GE Aerospace

Challenges of Gas Turbine Combustion with Zero-Carbon Fuels

Keith McManus
GE Aerospace Research

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Outline

- Introduction GE Aerospace Low-Carbon Vision
- Hydrogen activities - overview
- Ammonia and NH3/H2 blends
- Q&A

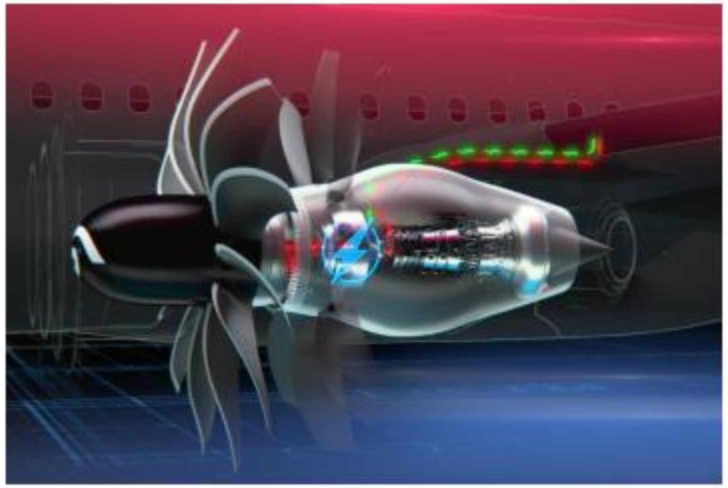
GE Aviation's breakthrough technology demonstrators

Hybrid Electric

MW-class hybrid electric propulsion system development with NASA … builds on GE's experience with motors, generators, power convertors and power management systems

CFM RISE

GE and Safran Aircraft Engines program maturing advanced engine architectures like open fan, compact core and electric technologies for >20% better fuel efficiency vs. today's engines



Hydrogen

CFM International* developing hydrogen combustion and fuel systems for Airbus ZEROe aircraft project … builds on 8M operating hours with hydrogen in GE land turbines

Ground and flight tests designed to show technology readiness this decade for multigenerational upgrade by mid-2030s

*CFM International is a 50-50 joint company between GE and Safran Aircraft Engines. RISE is a registered trademark of CFM.

Hydrogen

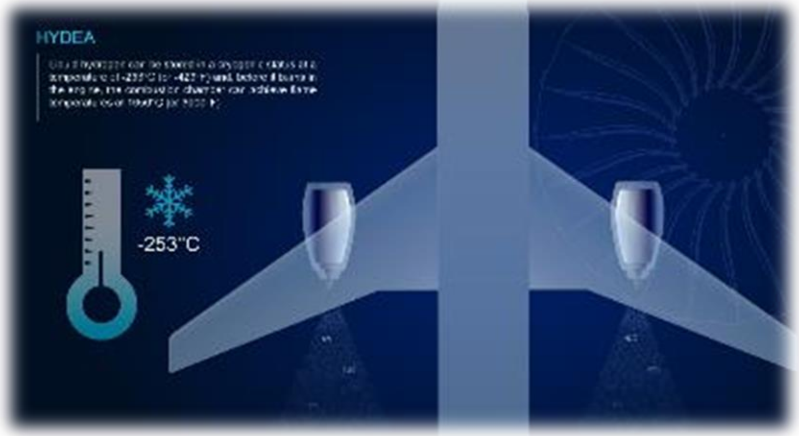
HYDEA

HYdrogen **DE**monstrator for **A**viation

HYDEA addresses fundamental questions related to the use of **liquid hydrogen** as an aviation fuel for gas turbine applications, defining a path for validating key technologies prior to Ground test.

In the 2023-2026 timeframe, HYDEA will:

- Mature and validate the **key enabling technologies** at engine sub-system level (e.g., combustor and fuel system) needed to demonstrate the H2 Combustion (H2C) **concept applicability** for both engine and aircraft;
- Perform **NOx optimization** studies for future H2C engines;
- Study and **model contrail** formation phenomena.



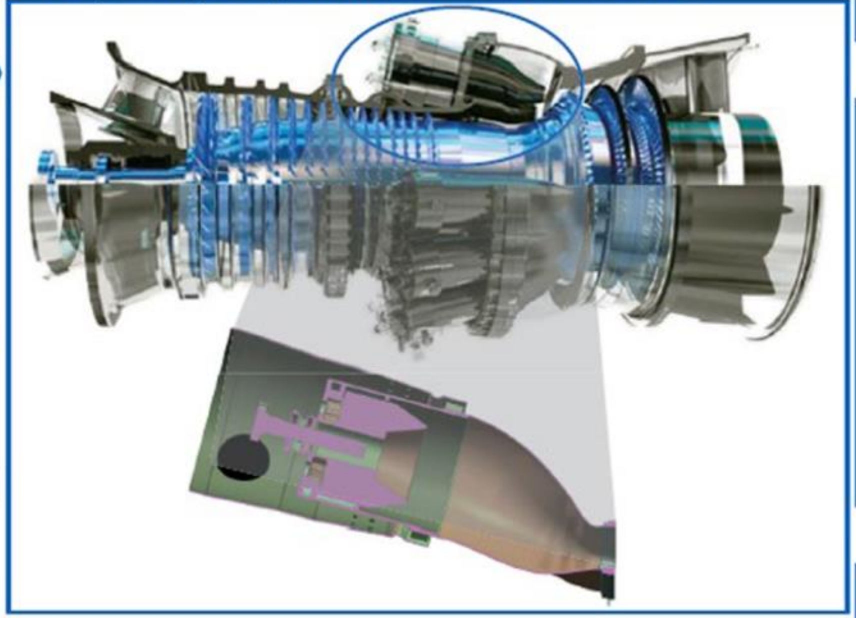
Avio Aero leads the HYDEA consortium in the ambition to reach net zero CO2 emissions by 2050

DOE H2 Rotating Detonation Program Overview

Demonstration of a Gas Turbine-Scale RDC Integrated with Compressor and Turbine Components at 7FA Cycle Conditions (2022 – 2026)

An 48-month, $8.75M project to develop and demonstrate rotating detonation combustion (RDC) technology in an integrated gas turbine system.

