ASCENT Project 51

Combustion Concepts for Next-generation Aircraft Engines

Massachusetts Institute of Technology

PIs: Raymond Speth, Jayant Sabnis, Steven Barrett (MIT)

Students: Yang Chen, Shayan Zahid

PM: Roxanna Moores, FAA

Cost Share Partner: NuFuels, LLC

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 concept at the system level
- **Combustor analysis** – Use cycle parameters and determine impact of new technology on emissions
- **Mission analysis** – Analyze trade-off between fuel penalty and emission reduction to evaluate feasibility for different missions

Major Accomplishments (to date):

A complete analysis of the impact of water injection technology on engine performance and total NO_x emissions for various mission ranges was conducted with different injection strategies on a conventional rich front-end engine.

Future Work / Schedule:

- Study of water injection and impact on the lean staged combustor engine.
- Investigation of fuel composition and additives as another means for emission reduction.

This research was funded by the U.S. Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 51 through FAA Award Number 13-C-AJFE-MIT under the supervision of Roxanna Moores. Any opinions, findings, conclusions or recommendations expressed in this this material are those of the authors and do not necessarily reflect the views of the FAA.

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

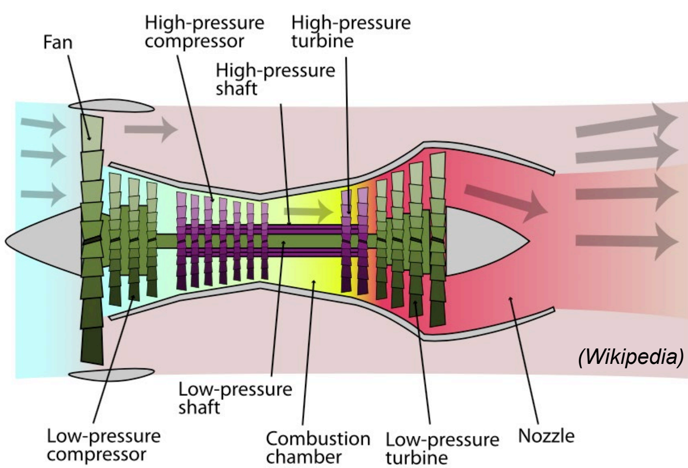
Water Injection

Assess the effects from **fuel consumption** and **emissions reduction** perspectives

Assess the potential consequences & caveats associated with new technology

Thermodynamic Cycle – Model

- Mass and energy balances used in thermodynamic cycle calculations
  - Compressor and turbine maps used to determine performance over operating conditions
- Combustor inlet conditions passed to combustor model (Pycaso)
- Mission analysis to evaluate overall feasibility of technology
  - Weight penalty vs. fuel/emissions benefit



Determine cycle parameters (required thrust, T_4 limits, etc.) defining engine model

↓

Use pyCycle to resize the engine for specified water-to-fuel ratio (WFR)

↓

Use Pycaso to determine the effect on NO_x emissions for WFR range

↓

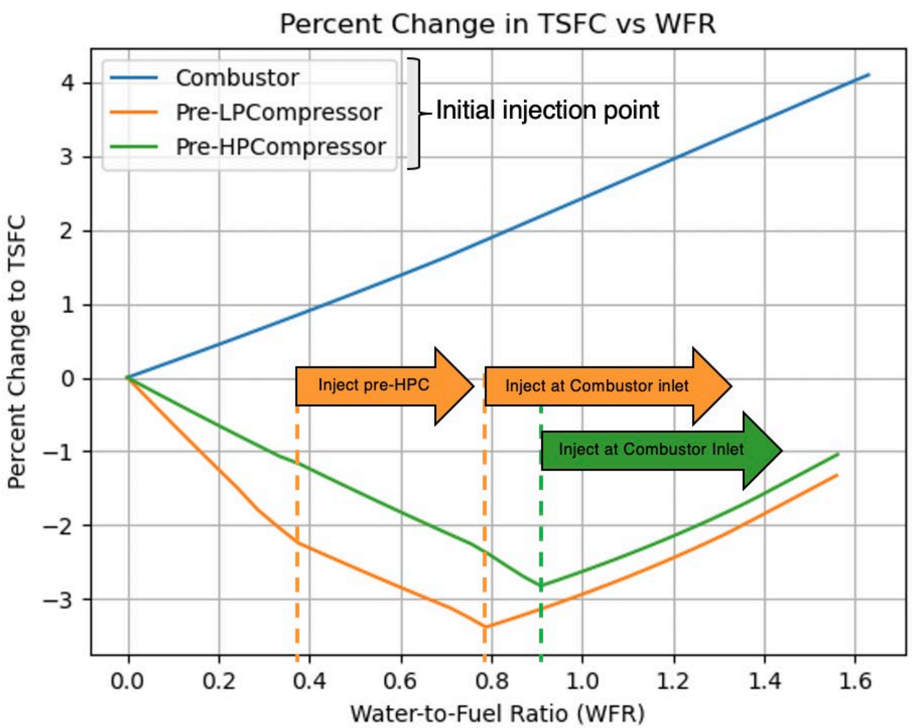
Overall mission analysis shows effect of water injection on fuel consumption and NO_x reduction

