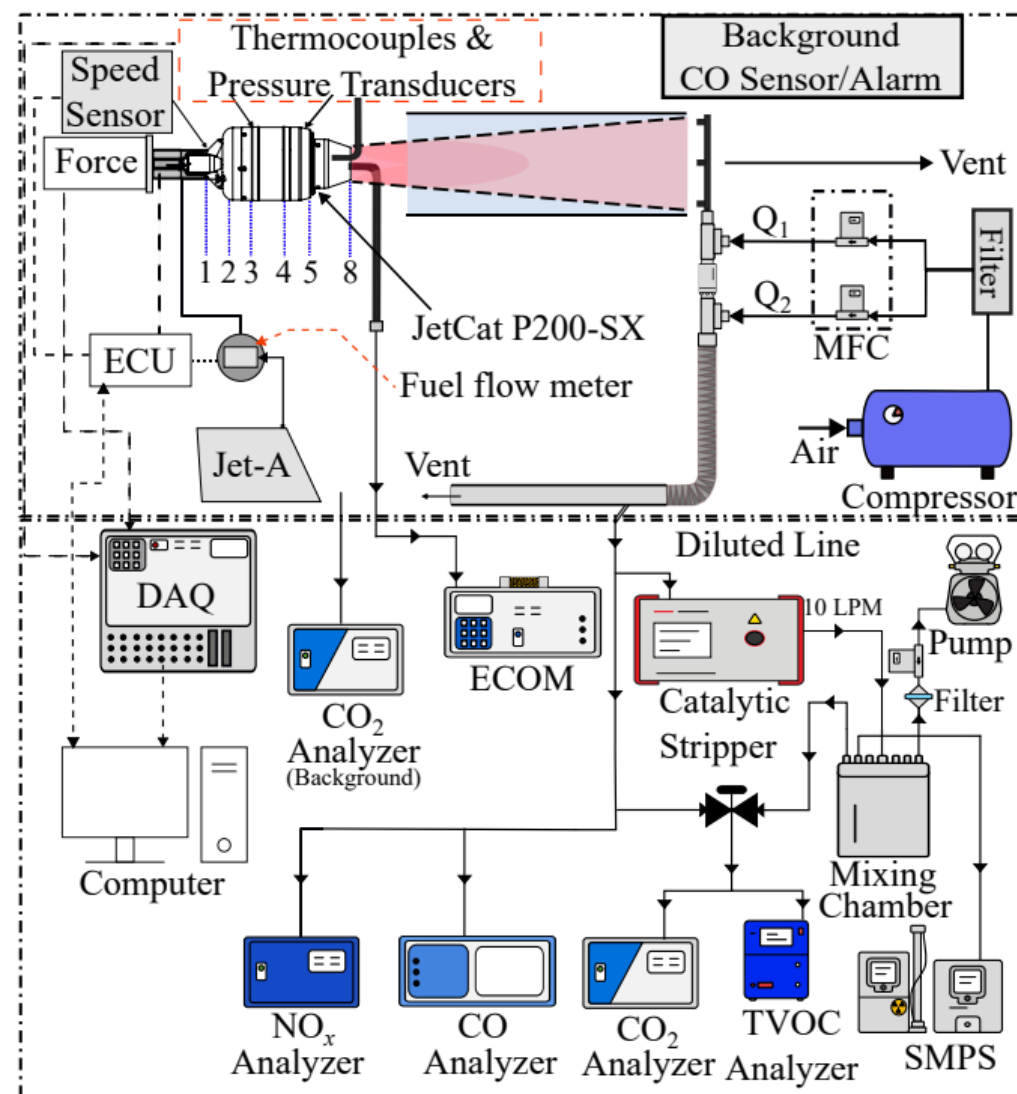


Engine Specifications:

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, where lubrication oil is ejected into a small gap between the inner casing and the axial turbine, **entering the gas path** rather than being recirculated.

METHODOLOGY: EXPERIMENTAL SETUP



Undiluted Sampling Line (Jet Core) Samples directly downstream of the nozzle using a Prandtl probe. Analyzed by an ECOM J2KN Pro for raw CO₂, CO, and NO_x concentrations.

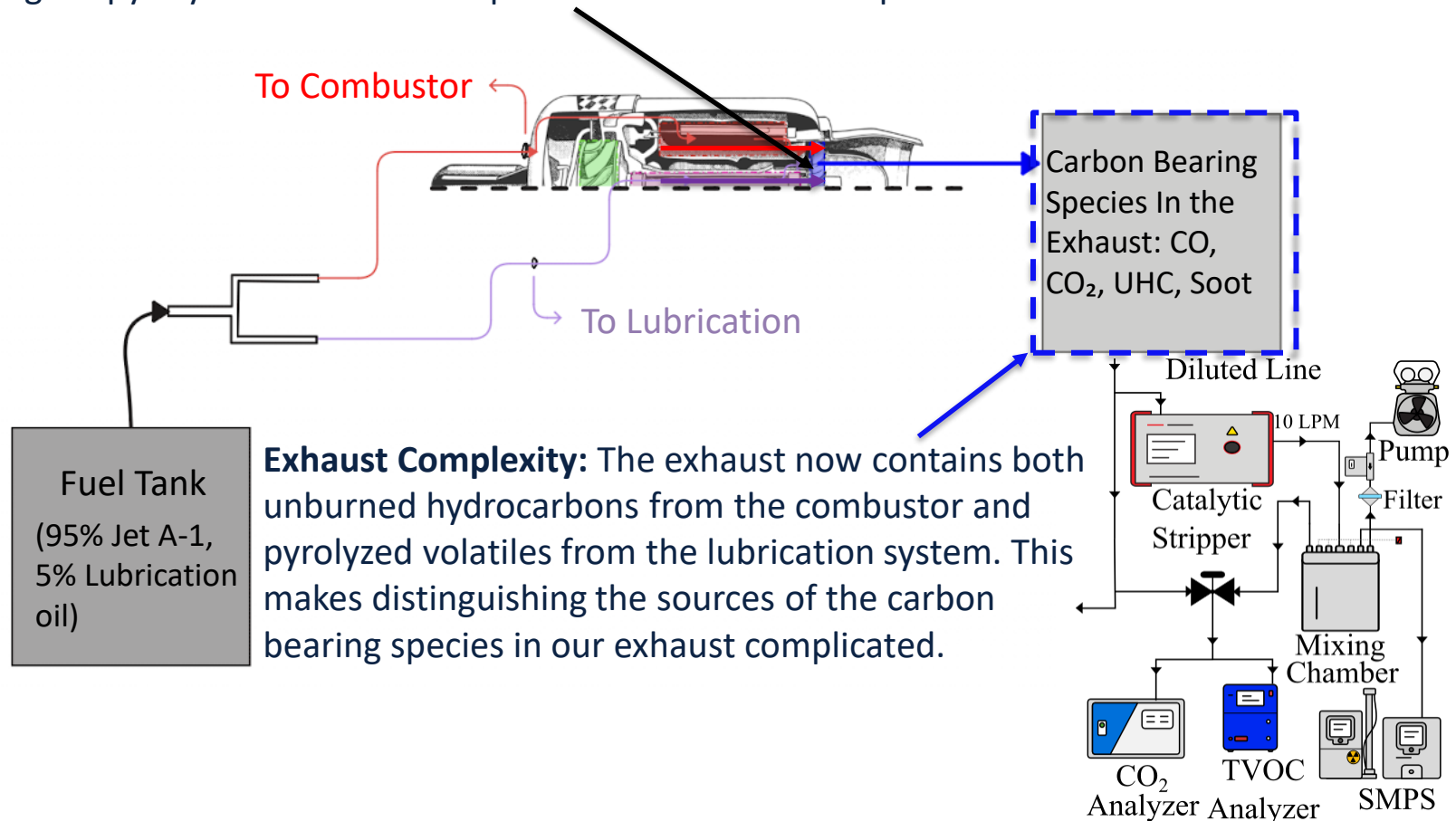
Diluted Sampling Line (Shear Layer & Centerline) Uses a multi-hole probe downstream of the first duct, passed through a 2-stage ejector diluter.

Gaseous Analyzers (Diluted) Monitored by dedicated 2B Tech 405nm (NO_x Analyzer), Teledyne T300U (CO Analyzer), and LI-COR LI-850 (CO₂ Analyzer).

Particulate Matter Measured via SMPS (nano-DMA) downstream of a **Catalytic Stripper**. The stripper removes semi-volatile organic compounds (SVOCs) allowing us to isolate non-volatile PM (soot).