Project Objective(s): Develop low-loss rotating detonation combustor, integrate with upstream and downstream turbomachinery components and verify overall systems performance at F-class turbine conditions.



Project Team

GE Aerospace Research

Deep expertise:
- RDC and gas turbine design
- Gas turbine testing
- Compressor/diffuser aero
- Turbine aero
- Cooling design, heat transfer

Computational Combustion and Aero
University of Michigan
Prof. Raman

Measurements and Diagnostics
UCF
Prof. Vasu

Georgia Tech
Prof. Steinberg

NC State University
Prof. Narayanaswamy

Project Deliverables

- Low-loss RDC design for turbine integration
- Experimental demos of compressor and turbine integration
- Turbine and compressor component performance estimates in integrated system from detailed test and measurement
- RDC-integrated GT performance estimates

Relevant Prior Work

- Air-cooled RDC demonstration
- RDC operation on natural gas at elevated T,P
- Preliminary gas turbine integration design
- RDC performance estimates
- USAF RDC Program

Technical Approach

- Design air-cooled RDC
- Test with Nat-gas H2 mixtures
- Integrate with compressor and turbine
- Test integrated system
- Verify performance based on high-fidelity data

Technical Challenges

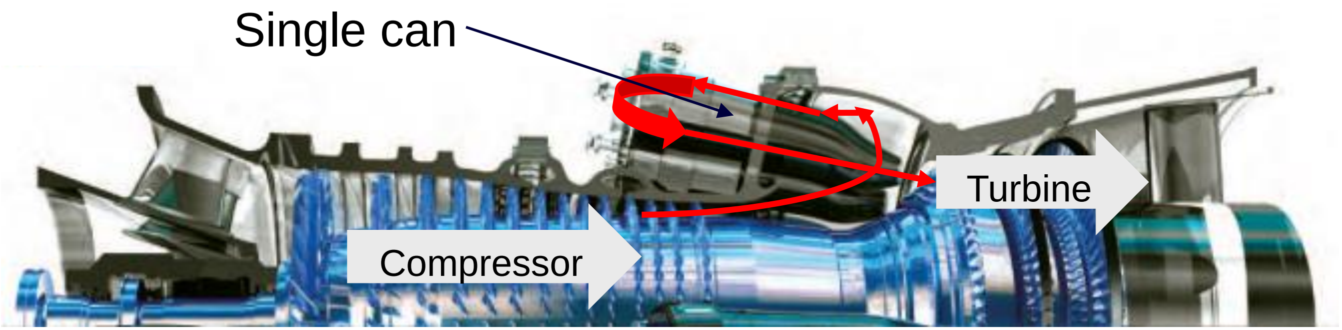
- RDC operation over large P,T range
- Low-loss RDC inlet design
- Fuel flexible operation
- Unsteady flow effects on compressor and turbine performance

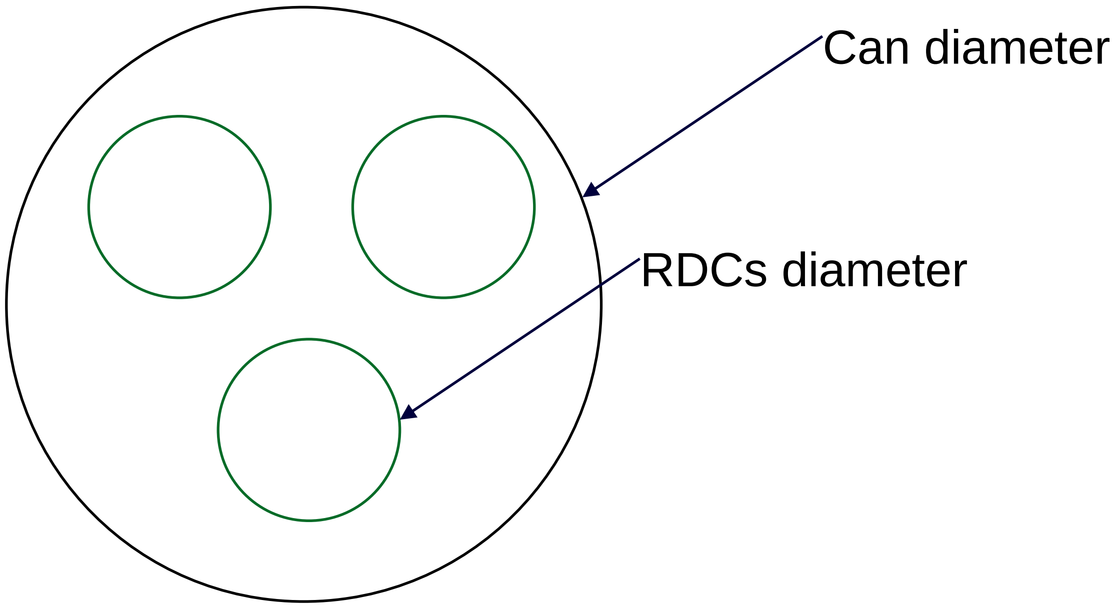
7FA Can Layout

- Study undertaken to understand how retrofit would look
  - Replacing current deflagration-based can architecture with an RDC based architecture
  - Needs to be able to operate over the full cycle (from baseload through turndown)
  - Evaluating multiple RDCs for optimal configuration

Source: *7FA Gas Turbine Test and Validation*, GE Energy, 2011.

https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7BFC2AC1A6-4F49-47C2-990C-17E64F9B0E82%7D

