Hydrogen and Decarbonisation Workshop:

Hydrogen and Low NOx

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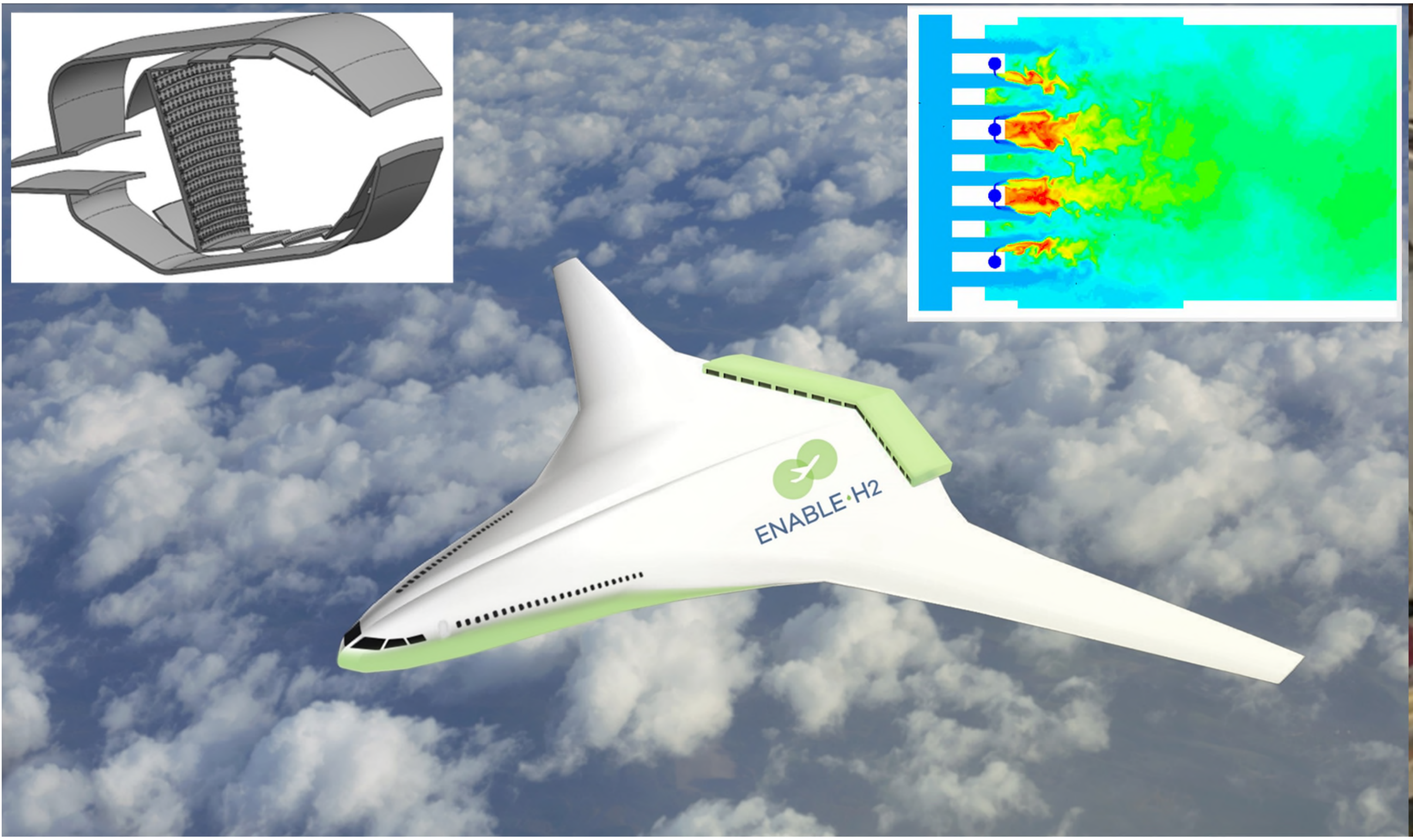
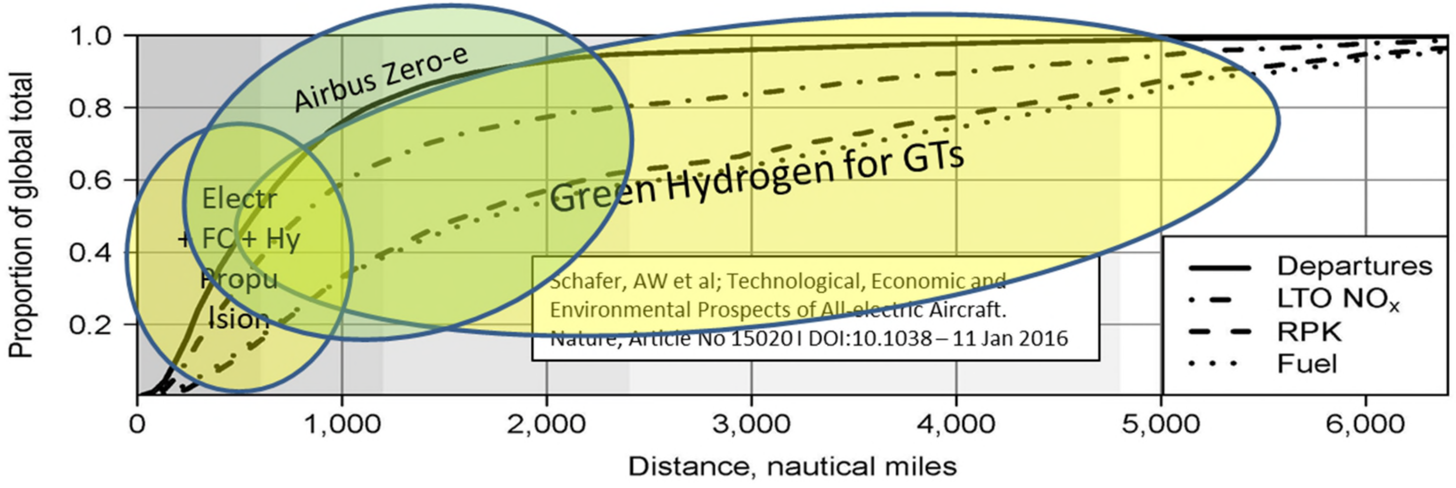
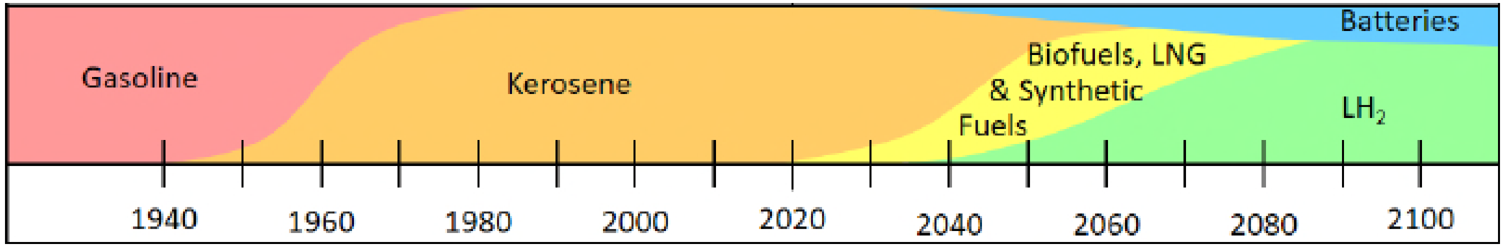


Civil Aviation Sustainability

Protect the Environment and the Economy!





Abbreviations
Electr: Electric
FC: Fuel Cells
GTs: Gas Turbines
Hy Propulsion: Hybrid Propulsion
LNG: Liquefied Natural Gas
LTO: Landing and Take-Off Cycle
RPK: Revenue per Passenger Kilometre

Low NOx H_2 Combustion Solutions are Key!

Sustainability

- **Decarbonise ⇒**
  Zero Carbon – Not "Net Zero"!
- **Minimise Non-CO_2 Emissions ⇒**
  NOx, Contrails, Noise
- **Improve Energy Efficiency ⇒**
  Advanced, Disruptive Tech.
- **Do not Curb Aviation Growth ⇒**
  Protect the economy!
- **Invest and Attract Diverse Talent ⇒**
  Infrastructure, R&D, Education

Gas Turbine Combustors:
Performance and Operability Requirements

- High combustion efficiency
- Good combustion stability
- Ease of Ignition
- Low pressure loss
- Clean exhaust
- Good temperature traverse quality
- Low emissions
- Design for minimum cost and ease of maintenance
- Size and shape compatible with engine envelope
- Durability
- Multi-fuel capability (particularly for land based applications)
- Low size and weight (aero)

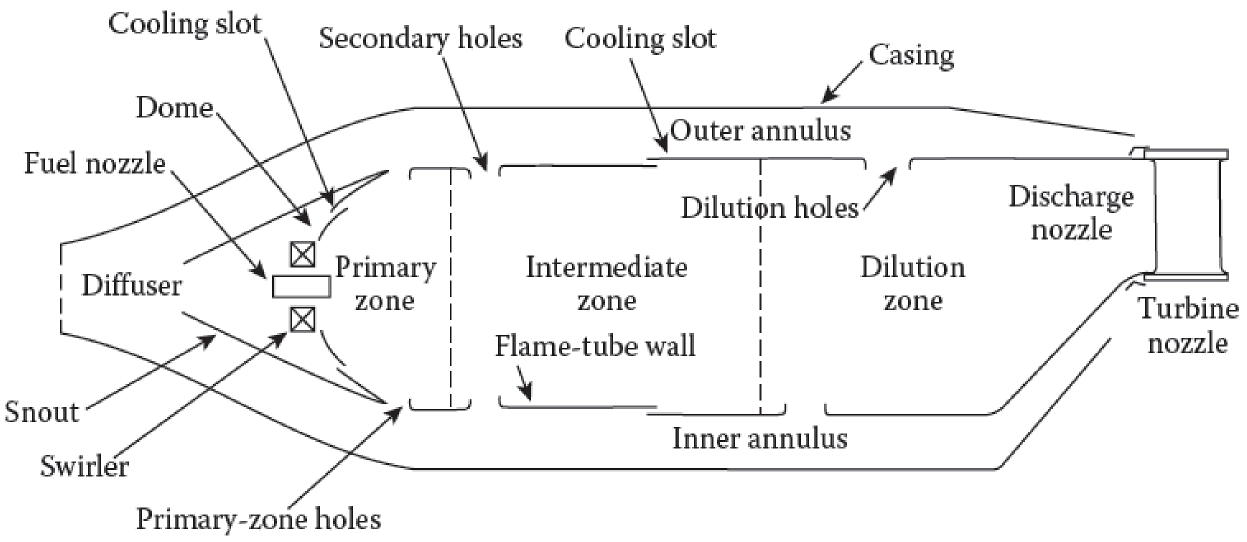


Image courtesy of: Lefebvre. A. H., 2010, “Gas Turbine Combustion”, 3rd Edition, McGraw Hill

