Enabling Cryogenic Hydrogen-Based CO_2-free Air Transport (ENABLEH2)

Deutsche Gesellschaft für Luft- und Raumfahrt Lilienthal-Oberth e.V. Bezirksgruppe Hamburg

Royal Aeronautical Society Hamburg Branch e.V.

ZAL

VDI Verein Deutscher Ingenieure Hamburger Bezirksverein e.V. Arbeitskreis Luft- und Raumfahrt

HAW Hamburg

Hamburg Aerospace Lecture Series
Hamburger Luft- und Raumfahrtvorträge

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Associate Prof. in Gas Turbine Combustion and Environmental Impact

Centre for Propulsion Engineering, School of Aerospace, Transport and Manufacturing

Cranfield University

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RAeS Hamburg in cooperation with the DGLR, HAW, VDI, & ZAL invites you to a lecture

Enabling Cryogenic Hydrogen-Based CO2-Free Air Transport

Dr **Bobby Sethi,** Associate Professor in
Gas Turbine Combustion and Environmental Impact, Cranfield University

Date:
Thursday 6 May 2021, 18:00 CEST

Online:
http://purl.org/ProfScholz/zoom/2021-05-06

Lecture followed by discussion
No registration required !
Online Zoom lecture

Long Range Aircraft, Maximum Synergy.
ENABLEH2 *copyright*

Greening civil aviation is key to our global future. So radical aircraft propulsion technologies must be developed urgently. Most likely to succeed in this grand challenge (promising full decarbonisation) are hydrogen (H2) and electrification. H2 is an inevitable solution for a fully sustainable aviation future, via hybrid/fuel cell technologies for short to medium range and H2 combustion in gas turbines for longer missions.

This presentation will provide an overview of the ongoing EU H2020 "ENABLing CryogEnic Hydrogen-Based CO2-free Air Transport" (ENABLEH2) project being coordinated by Cranfield University. The case for LH2 for civil aviation will be discussed followed by the strategic importance and overall scope of ENABLEH2. A summary of the key achievements to date will presented for the ENABLEH2 research on: Ultra-low NOx hydrogen micromix combustion; Fuel system heat management – to exploit the formidable heat sink potential of LH2; Safety and LH2 Aircraft "Technology Evaluation"

Upon completion of his PhD, Bobby joined the School of Engineering as a Research Fellow and was promoted to Lecturer in 2012. In 2019 he became Deputy Director of Research, School of Aerospace, Transport & Manufacturing and in 2020 he also became Associate Professor in Gas Turbine Combustion and Environmental Impact. He is currently Overall Project Coordinator and CU Principal Investigator for the ~ €4M EU H2020 "ENABLing CryogEnic Hydrogen-Based CO2-free Air Transport" ENABLEH2 project (20+ key EU civil aviation stakeholders – partners and industry advisory board members).

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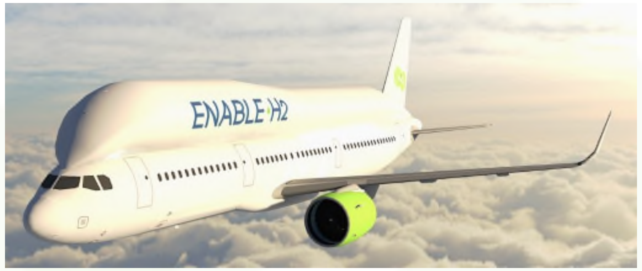
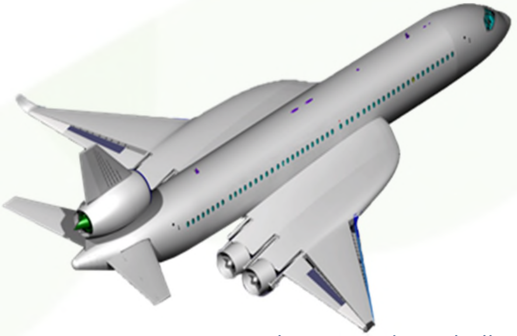
    - WP3: Hydrogen Micromix Combustion
    - WP4: Safety
    - WP5: Roadmapping, Thought Leadership and Impact