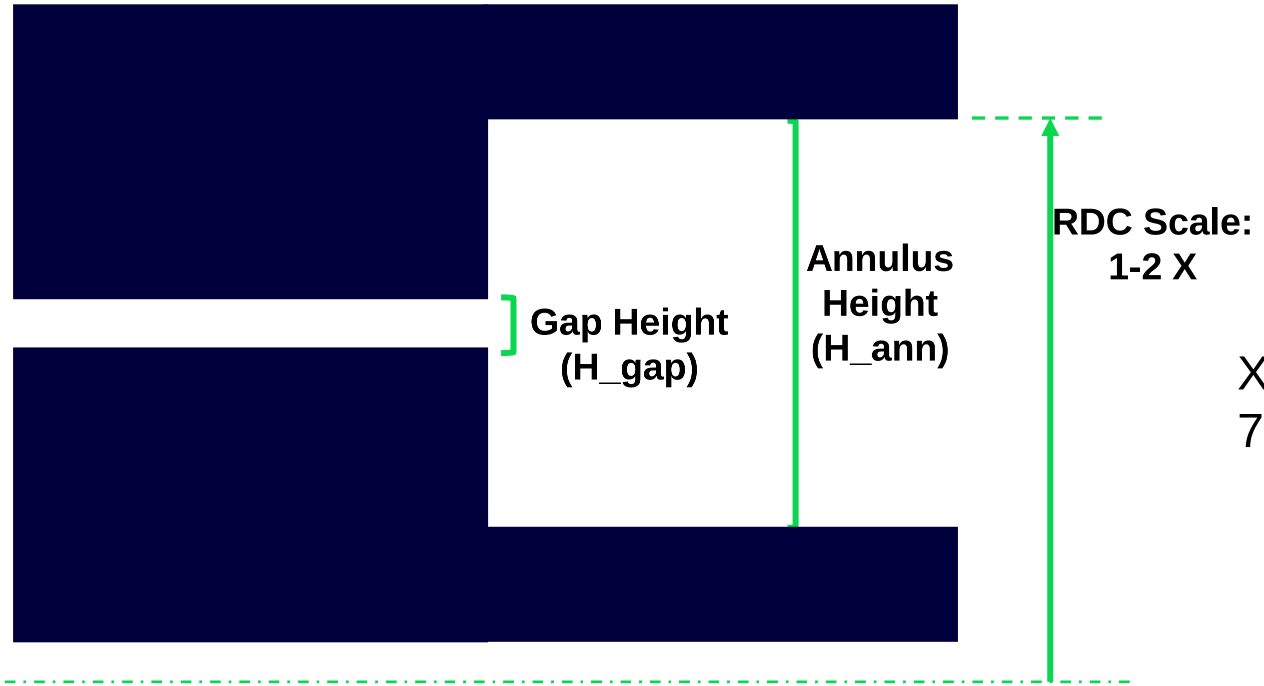




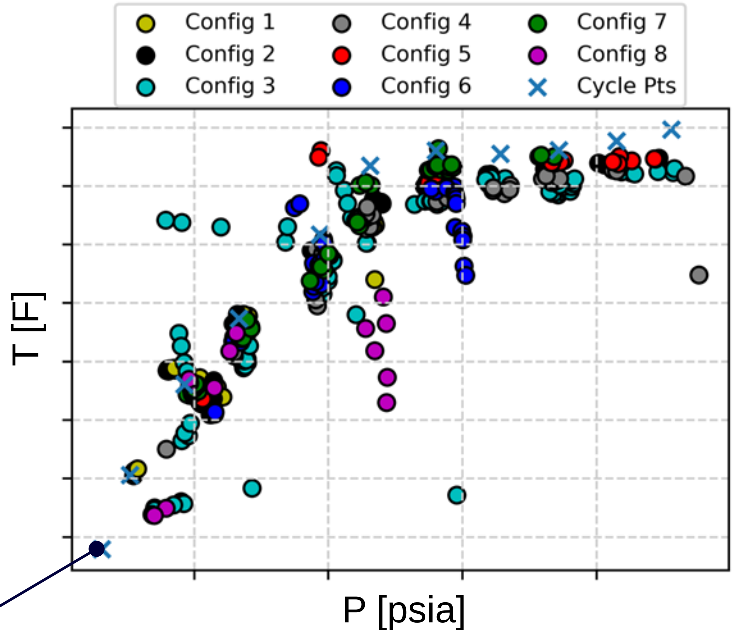
*Not representative of actual size or number of RDCs

Configurations Tested

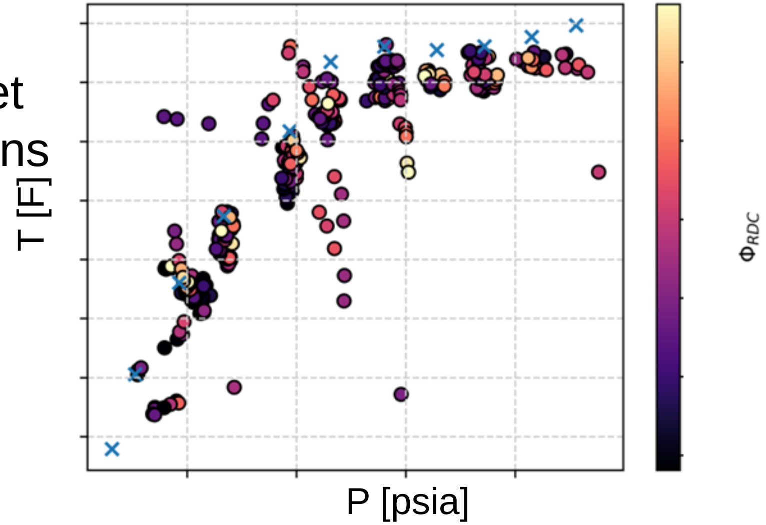
H_gap	H_ann	H_gap/H_ann	A_gap/A_ann	Fuel Inj. Distance
0.88-1.33x TSS	0.75-2.08x TSS	0.48-1.33x TSS	0.73-1.30x TSS	0.66-1.33x TSS



- Data range relative to final down-selected hardware
- Representative of single RDC in down-selected can architecture