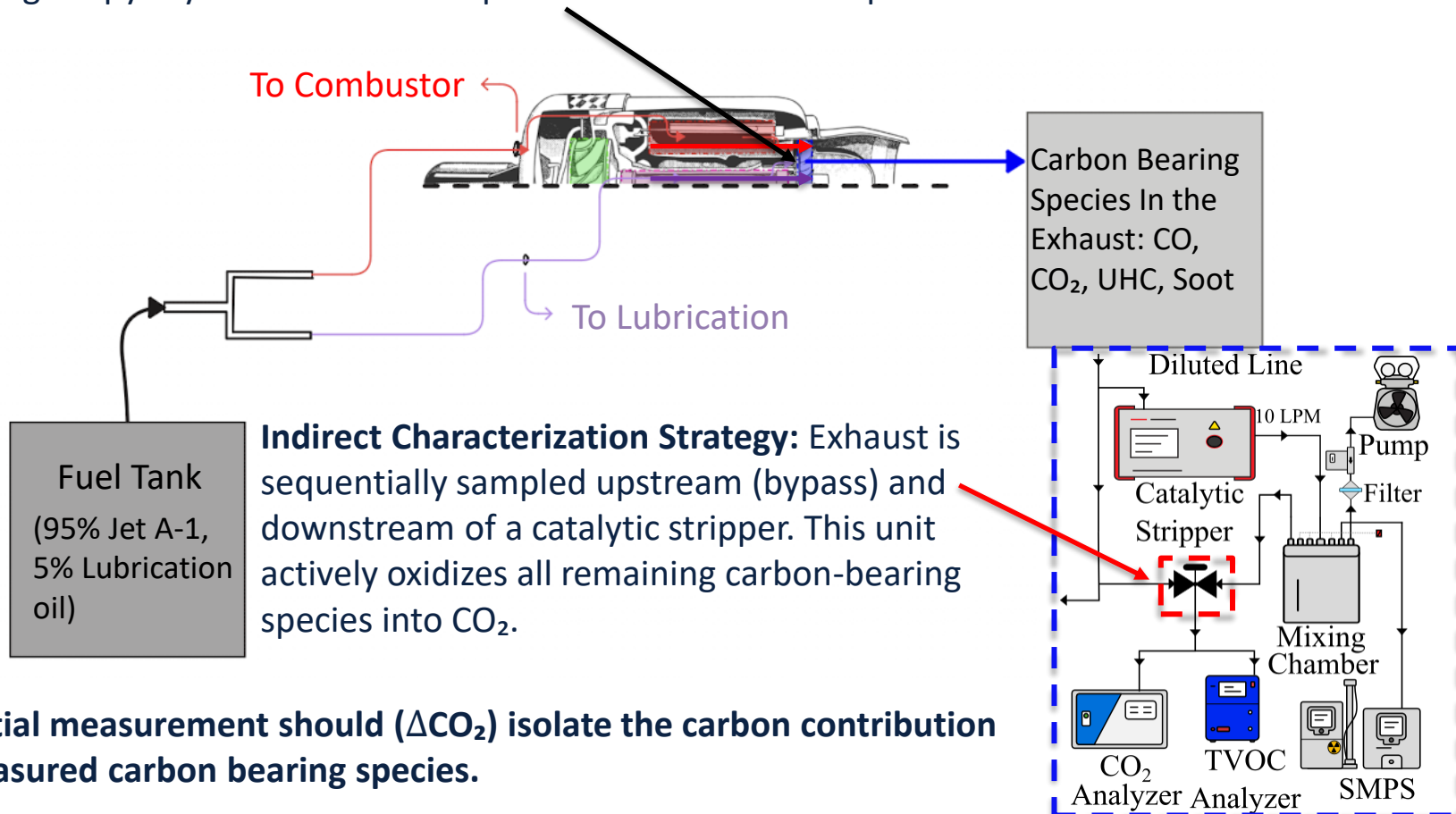
METHODOLOGY: INDIRECT UHC MEASUREMENT

Open-loop: The system splits a 95% Jet A-1 / 5% lubrication oil blend between the combustor and the open-loop lubrication path. Lubricant is ejected directly into the gas path upstream of the axial turbine ($T_{t4} \approx 1200 \text{ K} - 1400 \text{ K}$). Within this high-temperature, oxygen-depleted environment, the lubrication oil likely undergoes pyrolytic thermal decomposition rather than complete oxidation.



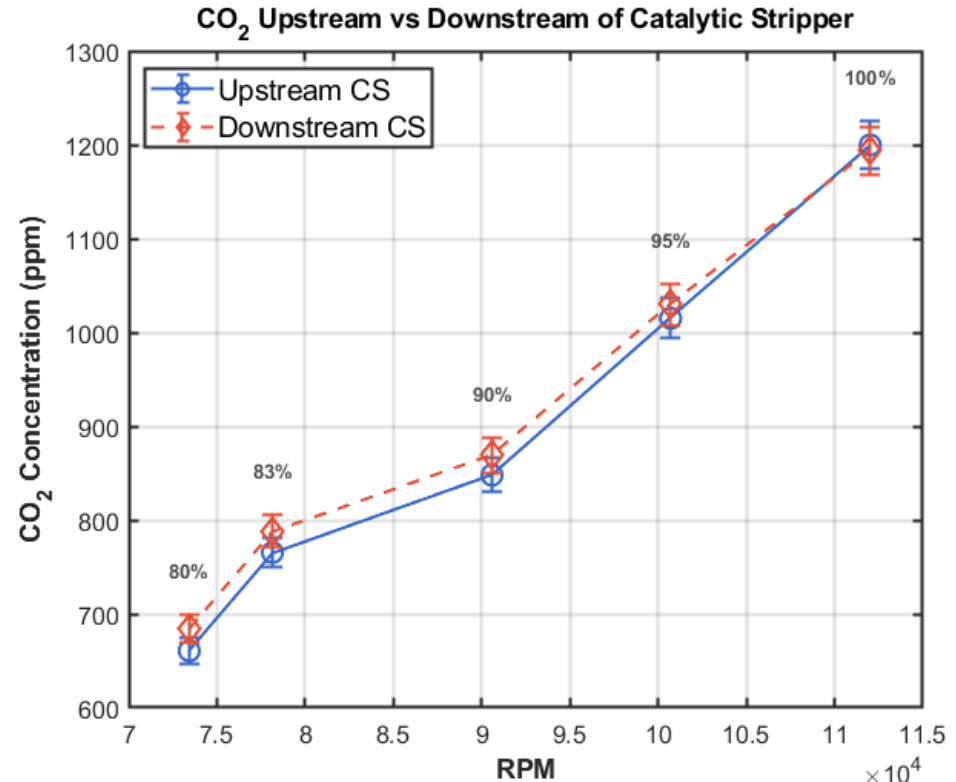
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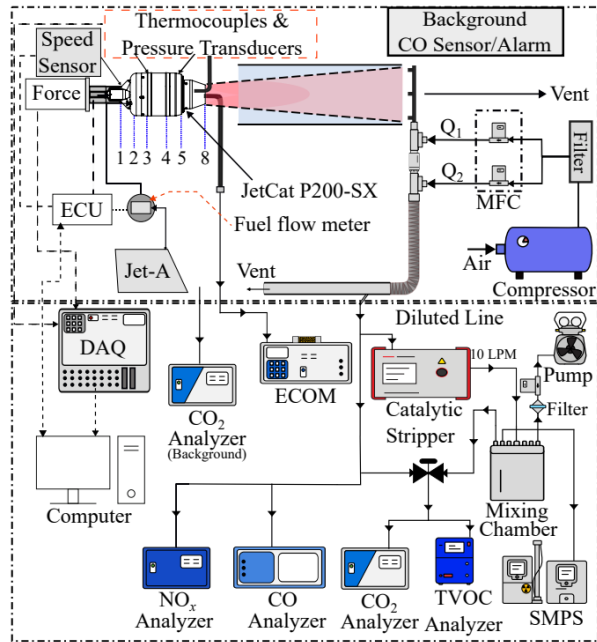
- **The ΔCO_2 Signal:** Downstream CO_2 (red) is consistently higher than upstream (blue), confirming the oxidation of unburned carbon species.
- **Load Dependency:** The measurable difference (ΔCO_2) is small and decreases as engine RPM increases.

It is interesting to note, that while the ΔCO_2 decreases with increasing RPM, the amount of lubrication oil flow rate also increases with the engine RPM.

