ASCENT Project 51

Combustion Concepts for Next-generation Aircraft Engines

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Cost Share Partner: World Energy

Objective:

Compare performance impacts and emissions-reduction potential of new **fuel types**, **engines** and **combustion concepts**

Develop and utilize in-depth engine cycle and chemistry models to evaluate impact of new combustion technologies on emissions.

Project Benefits:

Co-optimization of engine cycle and combustor can yield better efficiency and emissions, leading to greater long-term environmental sustainability as well as economic benefits for the aviation sector

Research Approach:

This project involves three steps:

- **Engine cycle analysis** – Study change in cycle performance with new technological concepts at the system level
- **Combustor analysis** – Use cycle parameters and determine impact of new technology on emissions
- **Mission analysis** – Analyze potential trade-offs during different flight segments to evaluate feasibility for different missions

Major Accomplishments (to date):

- Varied fuel distribution for a lean-burn radially-staged combustor to minimize NO_x emissions throughout all operating conditions
- Estimated the maximum $EINO_x$ reduction achievable at different phases of flight using a lean-burn radially-staged combustor with variable fuel distribution

Future Work / Schedule:

- Investigate the potential of duel-fuel lean-burn axially-staged combustors in reducing NO_x emissions

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Introduction

Emissions Reduction Strategies

Emissions can be reduced by lowering combustor peak temperature and altering chemical kinetic pathways:

- **Water injection** reduces combustor inlet temperature through evaporation, resulting in lower burner peak temperature
- **High-reactivity additives** can allow leaner operation, reducing concentrations of soot precursors
- **Staged combustor** achieves high-power lean-burn process, reducing the sizes of hot spots and stoichiometric zone

Staged Combustor

Fuel distributed between two stages/flame zones

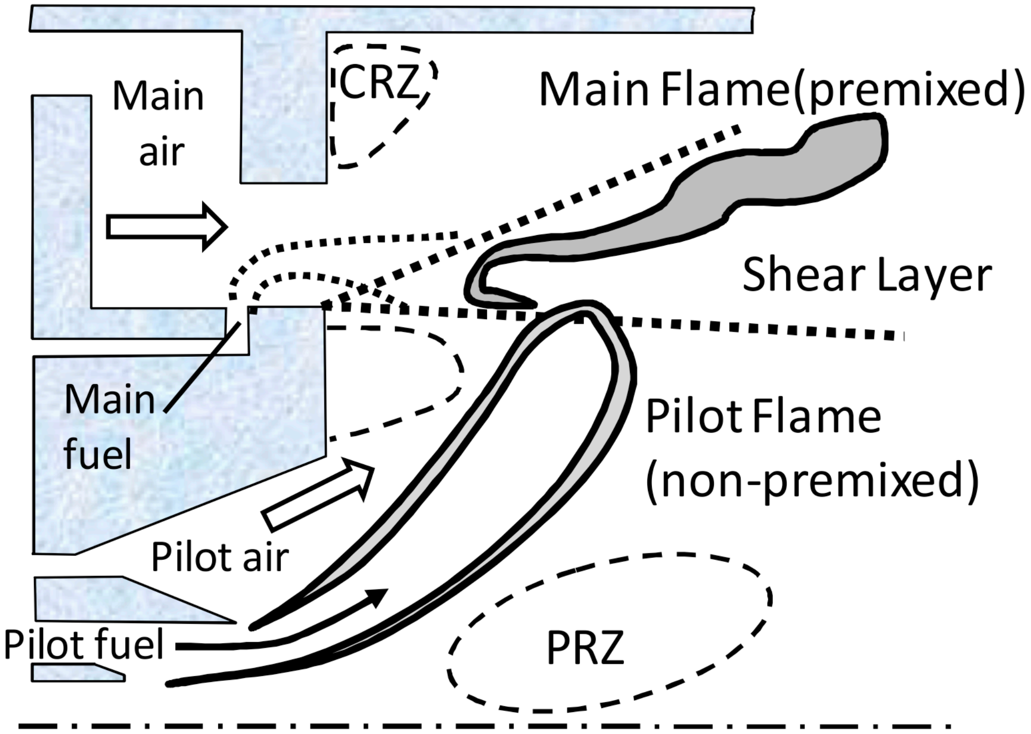
Flexible fuel distribution for different power levels / operating conditions