Formation of Thermal NO_x:
The Zeldovich Mechanism

<u>Zeldovich Mechanism</u>

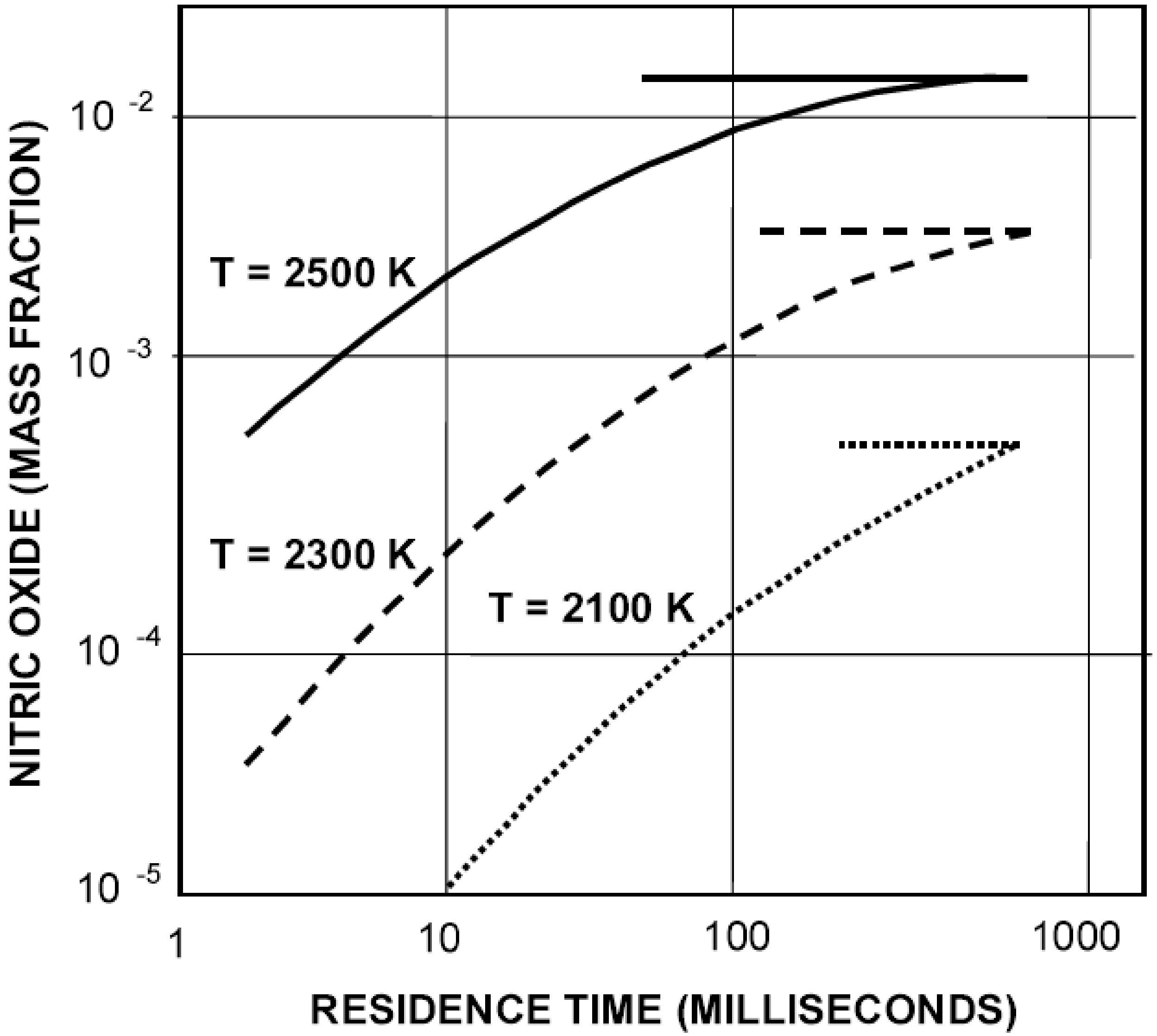
$$O_2 \rightleftharpoons 2O$$

$$O + N_2 \rightleftharpoons NO + N$$

$$N + O_2 \rightleftharpoons NO + O$$

<u>At Lower Temperatures</u>

$$2NO + O_2 \rightleftharpoons 2NO_2$$

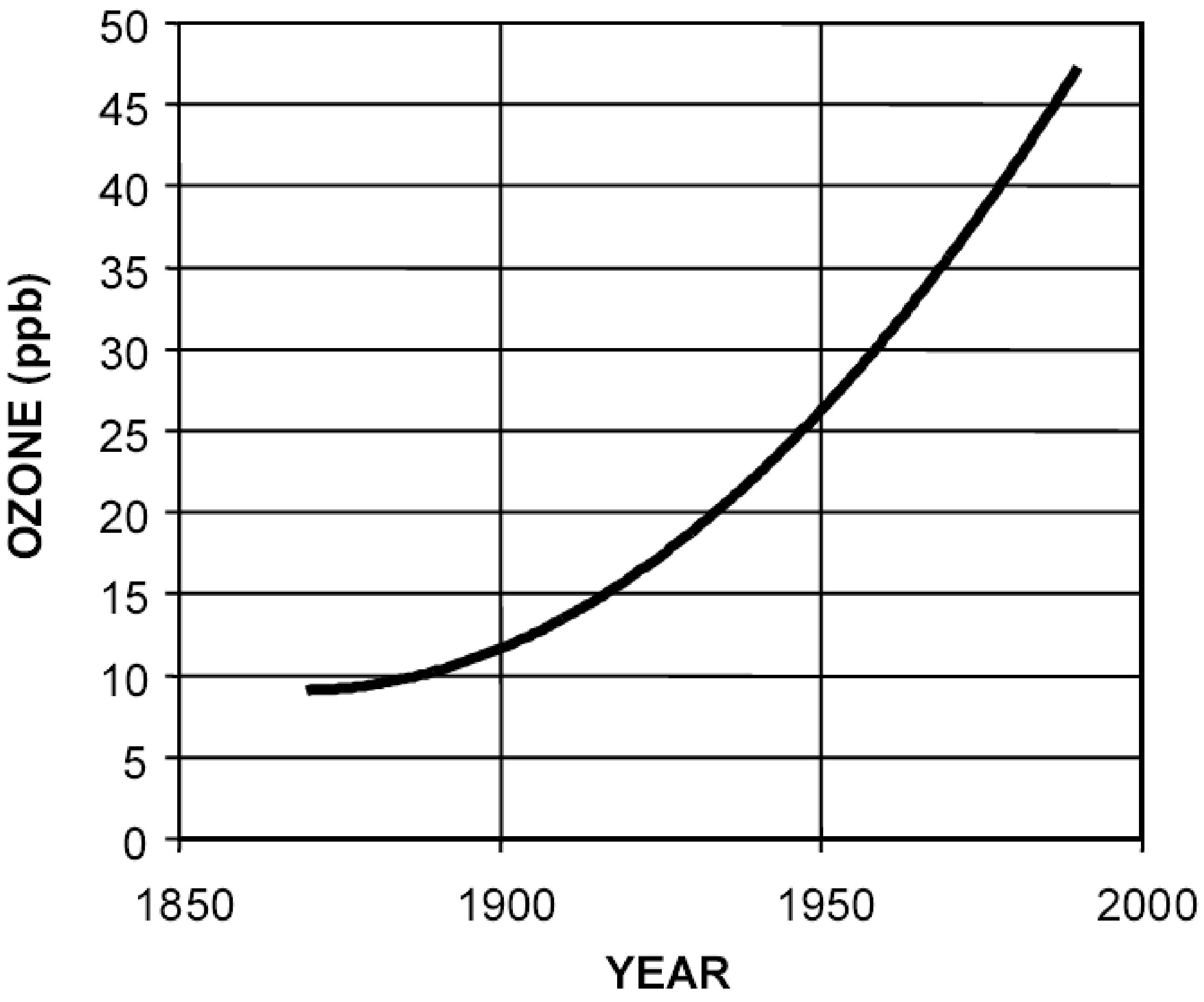


Effects of Products of Combustion:
NO_x

Ozone Formation in the Troposphere
(0km – 10/15km)

$$NO_2 + hv \rightleftharpoons NO + O$$

$$O + O_2 \rightleftharpoons O_3$$



Consequences

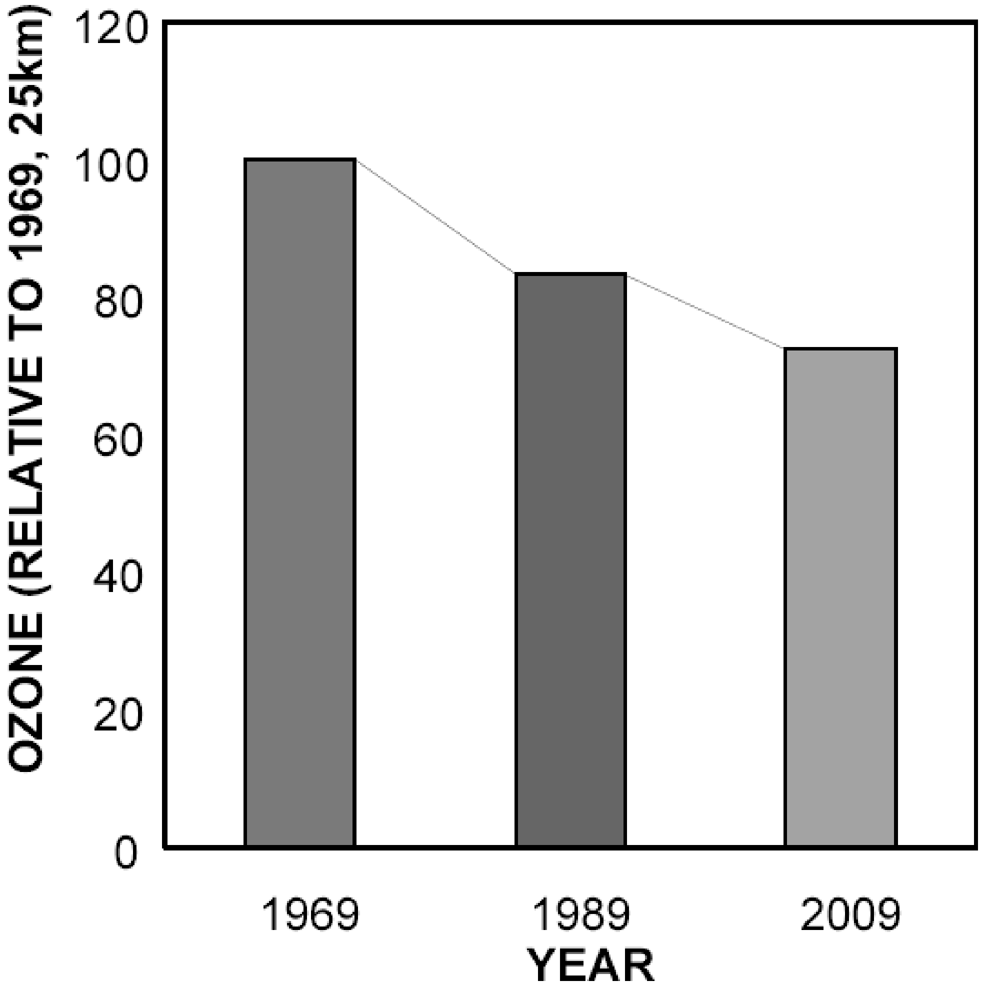
- Respiratory illness
- Impaired vision
- Headaches
- Hearing disorders
- Allergies

Effects of Products of Combustion:
NO_x

Ozone Depletion in the Stratosphere
(10/15km – 50/60km)

$$NO + O_3 \rightleftharpoons NO_2 + O_2$$

$$NO_2 + O \rightleftharpoons NO + O_2$$

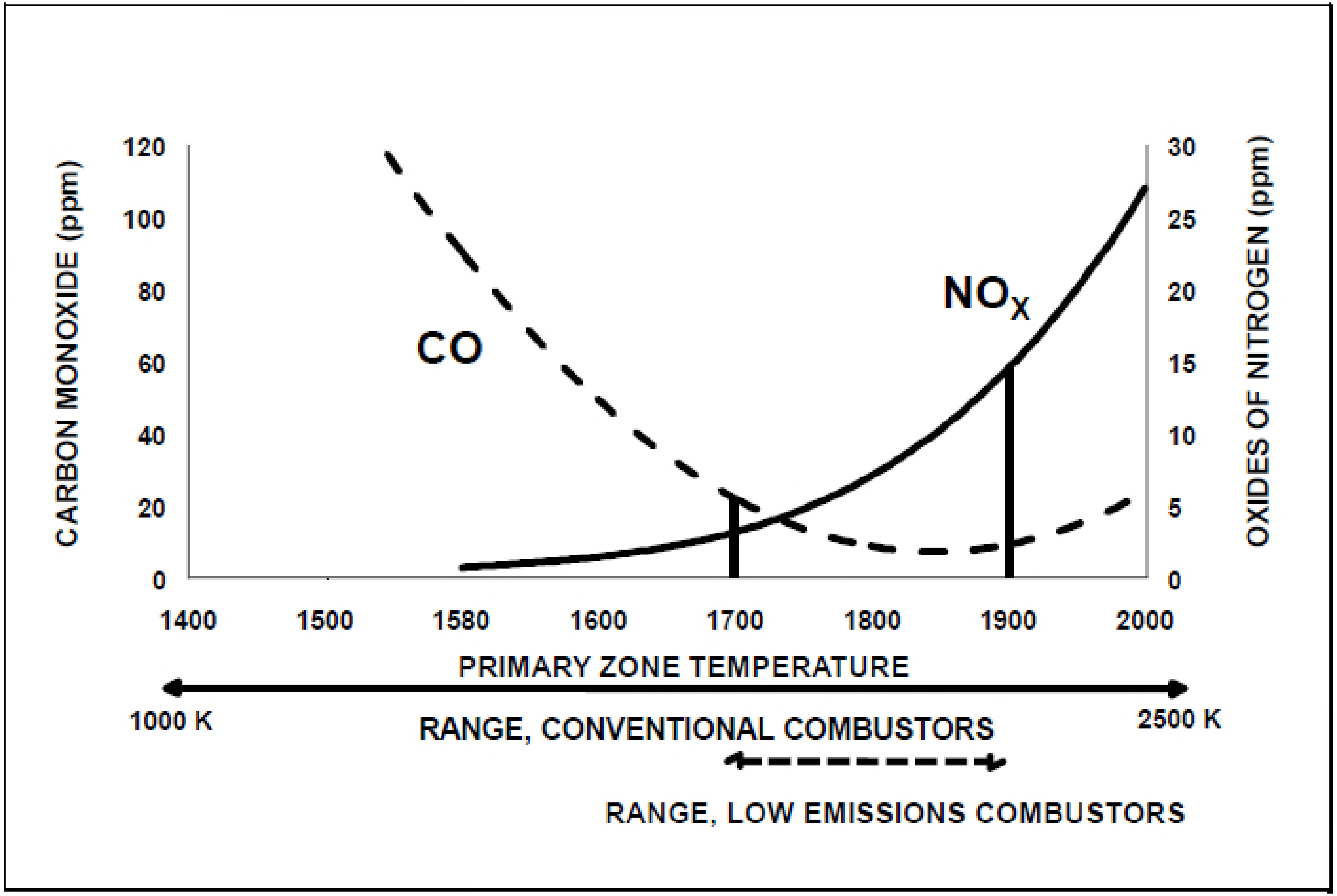


Consequences

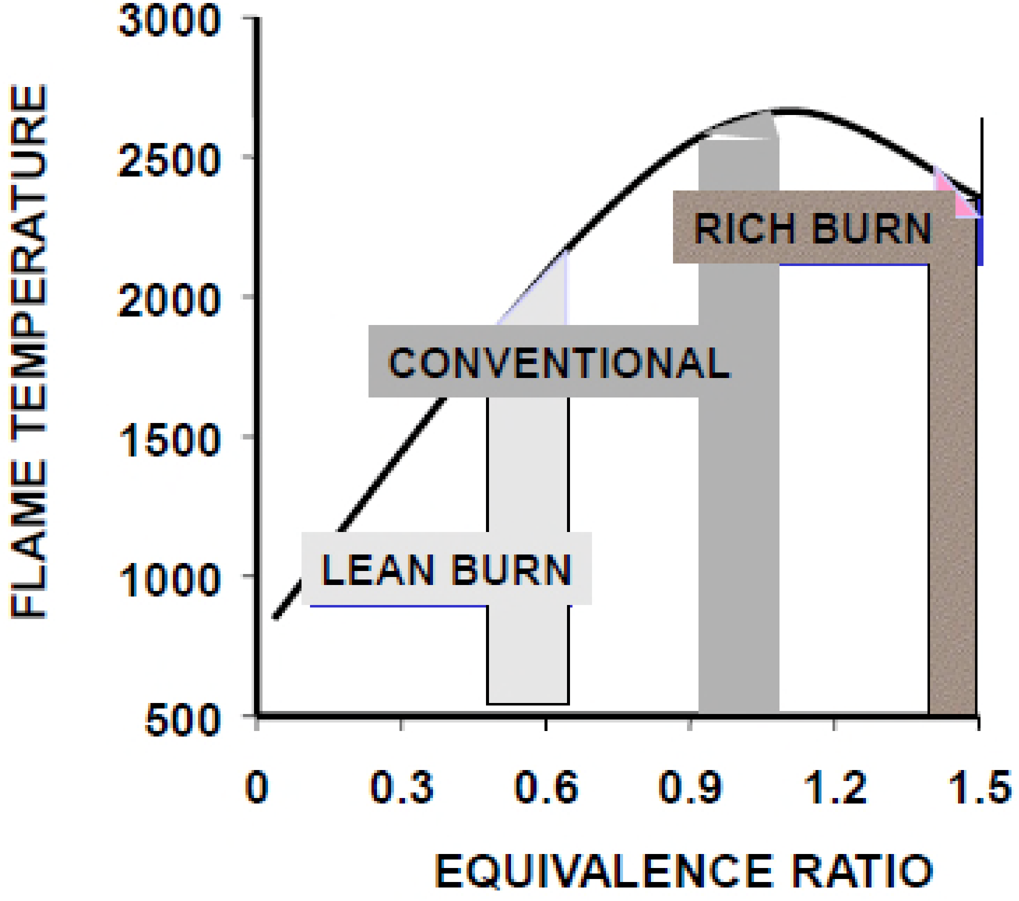
- Increase in ground level UV radiation
- Skin cancer
- Eye disease