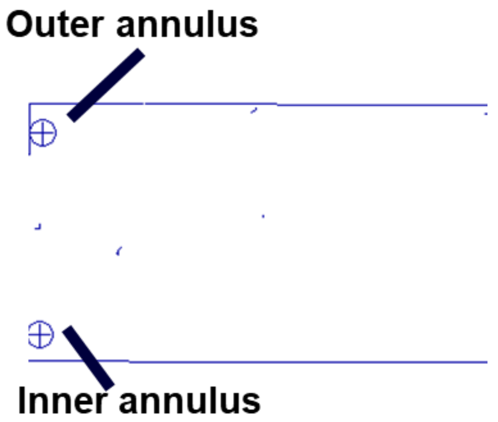


Xs represent target 7FA cycle conditions



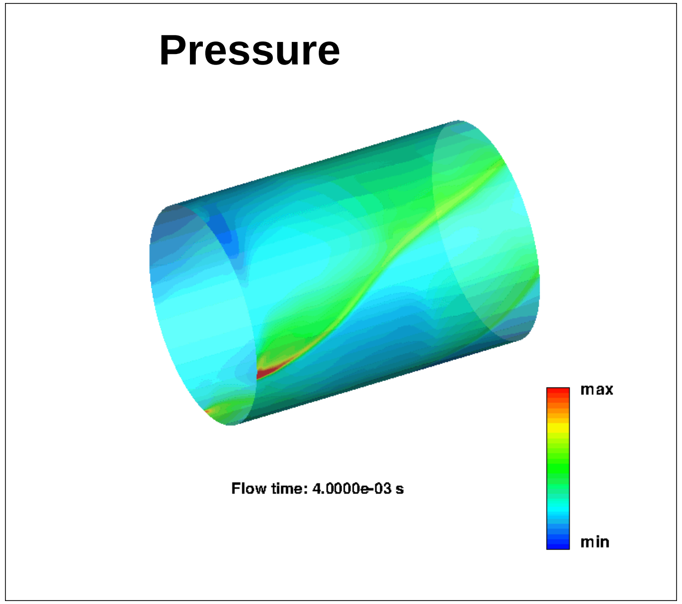
- Operability demonstrated over the 7F cycle
- All cases are sustained detonations

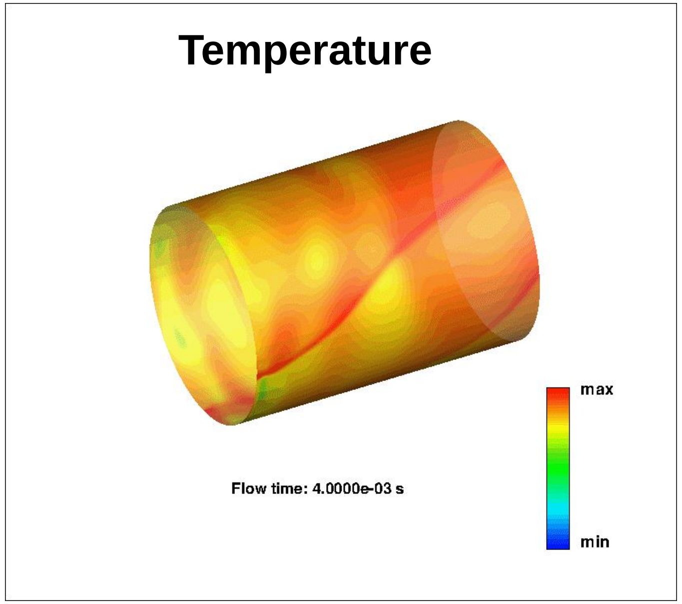
Steady-State Rig : CFD

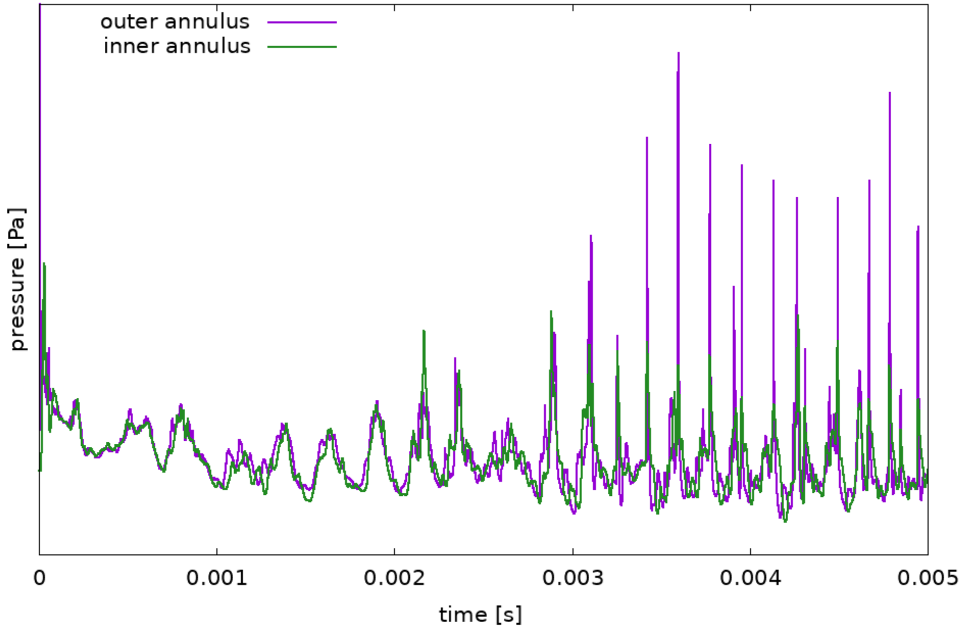


Example Reacting Flow Case for Axial Rig:

- Configuration 3 geometry
- CP3
- Detonation wave establishes after 3 ms





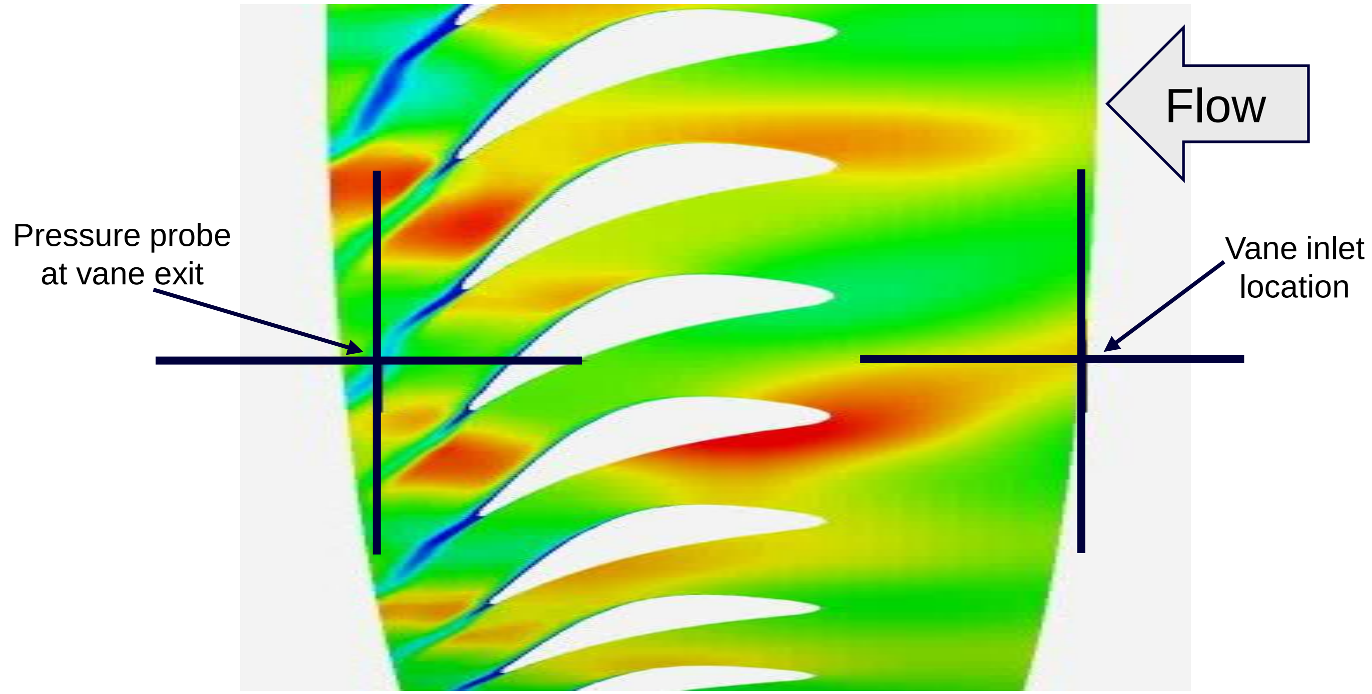


- One strong detonation wave (τ_{cycle} ~ 1.7E-04 sec) and one weaker wave predicted
- Time-averaged temperature & pressure data provided to thermal & mechanical teams to develop steady-state rig capabilities

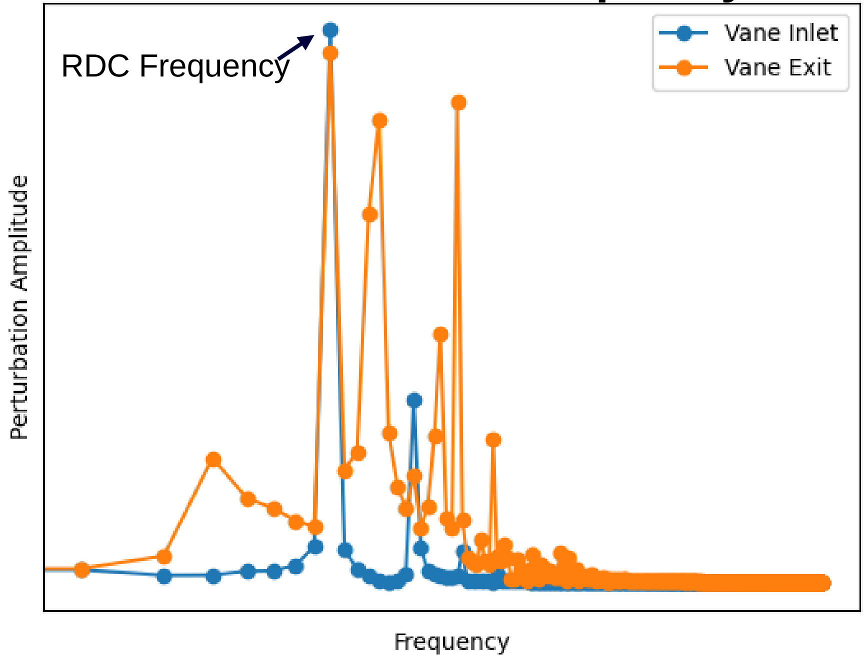
RDC Integration – Downstream Flow Path Simulations

- Multiple RDC combustors integrated within 7FA flow path (transition piece + stage 1 vane)
- RDC-representative pressure and temperature fluctuations introduced at domain inlet (combustor exit)
- Pressure/temperature waves at RDC forcing frequency diminish in amplitude through transition piece but persist with a measurable amplitude through the vane row
- Aspect ratio altered

Contours of Total Pressure



Pressure Probe Data -- Frequency Domain



– Ammonia

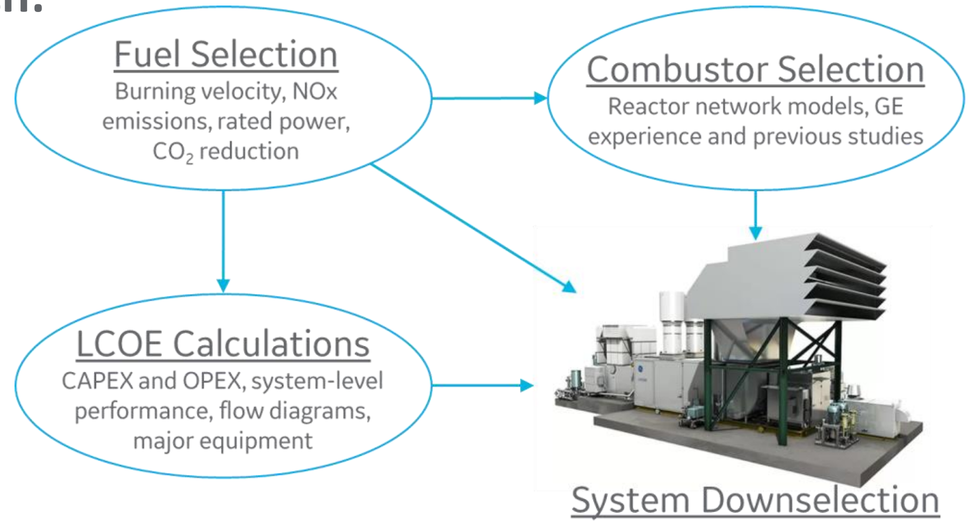
DOE ARPA-E REFUEL: Ammonia Combustion in Gas Turbines

General Electric (GE) Research

Overview and Objective:

- Assess feasibility of ammonia combustion in existing aeroderivative gas turbines
- Develop a roadmap for technology maturation
- 1 year effort funded by US DOE ARPA-E Renewable Energy to Fuels through Utilization of Energy-Dense Liquids (REFUEL) program