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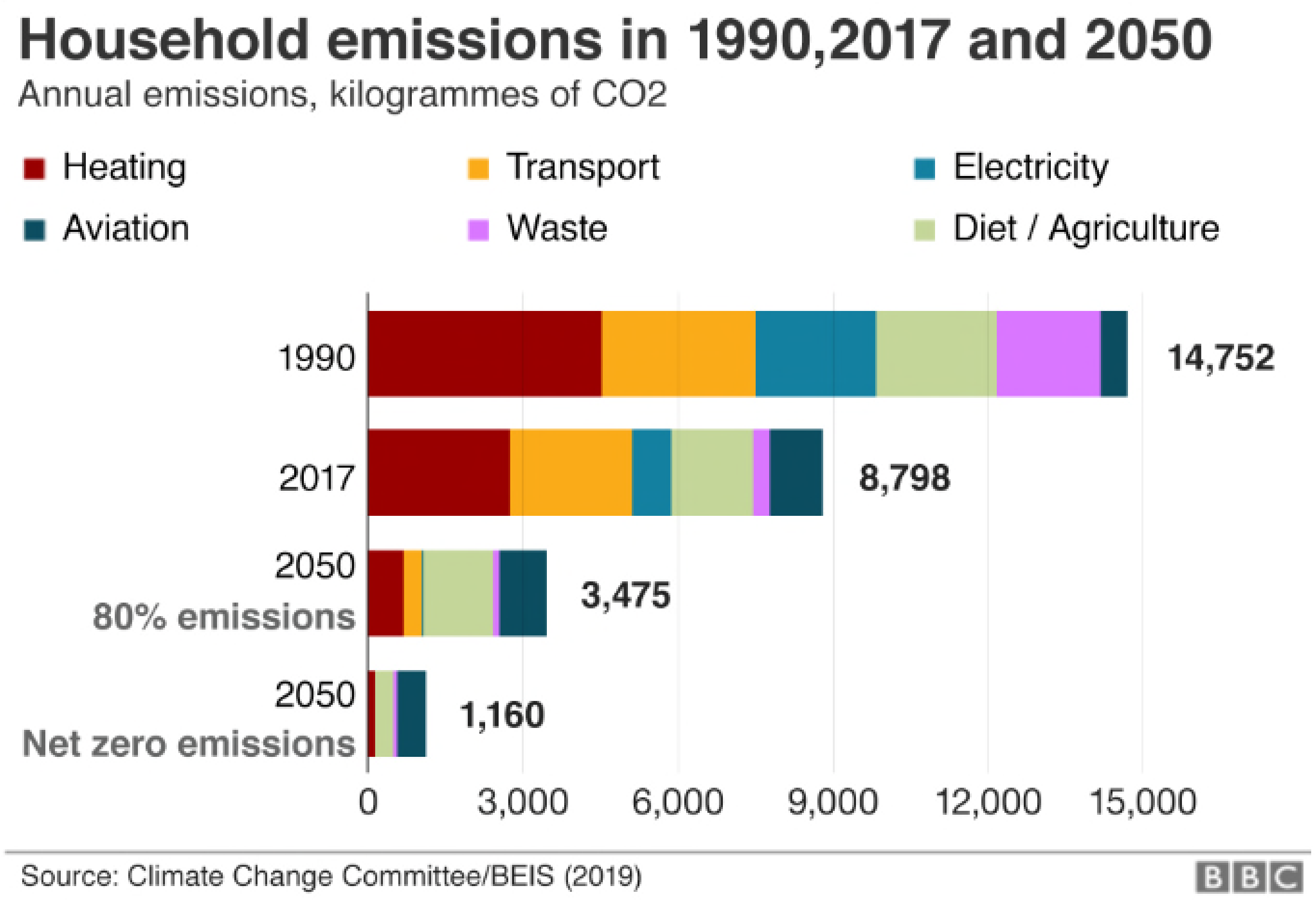
https://www.enableh2.eu