Thermodynamic Cycle – Results

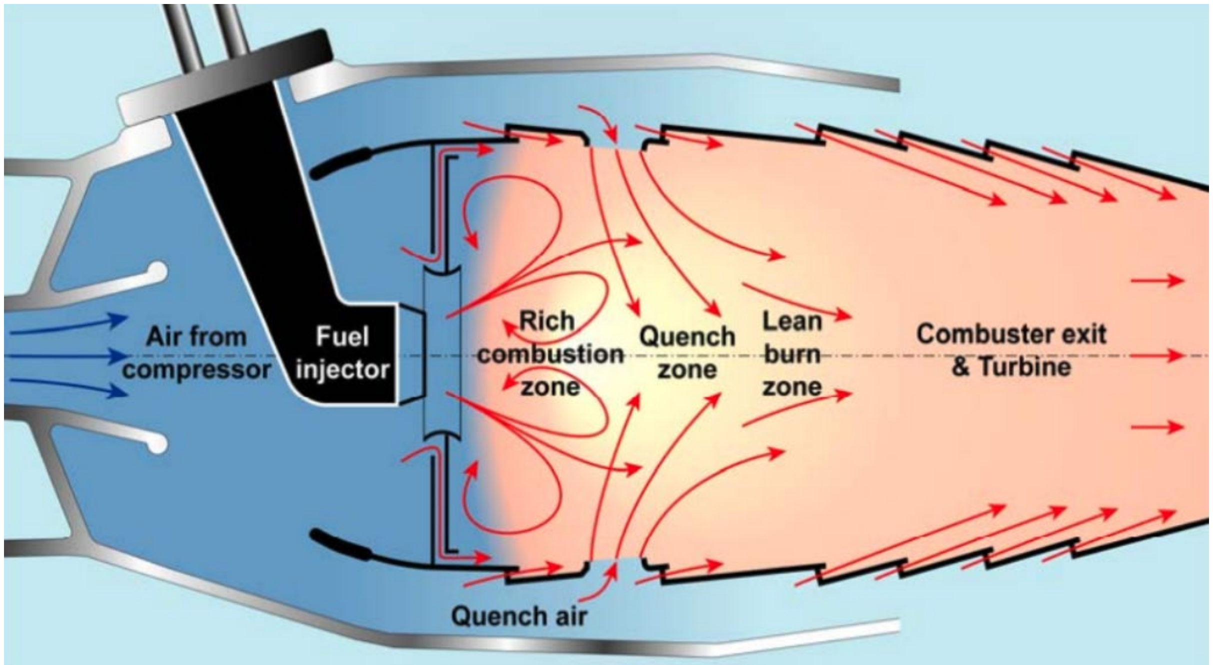
- *Three* water injection schemes studied based on saturation limits (determined via psychrometry):
  - Inject pre-LPC, then inject pre-HPC, followed by combustor inlet
  - Inject pre-HPC, followed by combustor inlet
  - Inject at combustor inlet

- Water injection upstream of compressors leads to TSFC improvement
  - Injecting water starting at the pre-LPC location yields **the most performance benefit per unit water added.**
  - Less compression work