Effects of Primary Zone Temperature:

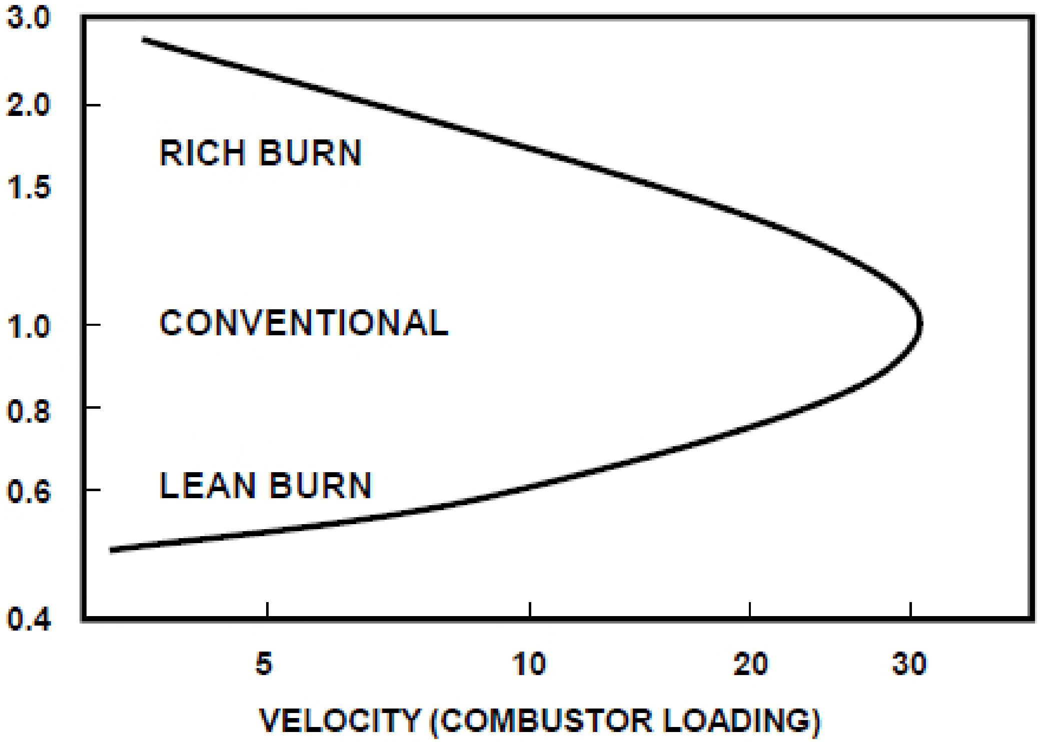
NO_x and CO



Effect of ϕ on Flame Temperature and Stability



Effect of ϕ on Flame Temperature



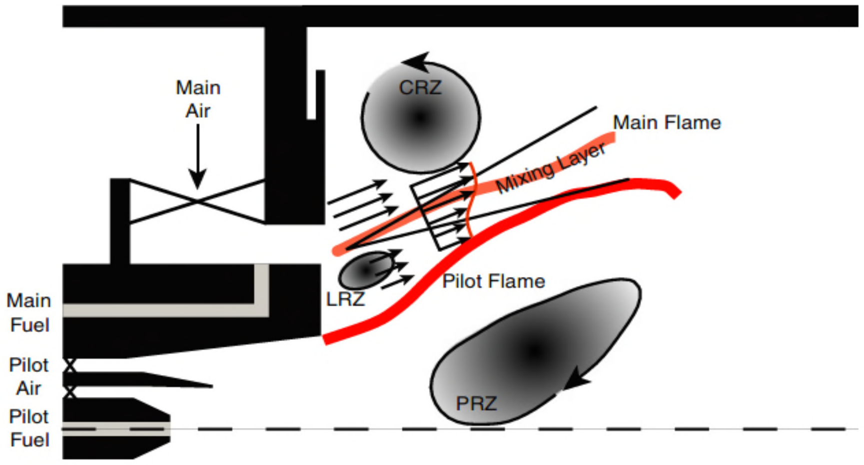
Effect of ϕ on Stability

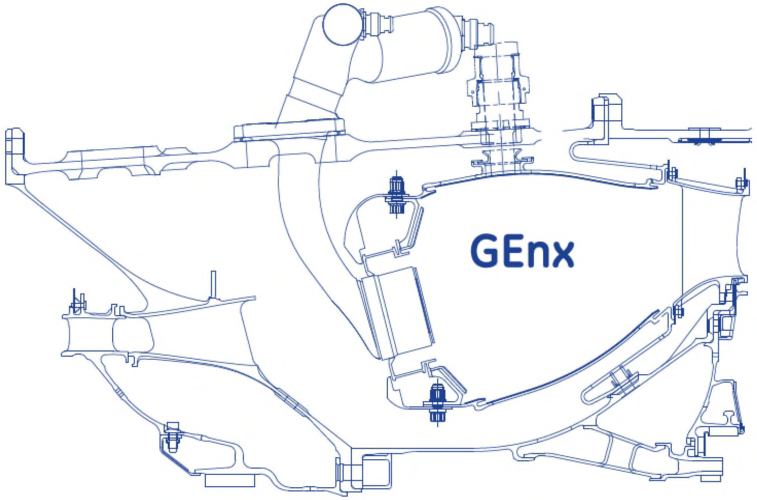
Low Emissions Combustors:

TAPS – Twin Annular Premixing Swirler (GE) (Example of State-of-the-art for Jet A-1)

TAPS Principle:

- Partially premixed main stage
- Internally staged
- Concentric pilot and main stages





Ref: Dhanuka, S.K., Temme, J.E., Driscoll, J.F., and Mongia, H., *"Vortex shedding and mixing layer effects on periodic flashback in a lean premixed prevaporized gas turbine combustor"*, Proceedings of the Combustion Institute, 32(2):2901–2908, 2009

Advantages:

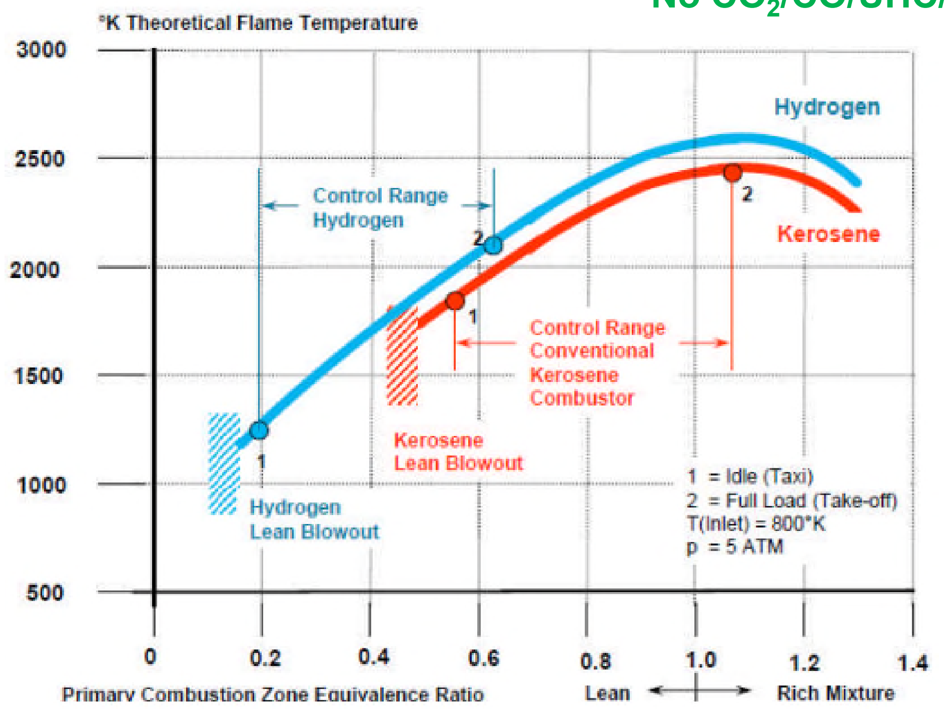
- Low NOx and soot due to lean partial premixing (small cavities reduce risk of auto-ignition)
- Easier control of RTDF rel. to DAC
- Pilot zone recess improves stability (reduces quenching from Main)
- Other than fuel injector design, combustor general arrangement similar to conventional
- High TRL (9)

Design Challenges:

- Ignitor location critical
- Complex fuel injection system
- Relatively larger frontal area of fuel injector $\Rightarrow$ more prone to coking
- Control of periodic unsteadiness resulting from Corner Recirculation Zone (CRZ)
- Control of Lip Recirculation Zone (LRZ) critical to provide good continuous ignition to main (but not too large to increase Tres $\Rightarrow$ NOx$\uparrow$)
- Thermoacoustic issues (Main and Pilot heat release rates)

Hydrogen Micromix Combustion

Why Hydrogen?



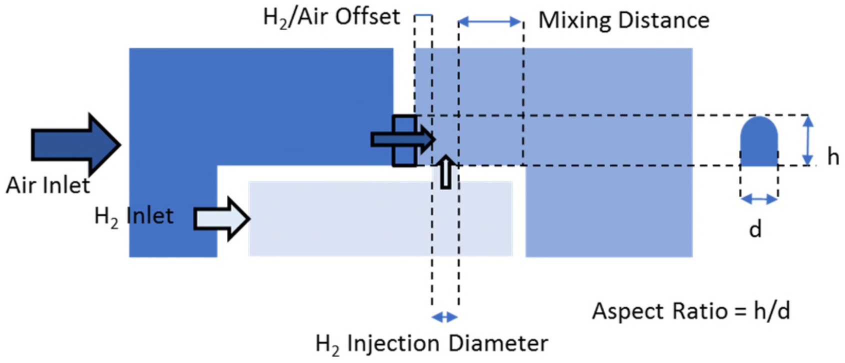
Ziemann J, Mayr A, Anagnostou A, Suttrop F, Lowe M, Bagheri SA, et al. Potential use of hydrogen in air propulsion. EQHHPP, Phase III.0-3. Final report, submitted to European Union (contract no. 5077-92-11 EL ISPD).

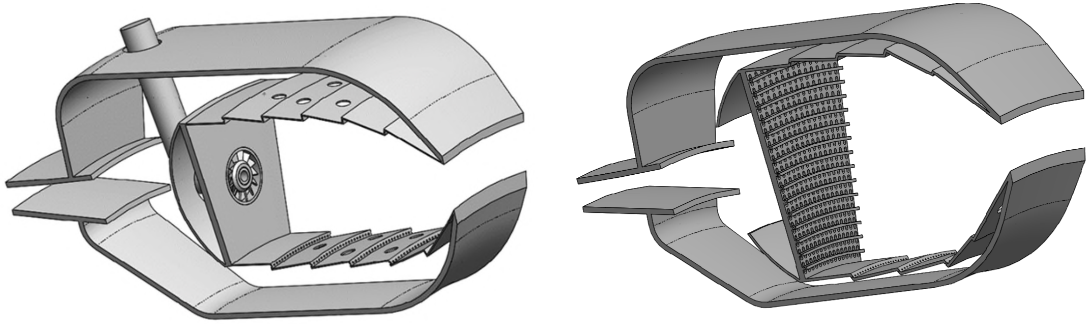
- No Carbon → **No CO_2/CO/UHC/Soot**
- No Carbon → Less Luminous Radiation → **Better liner durability**
- Wider stability limits → Leaner combustion → Lower flame temperature → **Lower thermal NOx**
- Higher burning velocity → Higher reaction rate → Lower residence time → **Lower thermal NOx** / **Shorter combustor**
- Higher diffusivity → Faster mixing → Higher reaction rate

Hydrogen Micromix Combustion

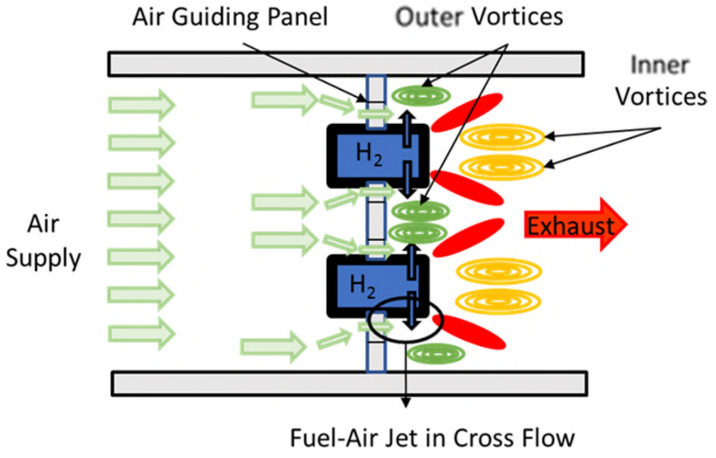
Why Micromix?

