Gaseous Emissions Results from a Three-Cup Flametube Test of a Third-Generation Swirl-Venturi Lean Direct Injection Combustion Concept

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Purpose and Approach

Purpose

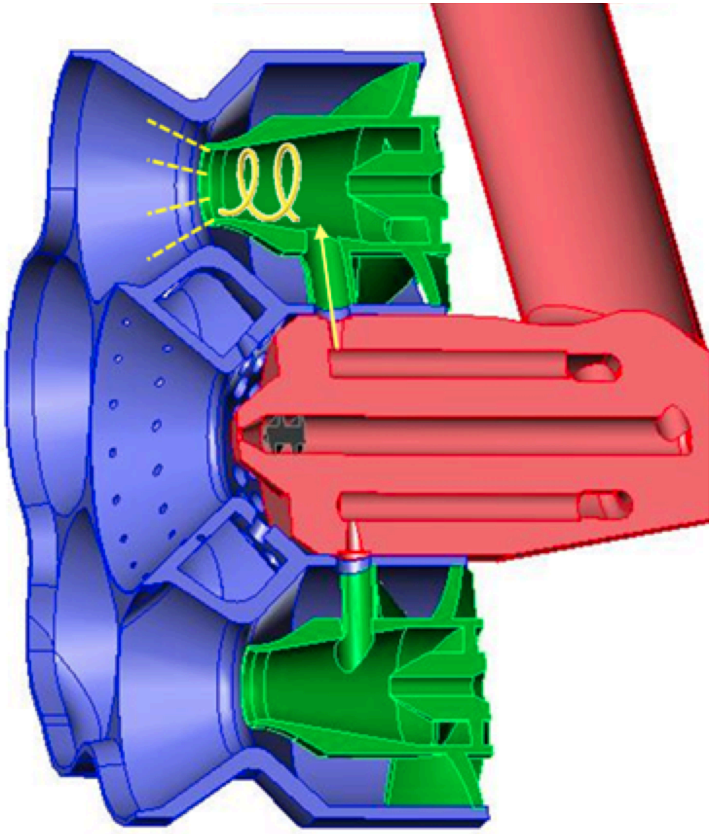
- Reduce NOx emissions
  - For the Advanced Air Transport Technology Project (AATT), small-core engine: single-aisle
  - **Goal: 80% NOx reduction** wrt CAEP/6
- Have acceptable low-power operability
- Reduce fuel line complexity and improve thermal management of the fuel

Approach

- Base design on the piloted lean direct injection (LDI) combustion concept developed under NASA's Environmentally Responsible Aviation (ERA) project
- Replace many fuel lines – each with only 1 injection point – with a single fuel line with multiple injection points
- Test configuration in a medium-pressure flametube
- Also Evaluate At: Commercial Supersonic Transport (CST) cruise. Goal: NOx < 5 EI

Results

- The new configuration met the NOx goals
- Operability good except at the 30% ICAO point
- Replaced 5 or 7 individual fuel lines by a single fuel stem with multiple injection points

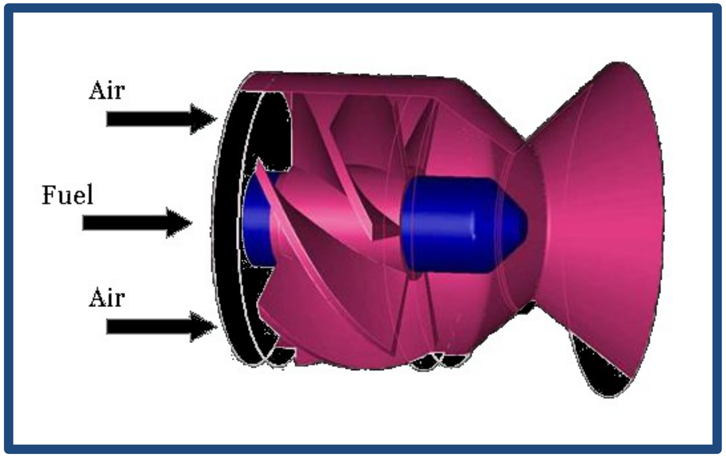


Outline

- Background/Motivation
- Setup
  - Flametube Hardware
  - Flametube Facility
- Results
  - Low-power conditions
    - 7% ICAO
    - 30% ICAO
  - High power CO emissions and combustion efficiency
  - High power NOx emissions and correlation equations
- Conclusions

Background

Swirl-Venturi Lean Direct Injection (SV-LDI)



- Fuel-lean combustor concept
- No geometrically-separated premixing zone
- Many small fuel-air mixers replaced one traditionally-sized fuel-air mixer
- Air swirler followed by a converging-diverging venturi
- Simplex, airblast, or pre-filming fuel injector

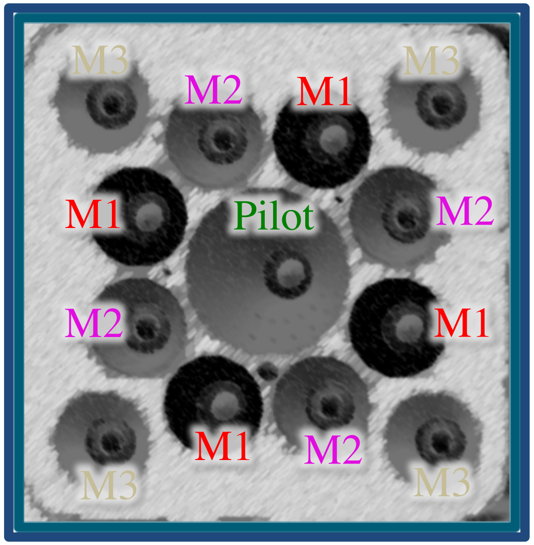
Baseline SV-LDI: LDI-1

- 9 fuel-air mixers in a 3 x 3 array
- Array square, 7.62-cm x 7.62-cm
- All fuel injectors are simplex
- All fuel-air mixers the same (except possibly swirler vane angle)

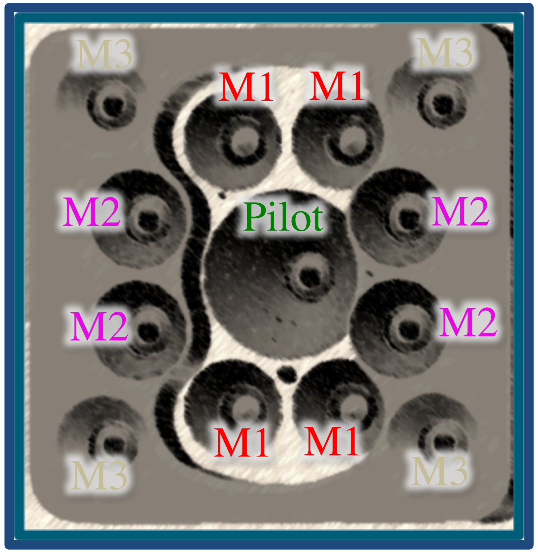
Baseline SV-LDI had low NOx emissions –
but poor low-power operability and a multi-line fuel stem

ERA SV-LDI: LDI-2

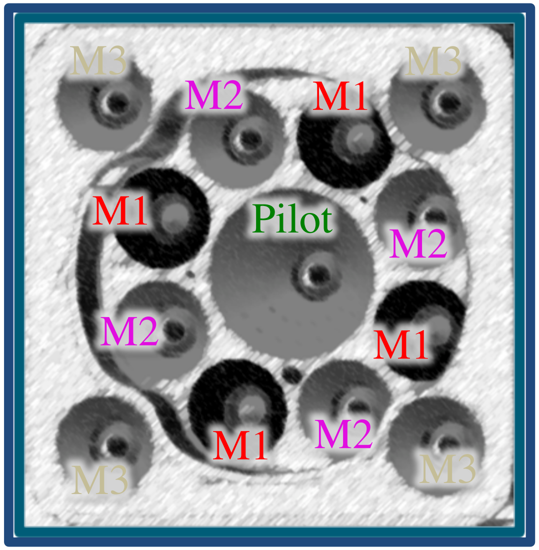
Flat Dome

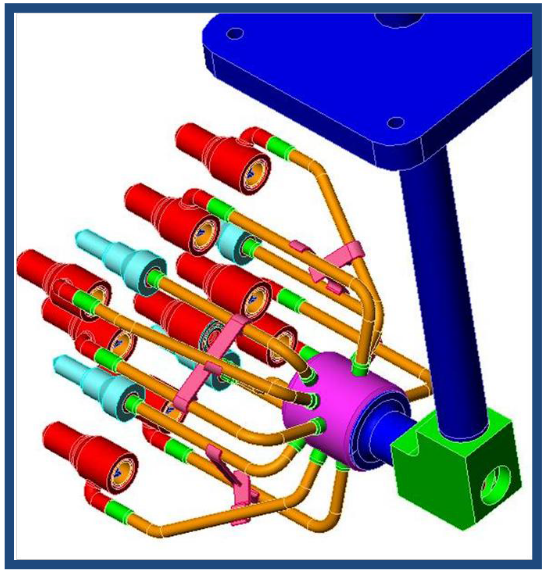


5-Recess



9-Recess





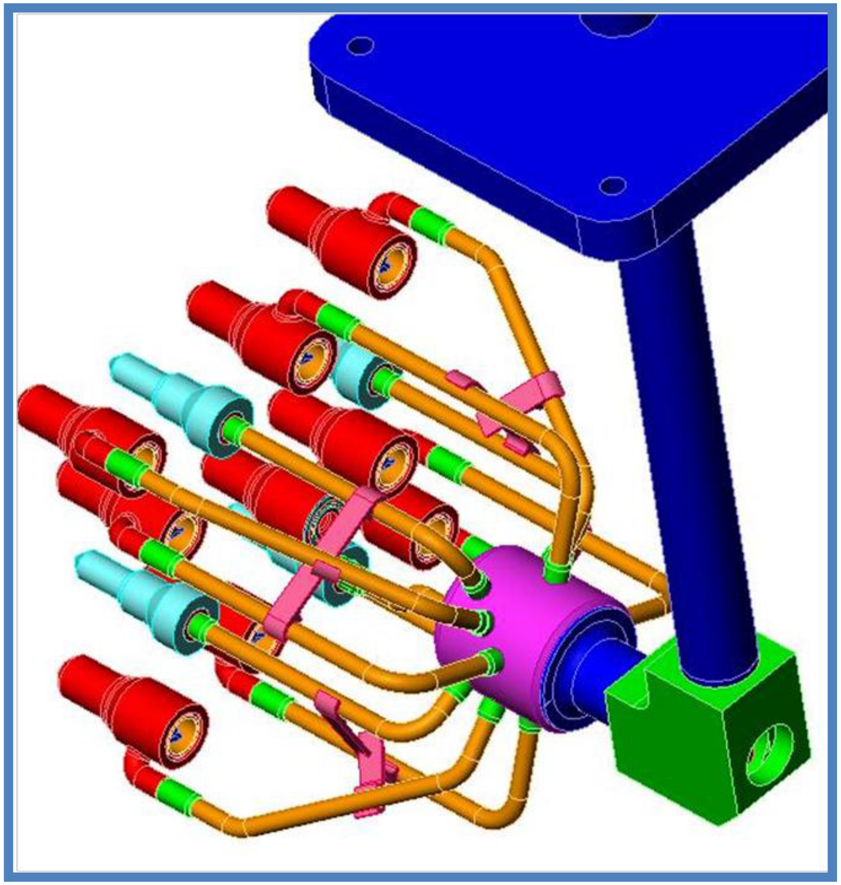
- 13 fuel-air mixers split into 4 stages
- Simplex or airblast fuel injectors
- Pilot has extended venturi
- 11.43-cm x 11.43-cm square cross-section

LDI-2 had low NOx emissions and acceptable low-power operability – but a multi-line fuel stem that would make thermal management of the fuel difficult.