- Water injection upstream of combustor inlet leads to TSFC penalty



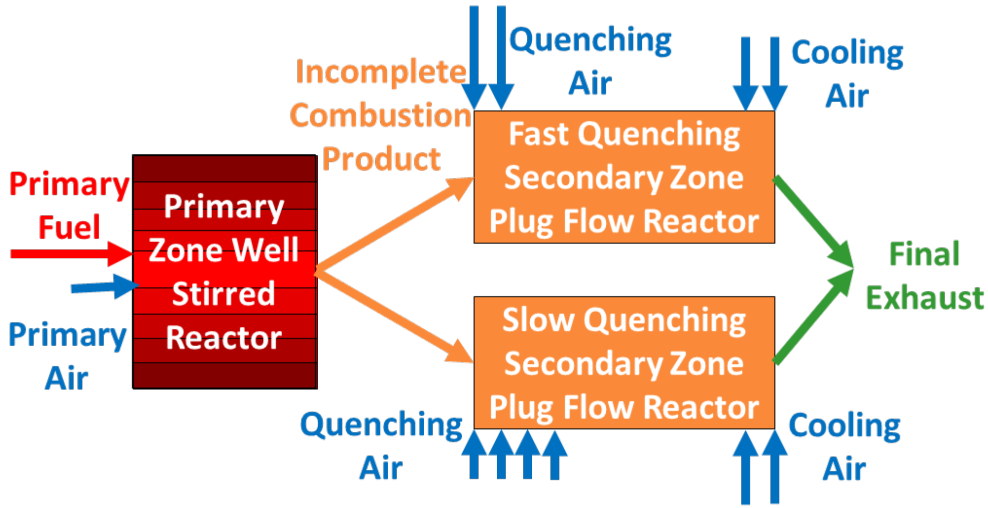
Combustor Chemistry – Schematic



*J. Faber *et al.*, "Lower NOx at higher altitudes policies to reduce the climate impact of aviation NOx emission," *CE Delft Solutions for Environment, Economy and Technology*, 2008

- Rich burn primary zone to avoid NO_x production
  - Represented by well stirred reactor (WSR)
- Quick quenching air to cool down the flow to minimize NO_x production
  - Represented by plug flow reactor (PFR)
- Dilution flow adding into the end to finally cool down the flow for turbine blades

Combustor Chemistry – Model



- 1D chemical reactor network – different reactor types represent distinct combustor regions

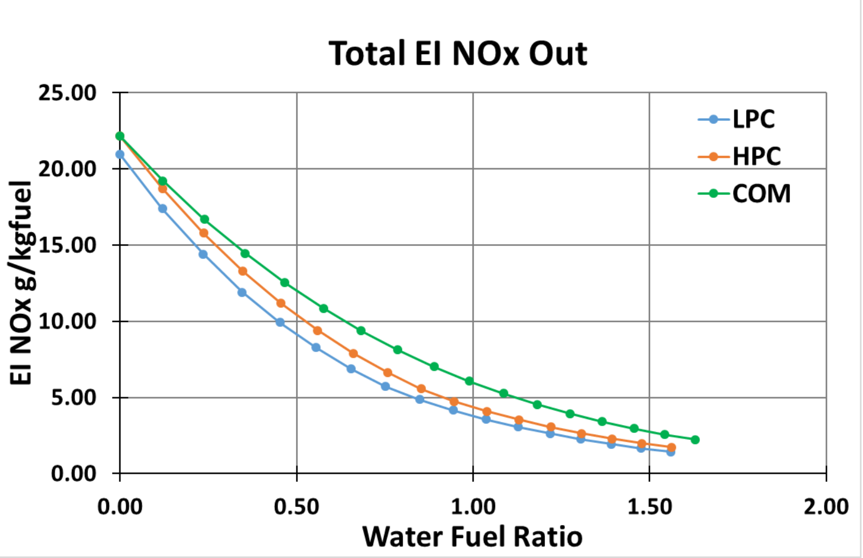
- RQL combustor
  - Primary zone **WSR** (Well Stirred Reactor)
  - Secondary zone **PFRs** (Plug Flow Reactor)

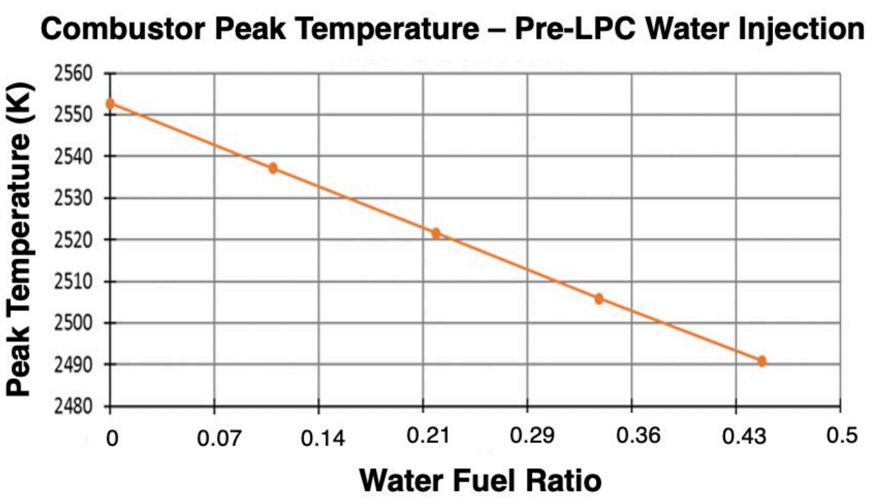
- Primary zone diffusion flame modeled by set of WSRs
  - Non-uniform *equivalence ratio* distribution captured in this region