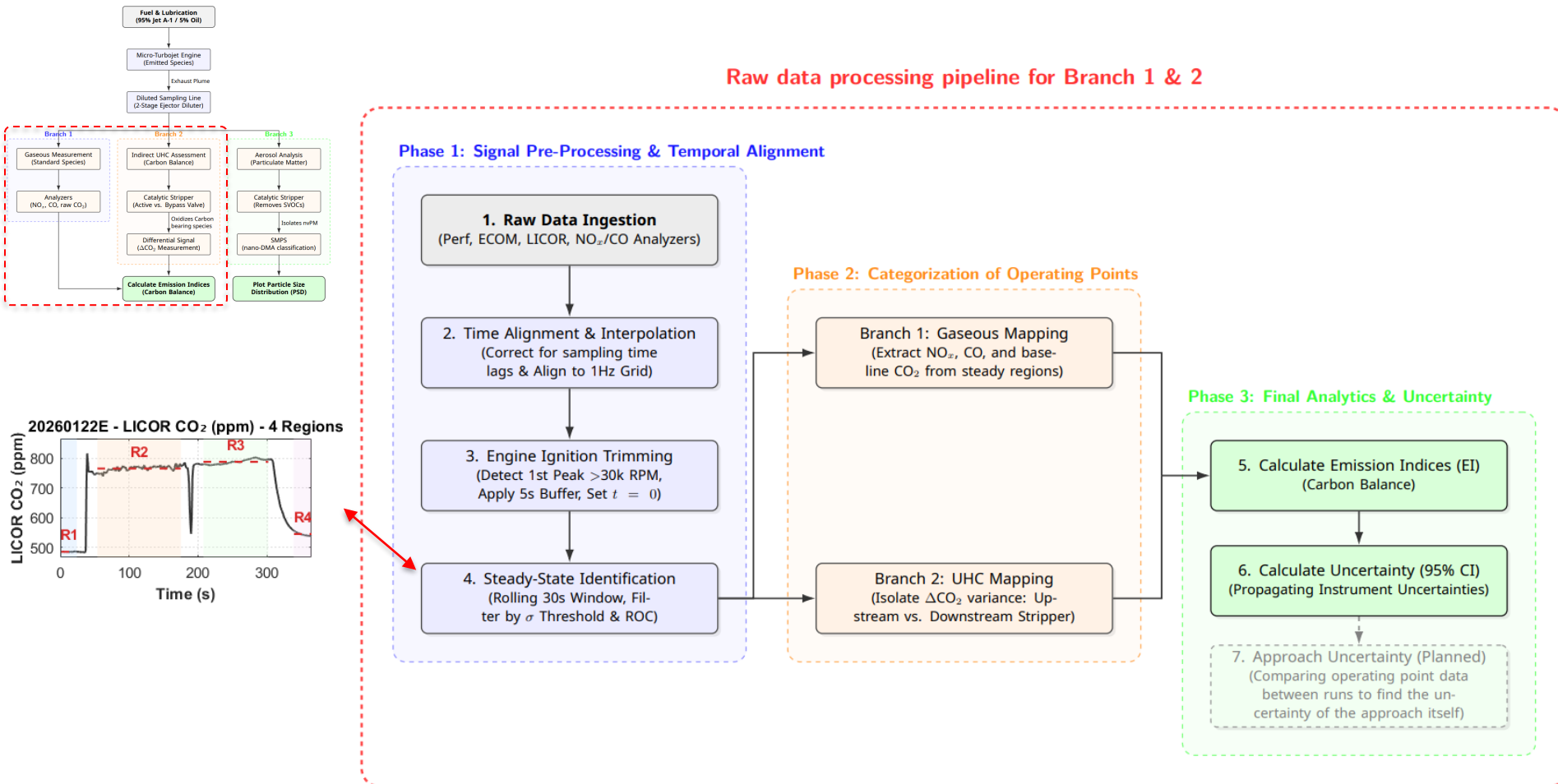


Functional validation of the indirect UHC measurement system. Diluted exhaust gas is sequentially routed through a bypass line and a heated catalytic stripper using a 2-way switching valve. The stripper actively forces the complete oxidation of any surviving unburned fuel and pyrolyzed lubrication volatiles into measurable CO_2 . This differential methodology isolates the total volatile carbon contribution without requiring complex chemical speciation.

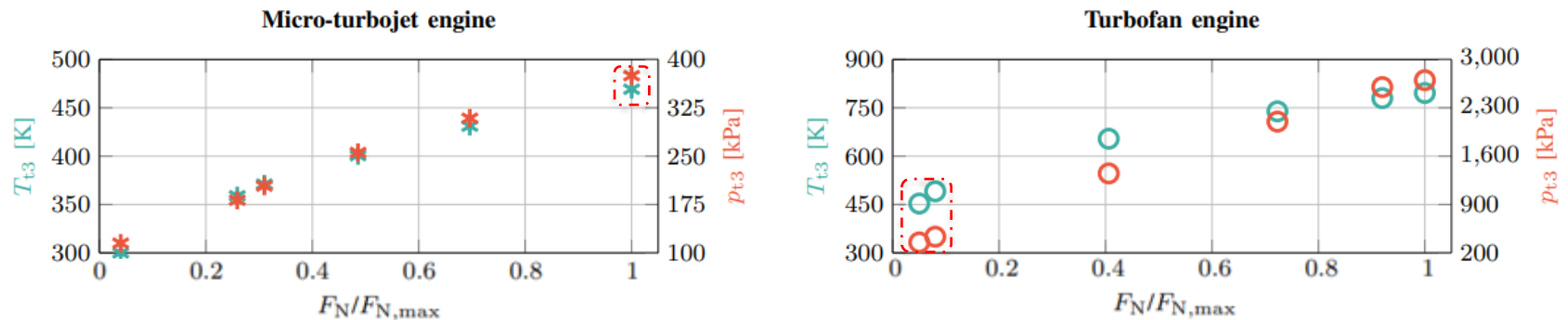
METHODOLOGY: DATA COLLECTION



METHODOLOGY: DATA PROCESSING



RESULTS: MICRO-TURBOJET VS TURBOFAN



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

	OPR	T_{t3}	P_{t3}
Micro-Turbojet @ max OP	≈ 4	469 K	374 kPa
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.

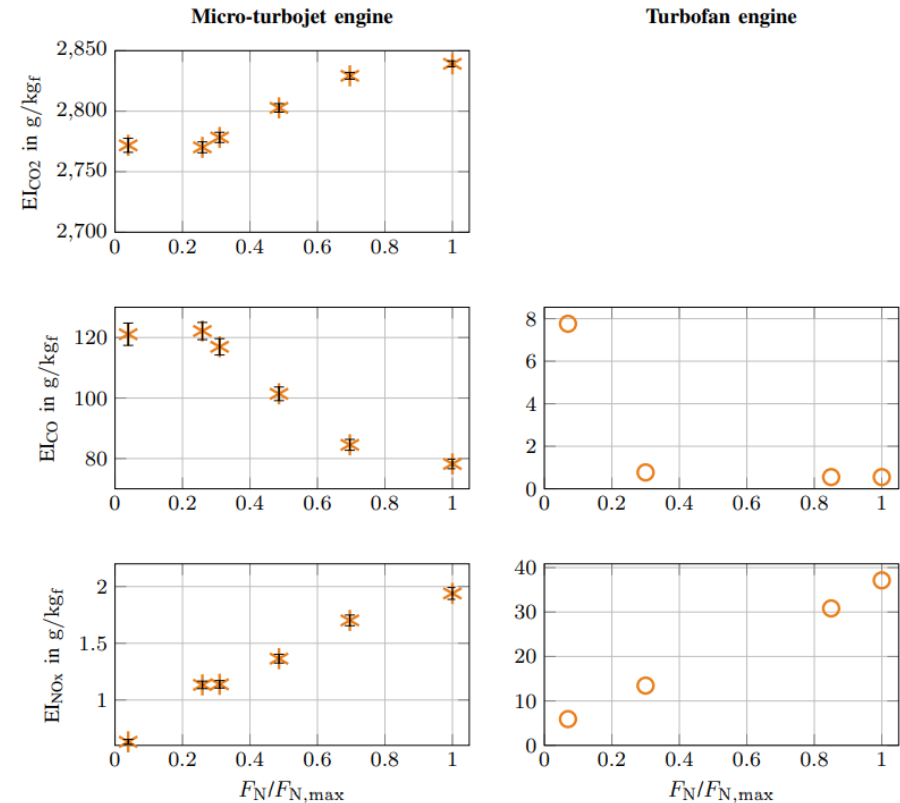
RESULTS: MICRO-TURBOJET VS TURBOFAN

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

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

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

- **EI CO:** Drops sharply from 120 to 80 g/kg as thrust increases, indicating improved combustion completeness.
- **EI NO_x:** Increases from 1.1 to 2.0 g/kg, consistent with thermal NO_x formation at elevated flame temperatures at higher operating points.
- **Qualitatively:** These trends mirror ICAO certification data for the V2500 engine. While absolute magnitudes differ due to residence time and scale, the preservation of directional trends confirms the facility's suitability for comparative fuel studies.