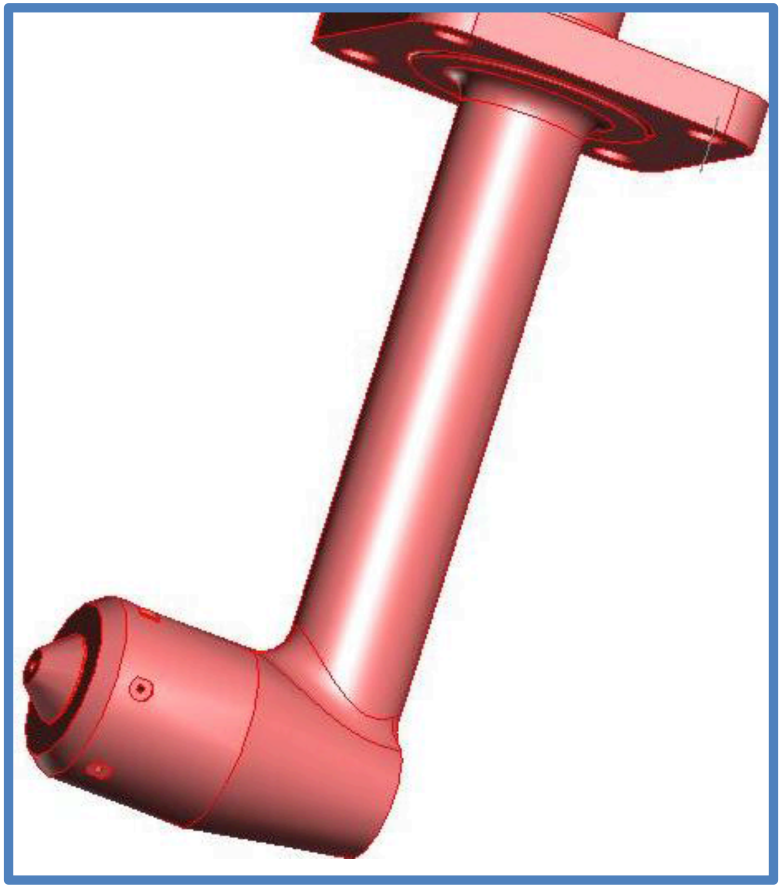
LDI-3 Hardware

Fuel Stems: LDI-3 vs. LDI-2

LDI-2

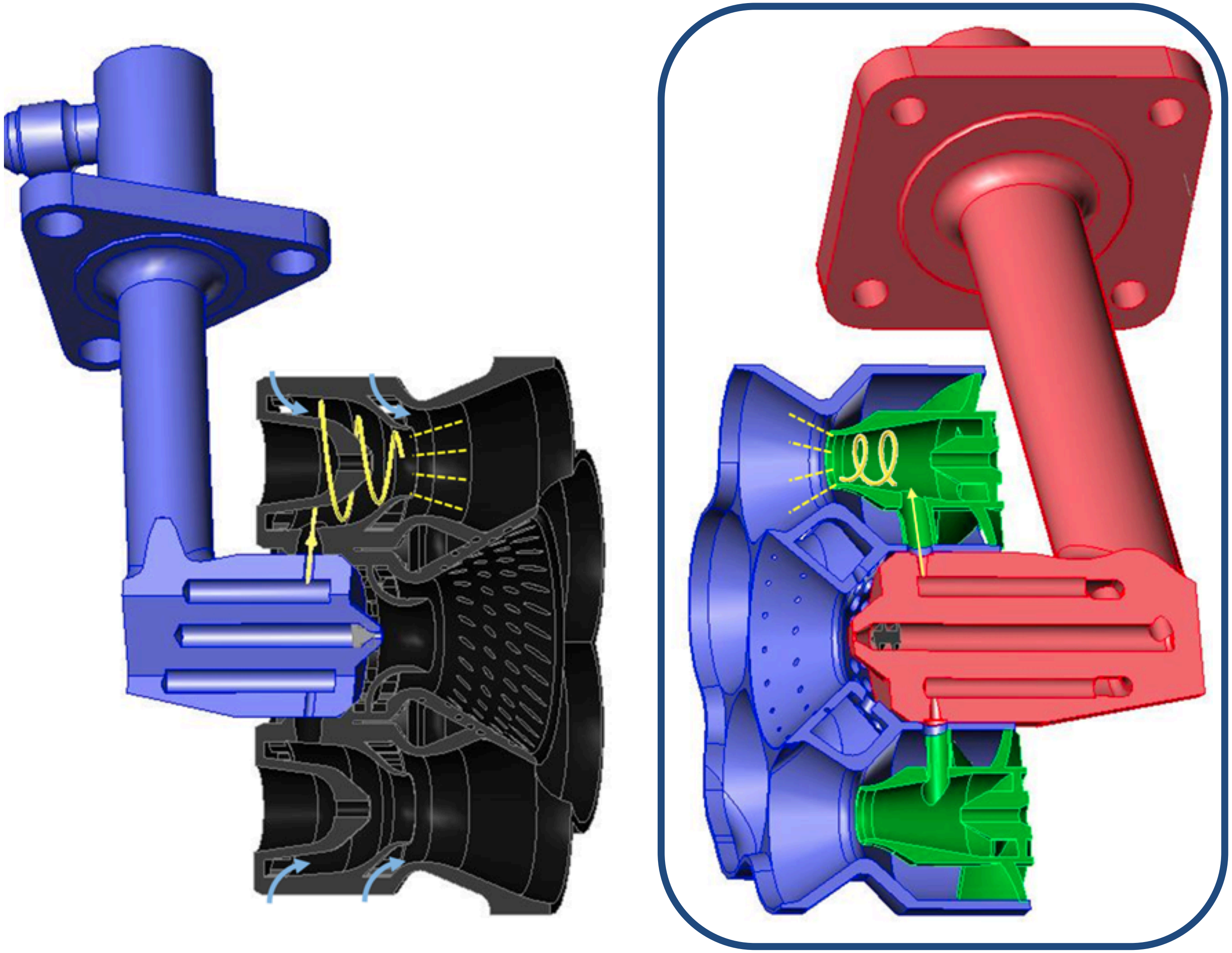


LDI-3



The LDI-3 fuel stem reduces fuel line complexity and should improve thermal management of the fuel!

SV-LDI-3

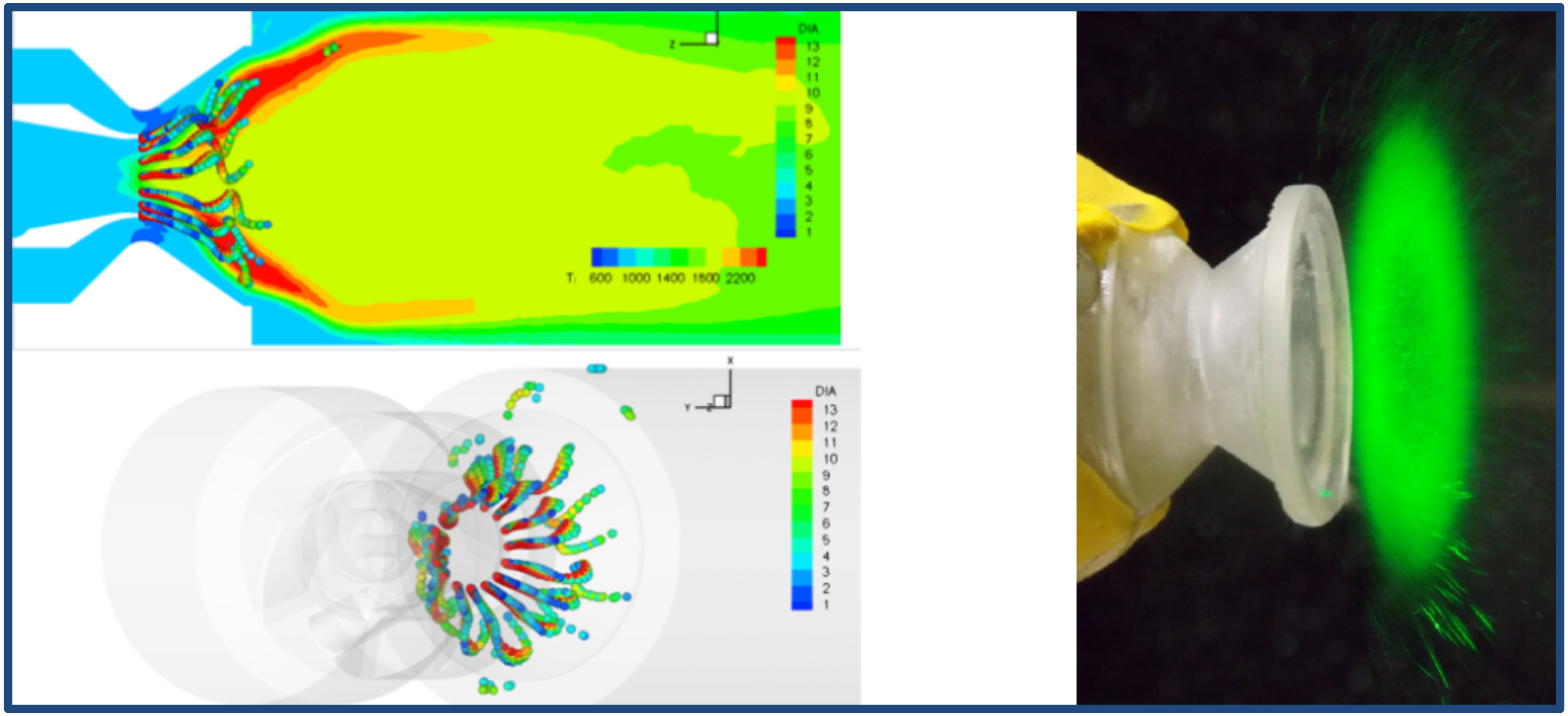


CFD Calcs
Ajmani et al
Early design
AIAA 2015-3785
Near-final design
AIAA 2016-4783

For the main fuel-air mixers, the fuel injection location changes.

Fuel Spray: SV-LDI-3

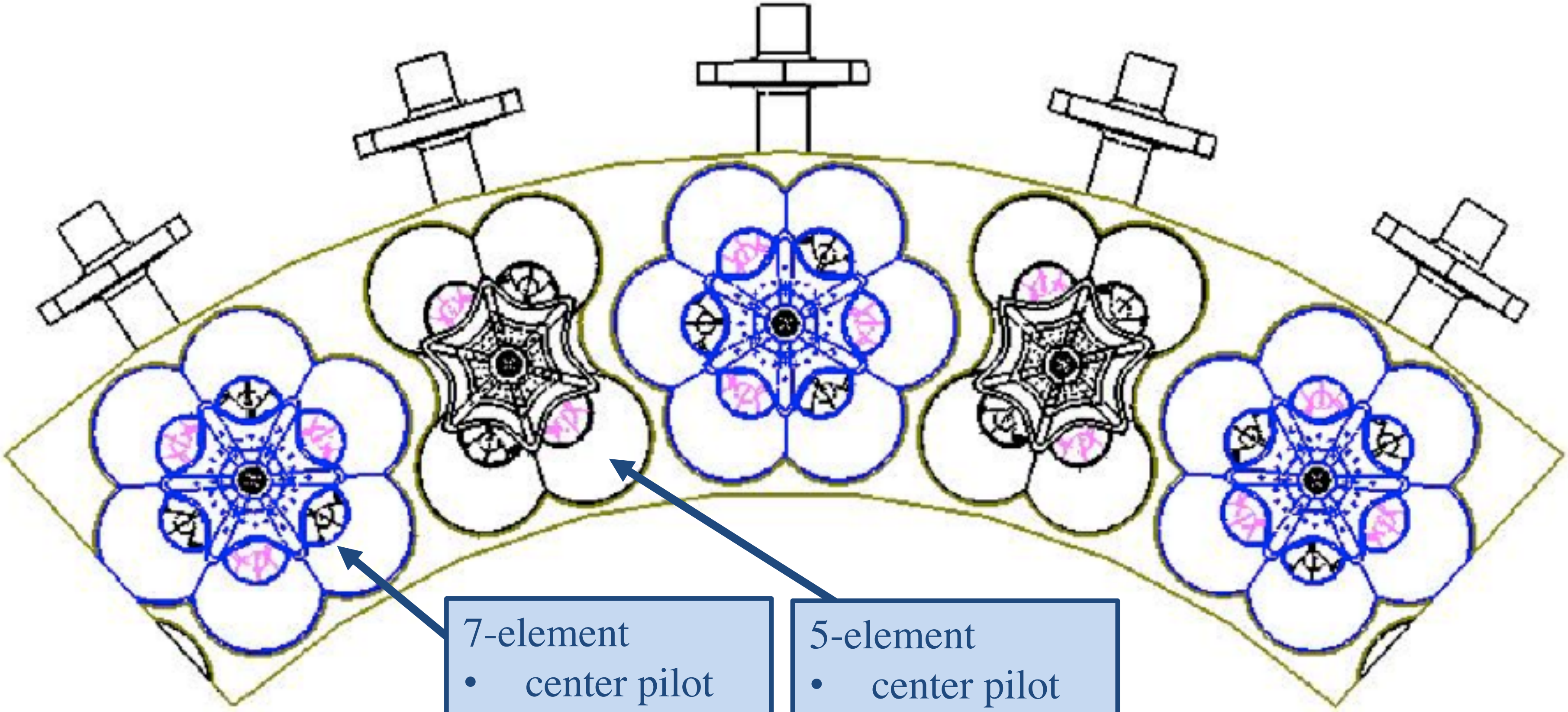
Fuel-air mixing in a main fuel-air mixer



From Ajmani et al AIAA 2016-4783

Good fuel-air mixing in the main fuel-air mixers

SV-LDI-3



7-element
- center pilot
- 6 outer mains

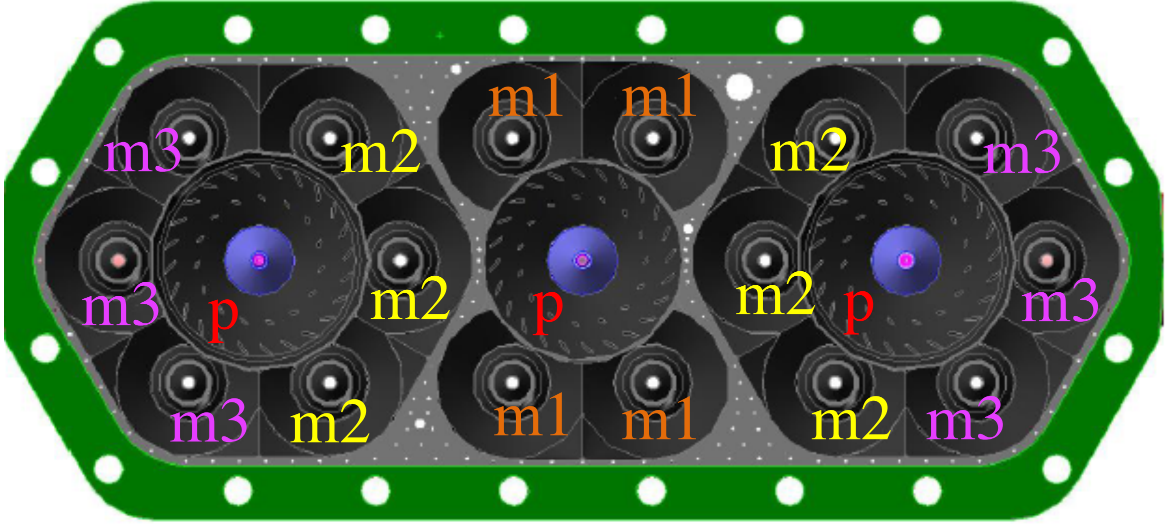
5-element
- center pilot
- 4 outer mains