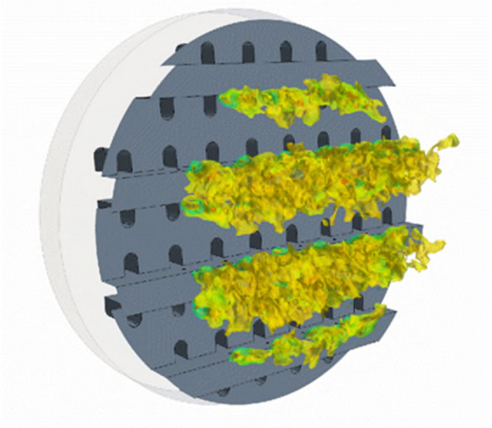
- Mixing length scale minimised while mixing intensity maximised
- Diffusion flame - reduces risk of flashback
- More flexibility for customised fuel scheduling:
    - Tailor outlet temperature distribution (without dilution zone)
    - Control of thermoacoustic instabilities





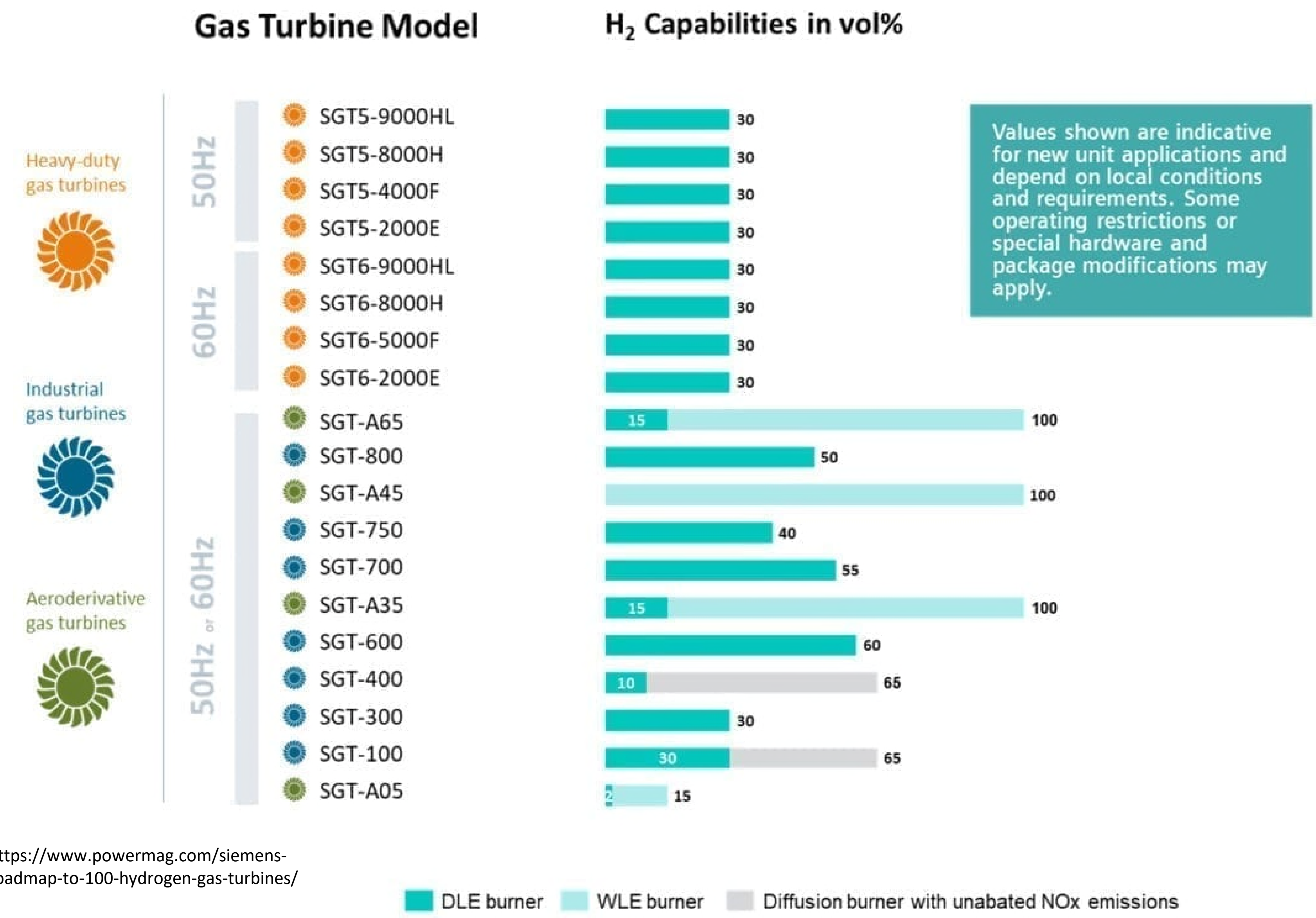
Conventional annular kerosene *vs* micromix combustor (conceptual)





Hydrogen Micromix Combustion

Why Micromix?



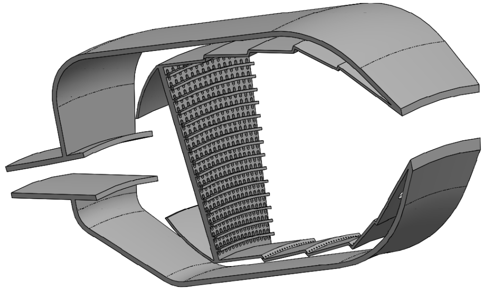
H_2 Micromix Combustion is one of the possible solutions for 100% H_2 (DLE)

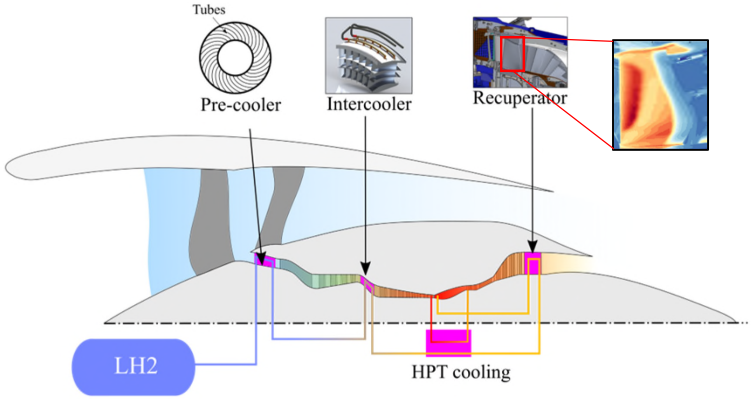
https://www.powermag.com/siemens-roadmap-to-100-hydrogen-gas-turbines/

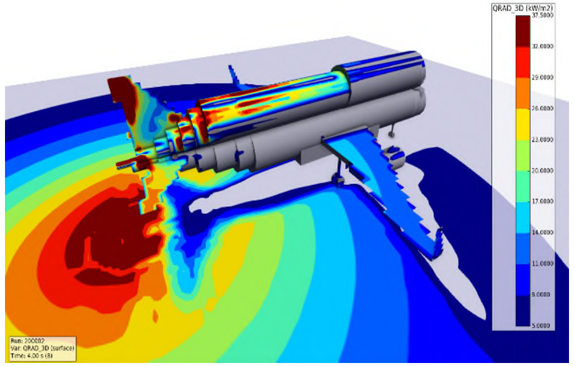
ENABLEH2

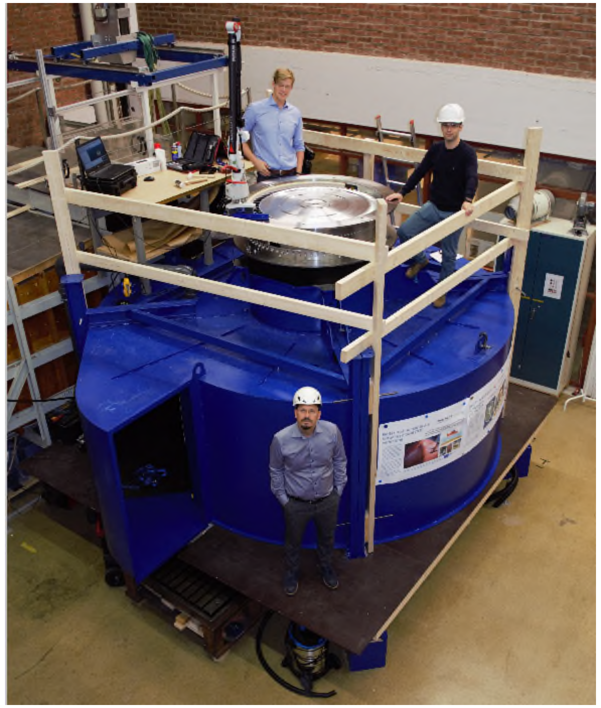
Project Overview

- EU H2020 Project ~4M€, 30+ Key Civil Aviation Stakeholders (partners + industry advisory board members)
- Maturing key enabling technologies for LH_2 which will contribute to decarbonising civil aviation (TRL 2 – TRL4):
    1. Hydrogen micromix combustion – ultra low NOx
    2. Fuel system heat management – exploiting LH_2's formidable heat sink potential
    3. Technology evaluation – Technoeconomic Environmental Risk Assessment (TERA)
- Addressing key challenges/scepticism – economic viability and safety
- Establishing roadmaps for the introduction of LH_2









ENABLEH2 WP3 "H2 Micromix Combustion"

Research Scope

Safety work package

Phase 1: Small-scale injector array tests
- Injector down-selection
- CFD validation & calibration

Phase 2: Full annular combustor segment tests
- Y2050 engine combustor sizing
- Performance characteristics
- NOx emissions

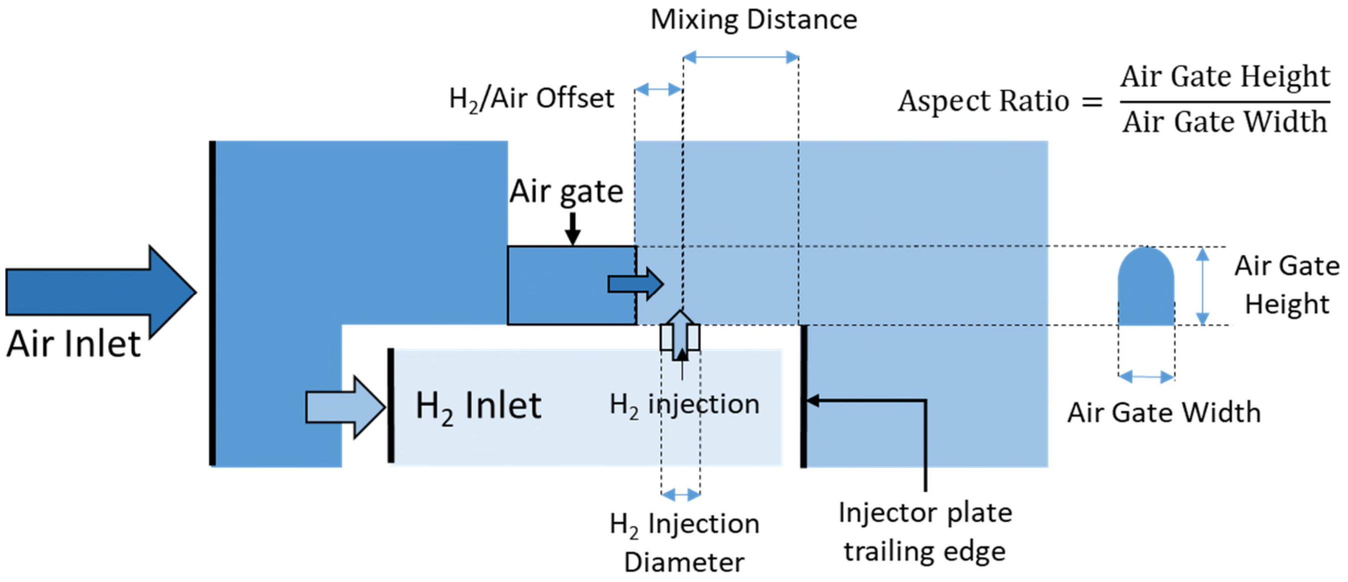
Phase 3: Sub-atmospheric tests
- Altitude relight capability