Control fuel distribution to minimize NO_x

Combustor Chemistry – Schematic

Fuel and air partitioned between two stages:

- Pilot Stage
  - Provide combustion stability
- Main Stage
  - Provide low NO_x emissions
  - <u>Only fueled during high-power operations</u>

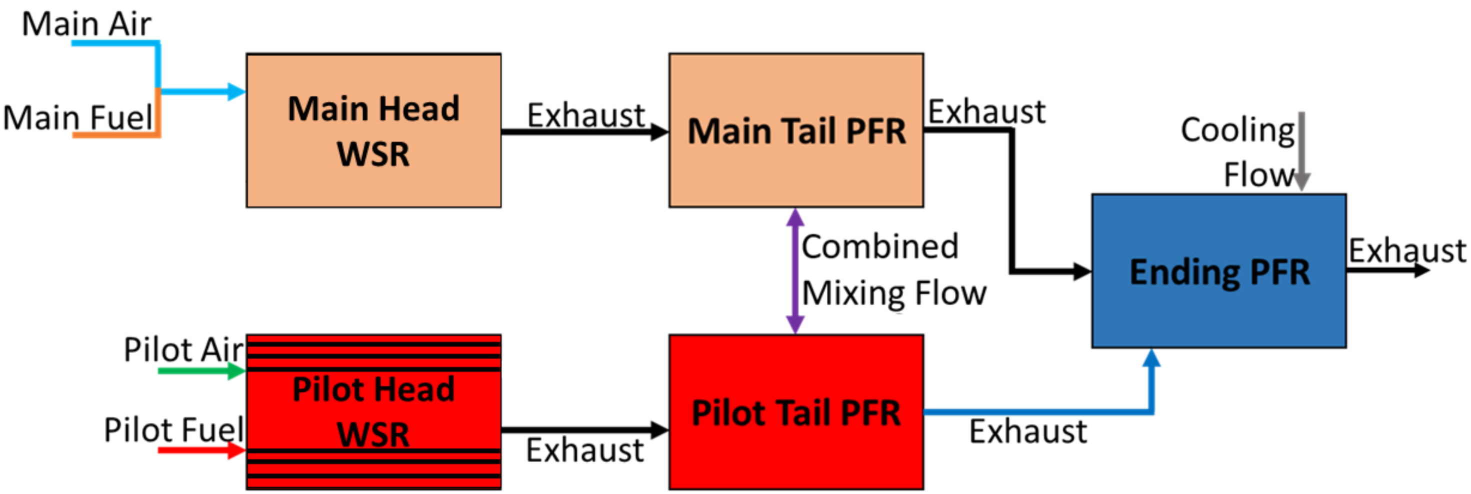


CRZ: Corner Recirculation Zone; PRZ: Primary Recirculation Zone

*Sulabh K. Dhanuka *et al.*, "Unsteady Aspects of Lean Premixed Prevaporized Gas Turbine Combustors: Flame-Flame Interactions," *Journal of Propulsion and Power*, 2011

How should fuel be distributed between the pilot and main stages to minimize NO_x emissions while maintaining combustor stability?