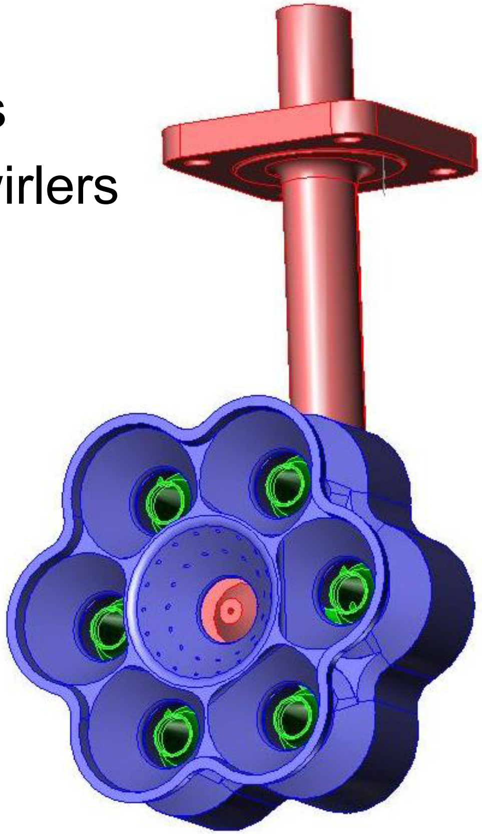
The number of fuel-air mixers in a “cup” alternates: 7-element or 5-element

SV-LDI-3 Flametube Hardware

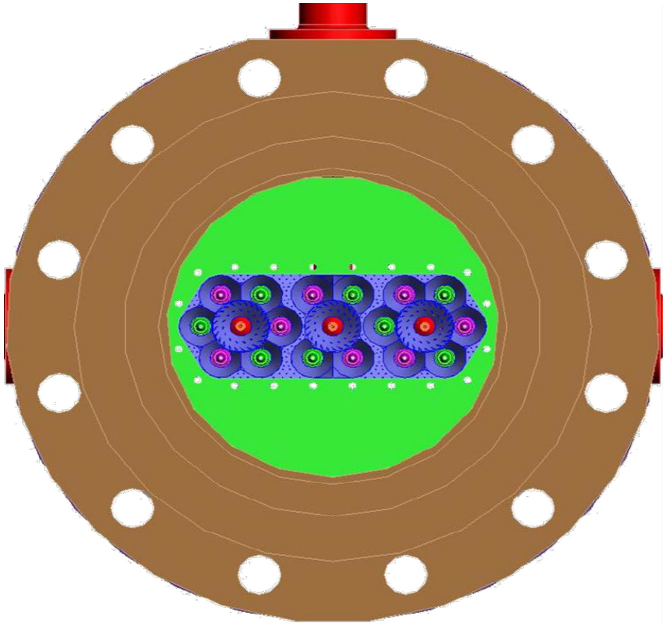
- 3 cups tested in a medium pressure flametube at NASA Glenn Research Center.
- Two 7-element cups and one 5-element cup: ⇨ 19-point
- 4 stages: pilot and 3 mains
  - Pilot stage: simplex fuel nozzle, radial air swirlers
  - Main stages: pre-filming fuel nozzles, axial air swirlers

3-cup “19-point ” flametube hardware

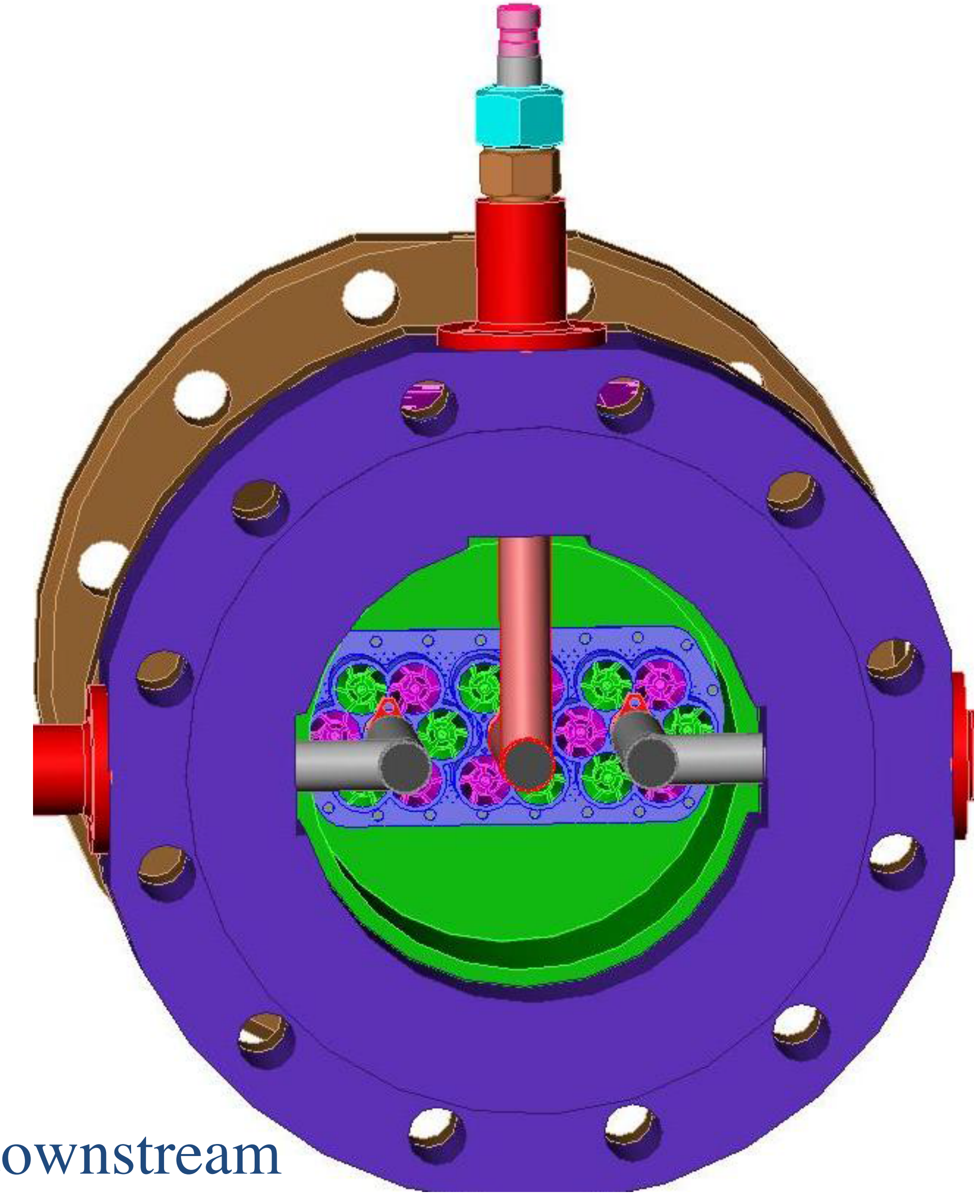




SV-LDI-3 Flametube Hardware



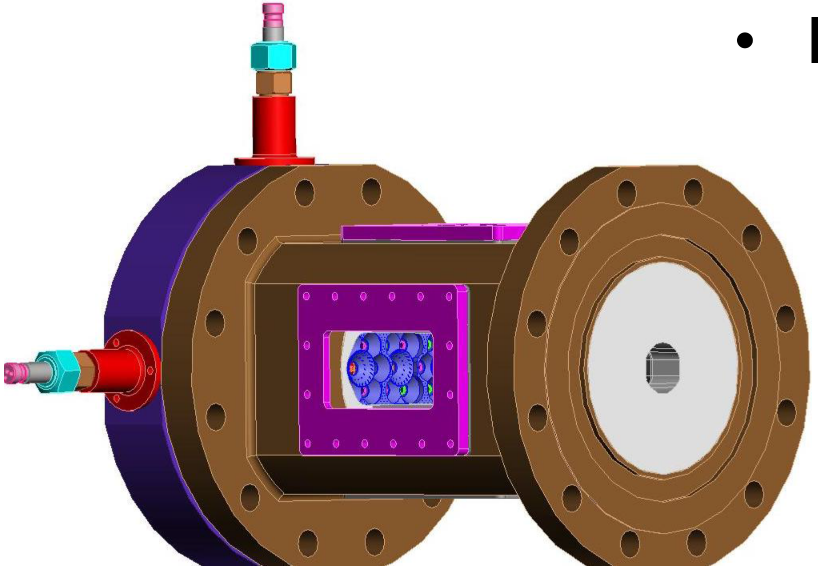
Looking upstream



Looking downstream

NASA Medium Pressure Flametube

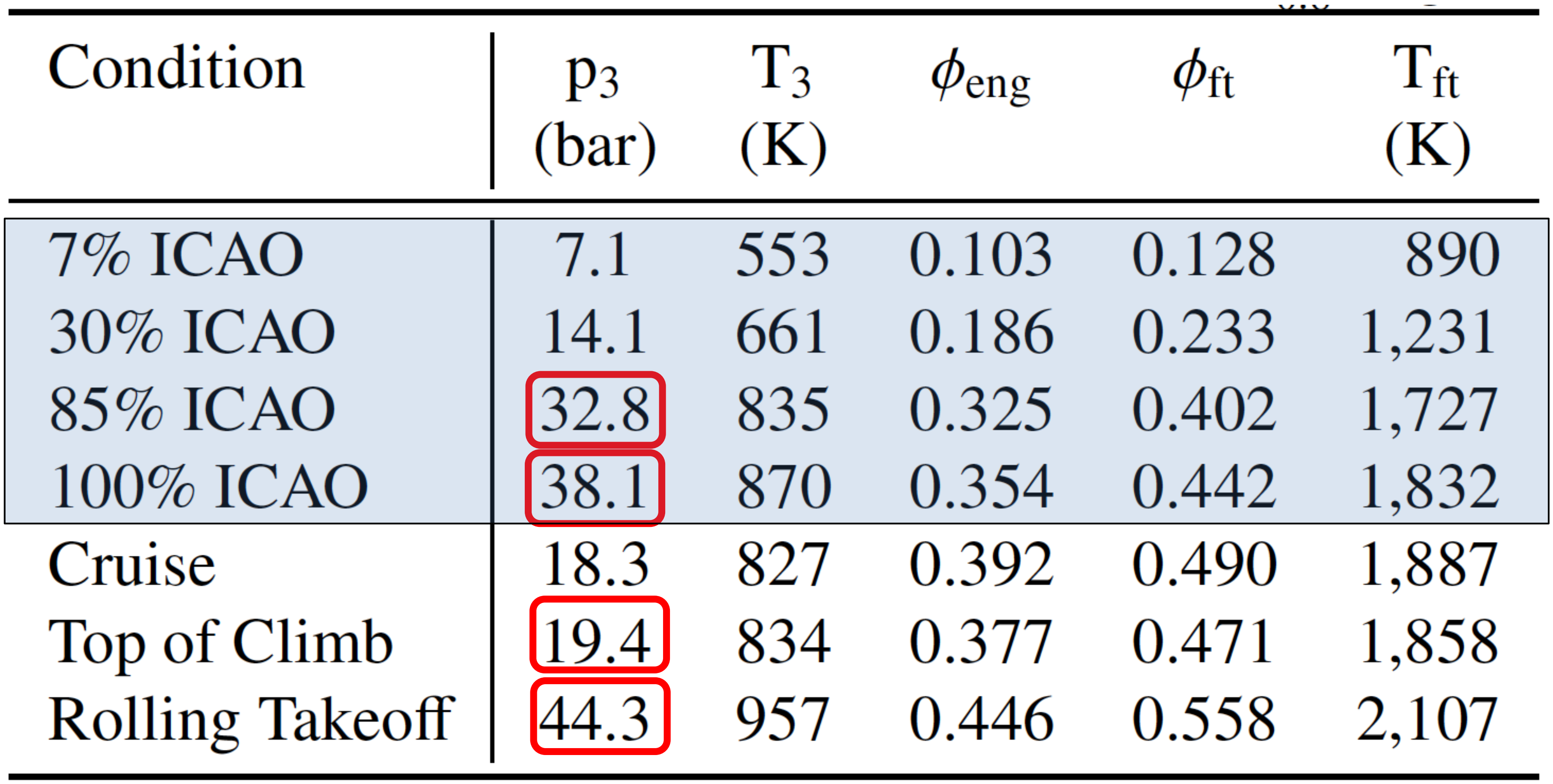
- Flametube capabilities
  - Inlet temperature to ~920 K
  - Inlet pressure to 19 bar
- Testing was done with a cast ceramic liner
  - Casting shape started out with a cross-section identical to that of the dome
  - Casting converged to a circular cross-section several inches downstream of the dome



- Instrumentation
  - Standard gas bench: SAE ARP 1256
    - Single, 5-hole gas probe
  - Steady-state recording of temperature, pressure, flow rates (1 Hz)
  - High-speed recording of pressure (20 kHz)
  - Particulate measurements: CPC, SMPS