Hi-fidelity LES

Thermoacoustic instability assessment

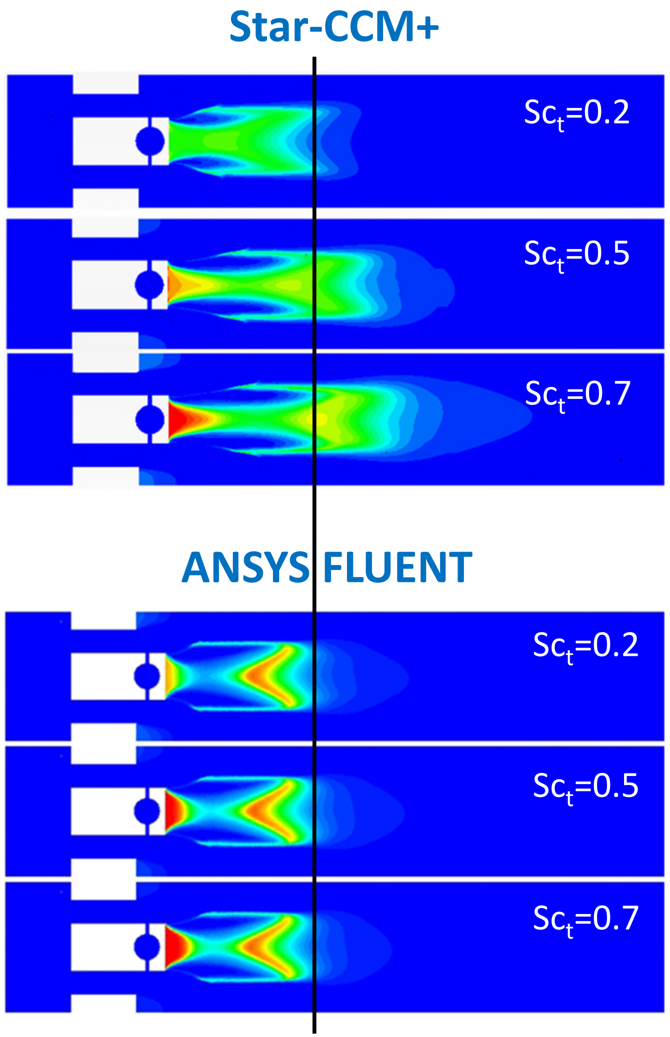
- NOx emissions prediction
- Hydrogen micromix combustor design
(Input for technology evaluator WP)

Micromix injector design



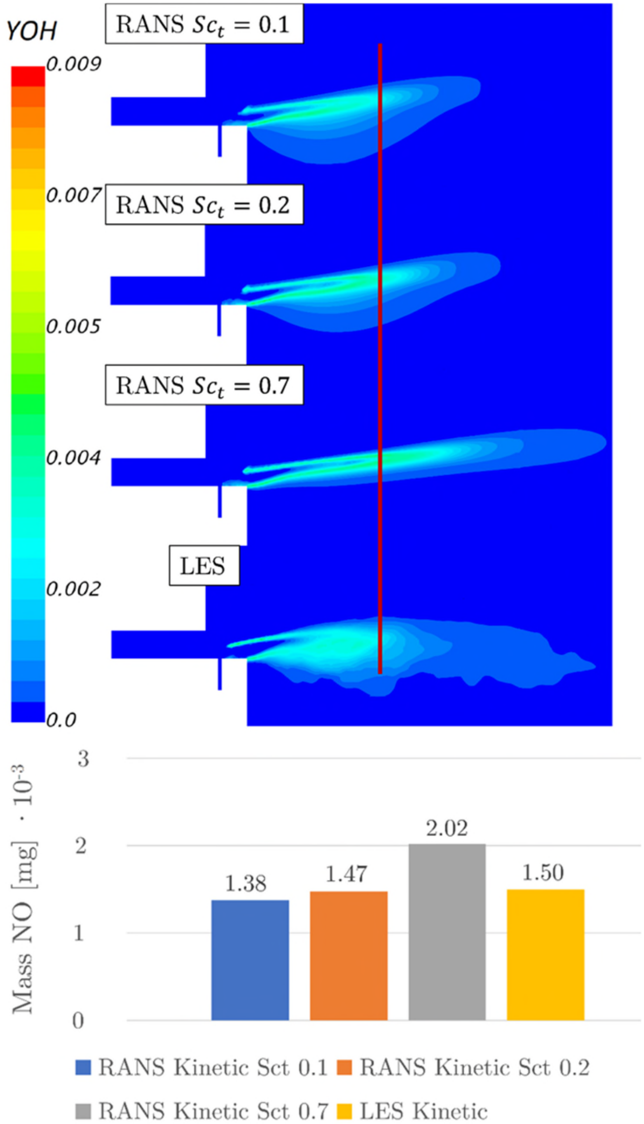
Hydrogen Micromix Combustion

Combustion Model Sensitivity Analysis



OH mass fraction (flame marker)

- For turbulent flow, hydrogen diffusion is a combination of molecular and turbulent diffusion
- For the state-of-the-art combustion model (FGM) with steady simulation, turbulent diffusion is controlled by model constants such as Sc_t
- FGM in Star-CCM+ is more sensitive to Sc_t effects than ANSYS FLUENT, therefore potentially more suitable to be calibrated for hydrogen diffusion modelling
- Would molecular diffusion be negligible within highly turbulent jet in cross flow?



MSc research by M. López Juárez

Hydrogen Micromix Combustion

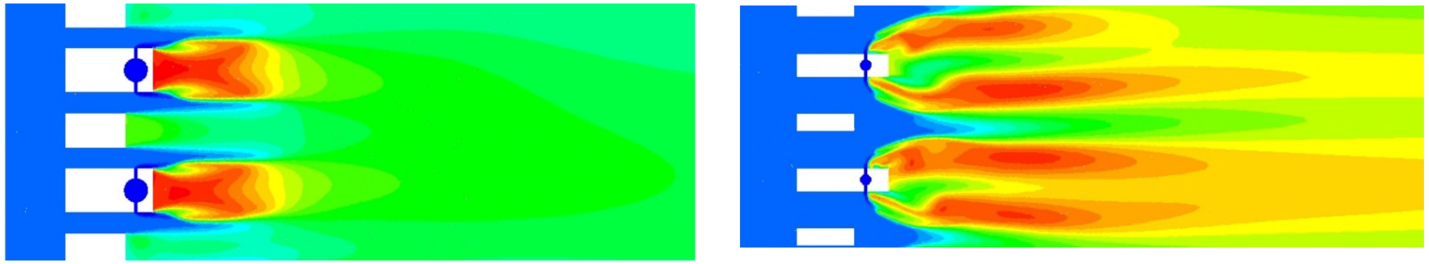
Selected Injectors for Rig Test

Injector Design Selection Criteria

- A range of momentum Flux Ratio (Penetration of H_2 in the air stream)
- Significant flame-flame interaction (attachment) between two H_2 injections with the same feed arm
- No flame-flame interaction with the same feed arm
- Various mixing distance
- Various H_2/air offset distances

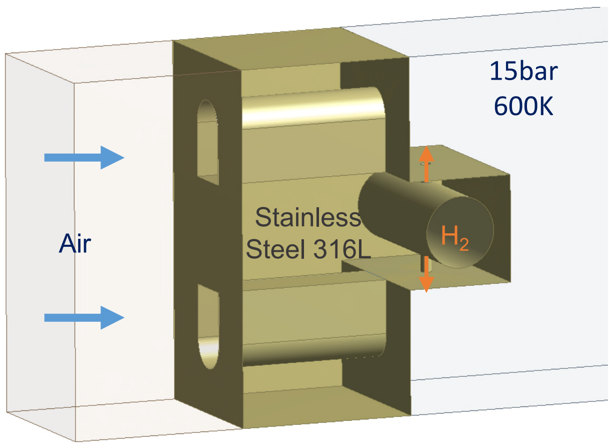
	D (Air) mm	Air Gate Height (mm)	Aspect Ratio	Momentum Flux Ratio	Hydrogen Offset Distance (mm)	Hydrogen Mixing Distance (mm)
Baseline	1.50	2.25	1.50	2.24	1.50	1.50
Design 14	1.18	1.77	1.50	0.85	0.84	1.42
Design 33	2.50	3.25	1.30	17.31	2.00	2.00

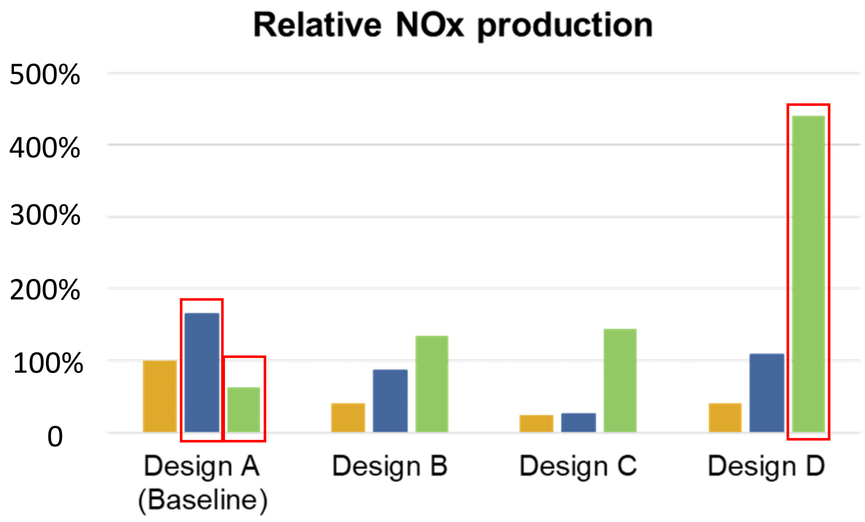
Example of flame patterns at with low (L) and high (R) hydrogen penetration

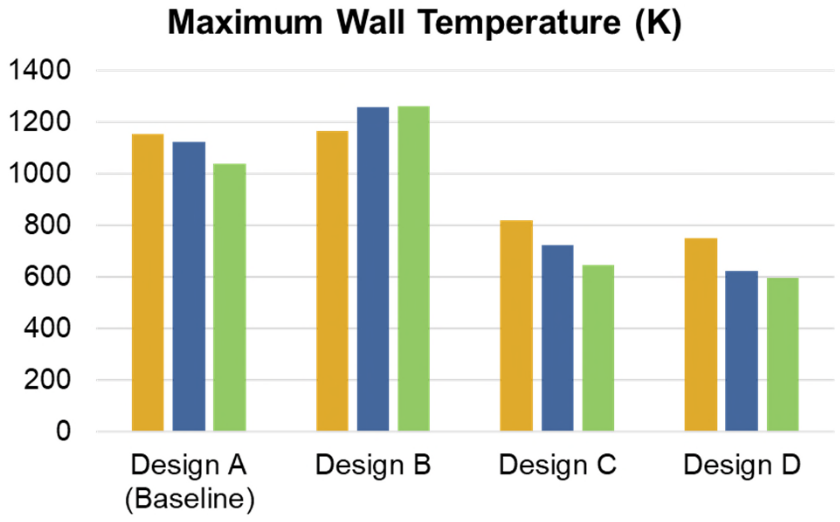


Hydrogen Micromix Combustion

Impact of Momentum Flux Ratio

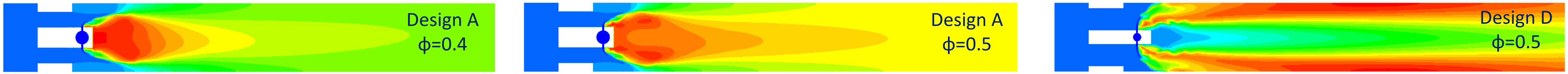






Equivalence ratio ϕ ■ φ=0.3 ■ φ=0.4 ■ φ=0.5

Temperature contour



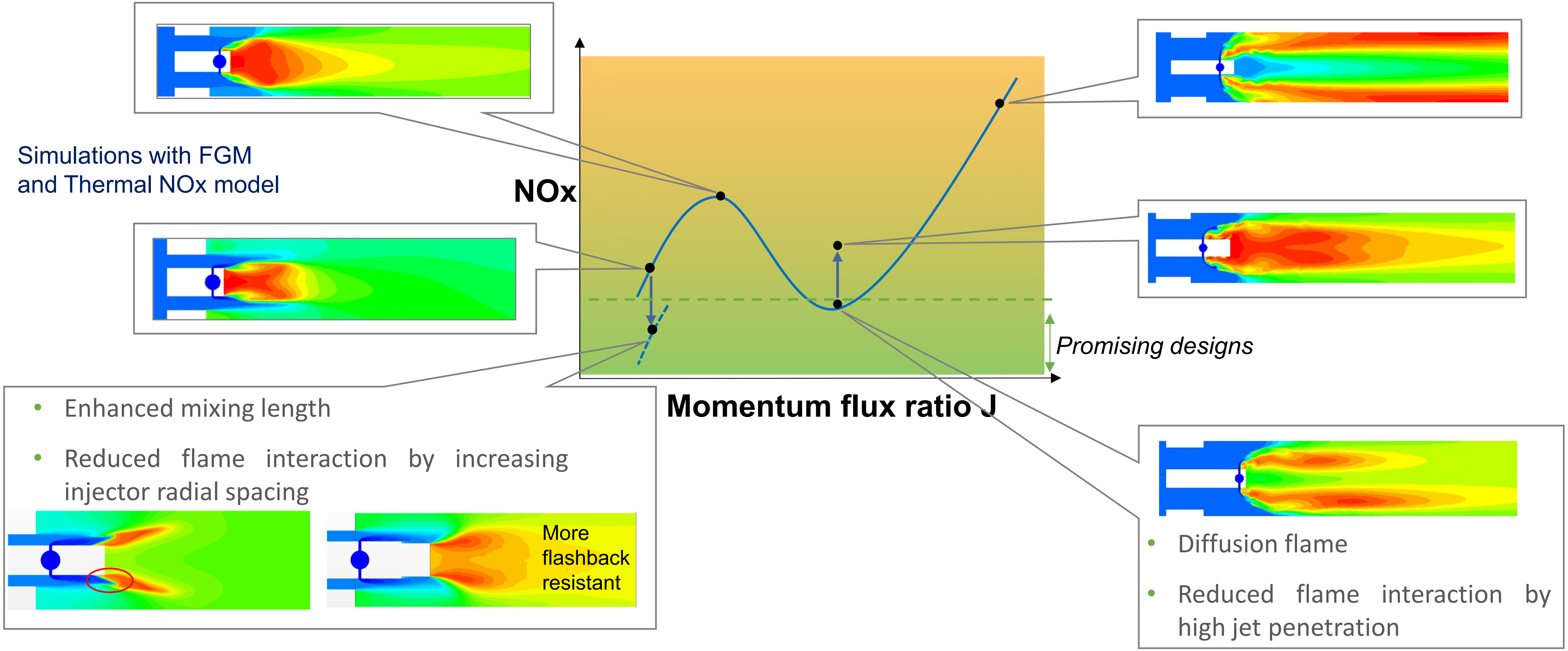
Mass fraction NOx contour

- High wall temperature at low penetration (low momentum flux ratio) due to flame attachment
- NOx strongly dependent on flame interaction and recirculation of hot products