Approach:



Challenges:

- Ammonia combustion
  - Fuel blend selection – NH_3, NH_3/H_2, NH/CH_4
  - Combustor selection – premixed, non-premixed, staged, etc…
- Plant-scale economics

Deliverables:

- Roadmap for Technology Maturation
  - Fuel blend and combustor architecture selected
  - Technoeconomic assessments for downselected system complete
  - *Schedule and budget developed for experimental ammonia combustor characterization*

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Combustor Design Strategy

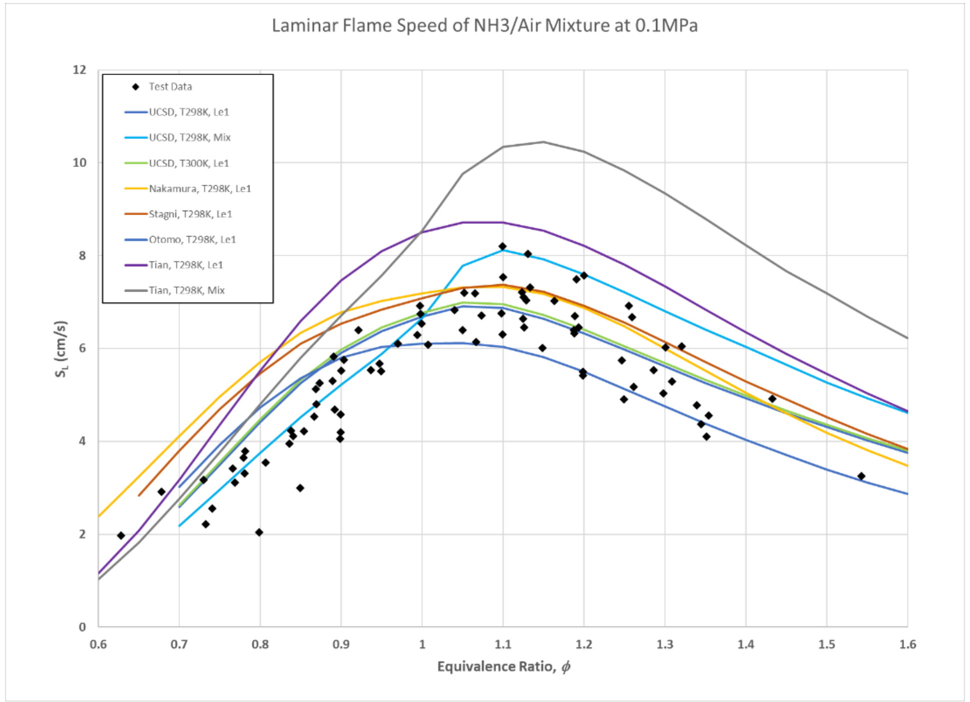
Team brainstorming sessions for nozzle/combustor selection

- Agreed on combustor key criteria and Pugh Matrix
- Nozzle/combustor selection will ultimately be informed by reactor network models, SME input, *CFD calculations, and experiments*

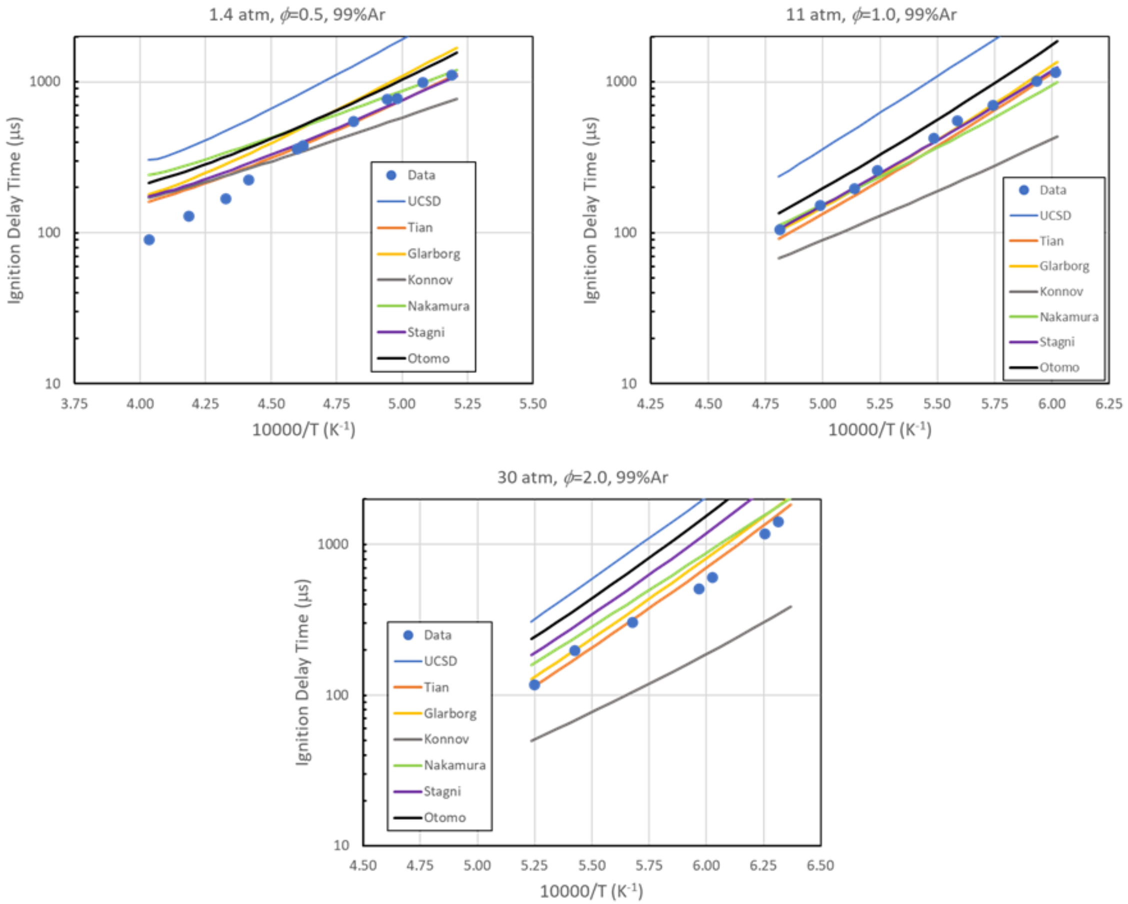
Reactor Network Models

Performed validation studies and selected the Tian chemical kinetics mechanism for ammonia combustion in Cantera software