Results

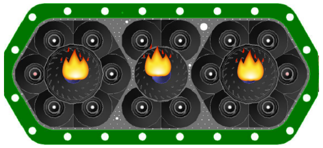
NASA N+3 Small-Core Cycle

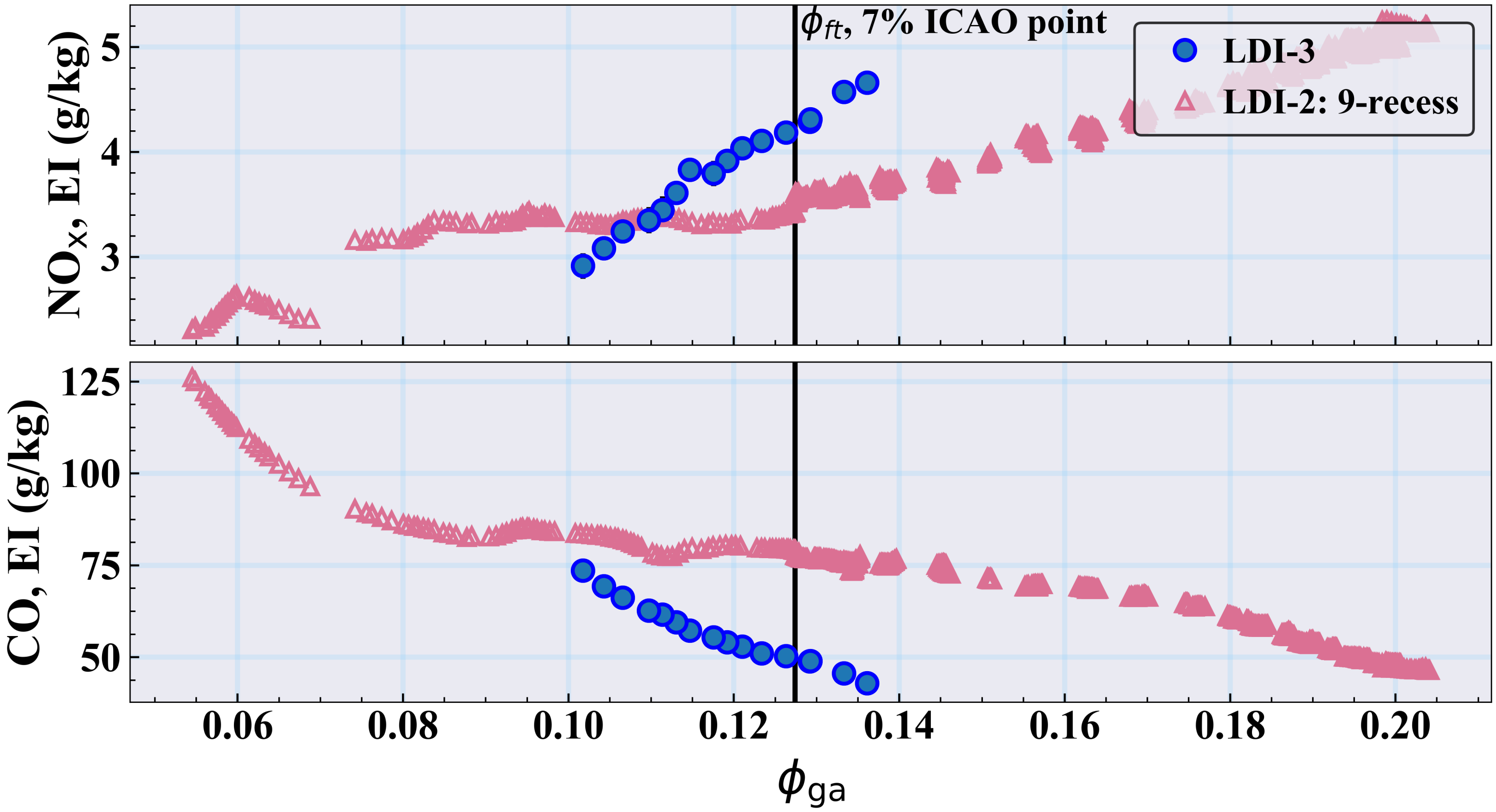


Condition	p_3 (bar)	T_3 (K)	ϕ_{eng}	ϕ_{ft}	T_{ft} (K)
7% ICAO	7.1	553	0.103	0.128	890
30% ICAO	14.1	661	0.186	0.233	1,231
85% ICAO	32.8	835	0.325	0.402	1,727
100% ICAO	38.1	870	0.354	0.442	1,832
Cruise	18.3	827	0.392	0.490	1,887
Top of Climb	19.4	834	0.377	0.471	1,858
Rolling Takeoff	44.3	957	0.446	0.558	2,107

The flametube cannot reach the inlet pressures at high power conditions.

7% ICAO Point (Pilot only)



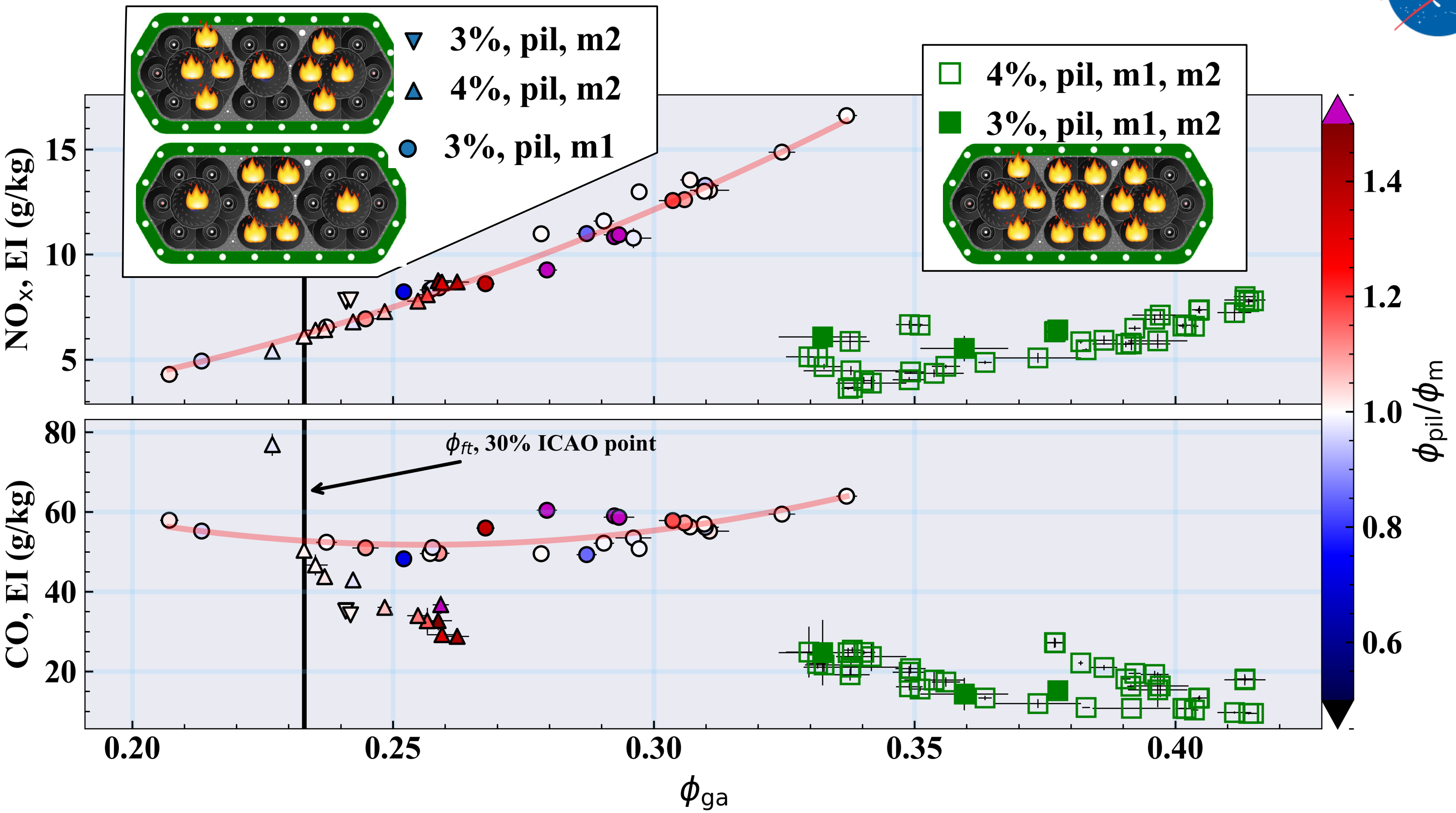


- NOx is 4.3 g/kg
- CO is 51 g/kg
- ~98% combustion efficiency

- Comparison with LDI-2: NOx higher, CO lower
  - Different air splits → different local f/a at pilot
  - Simplex vs. airblast pilot

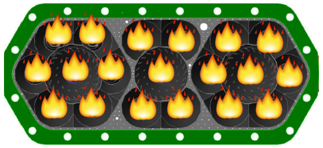
NOx and CO are acceptable

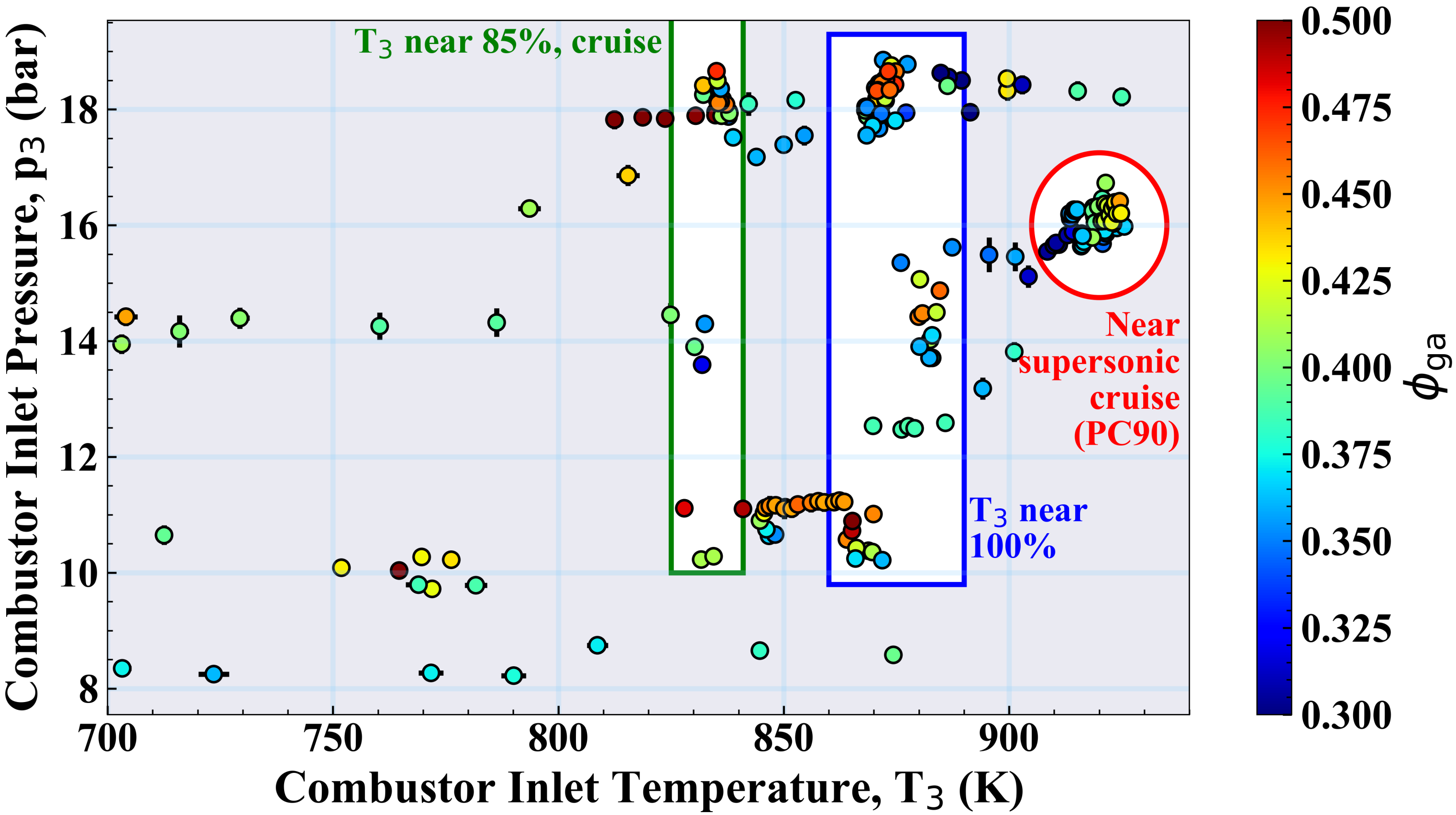
30% ICAO Point



- Difficult point for this configuration
  - Due to low equivalence ratio, could only use the pilot and one main circuit
- NOx and CO would both be lower if the equivalence ratio was higher
  - Check cycle
  - Change air splits