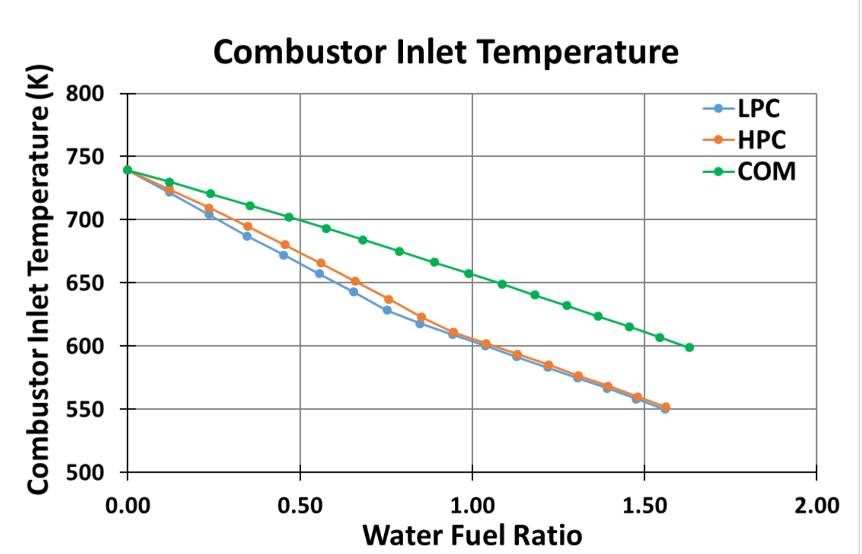
- Incomplete quenching *jet penetration* captured by two PFRs
  - Different quenching length scales

Combustor Chemistry – Results

- Combustor inlet conditions used as input
  - Determined by the *engine cycle model* running at cruise conditions
- Water injection reduces NO_x emission
  - Evaporative cooling; reduction of combustor inlet and peak temperatures
- Pre-LPC water injection gives **the most benefit** for NO_x reduction
  - Lowest combustor inlet temperature







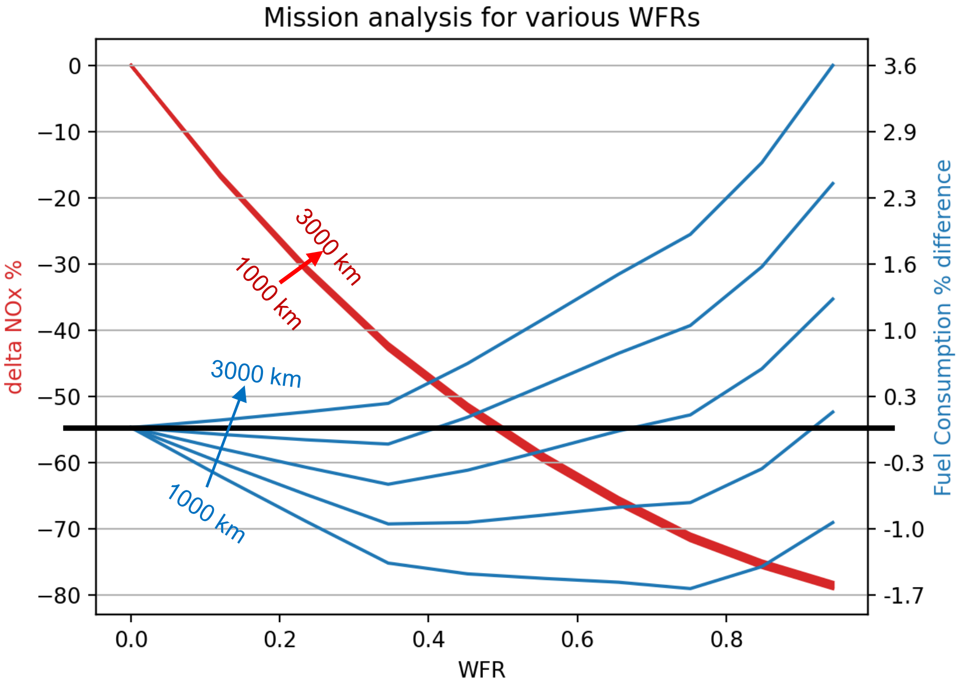
Mission Analysis for Overall Impact

Performance impact

- Fuel burn increases due to additional weight of water being carried
- This fuel burn increase is more than compensated by TSFC improvement *for shorter missions*