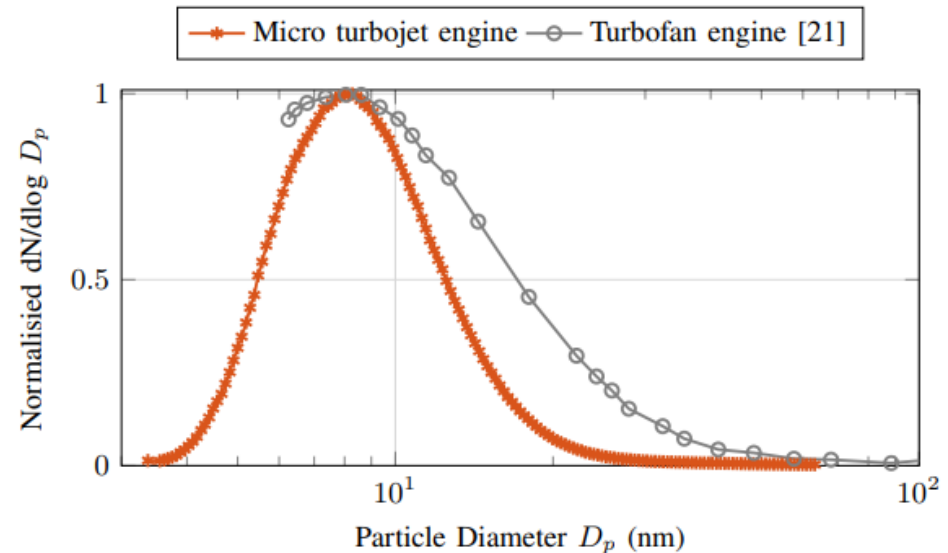
Emission indices across the normalized thrust envelope. Both engines demonstrate improving combustion completeness (decreasing CO) and rising flame temperatures (increasing NO_x) at higher loads. This qualitative trend alignment supports the micro-turbojet as a representative testbed for isolating fuel-property effects, despite expected scale-driven magnitude offsets. The ICAO emissions databank currently mandates reporting for CO and NO_x but does not provide EI CO₂ or uncertainty ranges in its standard certification data, which is why those specific plots are blank for the full-scale engine [16].

RESULTS: MICRO-TURBOJET VS TURBOFAN

Particle sampling line focused on the addition of the SMPS with the nano DMA to classify particles from 3 nm to 65 nm [19].

We compare the particle size distribution (PSD) of the micro-turbojet to a full-size turbofan at the “**micro-max / macro-idle**”, thermodynamic intersection [21].

- The measured distribution exhibits a distinct mono-modal peak with a mode diameter of 7.84 nm, **geometric mean diameter of 8.6 nm**, and geometric standard deviation of 1.44.
- Durdina et al. [21], reported mean geometric diameters 8 nm for Jet A-1 in a **CFM56-7B turbofan engine** and a GSD of around 2 at idle conditions. The nvPM numbers have been normalized to their maximum value.



Non-volatile particulate matter size distribution. Orange line: Micro turbojet engine at maximum thrust. Gray line: Turbofan engine in ground idle.

Physical Significance: Despite order-of-magnitude differences in engine scale and thrust, the nvPM emissions profile is preserved at this specific thermodynamic intersection.

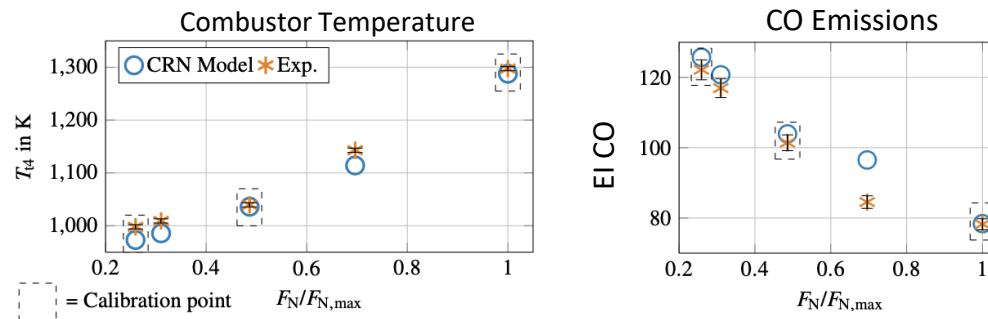
CONCLUSION & FUTURE WORK

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.
- The micro-turbojet thereby **constitutes a critical intermediate step in the fuel approval pathway**. By generating physically grounded datasets at the “**micro-max/macro-idle**” thermodynamic intersection, the facility enables calibration and validation of numerical scaling models.

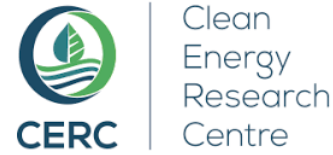
Future Work: Testing with SAFs, starting with FT-SPK, to identify fuel-specific sensitivities experimentally.

- Experimental data will be used to calibrate and validate a chemical reactor network model [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.



ACKNOWLEDGMENTS

- UBC Clean Energy Research Center (CERC)
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Supervisor: Dr. Steven Rogak

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THANK YOU, QUESTIONS?

INTRODUCTION: AERO ENGINE EMISSIONS

Aero engine emissions (depend on flight phase, fuel composition, engine architecture):

- **Products of Complete Combustion (Greenhouse Gases):**

- Carbon dioxide (CO_2) and water vapor (H_2O) are the primary natural byproducts of hydrocarbon combustion.
- Both are greenhouse gases, with water vapor playing a critical role in the formation of contrails at high altitudes.

- **Products of Incomplete Combustion (Low Power):**

- Carbon Monoxide (CO) and Unburned Hydrocarbons (UHC).
- These pollutants are predominantly generated during low-power engine settings, where combustion efficiency is lowest.

- **High-Temperature Byproducts (High Power):**

- Oxides of Nitrogen (NO_x), comprising NO and NO_2 .
- NO_x is formed via the thermal reaction of atmospheric nitrogen and oxygen at extremely high temperatures (above 1800 K, Thermal (Zel'dovich) mechanism), which typically occur during high-power settings like take-off and climb.

- **Particulate Matter (PM) and Impurities:**

- Non-volatile PM (nvPM): Primarily consists of ultrafine black carbon (soot) particles formed in fuel-rich regions of the combustor.
- Volatile PM (vPM): Formed when gaseous precursors (like volatile organic compounds) cool and condense after exiting the engine.

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, some are excellent, while others have incredibly poor combustion characteristics.

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

Why?

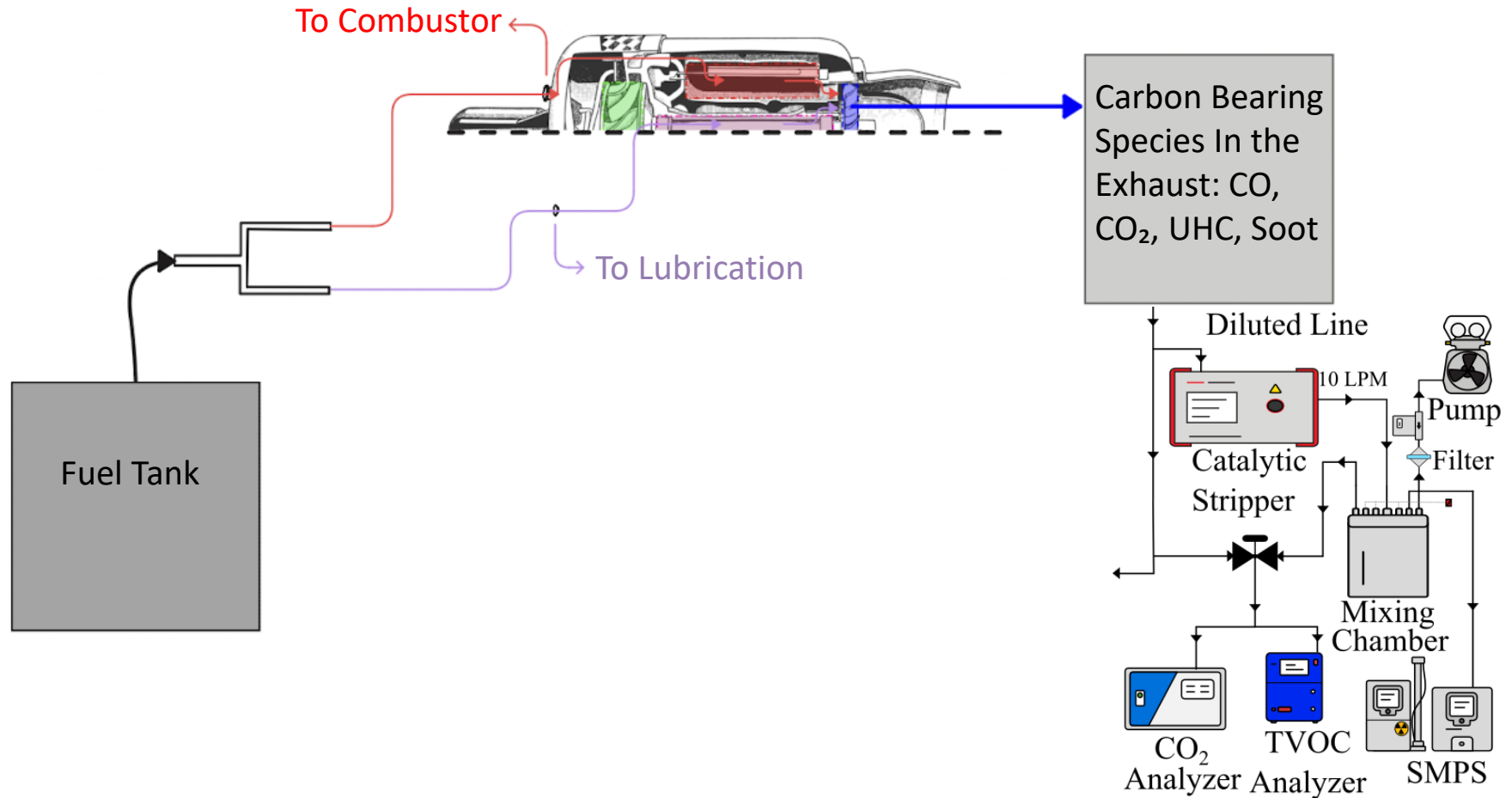
Isolates the Variables: Testing consecutively minimizes the impact of shifting environmental factors (temperature, humidity, atmospheric pressure) on combustion.