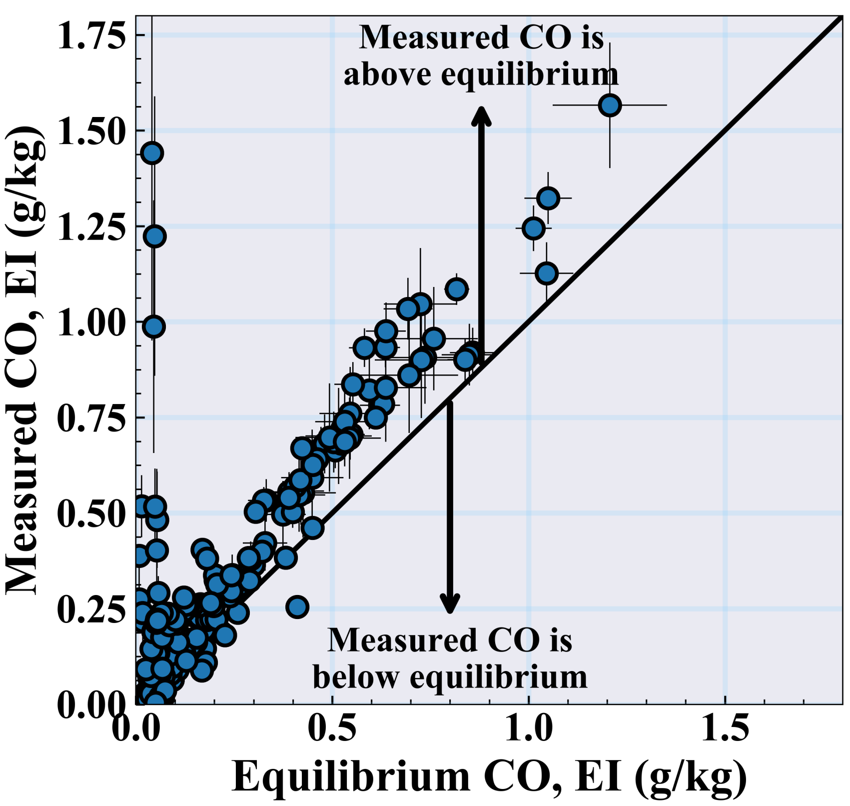
High Power Conditions

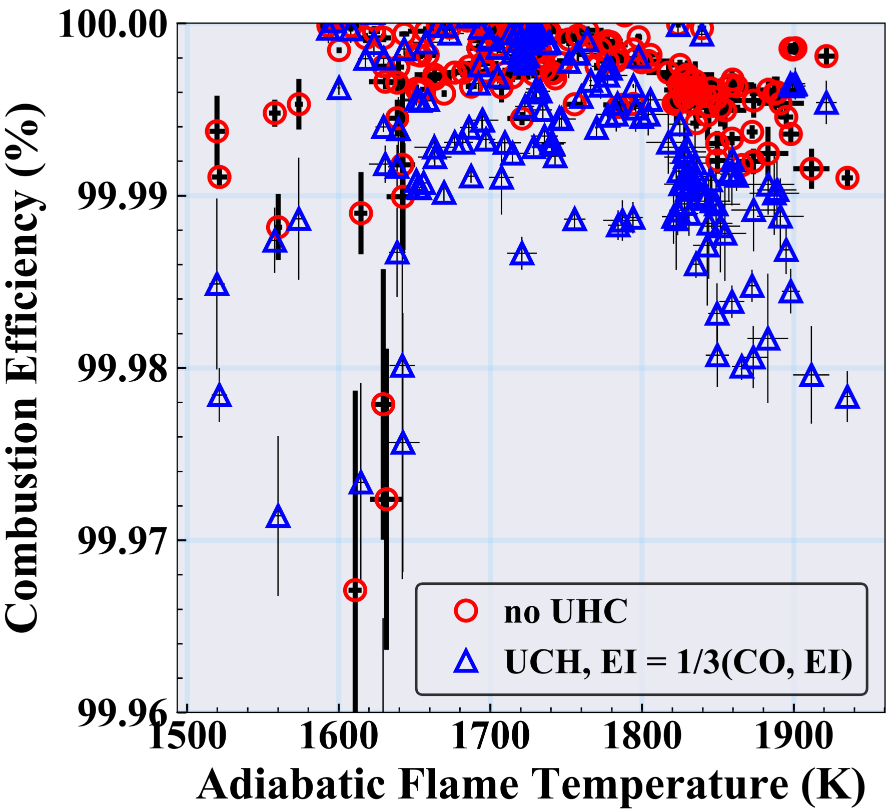




Match the inlet temperatures for the 85% and 100% ICAO points.
Vary pressure to aid in developing correlation equations.

CO and Combustion Efficiency at High Power Conditions

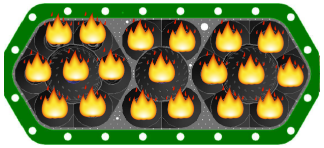


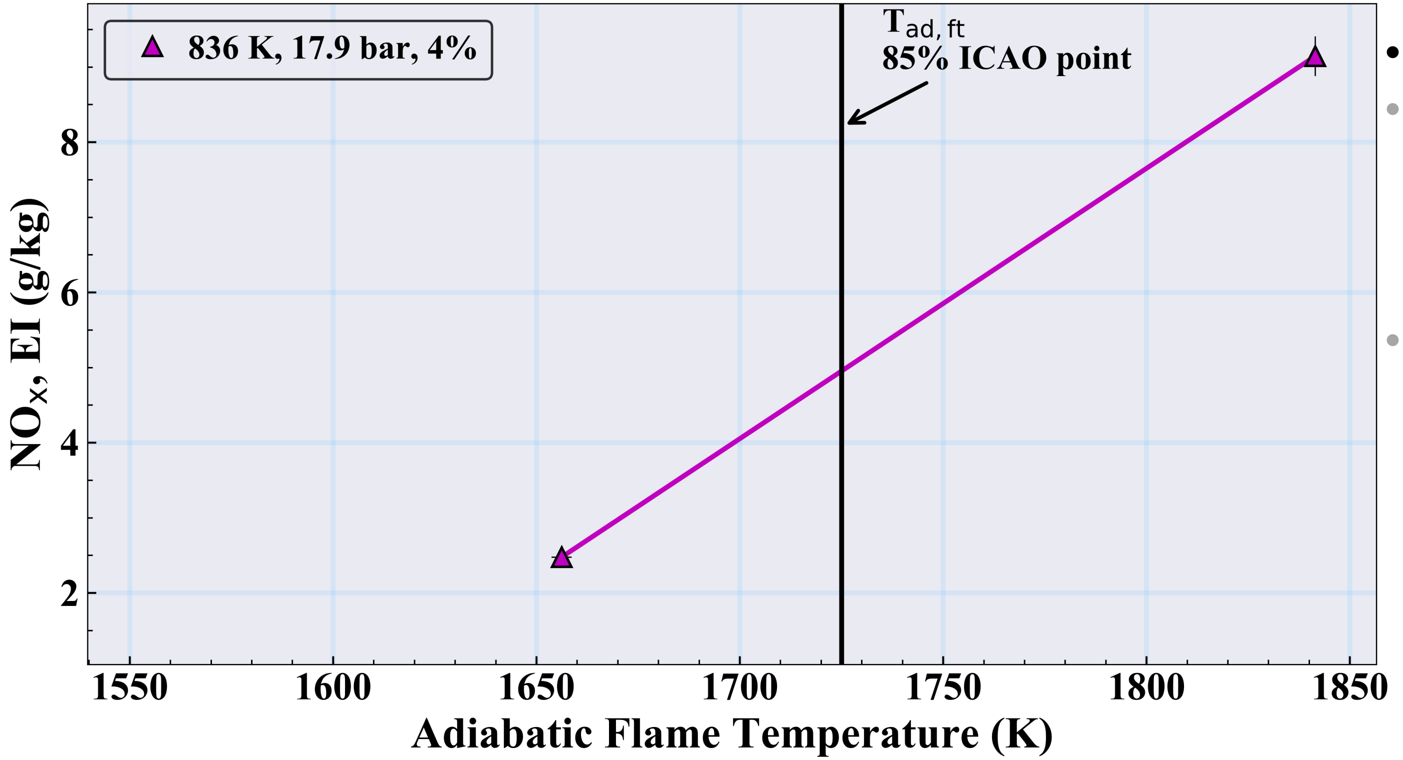


- CO is low, near the equilibrium value
- Combustion efficiency typically above 99.99%

High power combustion efficiency is good.

85% power ICAO Conditions

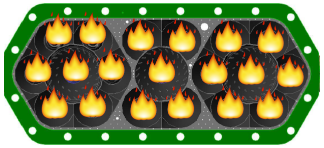


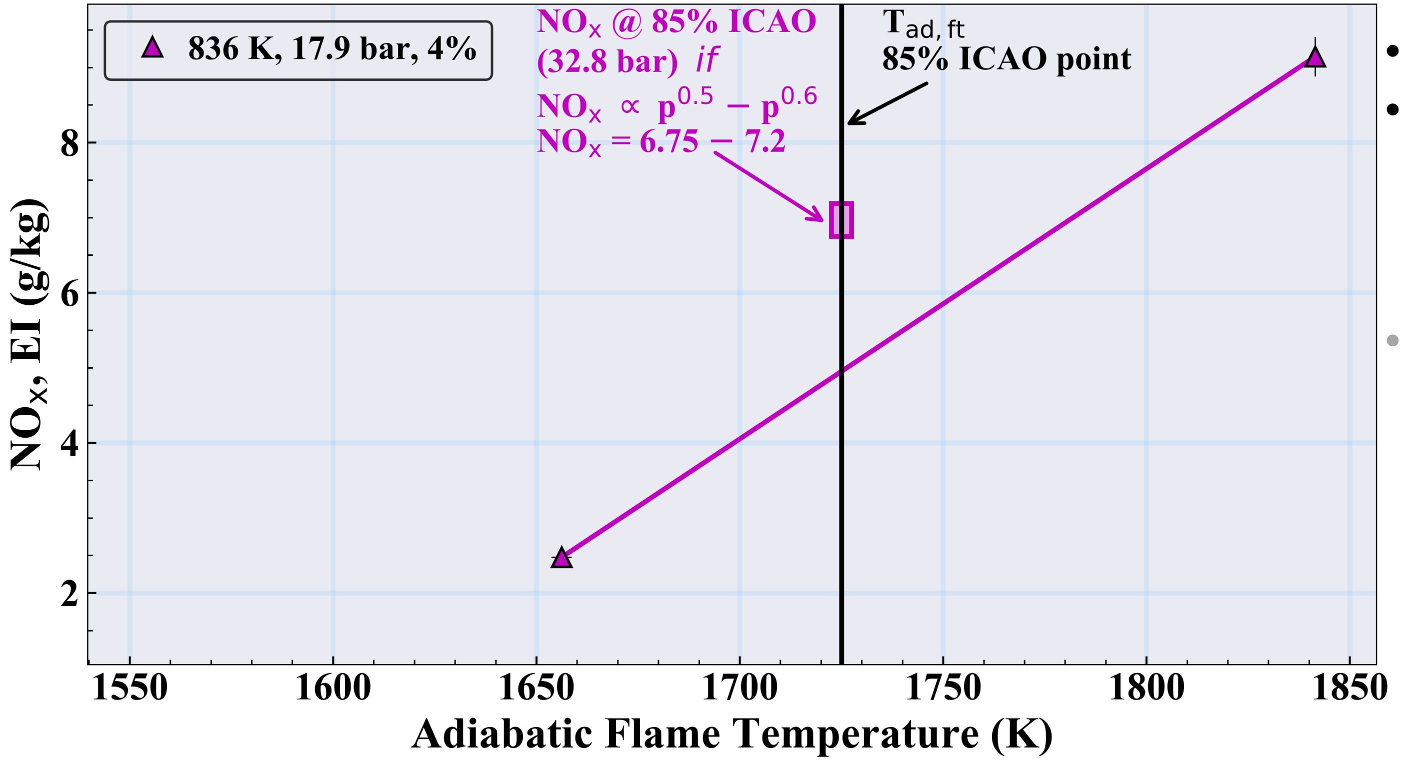


- Match T_3 and $\Delta p/p_3$
- Estimate NOx assuming previous p_3 trends: NOx $\propto p_3^{0.5} - p_3^{0.6}$
- Evaluate assumption at:
  - At $\Delta p/p_3$ = 4%
  - At $\Delta p/p_3$ = 3%

Need to extrapolate p_3 to 32.8 bar to estimate NOx at 85% power ICAO conditions

85% power ICAO Conditions





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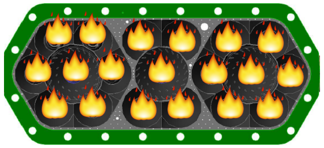
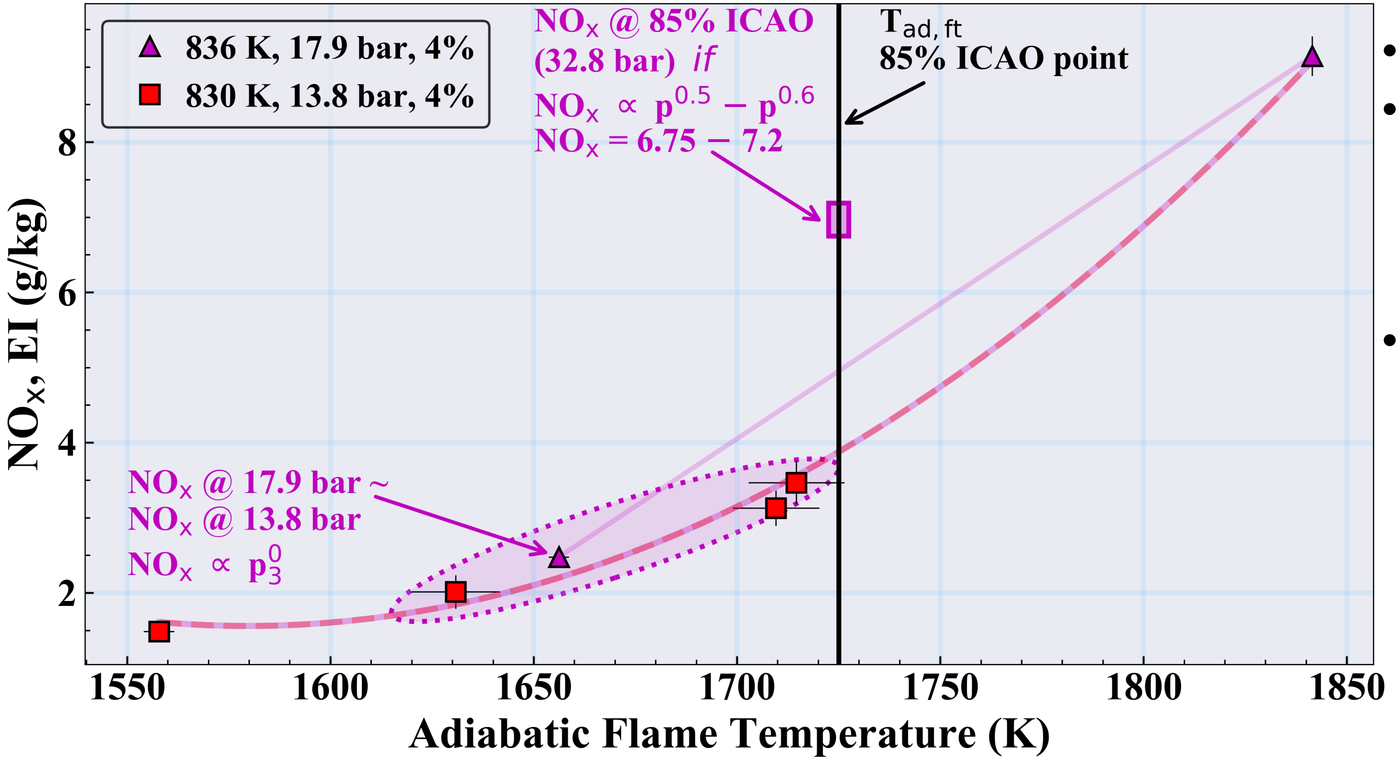
85% power ICAO Conditions