Hydrogen Micromix Combustion

Complex Micromix Injector Design Space

Simulations with FGM and Thermal NOx model

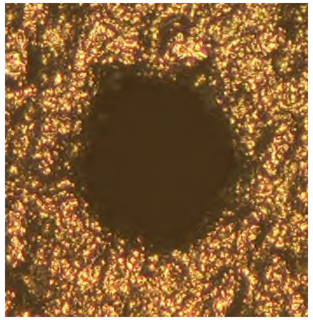


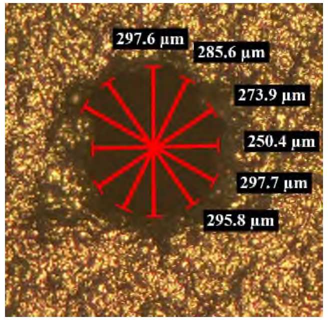
Hydrogen Micromix Combustion

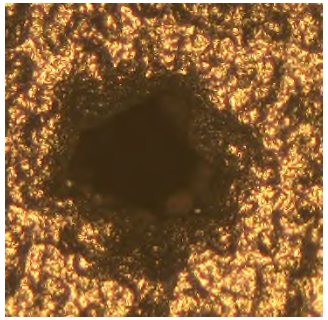
Manufacturing Challenges

Digital Metal SS316L plate using Binder Jetting

Hole diameter	0.3mm	0.5mm
Ave Actual/Design	90.4%	89.0%
Max Actual/Design	97.2%	98.5%
Min Actual/Design	76.7%	81.6%
Ave Standard deviation	17µm	15µm
Max Standard deviation	23µm	30µm
Min Standard deviation	7µm	8µm

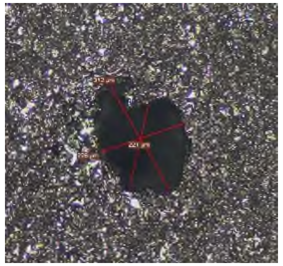


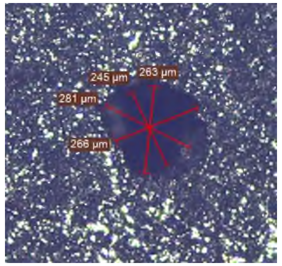


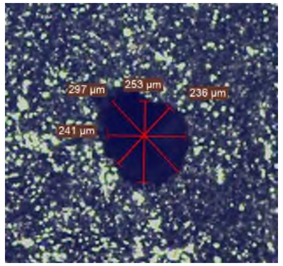


Hieta Inconel 625 plate using Direct Metal Laser Sintering

Hole diameter	0.3mm	0.5mm
Ave Actual/Design	87.2%	95.6%
Max Actual/Design	91.3%	98.6%
Min Actual/Design	84.0%	92.9%
Ave Standard deviation	20µm	13µm
Max Standard deviation	30µm	23µm
Min Standard deviation	10µm	6µm

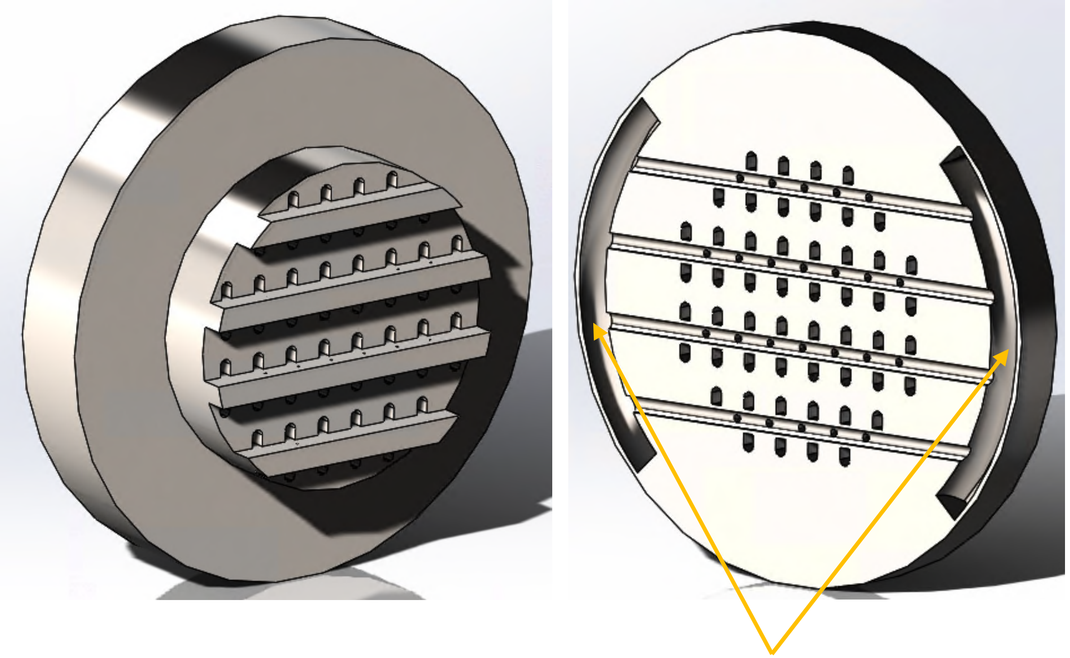


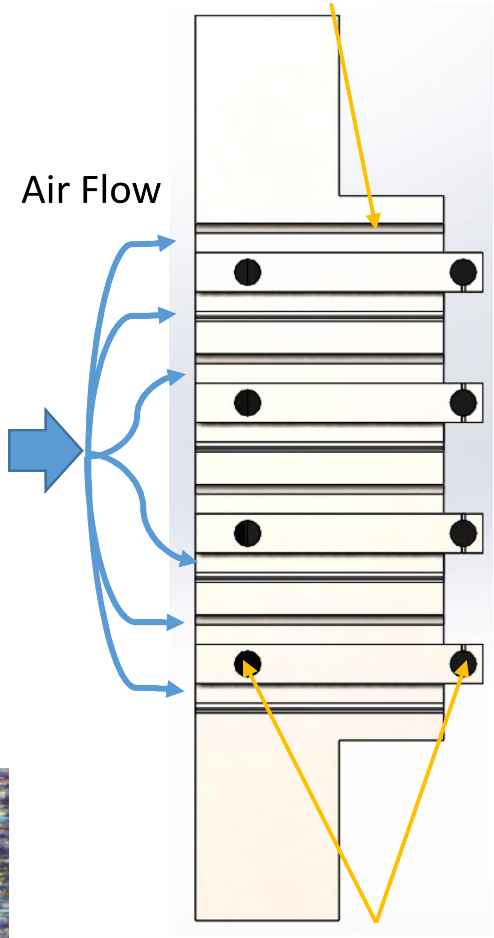


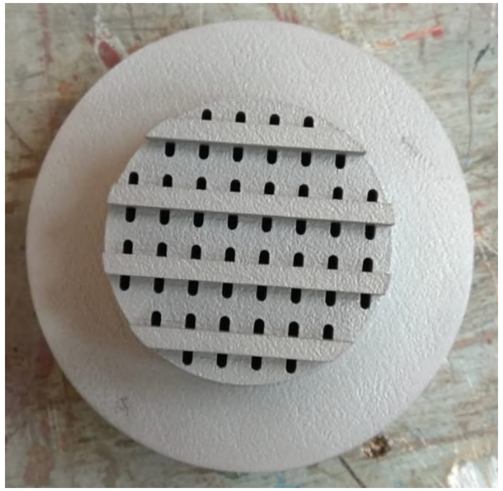


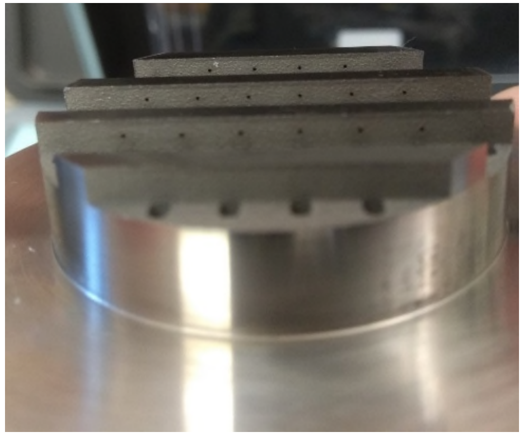
Examples of 0.3mm holes

Hydrogen Micromix Combustion
Manufacturing Choice

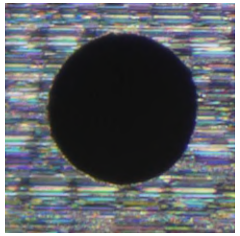






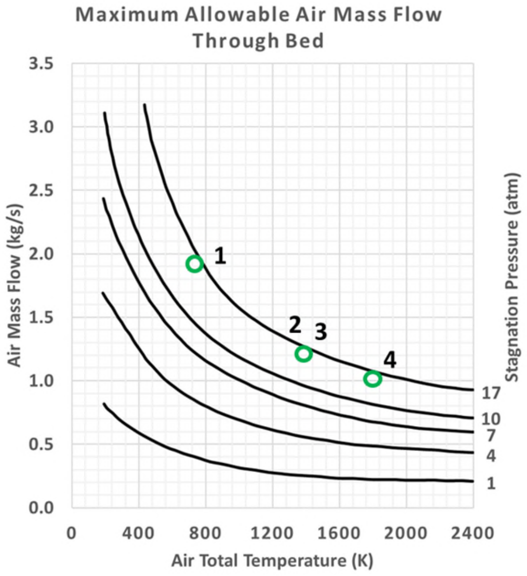


Hybrid manufacturing
3D printed plates (compromise on air gate)
Micro EDM hole drilling (D±10 microns)



Hydrogen Micromix Combustion

Phase 1 Experimental Rig: Pebble Bed Facility



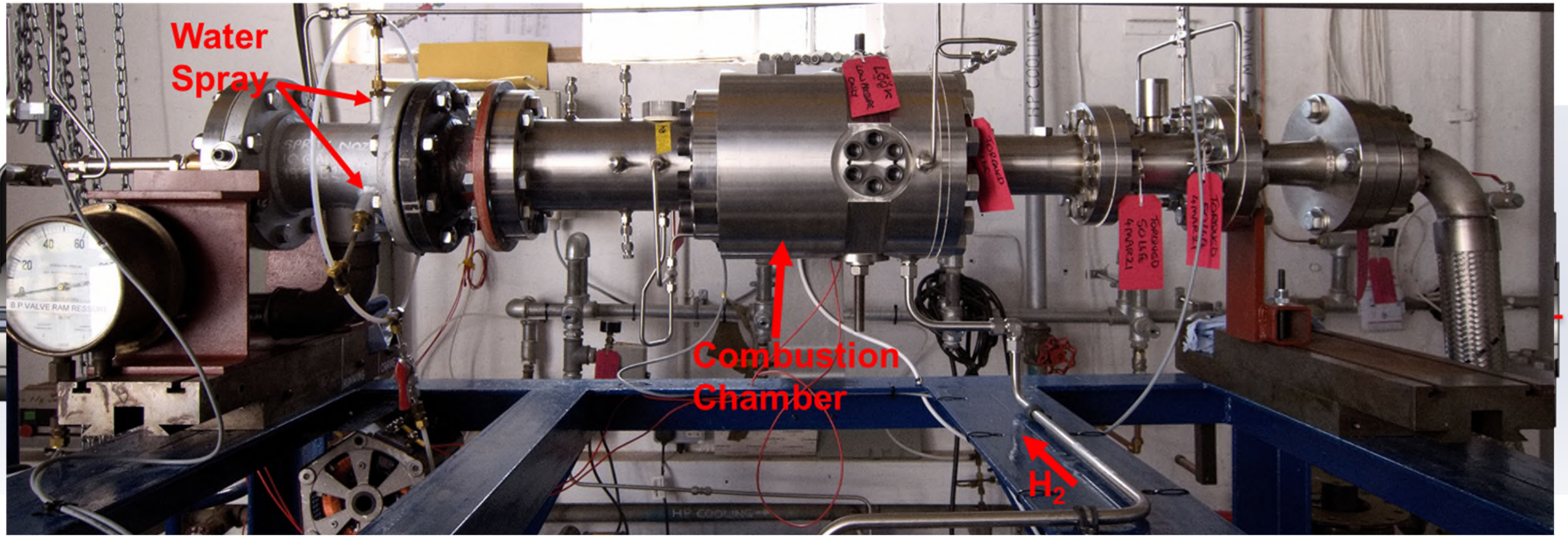
Condition No.	1	2	3	4
Pressure (bar)	15	15	15	15
Bed air temperature (K)	725	1400	1400	1800
Bed air mass flow (kg/s)	1.90	1.17	1.17	1.05
Dilution air mass flow (kg/s)	0.00	2.43	1.83	1.80
Test section inlet mass flow (kg/s)	1.90	3.60	3.00	2.85
Test section inlet temperature (K)	725	660	725	850