Combustor Chemistry – Model



- Chemical reactor network represents the lean-burn radially-staged combustor
  - Each stage modeled by a Well Stirred Reactor (WSR) and a Plug Flow Reactor (PFR) in series
- Parallel WSRs model the incomplete fuel-air mixing in the pilot stage
  - Modeled as a normal distribution of equivalence ratio (ϕ) across WSRs
  - Fully premixed fuel and air assumed for the main stage
- Combined mixing flow exchanges mass between the two stages along the length of the combustor
  - Represent the gradual mixing between the exhausts of two streams
- Main stage fuel introduced only at high power ($\phi_{main} > 0.4$)

Simulation Procedure – Model

Goal: Study effect of fuel distribution on emissions over all phases of flight

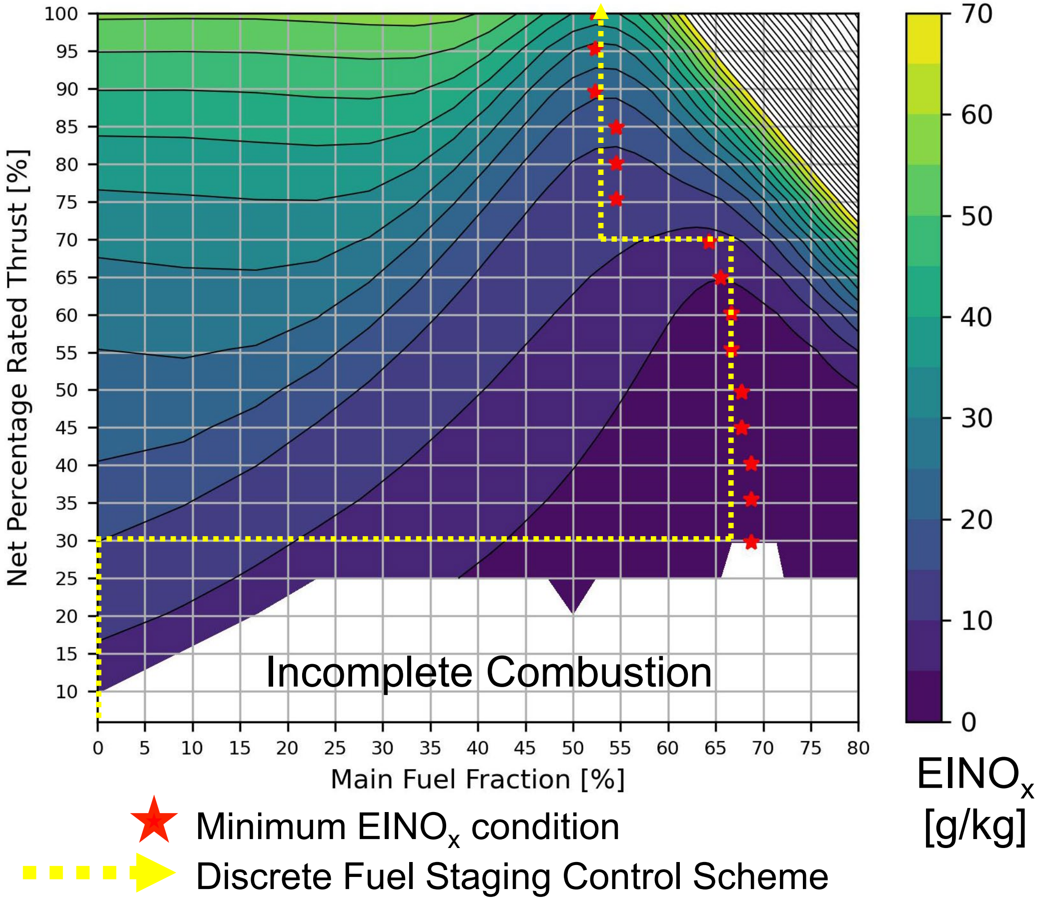
1. Transport Aircraft System OPTimization **(TASOPT)**
   - Calibrate against payload-range plot of a certain airplane
   - Taken a given flight mission with certain range and payload requirements
   - Calculate engine operating conditions for different phases of flight
     - Mach number; Temperature; Pressure; Thrust

2. Numerical Propulsion System Simulation **(NPSS)**
   - Calibrate against publicly available parameters for a certain engine
   - Taken engine operating conditions
   - Compute combustor operating conditions for different thrust level
     - Air flow rate; Fuel flow rate; Temperature; Pressure