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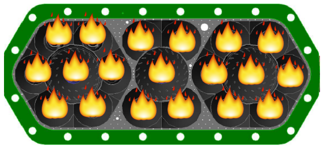
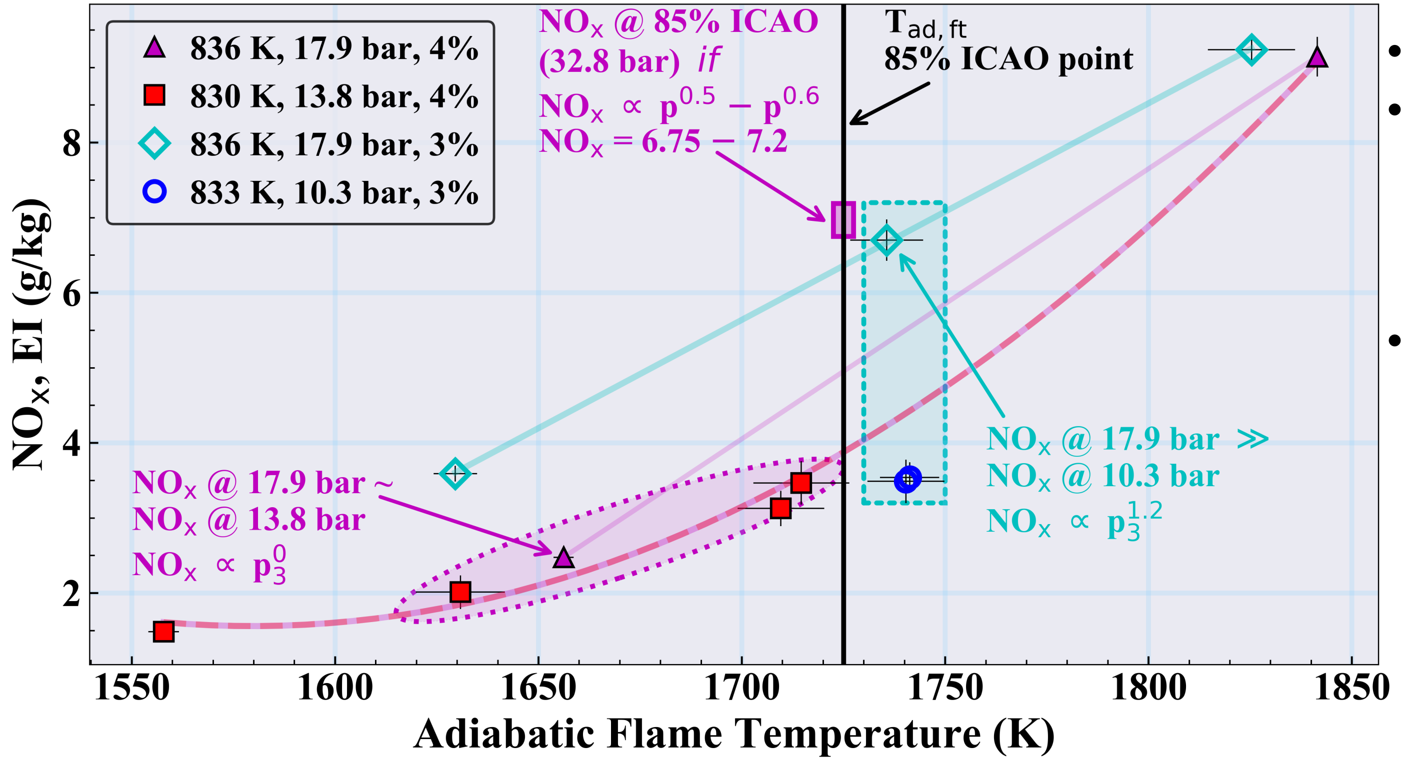
At 4% pressure drop, it looks like $p_3^{0.5}$ may overestimate NOx, but ...

85% power ICAO Conditions





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- Estimate NOx assuming previous p_3 trends: NOx $\propto p_3^{0.5} - p_3^{0.6}$
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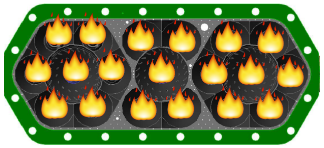
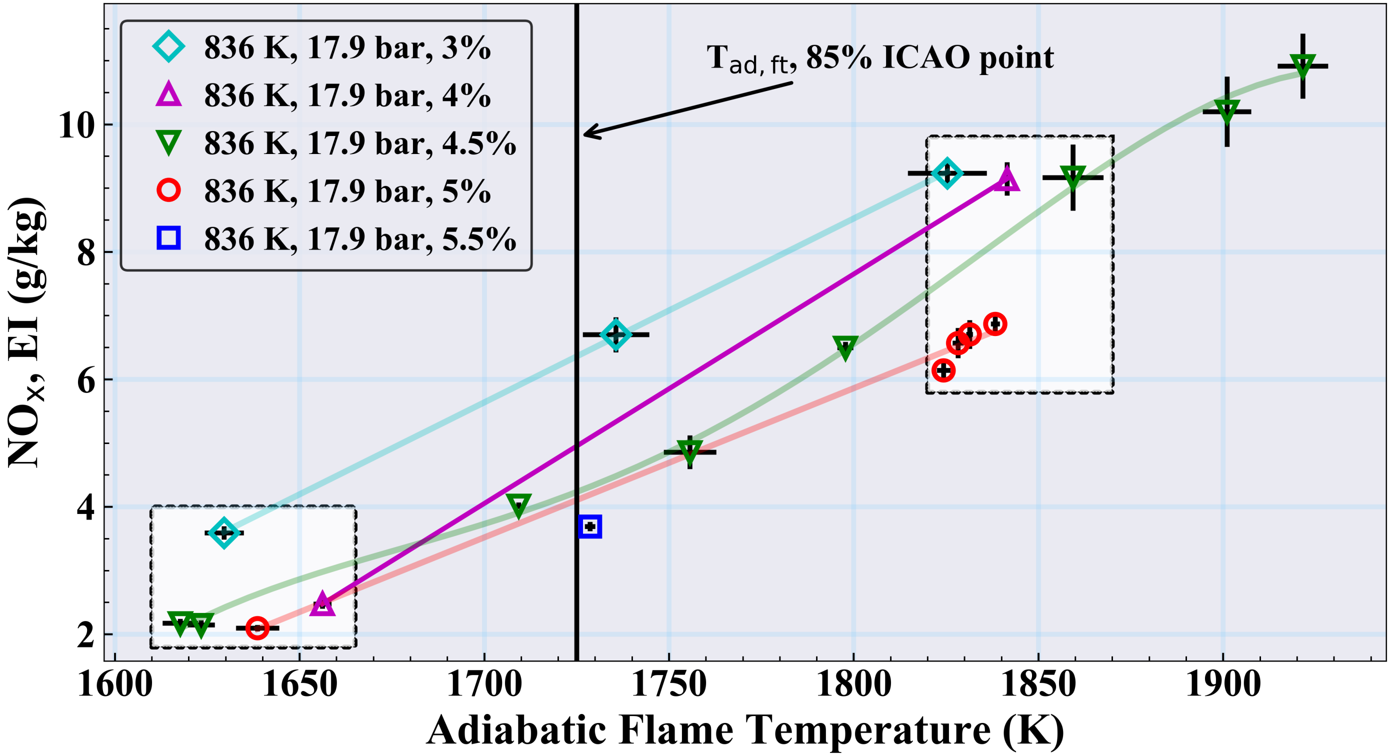
The effect of p_3 is not consistent!

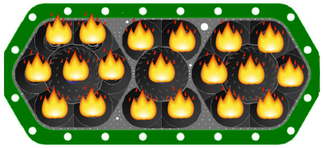
85% power ICAO Conditions: Pressure Drop

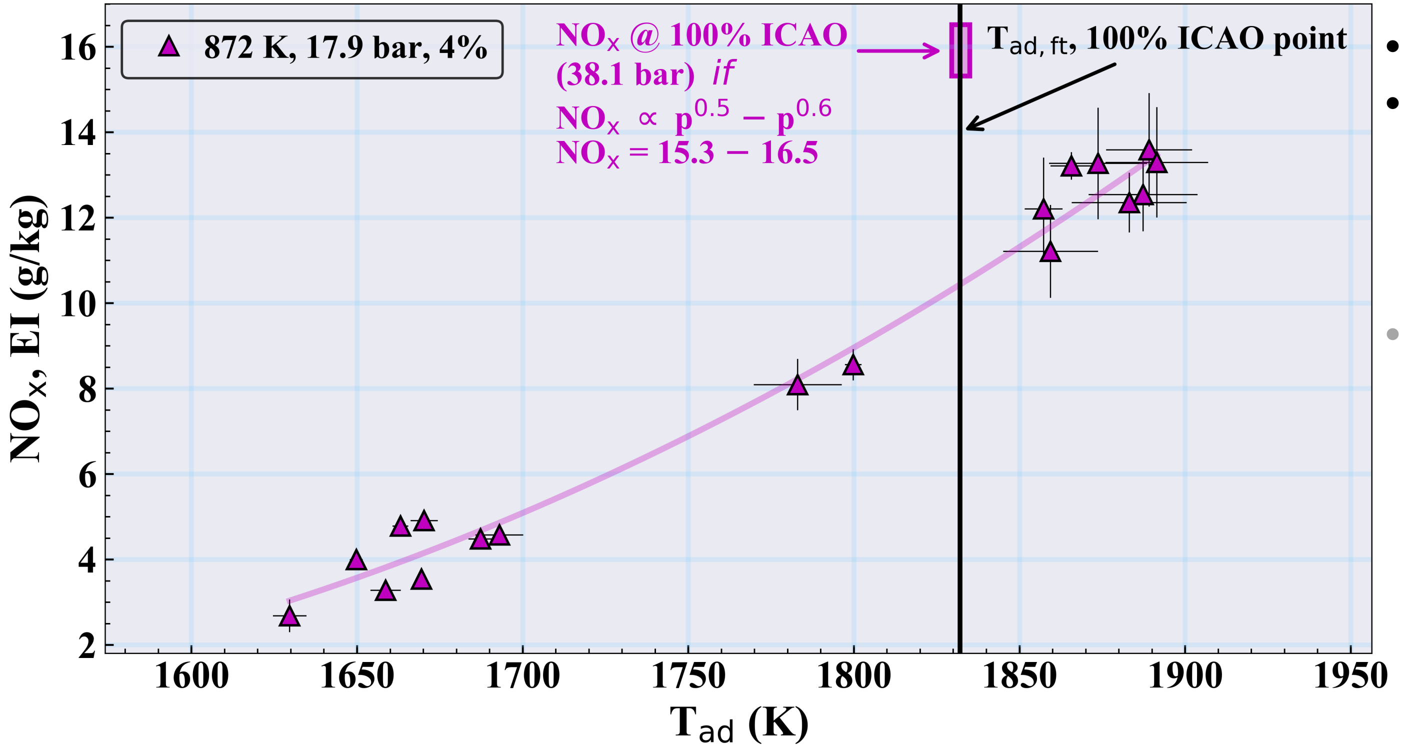




The effect of pressure drop is not consistent, either!

100% power ICAO Conditions



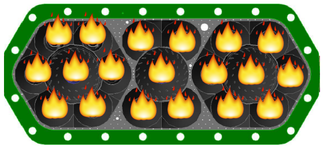


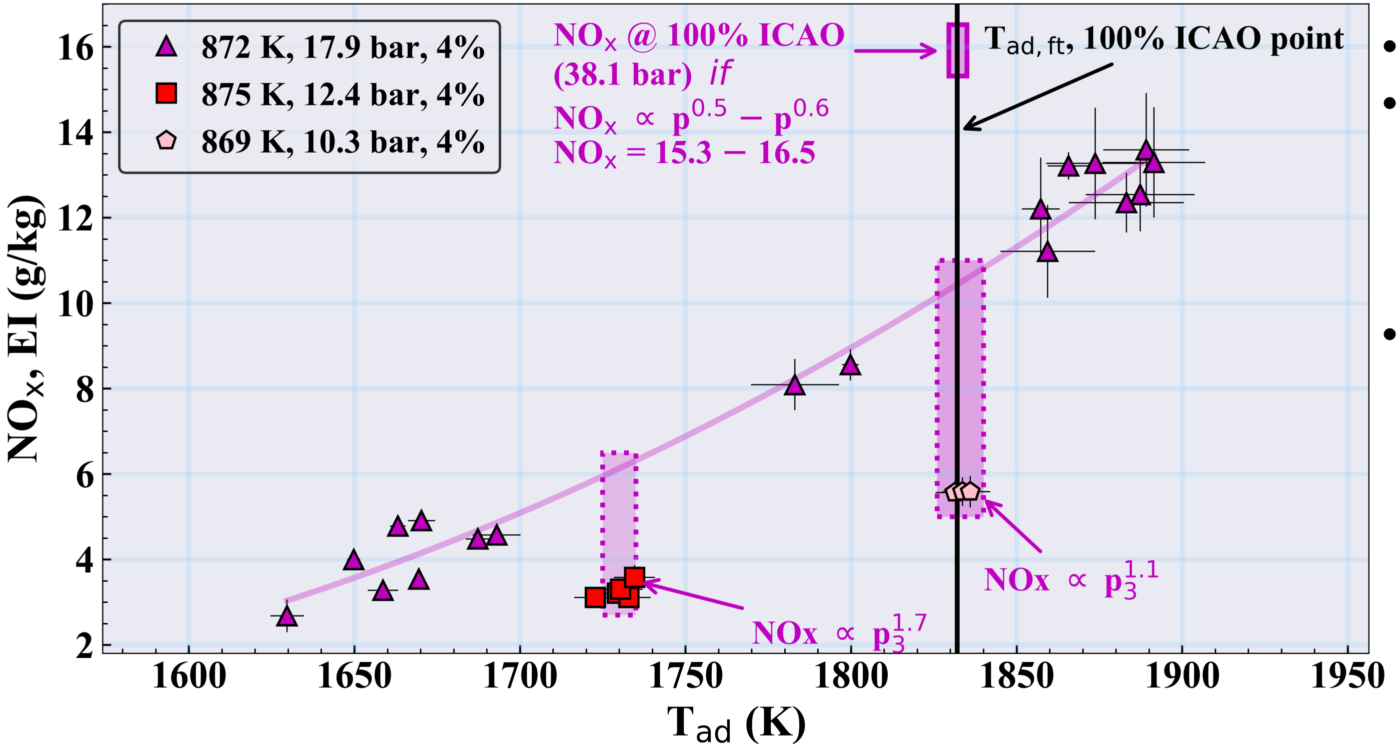
NO_x @ 100% ICAO (38.1 bar) *if*
$NO_x \propto p^{0.5} - p^{0.6}$
$NO_x = 15.3 - 16.5$