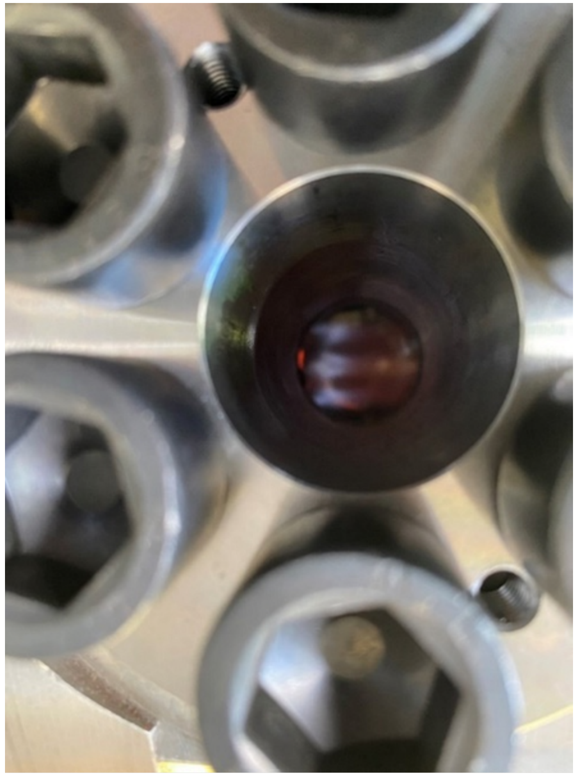
- Provides high mass flow, high temperature, high pressure non-vitiated air at representative gas turbine combustor inlet conditions
- It can be used for experimental R&D for both liquid (reacting and non-reacting) and gaseous (hydrogen and other) fuel low emissions combustion systems
- Data acquisition via state-of-the-art laser diagnostic, spray, thermoacoustic and gas analyser instrumentation
- Data generated is being used to evaluate, validate and calibrate SOA spray and combustion models in commercial CFD packages (e.g., STAR-CCM+)

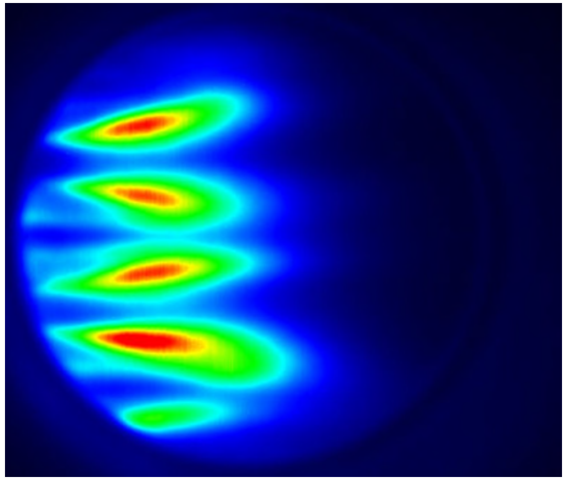
CU is certified with H&S standard: OHSAS18001 to run large scale experiments

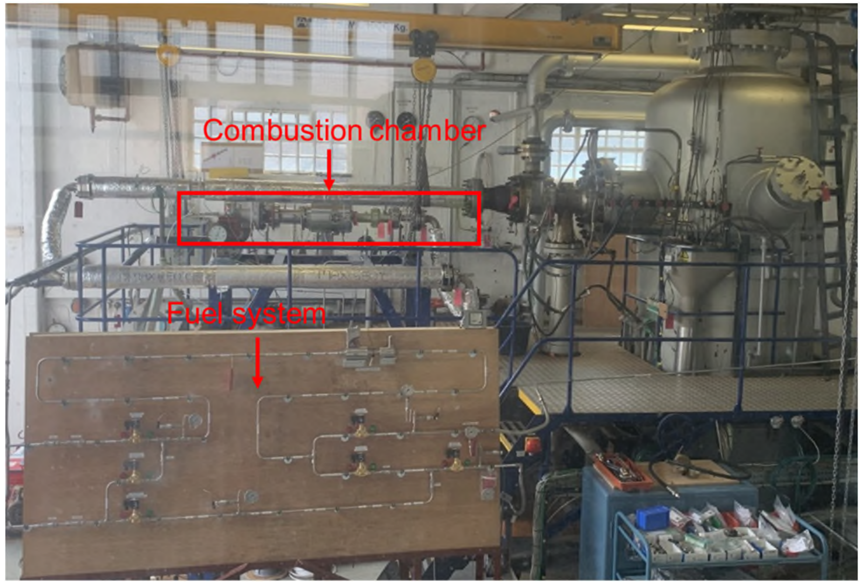
Hydrogen Micromix Combustion

Phase 1 Experimental Rig



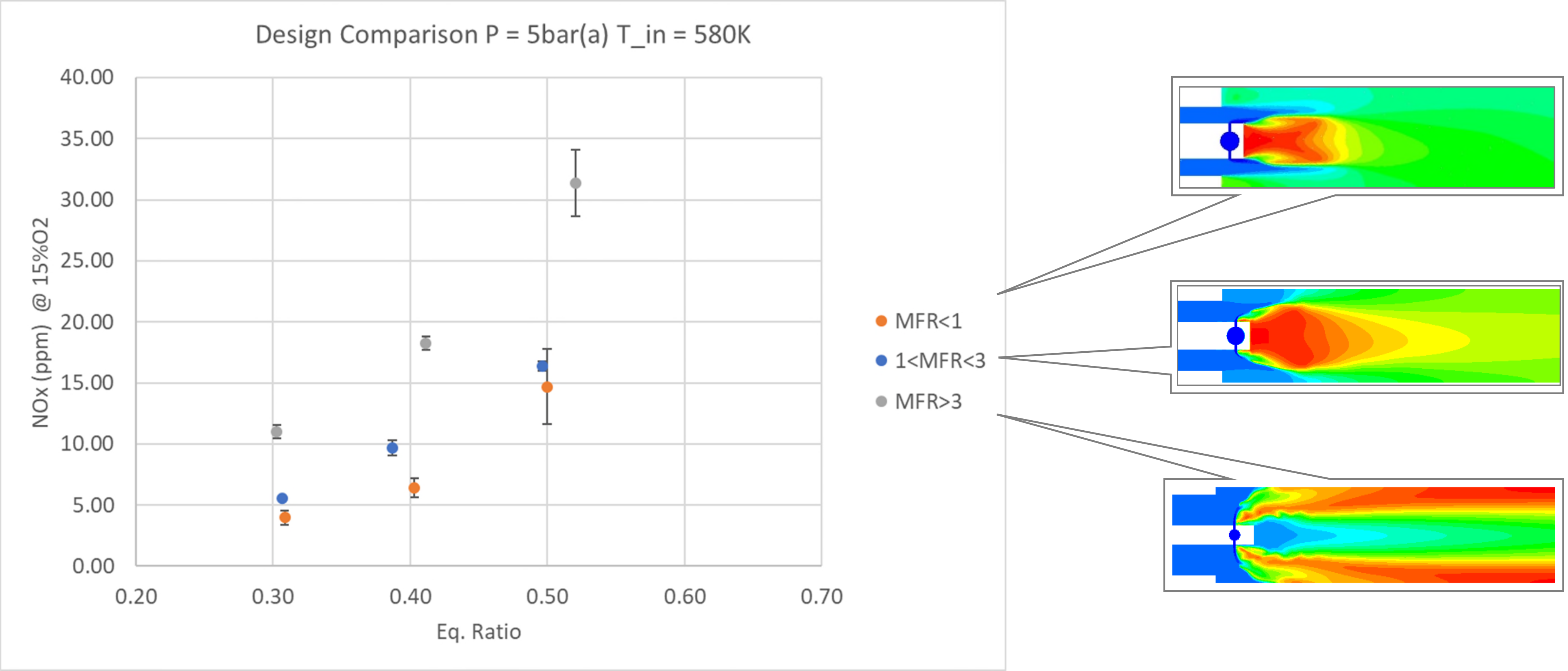






Hydrogen Micromix Combustion

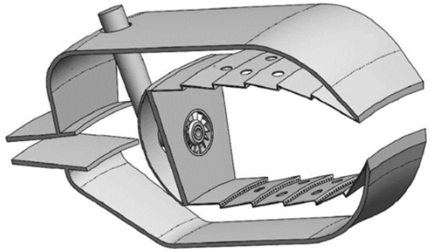
Preliminary Experimental Results



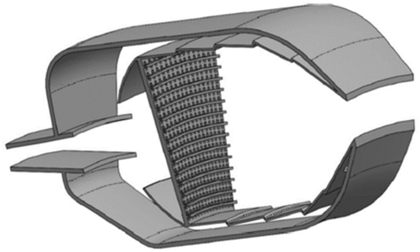
- Lower Momentum Flux Ratio (MFR) designs produces significantly lower NOx
- Above 0.4 (DP), equivalence ratio effect more significant

Hydrogen Micromix Combustion

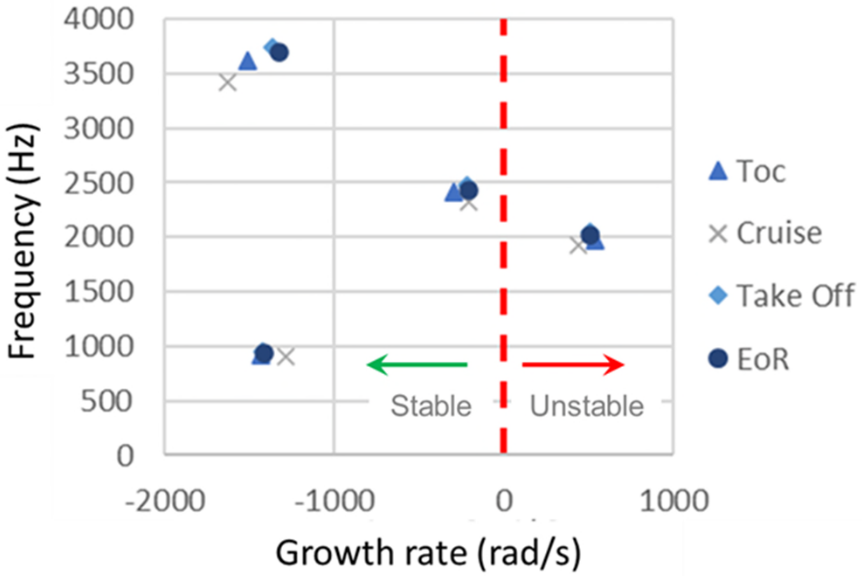
Thermoacoustic Instabilities Analysis



Conventional Combustor



Hydrogen Micromix Combustor

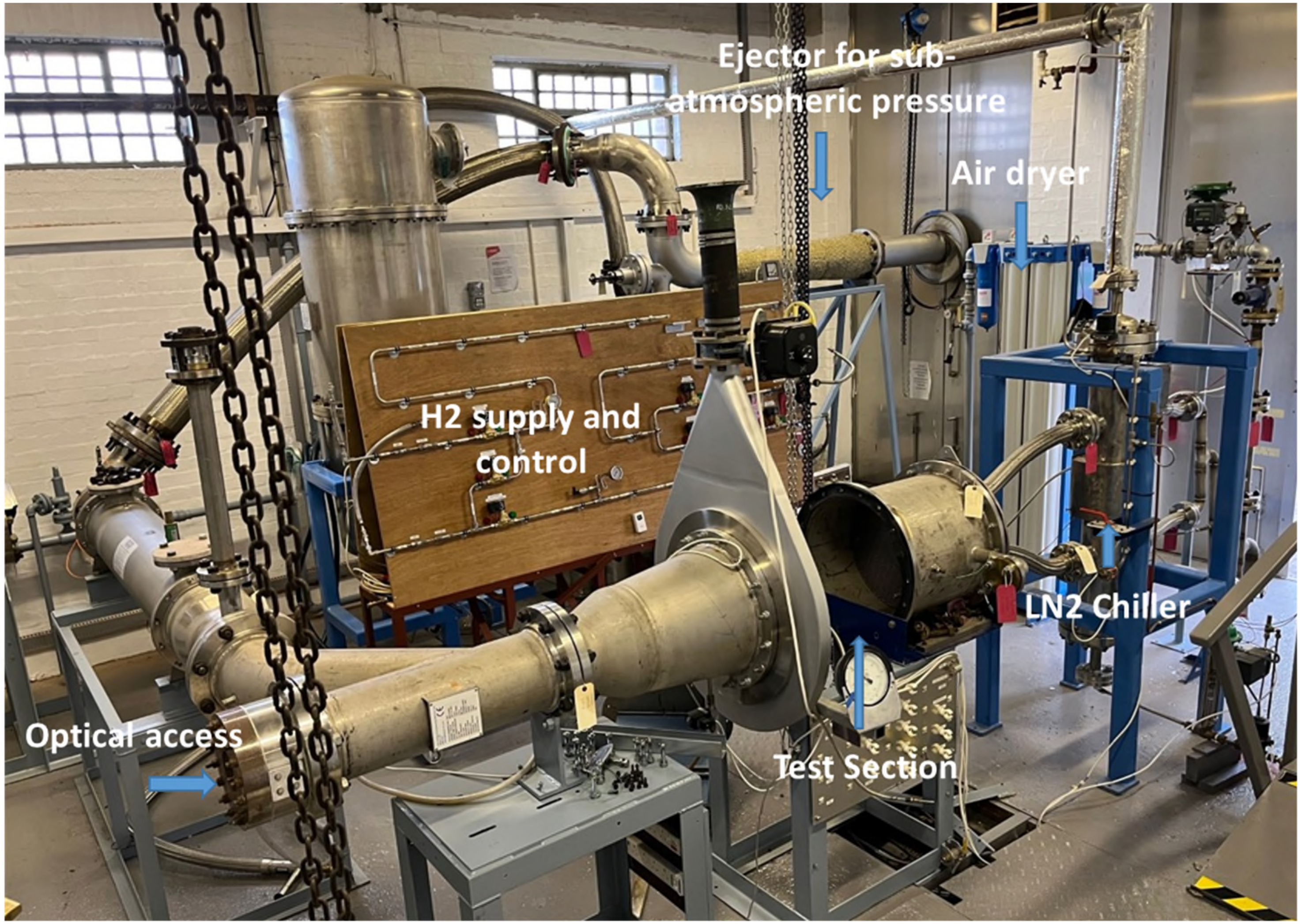


- Flame response (FTF) can be determined using RANS CFD or LES, but experimental validation needed to confirm most appropriate method
- Analysis to date suggests hydrogen micromix is less likely to produce thermoacoustic instabilities than LPP kerosene combustion, particularly at low frequency
- Micromix combustion can produce thermoacoustic instabilities, but high frequencies modes above about 1kHz tend to be favoured due to short characteristic flame times
- Unstable modes may be mitigated by combustor design