Emissions impact

- Significant overall NO_x reduction at mission level due to lowered flame temperatures
- Incremental reduction in NO_x emissions is largest at low WFR

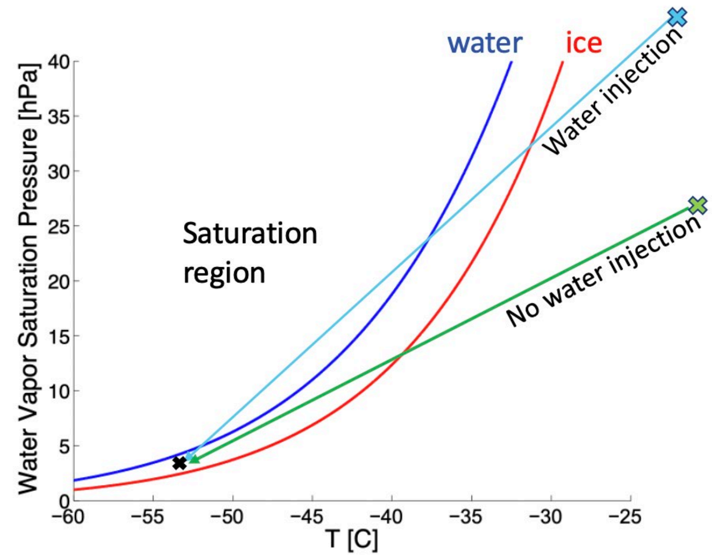


(L/D: 16, speed: 900 km/h)

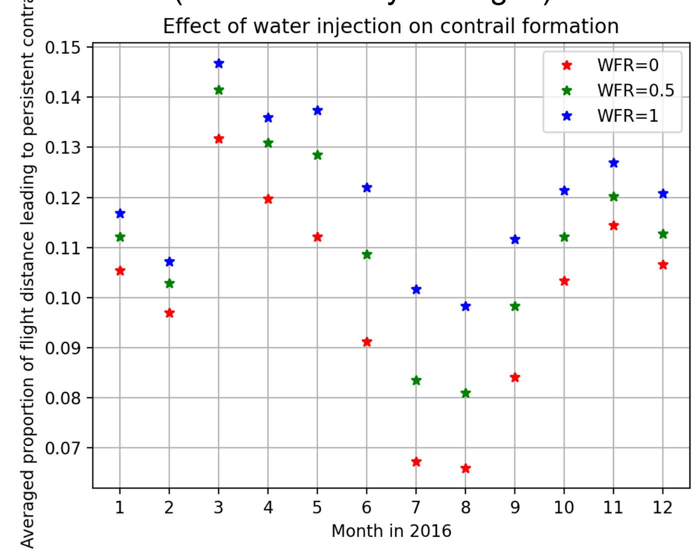
Contrails – Zero order analysis

- Contrails are a major component of aviation's climate impact
- Persistent contrails form when:
  - Ambient air is ice supersaturated
  - Schmidt-Appleman criterion is satisfied
- Schmidt-Appleman criterion depends on engine exhaust properties and ambient conditions
  - Directly proportional to EI of water
  - Water injection increases the water EI, increasing the range of conditions where the plume will pass through the water saturation region
  - Meteorological and flight data analyzed for a full year to study contrail formation

- Proportion of total flight distance leading to persistent contrails **increased significantly** with water injection
  - On average, a WFR of 1 leads to 30-35% increase in persistent contrail formation



(2016 – monthly averages)