- Match T_3 and $\Delta p/p_3$
- Estimate NOx assuming previous p_3 trends:
  NOx $\propto p_3^{0.5} - p_3^{0.6}$
- Evaluate assumption at:
  - At $\Delta p/p_3 = 4\%$
  - At $\Delta p/p_3 = 3\%$

Need to extrapolate p_3 to 38.1 bar to estimate NOx at 100% power ICAO conditions

100% power ICAO Conditions





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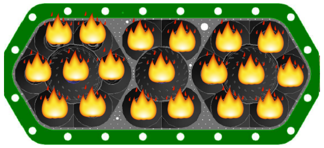
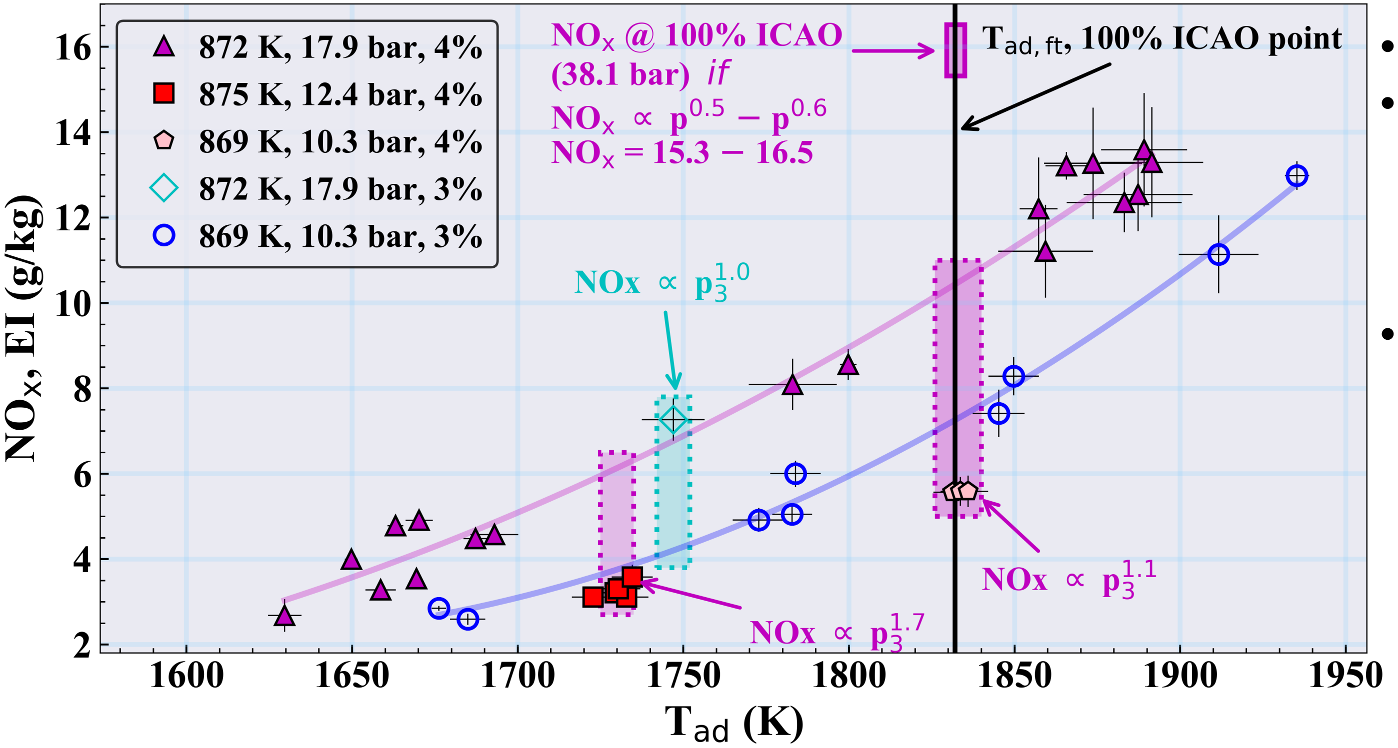
100% power ICAO Conditions





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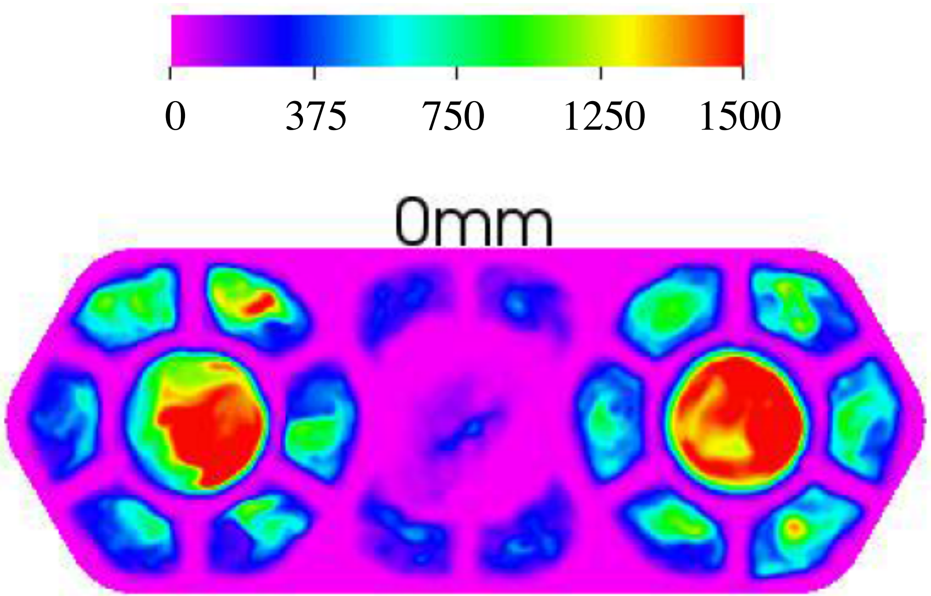
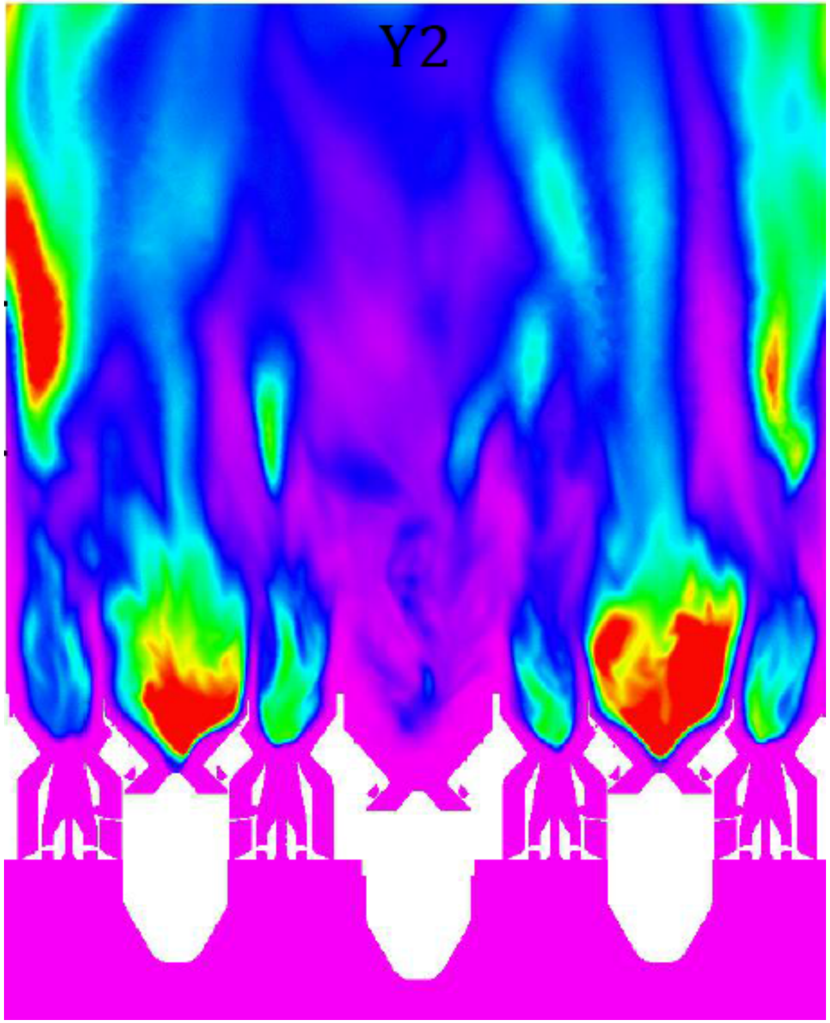
Need to extrapolate p_3 to 38.1 bar to estimate NOx at 100% power ICAO conditions

NOx correlation equations: Form

- Develop correlation equations based on previous correlation equations
- Complication: NOx emissions depend on the type of stage





From Ajmani et al AIAA 2017-5017

Solution: Split the correlation equation into separate terms for the pilot and main stages

NOx correlation equations: Form

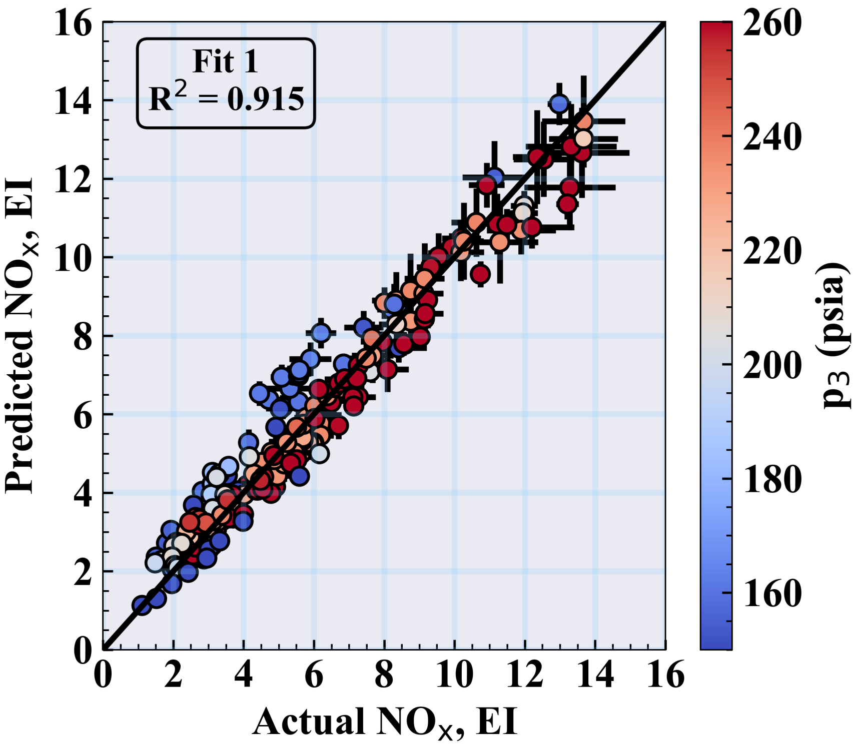
- Choose the form of the correlation equation based on previous correlation equations for SV-LDI
- Fit 1: Choose the exponent *a* of p_3^a, the divisor *b* of $e^{T_3/b}$, and the exponent c of Δp^c to be the same as in previous correlation equations
- Fit 2: Let *a* and *b* vary

$$\mathrm{NO}_x,\ \mathrm{EI} = p_3^a e^{(T_3/b)} \Delta p^c \left[\underbrace{d_p e^{(T_{\mathrm{ad,\,p}}/e_p)}}_{\text{Pilot-stage term}} + \underbrace{d_m e^{(T_{\mathrm{ad,\,m1}}/e_m)} + d_m e^{(T_{\mathrm{ad,\,m2}}/e_m)} + d_m e^{(T_{\mathrm{ad,\,m3}}/e_m)}}_{\text{Main stage terms}} \right]$$