3. Chemical Reactor Network Model **(Pycaso)**
   - Calibrate against ICAO Aircraft Engine Emissions Databank (EEDB)
   - Taken combustor operating conditions
   - Estimate emissions indices (Ex. $EINO_x$) with different combustor design parameters

Results: $\mathrm{EINO_x}$ at static conditions

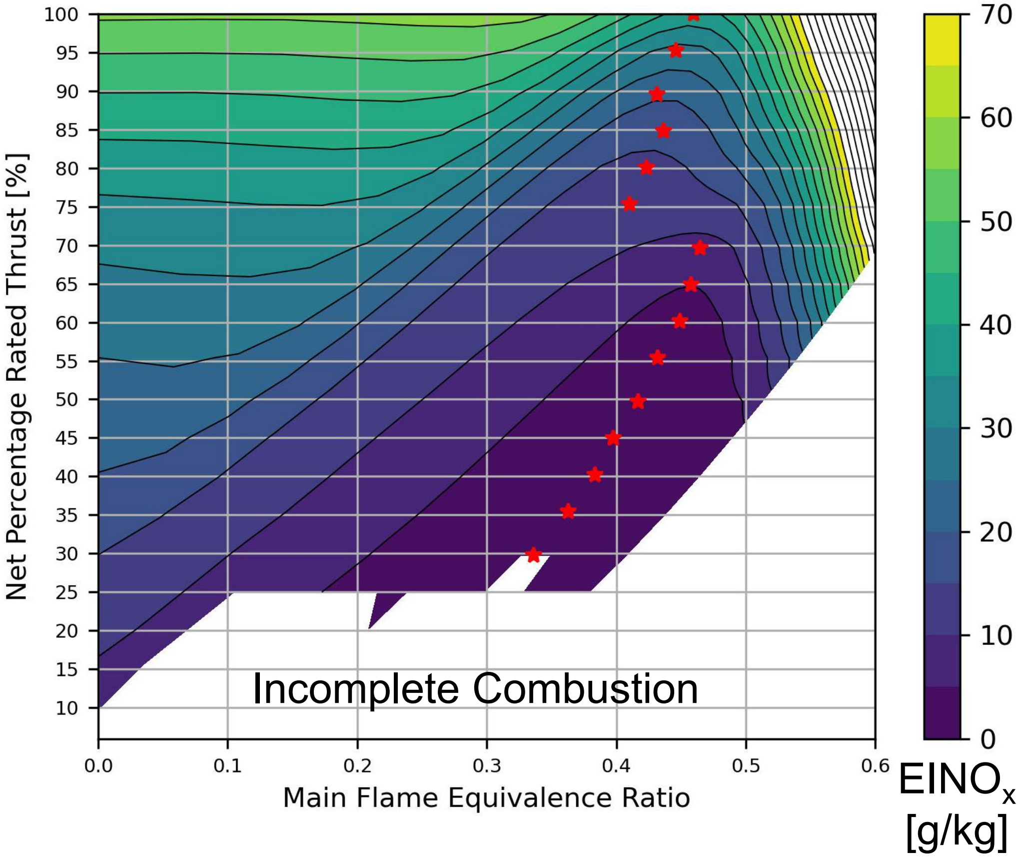
- **Pilot + main operation with varying Main Fuel Fraction (MFF)**
  - Main Fuel Fraction $\equiv \dfrac{\text{Main Fuel}}{\text{Pilot Fuel+Main Fuel}}$
- At different sea level static thrust condition, find the **MFF** with minimum **$\mathrm{EINO_x}$**



- ○ There exists an **optimal MFF** with minimum $\mathrm{EINO_x}$ at each thrust condition
  - ▪ A balance between $\mathrm{NO_x}$ emissions formation in pilot and main stages
- ○ The critical MFF varies in a semi-discrete fashion with 3 modes
  - ▪ Pilot-stage-dominated $\mathrm{NO_x}$ production mode
    - ➢ MFF ≈ 52%
    - ➢ 70% → 100% Thrust
  - ▪ Main-stage-dominated $\mathrm{NO_x}$ production mode
    - ➢ MFF ≈ 66%
    - ➢ 30% → 70% Thrust
  - ▪ Pilot only (MFF = 0) at low power