ENABLEH2 Strategic Importance:
The need to Decarbonise Civil Aviation



https://www.bbc.co.uk/news/science-environment-48122911

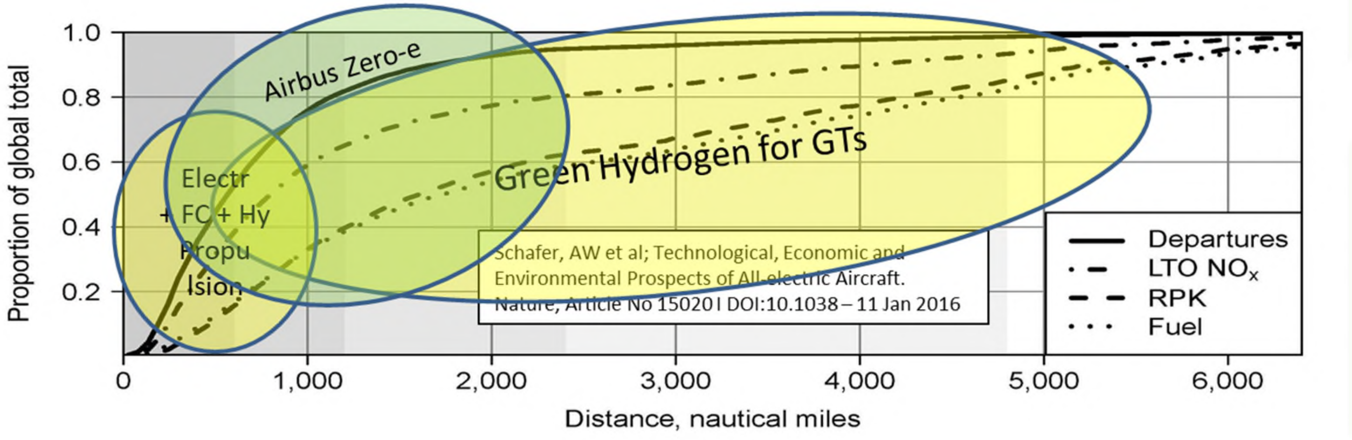
Don't curtail flying!

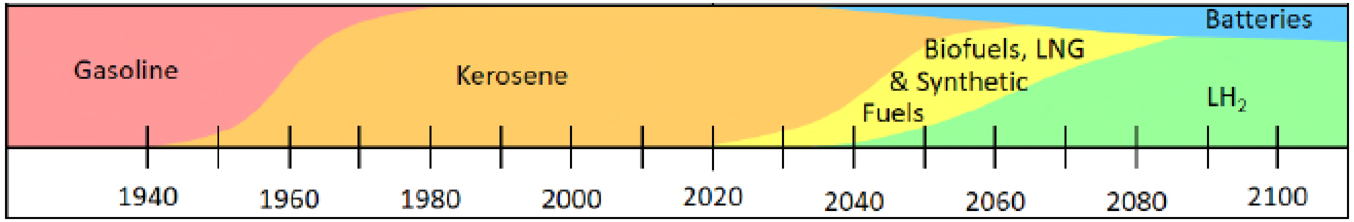
Example: Barbados – 45% of GDP is tourism