Ongoing Work

Evaporation Analysis

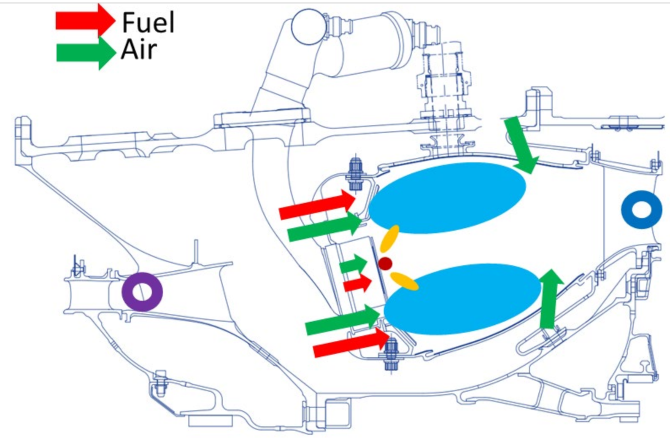
- Thermodynamic consistency of model ensured by psychrometry calculations
  - Can only inject water till the saturation limit
  - Residence time of air is very small; on the order of milliseconds
- **Question:** What spray characteristics (droplet sizes) are needed to ensure complete evaporation given the residence times available?
- Water evaporation being modeled using ODEs derived from first principles
  - species conservation
  - energy conservation
  - Cantera software used to extract fluid thermodynamic and transport properties

Water Injection Strategies

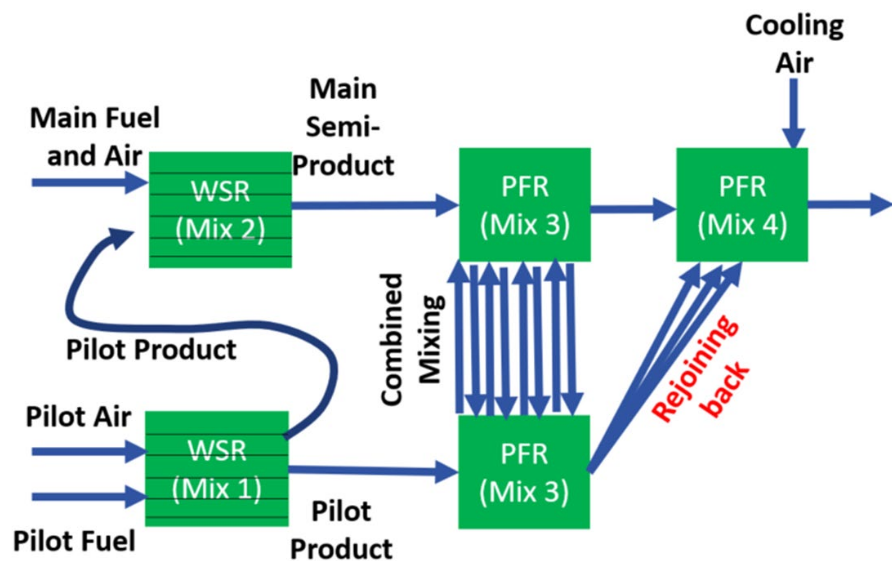
- Additional fuel burn arises from carrying more (water) weight on aircraft
- High-power operating conditions produce the most NO_x due to higher flame temperatures
- Emissions benefit can be maximized by injecting more water at takeoff and minimizing water injection at cruise to lower additional fuel burn
- Additional optimization of emissions reduction and fuel consumption by varying water injection rates at different parts of mission

Staged Combustor (In Progress)

- Lean burn can potentially provide opportunities for lower emissions
  - More and more engines being operated on lean burn strategy
- Staged lean burn combustor
  - Distribution of air flow is fixed by the burner geometry
  - Fuel flow staged through fuel supply system's valve control
- 1D reactor model captures the pilot ignition effect on the main stream lean mixture, and the mutual mass/heat exchange between downstream pilot and main flame
- Next step is to study the effects of water injection or other modifications on staged lean burn combustor



*Development of the GE Aviation Low Emissions TAPS Combustor for Next Generation Aircraft Engines, Michael J. Foust et.al.



Conclusion

- Water injection can be a feasible means to mitigate NO_x formation while preserving engine efficiency on engines with an RQL combustor configuration
  - **Key tradeoff:** Emissions and performance benefit vs. weight penalty
  - The additional fuel burn due to weight of water is *sufficiently offset* by the performance benefit gained with water injection *for shorter range flights*
  - Water injection strategies can be varied and optimized to give maximum emissions benefit while keeping performance intact
  - Evaporation time study is in progress

- The effect of water injection strategy on other combustor types (e.g. staged lean burn) is under study
  - Current analysis being updated, and engine cycle deck is being calibrated against EDB data for reliable results

- Water injection will result in increased contrail formation
  - Avenue for further research

Questions?