Results: $EINO_x$ at static conditions

- **Equivalence Ratio**
  - $\phi \equiv \frac{\text{Fuel Air Ratio}}{\text{Stoichiometric Fuel Air Ratio}}$
- Same $EINO_x$ plot but against the **Main Stage Equivalence Ratio**

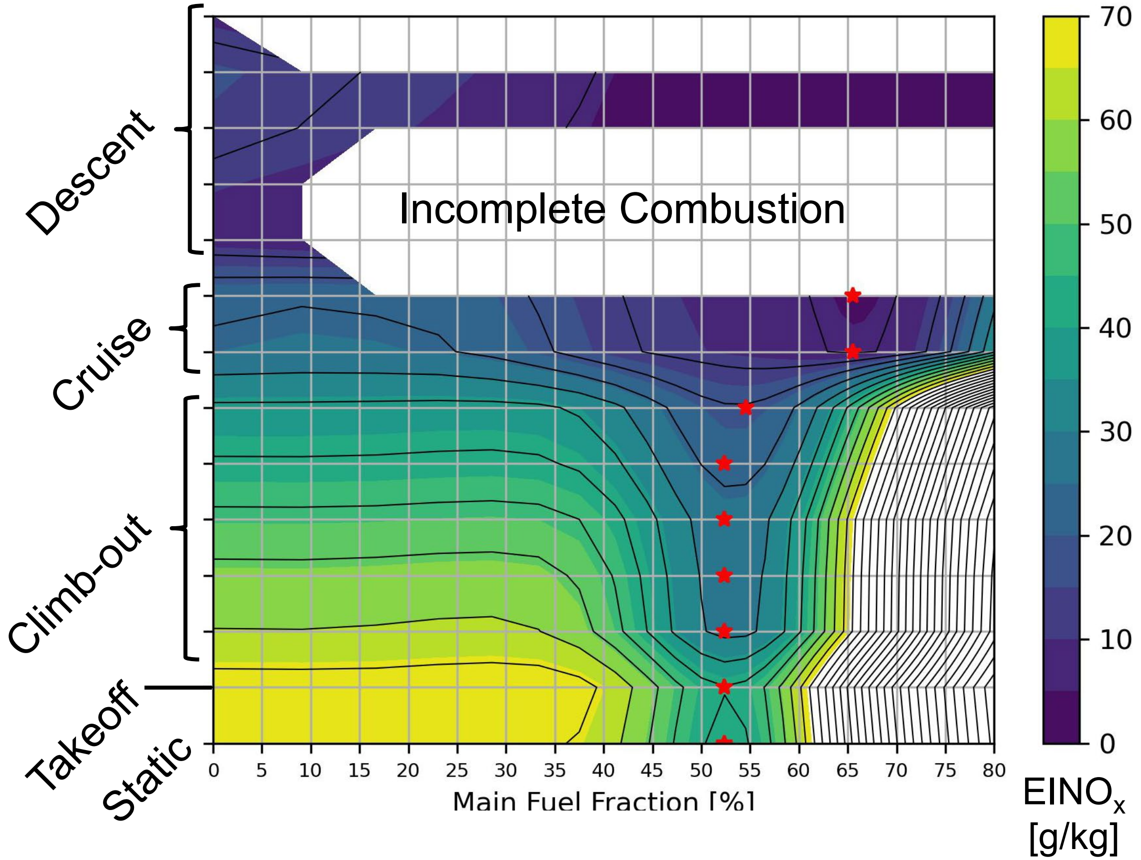


★ Minimum $EINO_x$ condition

- ○ There exists an **upper limit** for the main stage equivalence ratio above which $EINO_x$ quickly increases
- ○ Due to the partially premixed fuel-air condition in main stage
  - ○ Flow temperature rises **globally and quickly** as ϕ_{main} approaches unity
  - ○ Flow temperature stays **uniform and low** when ϕ_{main} is far from unity
  - ○ Main stage only produces low NO_x emissions under medium power operation