Technology investments to protect
the environment AND wealth generation

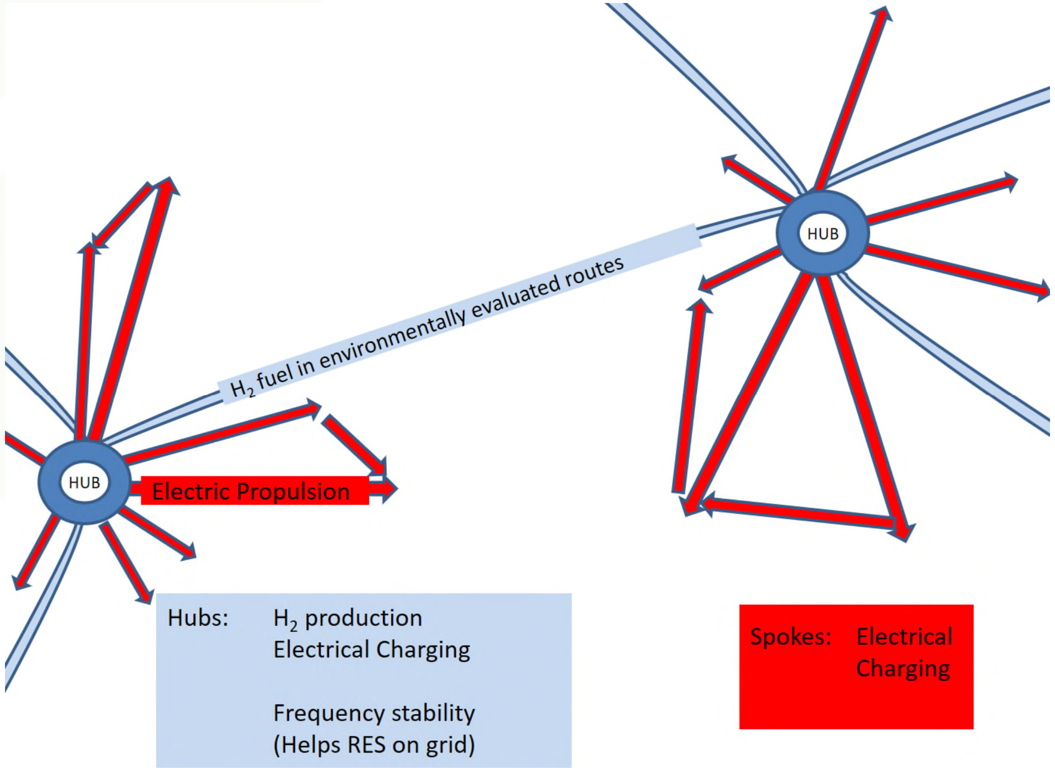
CU Research Strategy “Decarbonising Aviation”
Decarbonisation Portfolio

Opportunities for Decarbonisation and CU’s Vision for the Route Towards Decarbonisation





Judicious synergy between Electrification and Hydrogen



- Synergies with other industries e.g. power generation from renewables (frequency balancing in grids)

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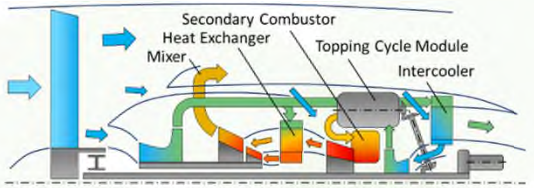
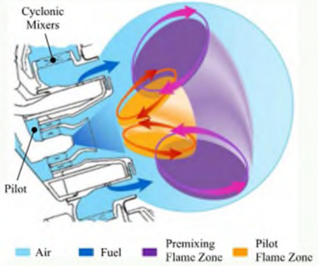
ENABLEH2 Strategic Importance



Geared Turbofan Engine with Intercooling, Secondary Combustion, Nutating Disc Topping Cycle Modules and an Air Bottoming Cycle



Disruptive propulsion, aircraft and electrical technologies to improve propulsive efficiency and overall airframe and engine integration

Disruptive propulsion core technologies for enhancing thermal efficiency and reducing NOx

\+

LH_2 is a key ENABLER for many of these advanced aircraft, propulsion system and more electrical disruptive technologies

CO_2↓,CO ↓, UHC ↓, Soot ↓ NOx↓,
Environmental Impact ↓

~~CO_2,CO, UHC, Soot,~~ NOx↓ ↓ ↓,
Mission Fuel Burn ↓↓↓
Environmental Impact ↓↓↓
(with appropriate mission management and LH_2 production methods)