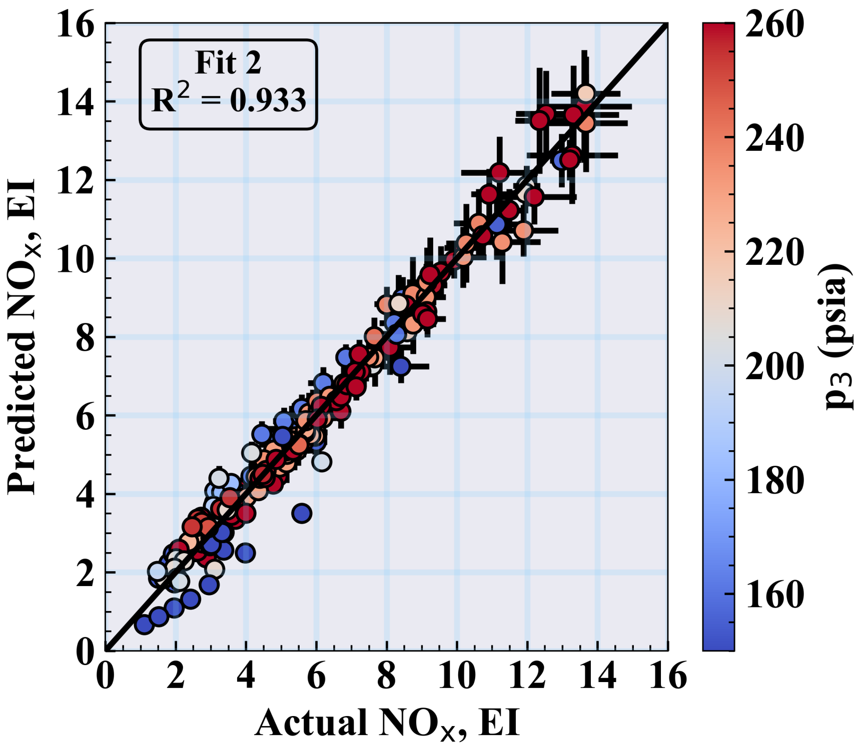
Configuration	Fit	a	b	c	d_p	e_p	d_m	e_m	R^2
LDI-3-3	Fit 1	0.500	340	-0.600	1.12×10^{-3}	448	2.62×10^{-6}	173	0.915
LDI-3-3	Fit 2	0.931	234	-0.829	4.97×10^{-6}	246	7.36×10^{-7}	187	0.933

NOx correlation equations

Fit 1



Fit 2



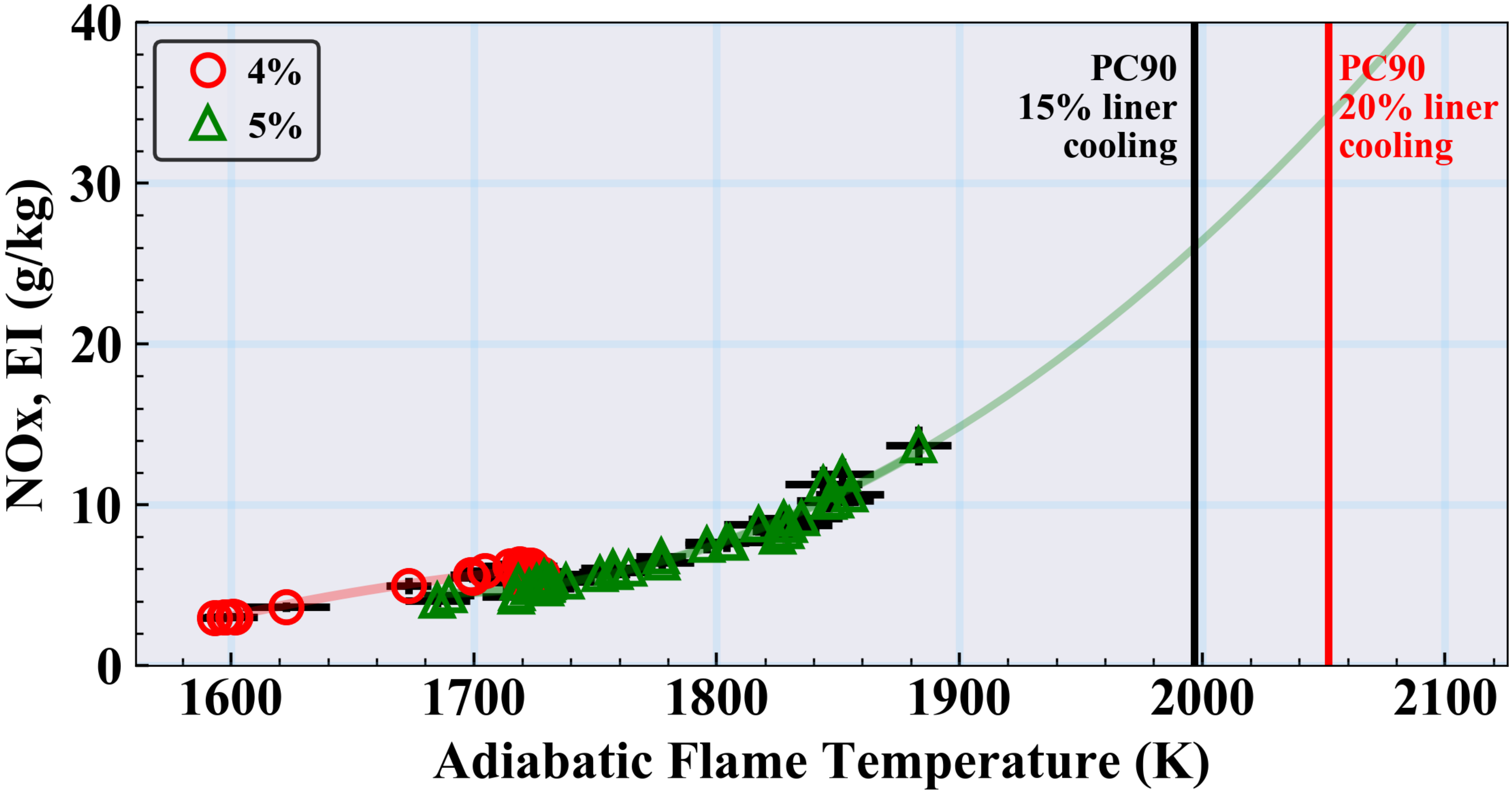
Both correlation equations look reasonable, but Fit 2 seems to model the effect of p_3 better.

ICAO NOx Emissions

Condition	**Meas. NOx (g/kg)**	**NOx $NOx \propto p_3^{0.6}$ (g/kg)**	**NOx Flt 1 (g/kg)**	**NOx Fit 2 (g/kg)**	**NOx $NOx \propto p_3^{0.931}$ (g/kg)**
7% ICAO	4.3				
30% ICAO	6.25				
85% ICAO		7	6.8	8.2	8.8
100% ICAO		17	12.8	18.8	21.2
NOx Sereverity Parameter, D_p/F_{00} (g/kN)		13.80	12.32	15.03	15.97
NOx reduction wrt CAEP/6		87%	89%	86%	85%

Exceeded the NOx reduction goal of 80% reduction wrt CAEP/6

Supersonic PC90



Difficult point to reach: high Δp and uneven fuel staging required.
Did not meet the supersonic cruise NOx goal of NOx, EI < 5 g/kg.

Summary

Summary

- Woodward, FST, and NASA developed a third-generation, low-NOx, swirl-venturi lean direct injection combustor concept, SV-LDI-3.
- SV-LDI-3 reduces fuel line complexity compared to LDI-1 and LDI-2 designs.
  - This should improve thermal management of the fuel.
- SV-LDI-3 met the AATT NOx reduction goal of 80% reduction wrt CAEP/6.
- Also evaluated at supersonic conditions.
  - Did not meet supersonic cruise goal of NOx, EI < 5 g/kg.

Recommendations for Future Work

- Adjust air splits between the pilot and the main fuel stages
- Change the pilot to lower NOx, especially at the 7% ICAO power point
  - Change injector type
  - Reduce air swirl
- Use additional gas analysis probes
- Test at higher pressure if a higher-pressure flametube becomes available. Or do a sector test.
- Increase the physics in the correlation equations

Acknowledgments

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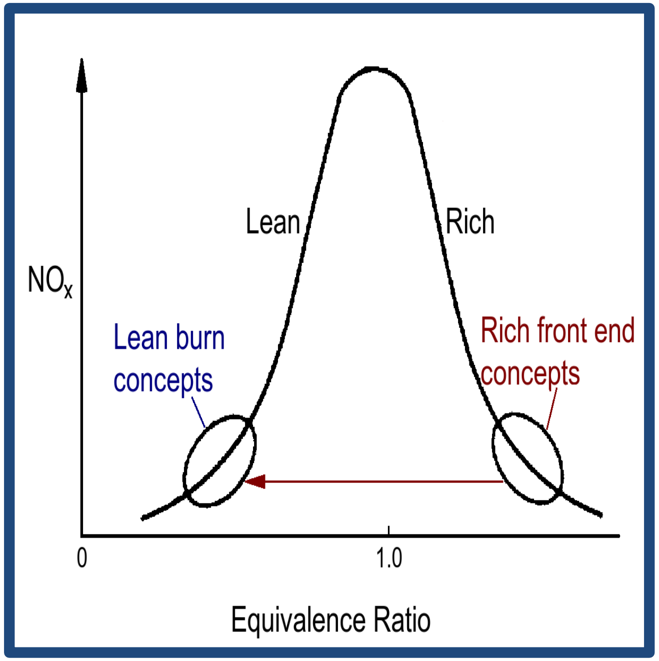
Backup

Background: Lean Direct Injection



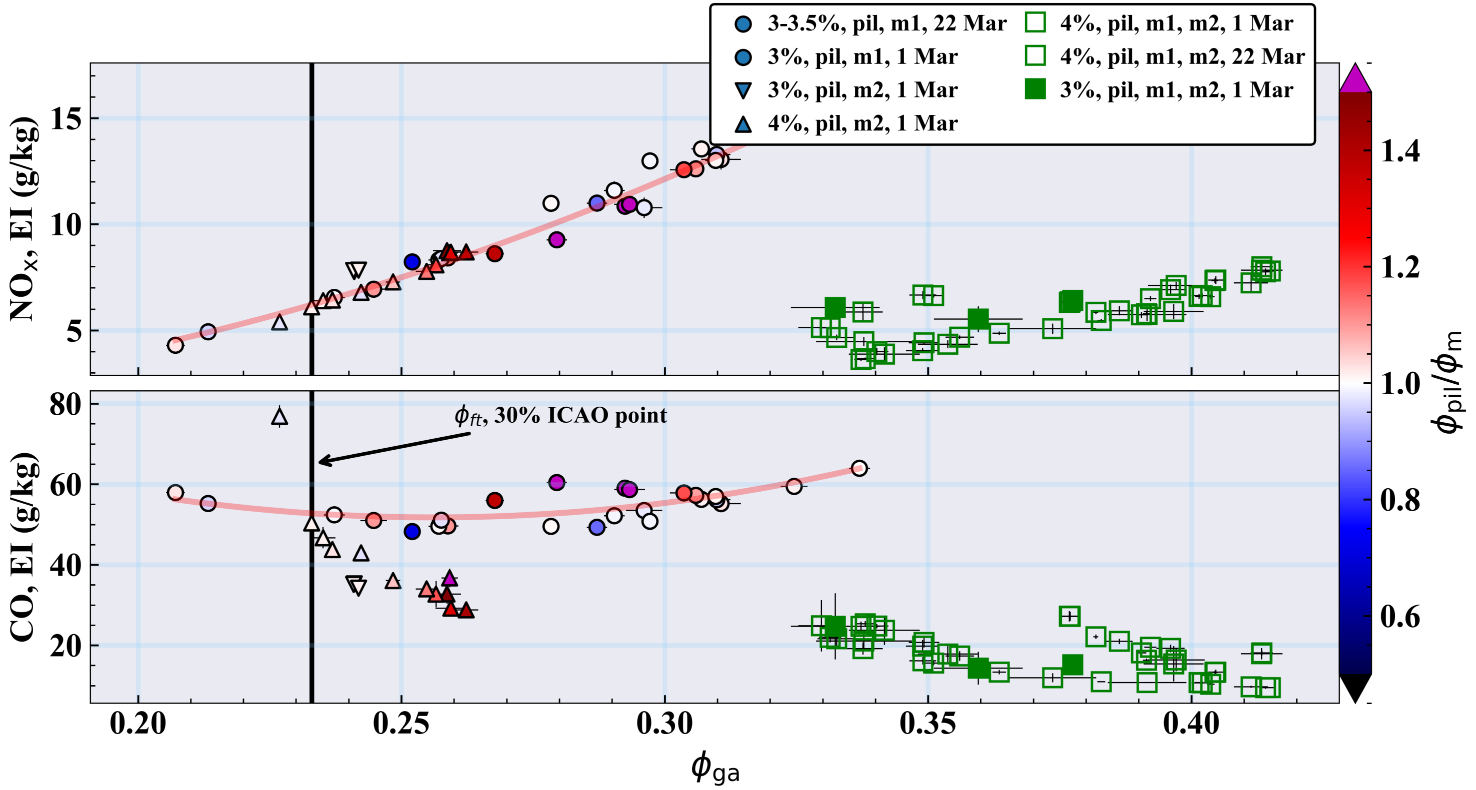
Lean burn concepts

- Lean, premixed, prevaporized (LPP)
- Lean partially premixed
- **Lean direct injection (LDI)**

- Fuel lean: no rich front end
  - All *combustion* air enters through the dome
- Fuel is injected directly into the flame zone
  - Reduces problems with autoignition, flashback, and combustion instabilities
- Requires fine atomization and rapid, uniform fuel/air mixing
- Several small fuel/air mixers replace 1 conventionally-sized fuel/air mixer
- Many fuel/air mixing strategies
  - Swirler: **radial, axial**, or discrete jet
  - Venturi: **placed downstream of swirler** or omitted
  - Fuel injector: type and flow number

Results are presented here for Swirl-Venturi LDI (SV-LDI)

30% ICAO Point



- Difficult point for this configuration
  - Due to low equivalence ratio, could only use the pilot and one main circuit
- NOx and CO would both be lower if the equivalence ratio was higher
  - Check cycle
  - Change air splits

All High-Power Data