Results: Main Fuel Fraction in Flight

- **Example Flight Mission: 2500 nmi range**

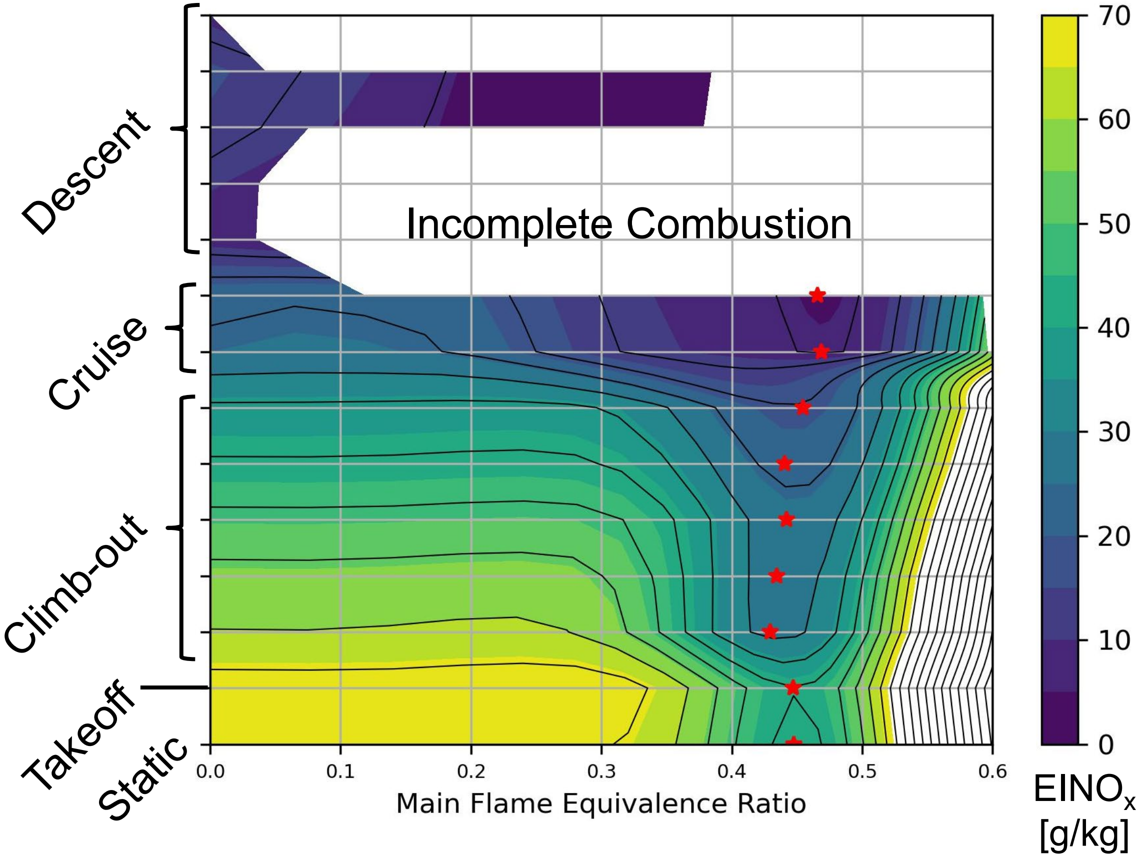


★ Minimum $EINO_x$ condition

- ○ Similar ideal main fuel fractions (MFF) as ground test
  - Takeoff and Climb-out
    - MFF ≈ 52%
  - Cruise
    - MFF ≈ 66%
  - Pilot only (MFF = 0) during descent
- ○ Ideal MFF depends weakly on engine/combustor inlet conditions (T_3, P_3,..)