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.

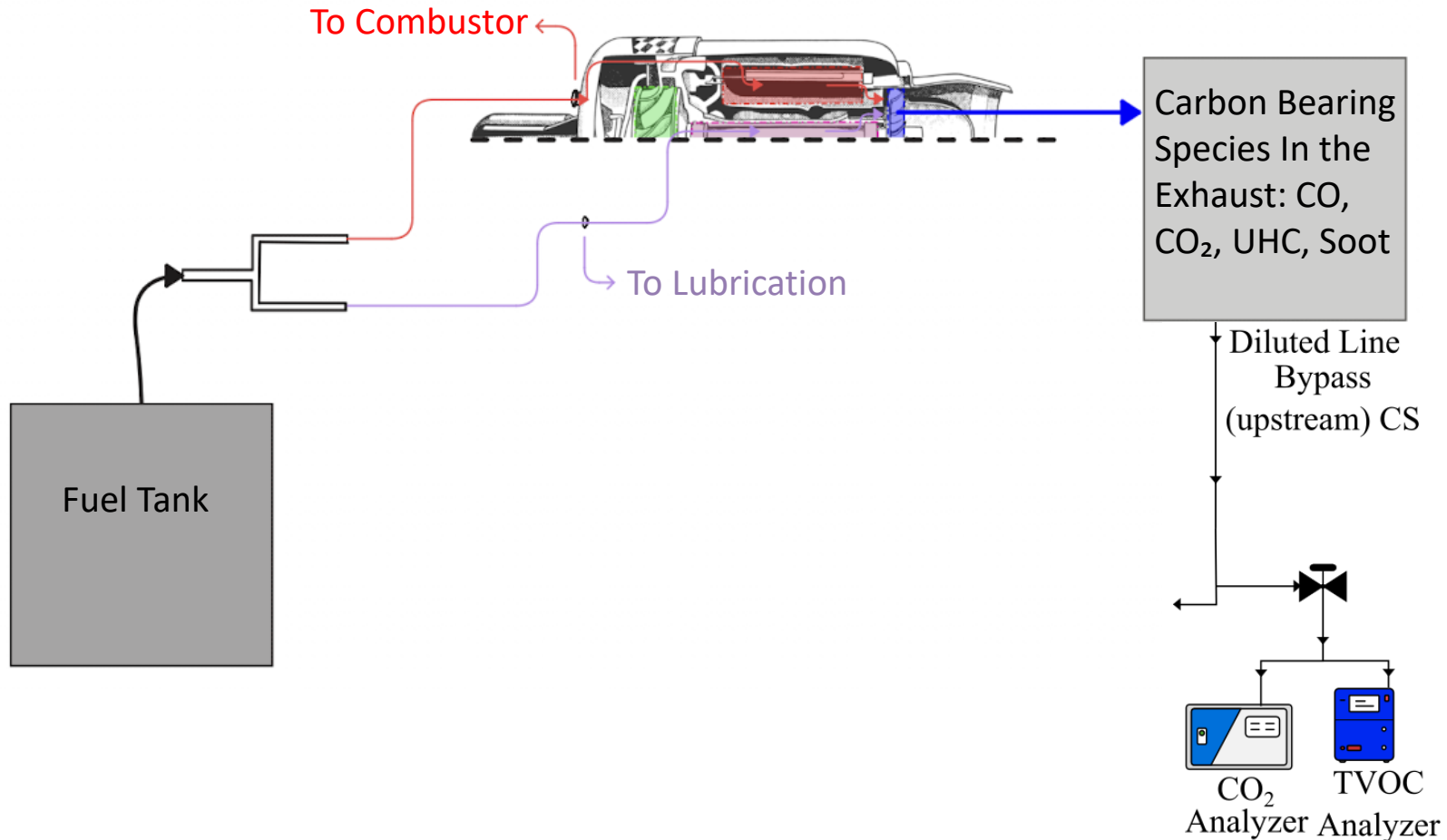
Captures Relative Sensitivities: Focuses on generating highly accurate differential data (e.g., EI_{CO} between SAF and Jet A-1) rather than just absolute magnitudes.