Laminar flame speed and ignition delay time calculations compared to literature



- Worked to to assess and validate software predictions for NOx emissions and flame speed at gas turbine conditions



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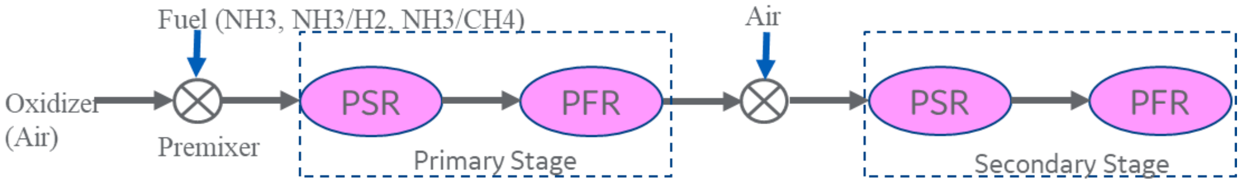
GE Public Information

Combustor Architecture Studies

- Assessed simple air-staged combustor geometries at relevant gas turbine conditions

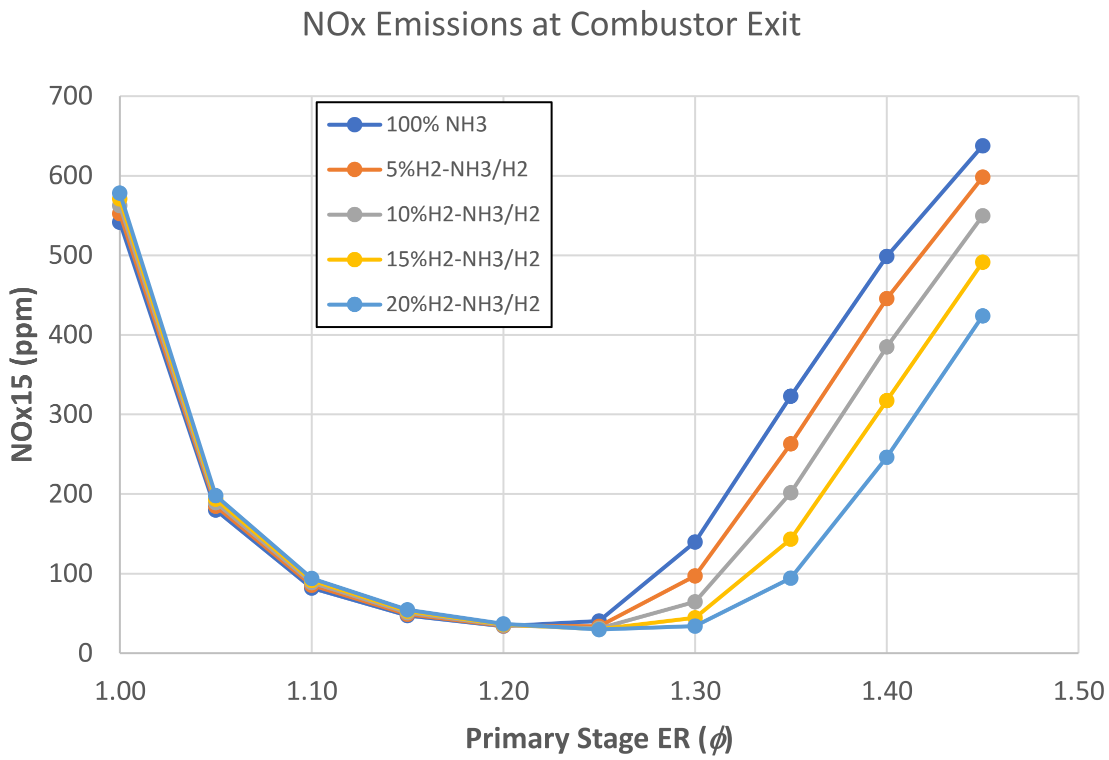
- Literature reviews and preliminary modeling work suggest that staged combustors are promising options for achieving low NO_x performance



Conditions:
- P4=329psi
- T3=902 F
- Tfuel = 77 F
- Texit = 2643 F

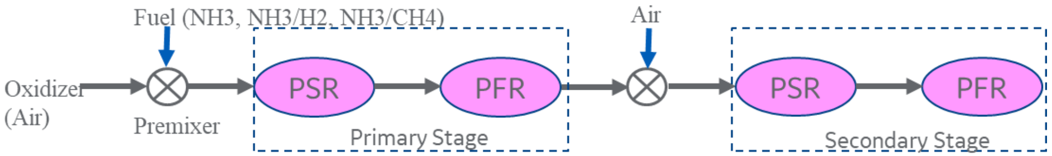
Primary Stage:
- 2 ms for PSR
- 5 ms for PFR

Secondary Stage:
- 1 ms for PSR
- 2 ms for PFR



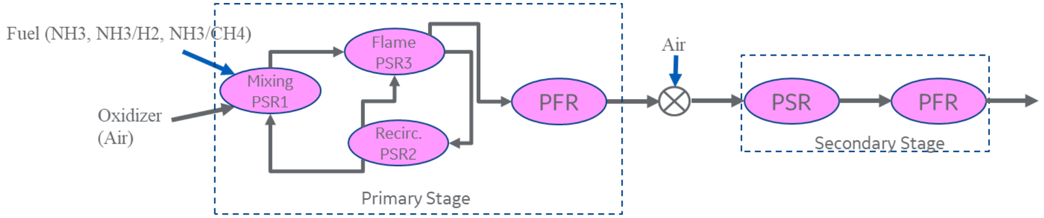
Parametric Studies of Air-Staged Combustors

- Simple primary stage (87 total cases)



Conditions:
- P4=329psi
- T3=902 F
- Tfuel=160 F
- Texit=2643 F

- Staged combustor with recirculation (104 cases)