Results: Equivalence Ratio in Flight

- **Example Flight Mission: 2500 nmi range**

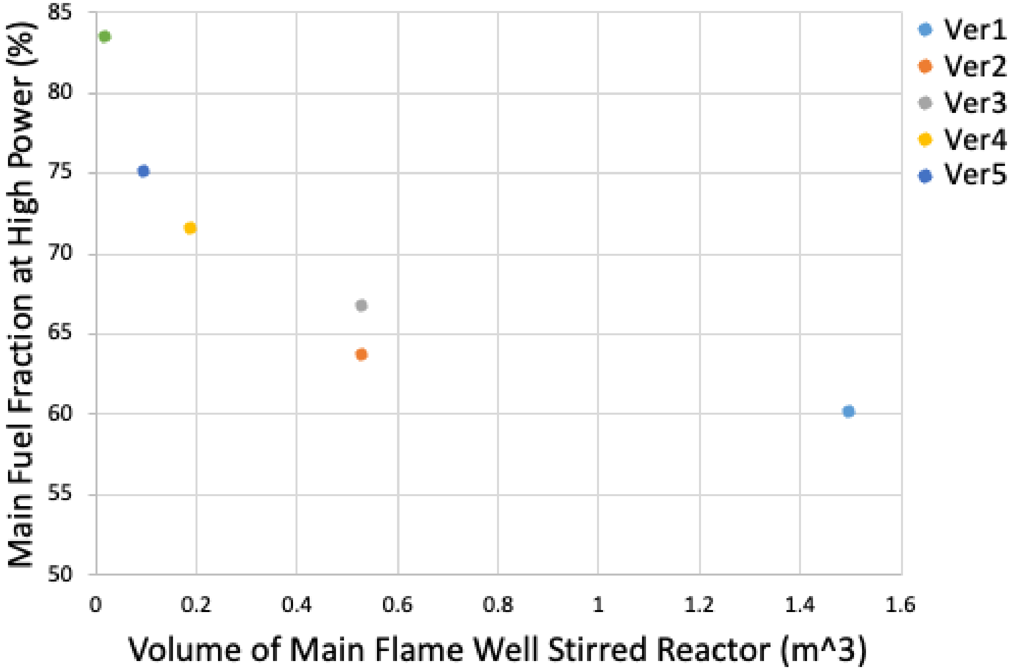


★ Minimum EINO$_x$ condition

- ○ Same **upper limit (≈ 0.46)** for the main stage equivalence ratio above which EINO$_x$ quickly increases
- ○ Ideal MFF depends weakly on engine/combustor inlet conditions (T_3, P_3,..) but strongly on the main flame equivalence ratio