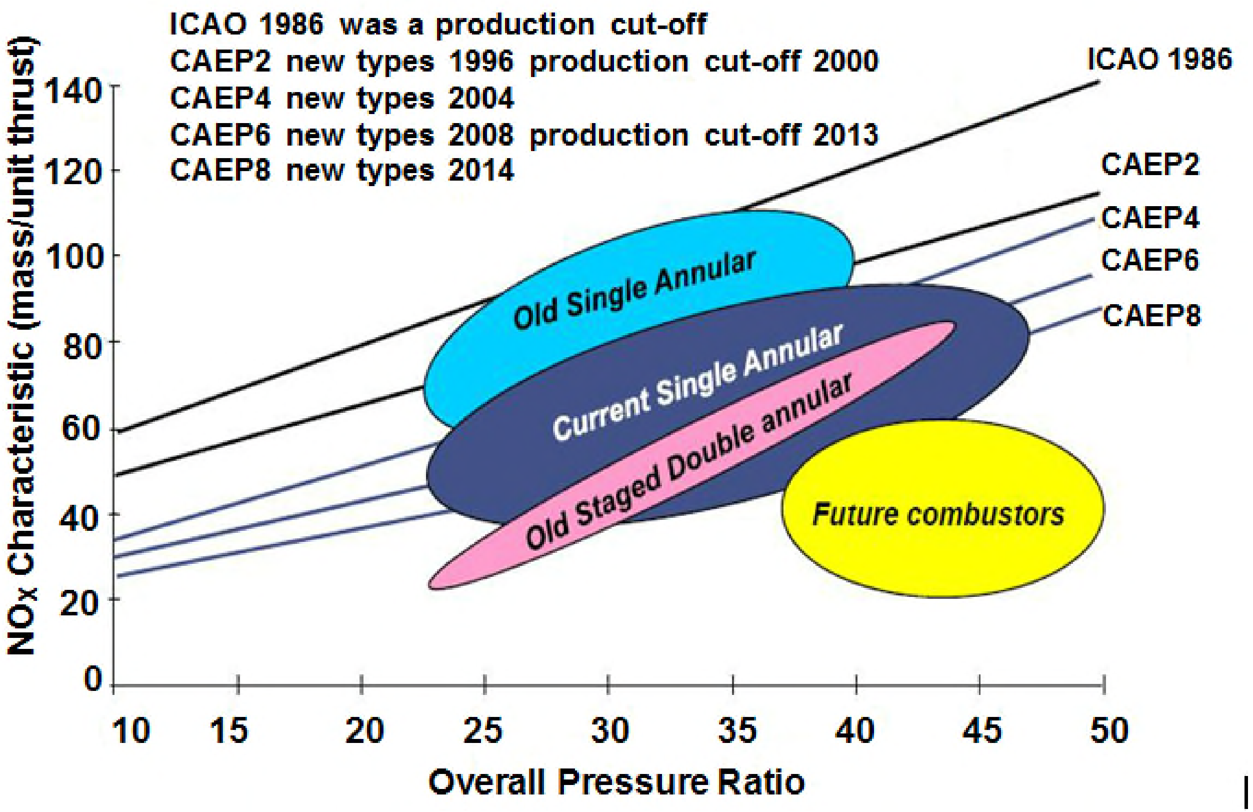
Hydrogen Micromix Combustion

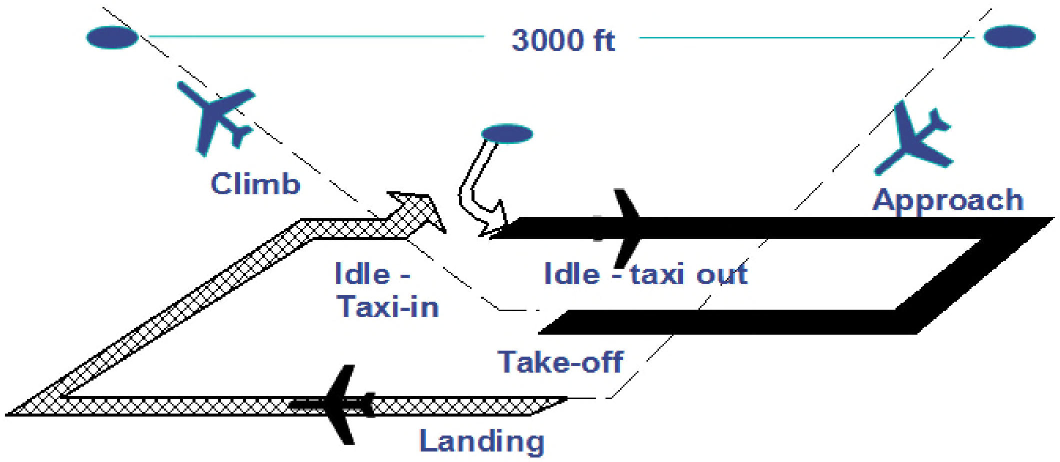
Phase 3 – Altitude Relight Rig

- Pressure and temperature corresponding to four altitude conditions 15000-30000 ft.
- Various combustor inlet Mach and FAR
- Lean Blow-out and Relight will both be tested
- Visualisation of flame (from downstream) with temperature measurement to assess success of ignition
- Rig commissioning in progress



ICAO Technology Certification / Goals for NOx





Typical Operation

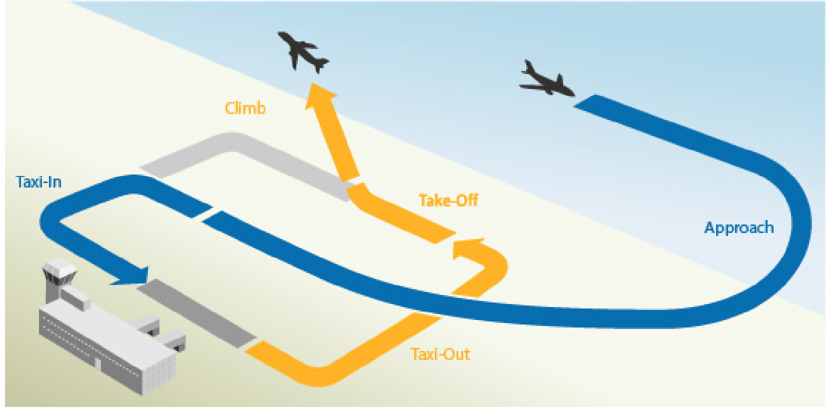
	Power Setting (%)	Time in Mode (min)
Taxi (In and Out)	7	26
Final Approach	30	4
Take-Off	100	0.7
Climb	85	2.2

P. Madden, "CAEP Combustion Technology Review Process and CAEP NOx Goals," Rolls-Royce, 7 2014.

Quantifying NOx Emissions: Metrics

LTO cycle test measured data

- **Emission Index (g NOx/kg fuel)**



- LHV of hydrogen is ~2.8 times of Jet-A1
- For same engine cycle, ~65% less fuel in mass is needed if burning hydrogen
- EINOx is no longer a fair comparison

ICAO certification standard

- **Dp/Foo (g NOx/kN)**
  - Independent of fuel mass flow rate (No correction required)
  - Can be retained for different types of fuel

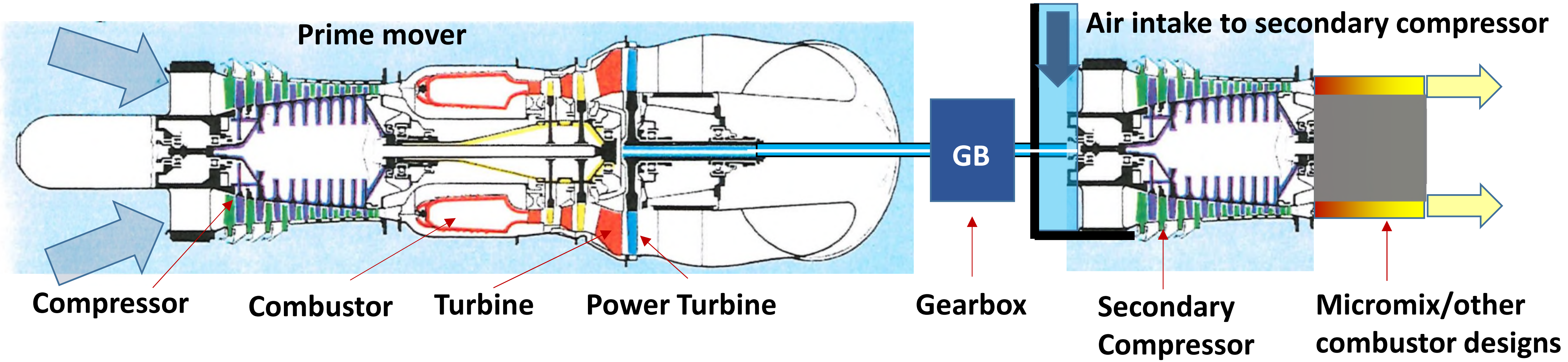
- **Energy Emission Index for NOx:**
  EEINOx (g NOx/MJ)
  - NOx produced can be compared on energy base for different fuels

Low NOx Hydrogen Combustion:
Research Gaps and Work Beyond ENABLEH2

- Flow physics - hydrogen-air mixing, reaction and flashback (addressing lessons learnt from ENABLEH2) – RANS, LES and DNS
- Alternative hydrogen combustion technologies development (first generation and ultra-low NOx)
- Advanced manufacturing methods for H_2 combustion systems (for cost effective manufacturing of intricate designs of fuel systems) (building on ENABLEH2)
- Fuel staging and control of H_2 micromix combustion systems (exploiting the potential of fuel staging to improve combustor performance, emissions and thermoacoustics as well as turbine blade life) (building on ENABLEH2)
- Annular combustor segment testing of H_2 micromix combustion systems (at elevated temperatures and pressures) using ENABLEH2 H2 rigs (performance, emissions, thermoacoustics etc.) (complementing numerical studies providing data for validation)

Low NOx Hydrogen Combustion:
Research Gaps and Work Beyond ENABLEH2

- Conversion of CU 1 MW gas turbine combustion, fuel and control system from Jet A-1 to H_2
- Ground-level performance and emissions analysis of H_2 fuelled 1 MW Gas Turbine
- Provide support to engine and aircraft OEMs to better define hydrogen combustion systems (either Micromix or other concepts) for large engines



Cranfield University Micromix Combustion Publications

1	P Murthy, B Khandelwal, V Sethi, R Singh	Hydrogen as a Fuel for Gas Turbine Engines with Novel Micromix Type Combustors	47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA-2011-5806	2011
2	B Khandelwal, Y Li, P Murthy, V Sethi, R Singh	Implication of Different Fuel Injector Configurations for Hydrogen Fuelled Micromix Combustors	ASME Turbo Expo GT2011-46845	2011
3	R Ben Abdallah, V Sethi, P Q Gauthier, A Rolt, D Abbott	A Detailed Analytical Study of Hydrogen Reaction in a Novel Micromix Combustion System	ASME Turbo Expo GT2018-76586	2018
4	P Agarwal, X Sun, P Q Gauthier, V Sethi	Injector Design Space Exploration for an Ultra-low NOx Hydrogen Micromix Combustion System	ASME Turbo Expo GT2019-90833	2019
5	J McClure, D Abbott, P Agarwal, X Sun, G Babazzi, V Sethi, P Gauthier,	Comparison of Hydrogen Micromix Flame Transfer Functions Determined Using RANS and LES	ASME Turbo Expo GT2019-90538	2019
6	M López-Juárez, X Sun, B Sethi, P Gauthier, D Abbott	Characterising Hydrogen Micromix Flames: Combustion Model Calibration and Evaluation	ASME Turbo Expo GT2020-14893	2020
7	X Sun, P Agarwal, F Carbonara, D Abbott, P Gauthier, B Sethi	Numerical Investigation into the Impact of Injector Geometrical Design Parameters on Hydrogen Micromix Combustion Characteristics	ASME Turbo Expo GT2020-16084	2020
8	M Zghal, X Sun, P Q Gauthier, V Sethi	Comparison of Tabulated and Complex Chemistry Turbulent-Chemistry Interaction Models with High Fidelity Large Eddy Simulations on Hydrogen Flames	ASME Turbo Expo GT2020-16070	2020
9	A Giannouloudis, X Sun, M Corsar, S Booden, G Singh, D Abbott, D Nalianda, B Sethi	On the Development of an Experimental Rig for Hydrogen Micromix Combustion Testing	European Combustion Meeting	2021
10	D Abbott, A Giannotta, X Sun, P Gauthier, V Sethi	Thermoacoustic Behaviour of a Hydrogen Micromix Aviation Gas Turbine Combustor under Typical Flight Conditions	ASME Turbo Expo GT2021-59844	2021
11	X Sun, D Abbott, A V Singh, P Gauthier, B Sethi	Numerical Investigation of Potential Cause of Instabilities in a Hydrogen Micromix Injector Array	ASME Turbo Expo GT2021-59842	2021
12	J Berger	Scaling of an Aviation Hydrogen Micromix Injector Design for Industrial GT Combustion Applications	Aerotecnica Missili & Spazio, 2021, 100(3): 239-251.	2021
13	X Sun, H Martin, P Gauthier, B Sethi	Sensitivity Study on Species Diffusion Models in Turbulent Combustion of Hydrogen/Air Jet in Crossflow Structure	ASME Turbo Expo GT2022-83097	2022

ENABLE H2

The ENABLEH2 project is receiving funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 769241

Thank you!

Cranfield University

London South Bank University

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This project has received funding from the EU Horizon 2020 research and innovation programme under GA n° 769241