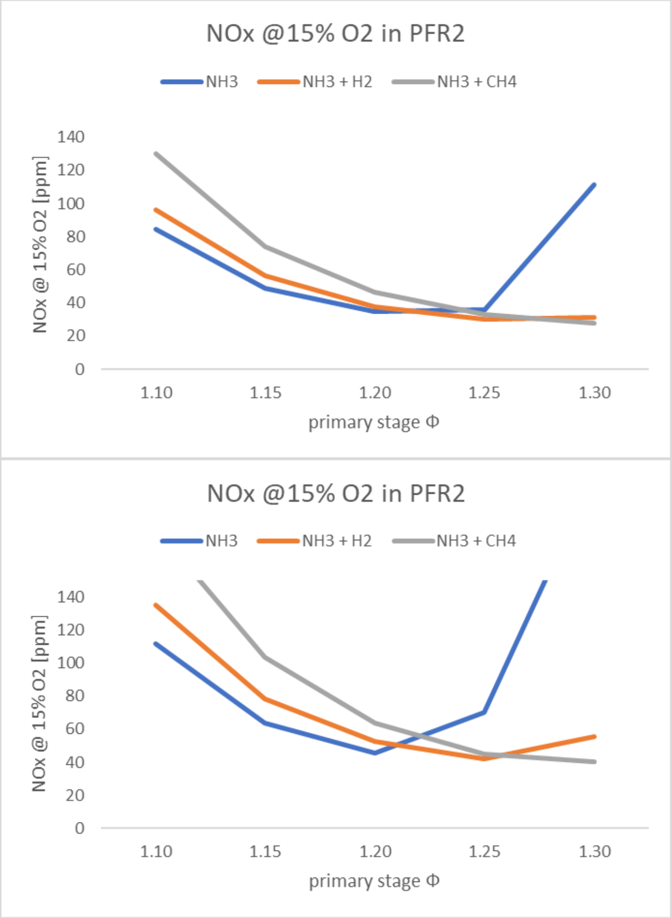


- Primary stage equivalance ratio = 1.1 – 1.3
- Total combustor residence time = 6 ms or 10 ms
- Primary PSR and PFR residence times = 0.5 – 5 ms
- Secondary PSR and PFR residence times= 0.5 – 4 ms
- Fuels: NH_3, NH_3 + 20% H_2, NH_3 + 20% CH_4
- Outputs @ each component: NO_x, NH_3, CO, CO_2, N_2O, HNO, OH, NH, NH_2, NNH

- Primary stage equivalance ratio = 1.1 – 1.3
- Total combustor residence time = 6 ms or 10 ms
- Primary PSR and PFR residence times = 1.5 – 4.5 ms
- Secondary PSR and PFR residence times = 0.5 – 4 ms
- Primary stage recirculation fractions = 0.1 – 0.9
- Unmixedness study
- Fuels: NH_3, NH_3 + 20% H_2, NH_3 + 20% CH_4
- Outputs @ each component: NO_x, NH_3, CO, CO_2, N_2O, HNO, OH, NH, NH_2, NNH

Parametric Studies - Summary

- NOx emissions of <50 ppm achievable in air-staged combustion systems
- Primary stage equivalence ratio ~1.2 gives minimum NO_x emissions
  - NO_x performance of combustors with shorter overall residence time are more sensitive to primary stage equivalence ratio
- N_2O and unburned NH_3 are < 1 ppm for all cases
- NO_x emissions insensitive to primary or secondary stage PSR residence time, secondary stage PFR residence time, primary stage recirculation factors
- NO_x emissions most sensitive to Primary Stage PFR residence time
  - Long (> 2ms) primary stage PFR residence time required for < 50 ppm NO_x performance
- At unmixedness levels studied (Gaussian distribution of primary stage ϕ, mean = 1.2, σ = 0.05), NO_x emissions are typically ~10-30% higher than perfectly mixed cases



NO_x emissions for simple air-staged combustion system with varying primary stage equivalence ratio; (top) total residence = 10 ms, (bottom) total residence time = 6 ms.

Overall Objectives – Reference System

Ammonia as a Liquid for the Future of Aviation

"retrofit" for "zero emission aviation":

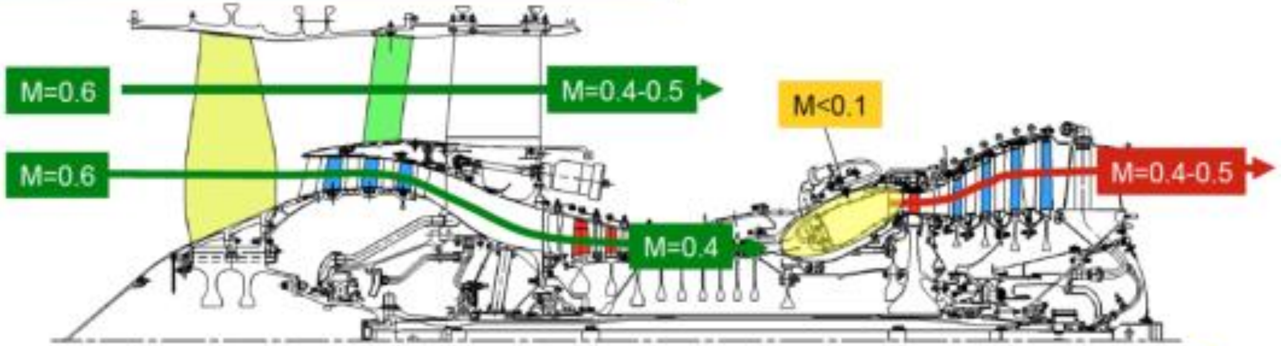
Selected (in order to perform techno-economic feasibility):
Orlando International Airport (MCO), 7th busiest airport worldwide in 2021: reference airport.
United Airlines, which operate 200+ of B737 variants: **reference airline**.

9 gates at MCO (gate 40 – 48) that are used by United Airlines: **reference gates**.

MCO – EWR (Newark) flight, with max PAX-miles at MCO: **reference flight**.

Seats (2-class)	162-178	Max cargo (m3)	43.6
Range (km)	6570	Usable fuel (L)	25,817
Length (m)	39.52	Max taxi weight (kg)	82,871
Wing span (m)	35.90	Max takeoff weight (kg)	82,644
Op Empty Wt (kg)	66,090	Max zero fuel weight (kg)	65,952

Representative engine cross-section and Mach numbers:



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