Quantify EINO$_x$ Reduction – Calibration

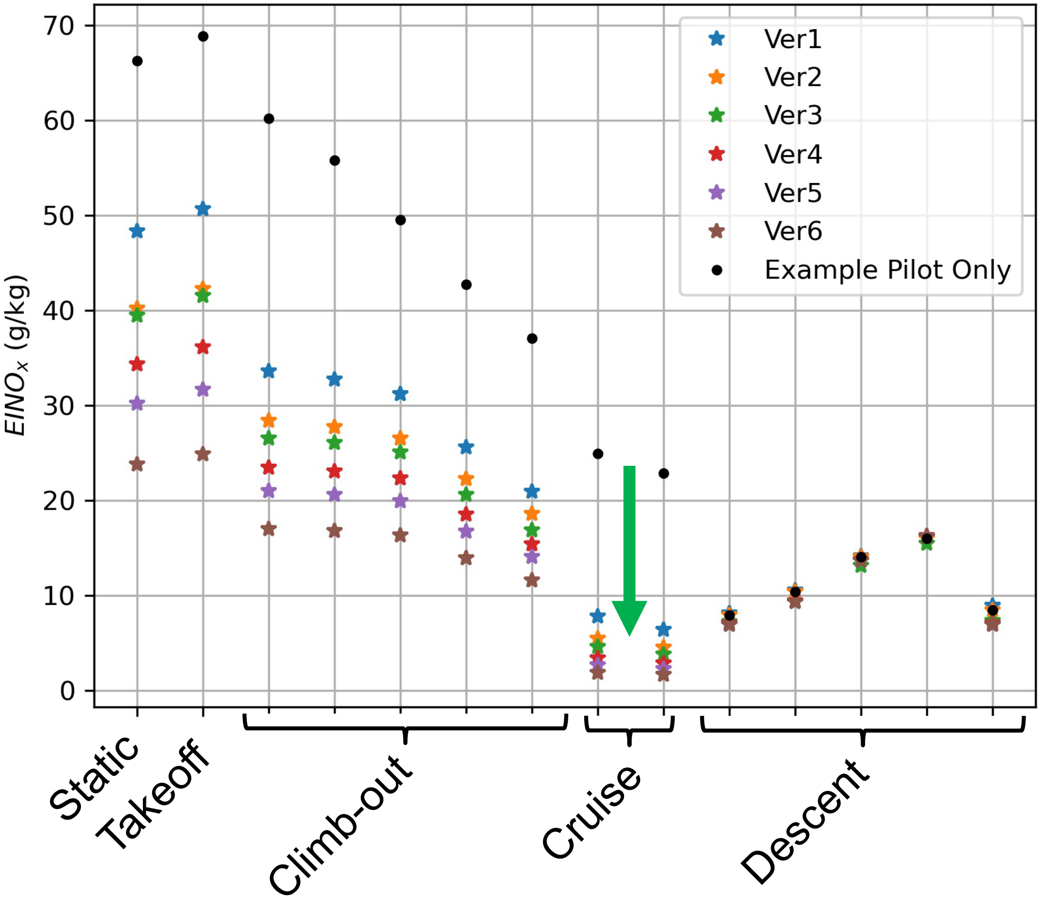
- Use **multiple versions** of the chemical reactor network model to bracket the uncertainty in EINO$_x$ estimation
- Each model calibrated against ICAO Emissions Databank EINO$_x$ and EICO Data



- The existence of different versions stems from uncertainty in combustor model parameters
- For the same EINO$_x$ level, smaller main flame WSR:
  - Allows more main-fuel and higher main flame temperature
  - Might suffer stability problem which is not represented in the reactor network model

Quantify $EINO_x$ Reduction – Results

- Use multiple calibrated **versions** of the chemical reactor network model to bracket the uncertainty in $EINO_x$ estimation
- $EINO_x$ **with and without** the main flame at each **phase of flight**
- Adjust **MFF** at each point to minimize $EINO_x$



- The green arrow represents the $EINO_x$ reduction benefit obtainable by fueling the main stage
- Percentage $EINO_x$ reduction
  - Takeoff
    - 42% ± 22% reduction
  - Climb-out
    - 50% ± 20% reduction
  - Cruise
    - 75% ± 10% reduction

Conclusions

- There exists an ideal main fuel fraction (MFF) with minimum $EINO_x$ at each thrust condition
- This ideal MFF varies in a discrete fashion as thrust increases & through the mission with 3 discrete modes
- The modes correspond to conditions that keep ϕ_{main} approximately constant
- Compared to operating the combustor in pilot-only mode, staging can reduce $EINO_x$ by ~75% at cruise and ~50% at climb-out

Next Steps

Understanding current combustor configuration

- Investigate effect of air partitioning on emissions
  - Air split between pilot and main does not greatly impact the NO_x-minimizing main fuel fractions
  - However, it does change the thrust settings at which the ideal MFF changes
  - **Air reserved for cooling** greatly impacts the overall NO_x emissions
- Evaluate control options provided by **circumferential variation** in fuel staging

Exploring additional combustor design concepts

- Assess the emissions impact of using **different fuel types** on the second stage of a lean-burn axially-staged combustor
- Evaluate impacts of using **plasma assisted combustion** to stabilize low power operations and provide combustor design flexibility

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Questions?