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

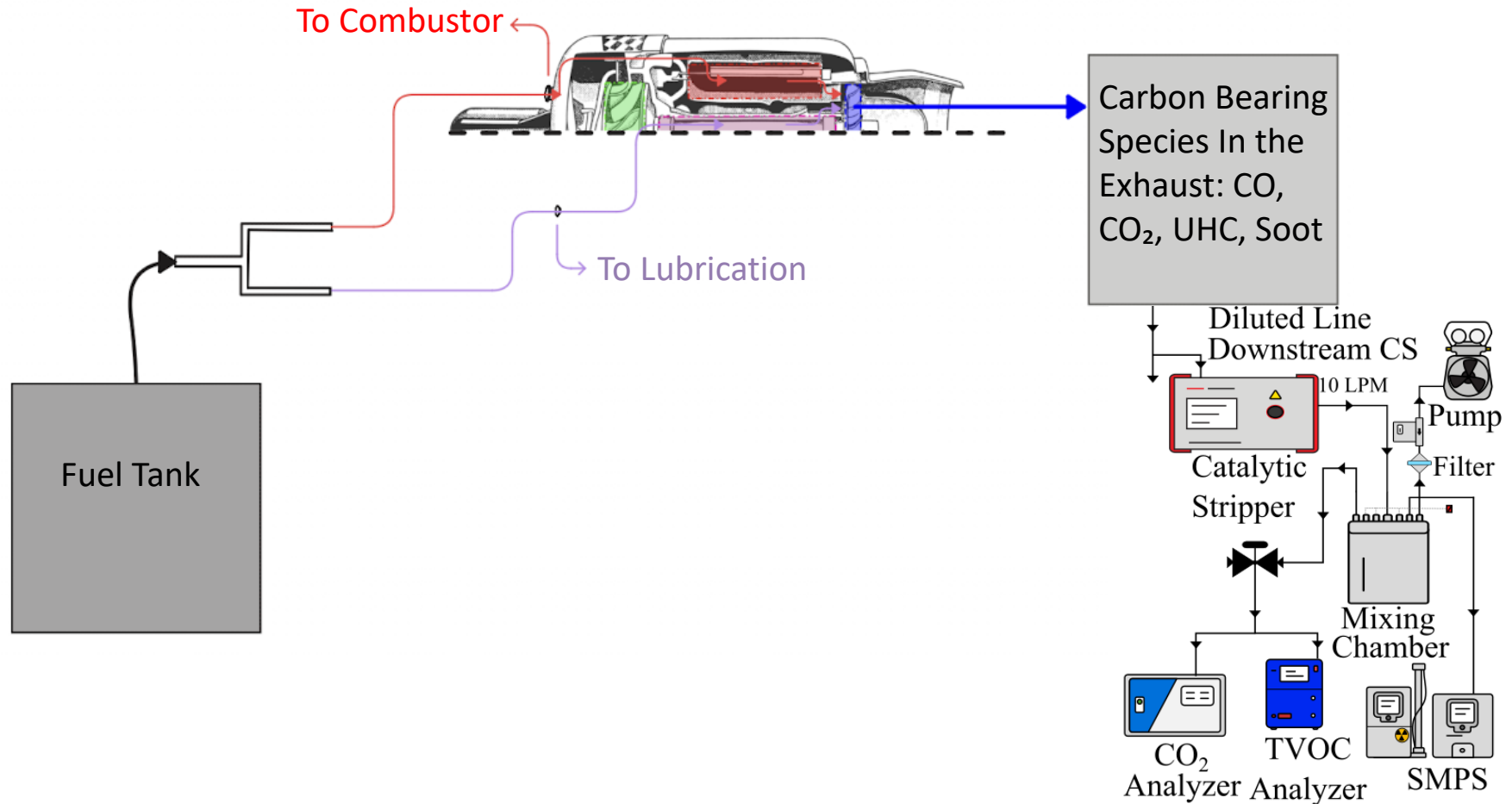
METHODOLOGY: INDIRECT UHC MEASUREMENT



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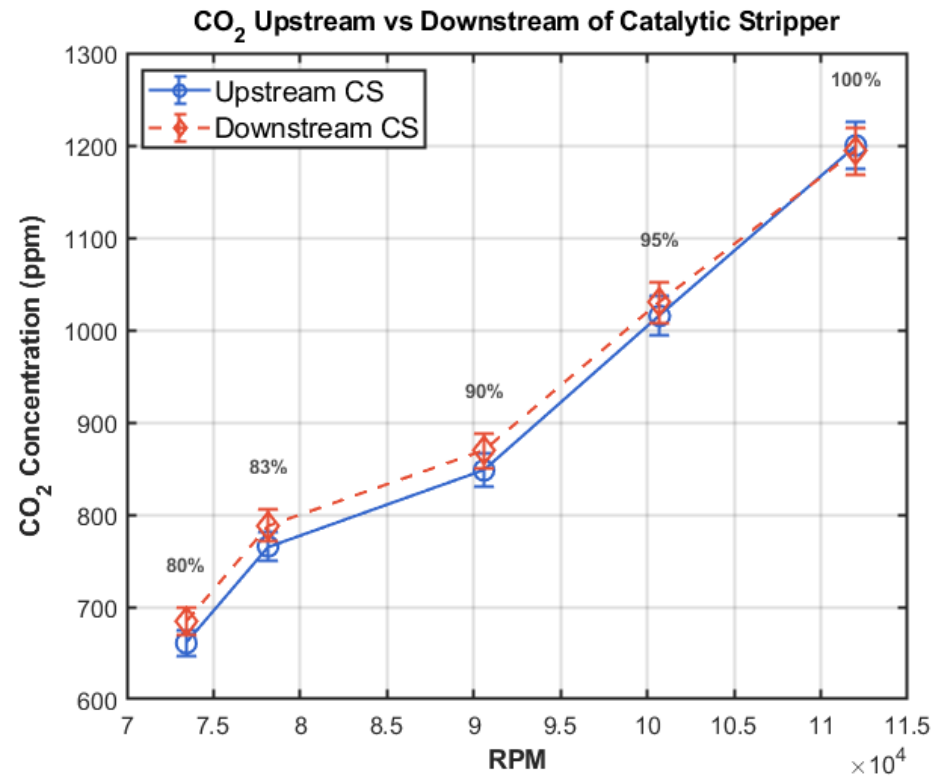


System Split: Consistently, approx. 88% of the total flow reaches the primary combustor, while approx. 12% feeds the open-loop lubrication path.

At 100% thrust, the absolute mass of oil ejected into the exhaust is roughly four times higher than at idle (90 mL/min vs. 22 mL/min).

Thermal Oxidation: Despite this massive increase in injected oil, the ΔCO_2 gap shrinks to almost zero at max thrust.

Physical Conclusion: At maximum load, extreme turbine inlet temperatures ($T_{t4} \approx 1200 \text{ K} - 1400 \text{ K}$) likely cause the slipstream mixture to auto-ignite and fully oxidize before reaching the exhaust plane.



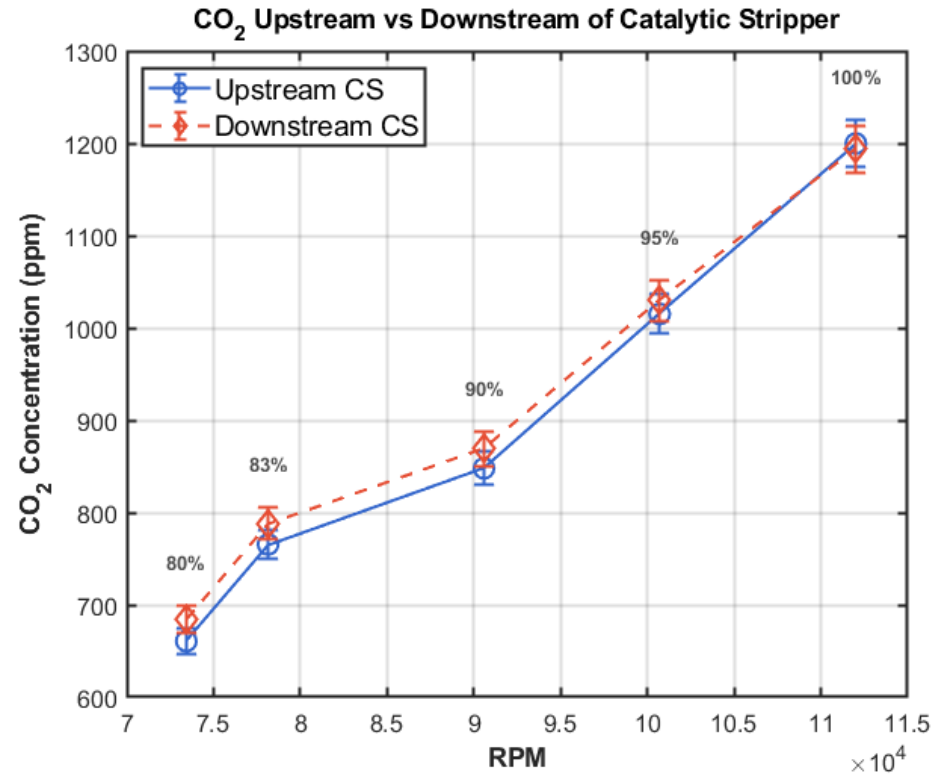
METHODOLOGY: INDIRECT UHC MEASUREMENT

Low-Load Inefficiency is the Real Culprit:

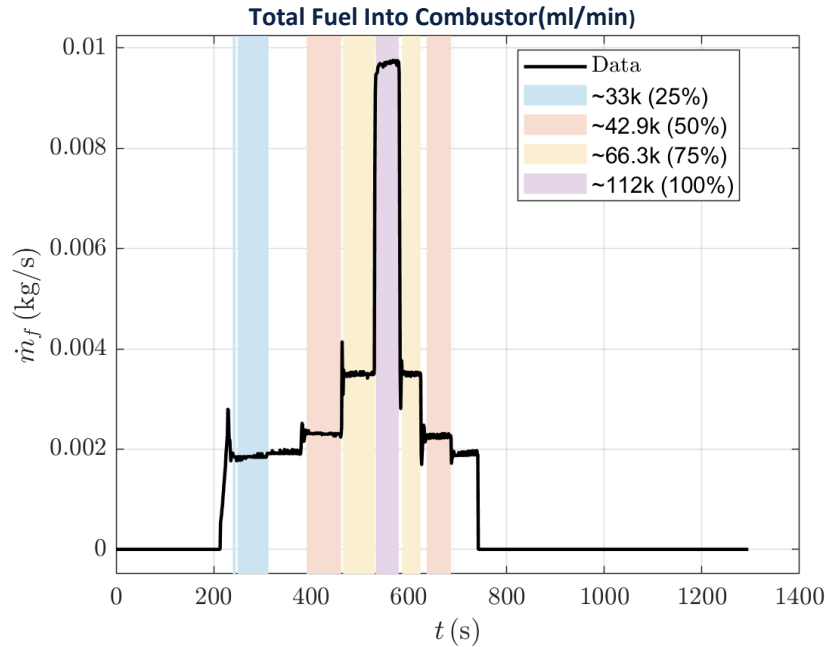
At lower RPMs (like 33k to 42k), temperatures are lower. The 22 mL/min of lubrication oil doesn't fully burn, and the primary combustor is operating inefficiently, dumping out primary UHCs. That's is likely why the ΔCO_2 gap is widest there. This is still speculation, we do not know for sure, but that's what I got out of this.

If 12% of the fuel was just slipping out of the engine unburned, the carbon balance would be off by 12%, and we had a max deviation of 6% at the lowest operating point.

Because the catalytic stripper proves the unmeasured carbon is negligible at high loads, we have proof that treating the exhaust as "fully oxidized" at the micro-max condition is a perfectly valid assumption.



MASS FLOW RATE OF FUEL TO COMBUSTOR



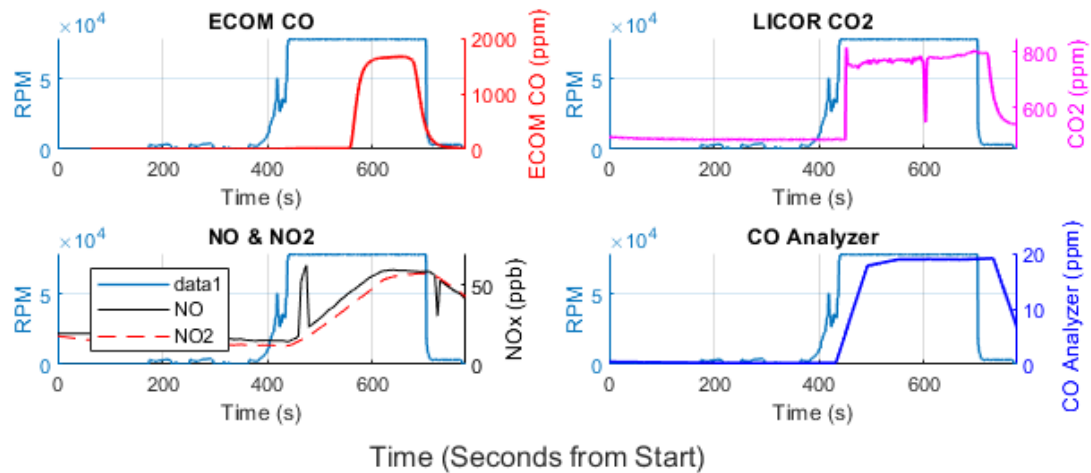
$$\dot{m}_f(t) = \rho_f \frac{\dot{V}_{f,comb}(t)}{60000}, \quad \text{with } \rho_f \approx 0.80\text{--}0.82 \text{ kg L}^{-1}$$

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

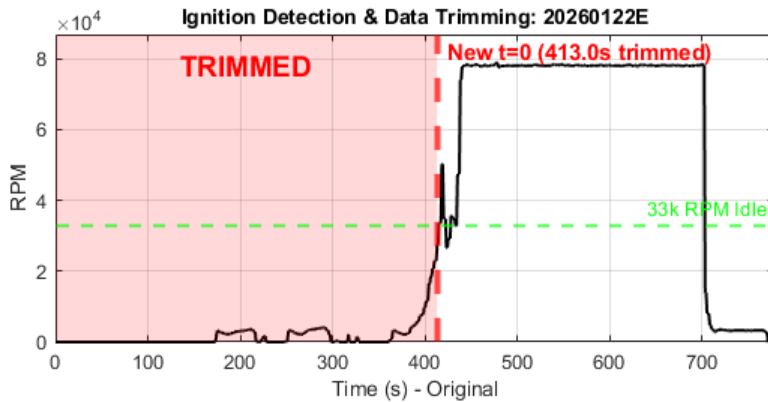
- Jan provided lookup data relating thrust command (%) to total fuel flow (mL/min)
- A fraction of this total flow actually reaches the combustor ($\approx 87\text{--}89\%$)
- By comparing combustor flow to total flow across all setpoints, an average ratio of ~ 0.88 was established
- Converted volumetric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

Time Alignment & Interpolation

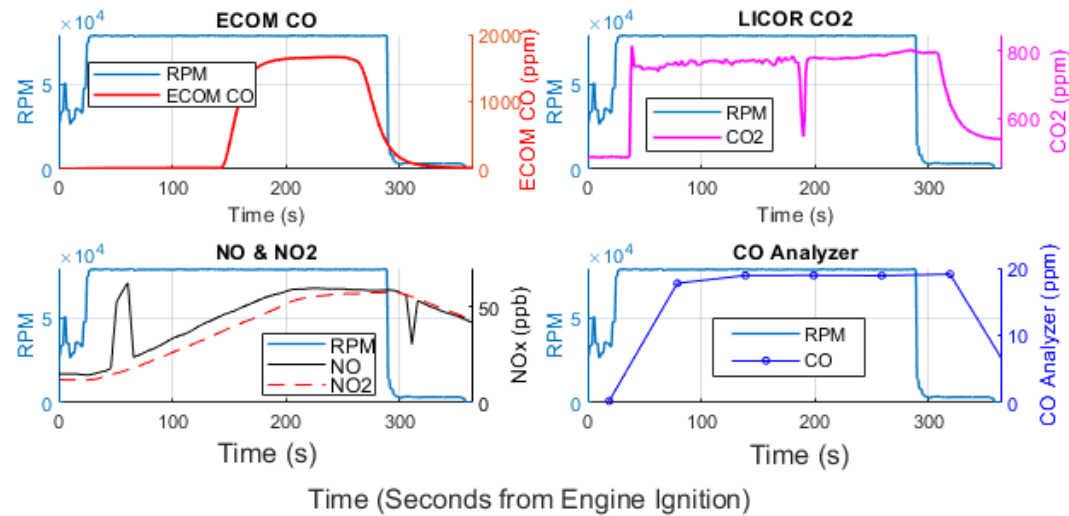
Aligned Data vs Seconds: 20260122E



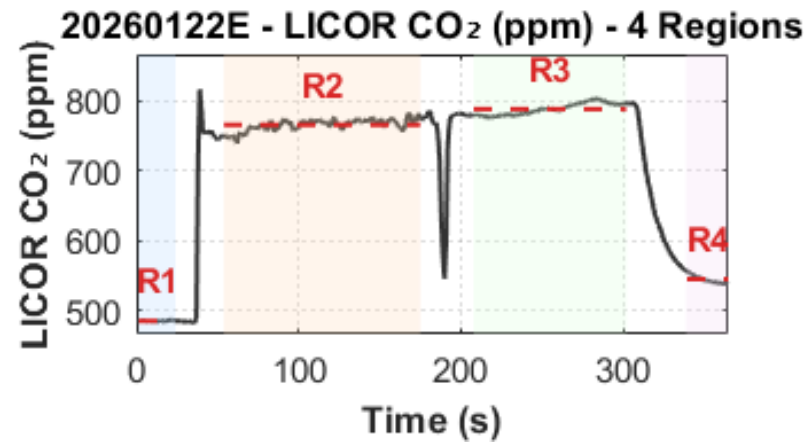
Ignition Based Trimming



Ignition-Aligned Data: 20260122E



Steady State Identification



Micro (JetCat)

- **Surface-to-volume:** High (significant wall quenching).
- Thus, **lower peak flame temperature:** Thermal NO_x is exponentially dependent on temperature. We see **much lower EI NO_x** for micro-turbojet which is consistent.
- Residence Time: ≈ 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_x production, illustrated in **significantly higher in EI NO_x** 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: PHYSICS SURROUNDING COMPARISON

	OPR	T_{t3}	P_{t3}
Micro-Turbojet @ max OP	≈ 4	469 K	374 kPa
Full size Turbofan @ idle OP [14]	$\approx 3.5-4$	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)).

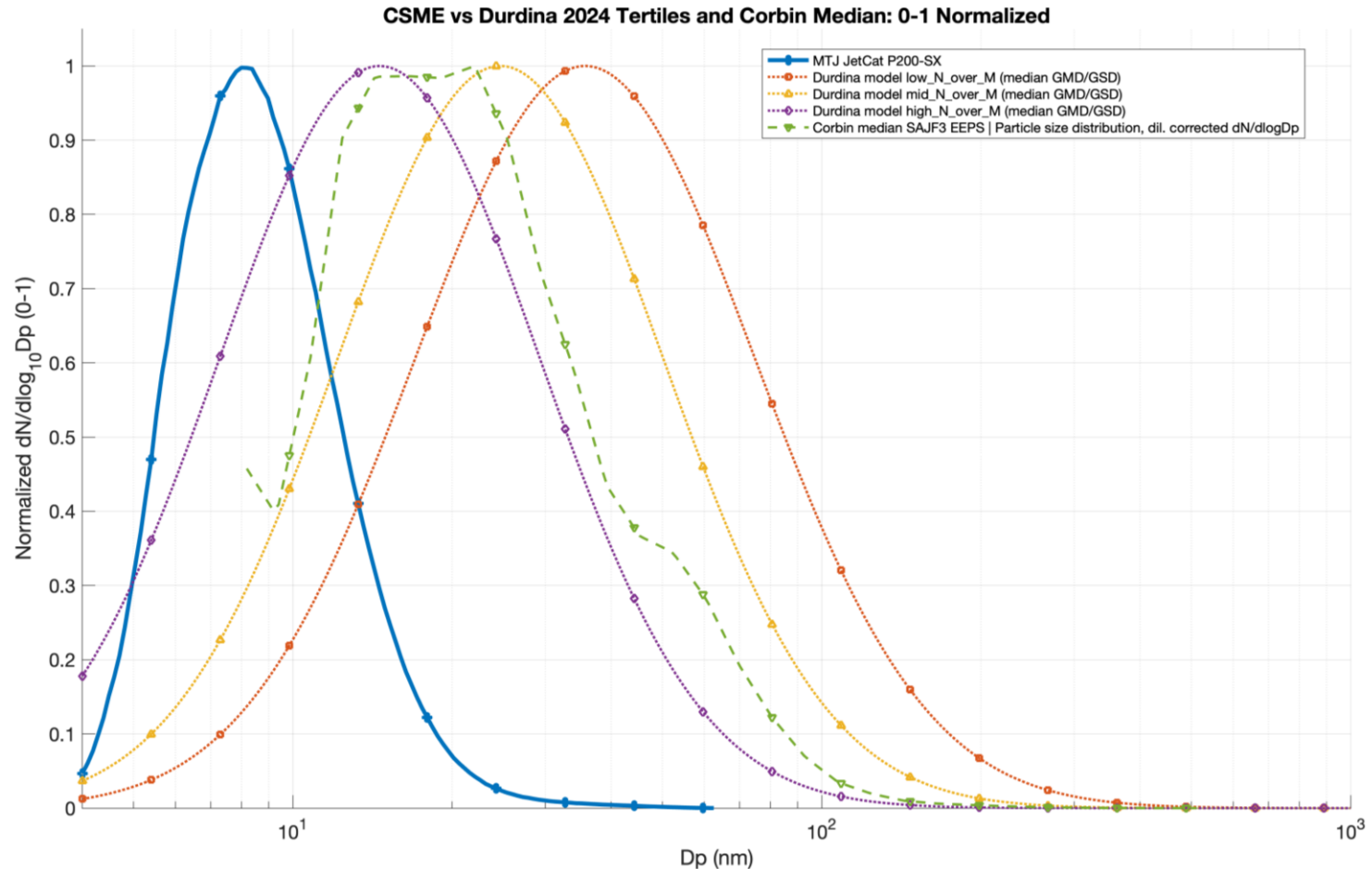
T (Temperature): The local thermodynamic temperature (469 K).

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.

Instrument	Species	Units	Accuracy
2B 405 nm	NO _x	PPB	±2 %
T300U	CO	PPM	±1 %
LI-850	CO ₂	PPM	±1.5 %

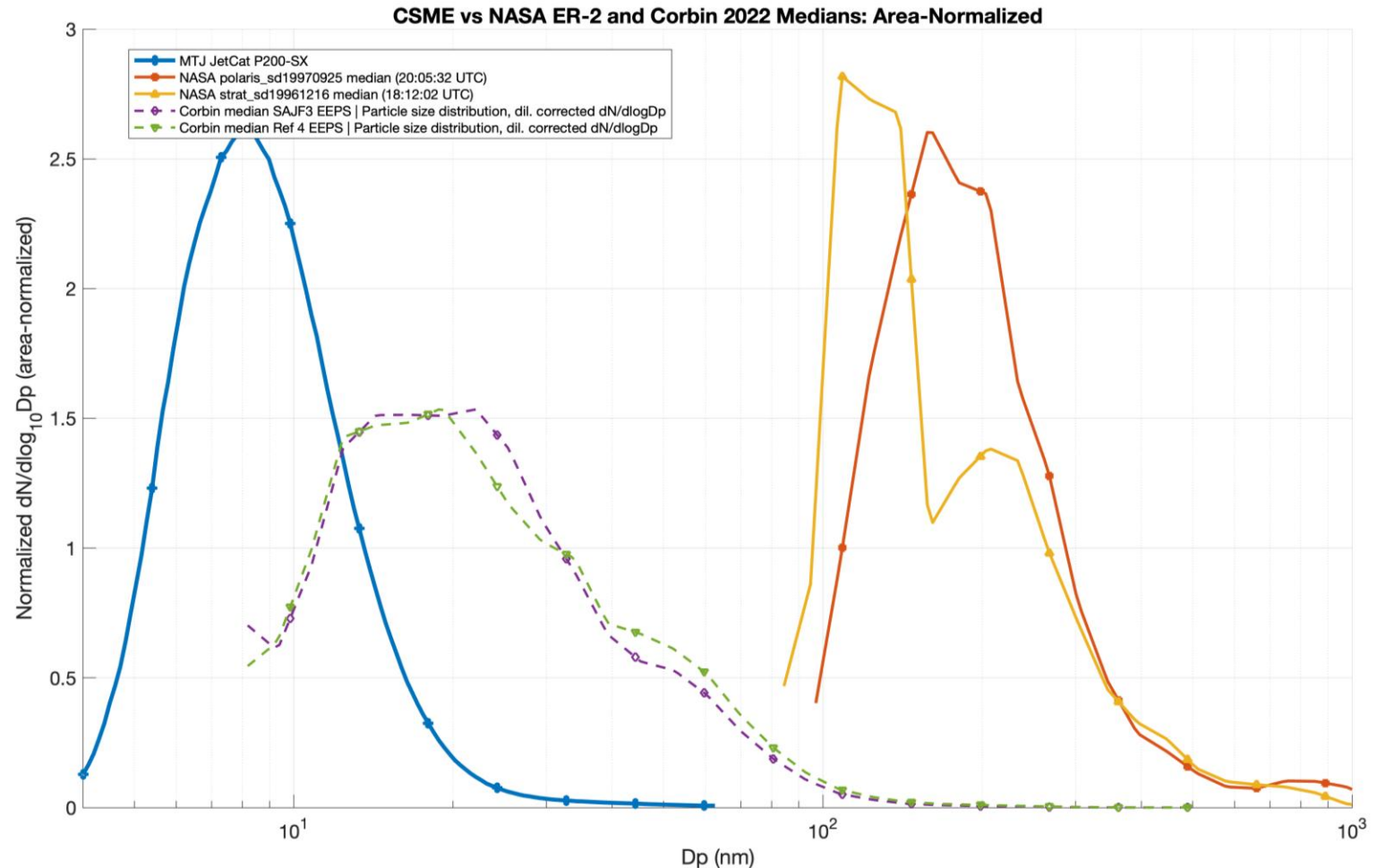
RESULTS: MICRO-TURBOJET VS TURBOFAN (NVPM)

The measured distribution exhibits a distinct mono-modal peak with a mode diameter of 7.84 nm, **geometric mean diameter of 8.6 nm**, and geometric standard deviation of 1.44.



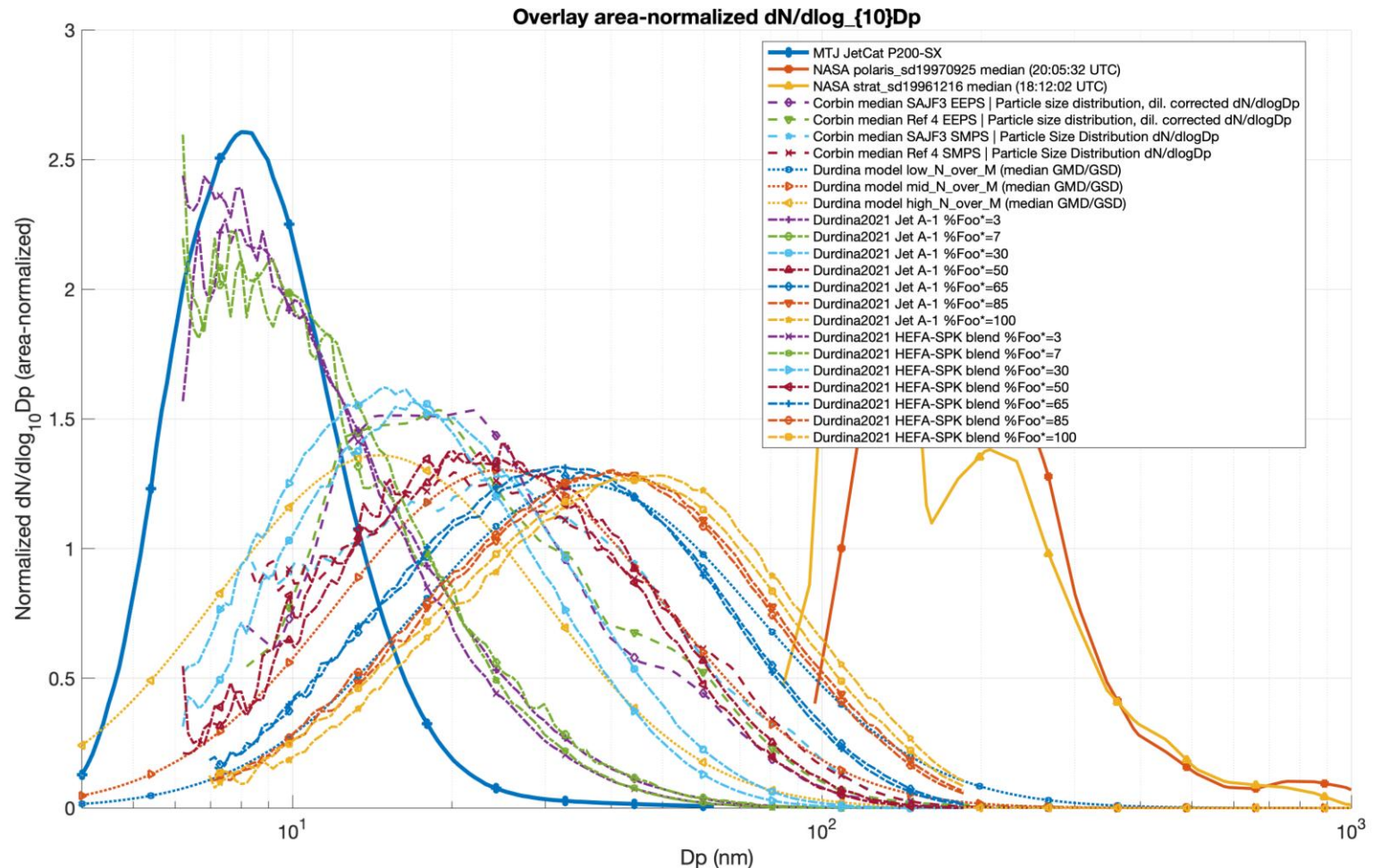
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