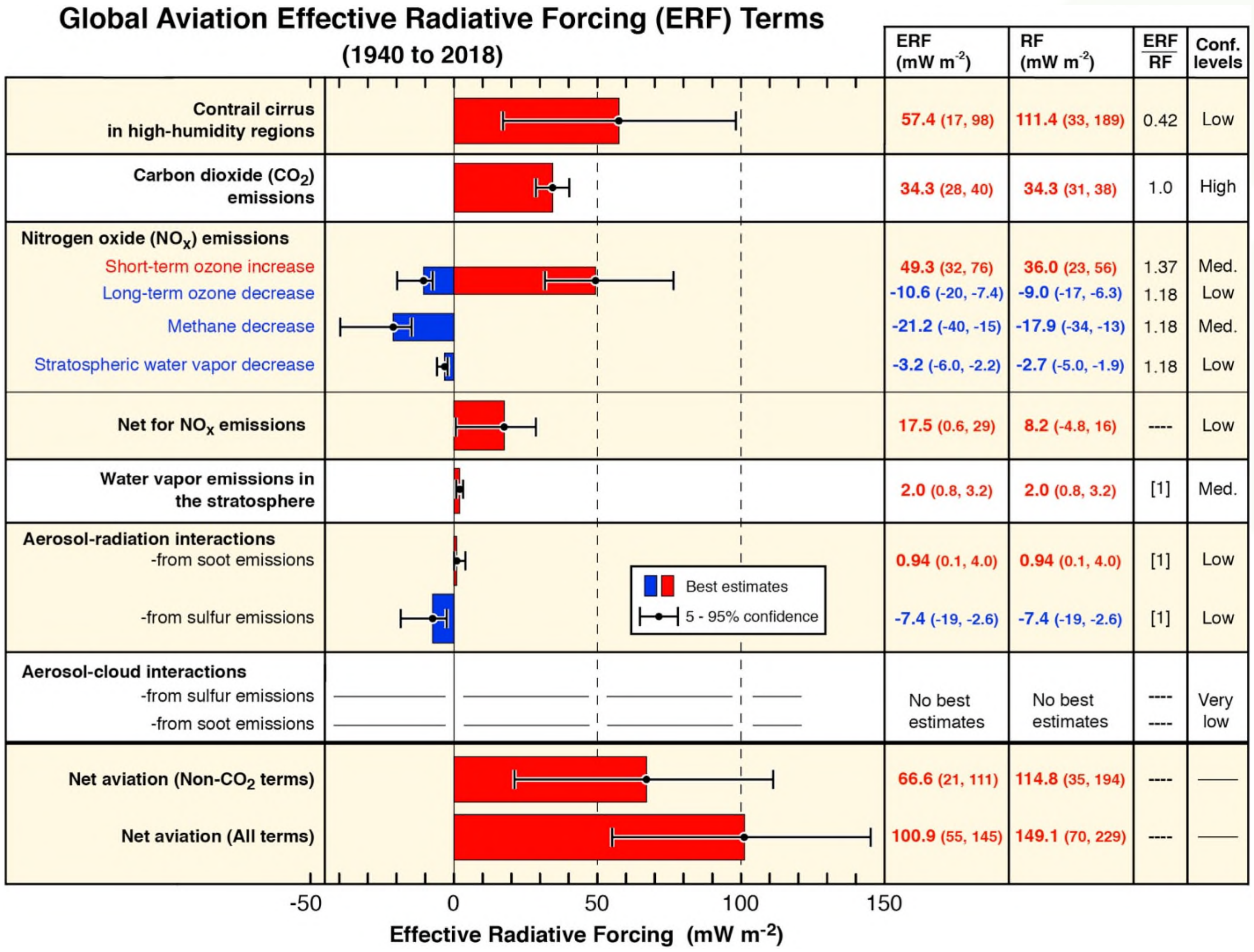
Images courtesy of GE, NASA and EU H2020 ULTIMATE Project

The Case for LH_2 for Civil Aviation

Alternative Fuels and Production Routes		Drop-in replacements		LNG			LH_2	
		Bio-fuels (from algae)	Synthetic Kerosene	Conventional / Fracking	Biomass	Synthetic LNG	Non-renewable	Renewable / Nuclear
Effect on Emissions relative to Jet-A1								
At Mission Level	CO_2							
	Energy Efficiency							
	NO_x							
	CO and UHC							
	Soot / Particulates							
	Water Vapour							
	Contrails							
Over the Life Cycle (well to wake)	CO_2 emissions							
	CH_4 emissions (leakage)							
	Long Term Sustainability							
Effect on Costs relative to Jet-A1								
Short-Medium Term (up to 2050)	Fuel Production Costs							
	Aircraft Engineering Costs							
	Airport Integration Costs							
	Life Cycle Costs							
Long Term (beyond 2050)	Fuel Production Costs							
	Aircraft Engineering Costs							
	Airport Integration Costs							
	Life Cycle Costs							
Effect on Safety relative to Jet-A1								
Actual Safety Record in Transportation								
Likely Public Perception of Safety								

Key						
				Inferior to Jet-A1		No clear benefit re. Jet-A1
		Indicates greater uncertainty		Superior to Jet-A1		Significant benefit re. Jet-A1

LH_2 - What About Contrails?

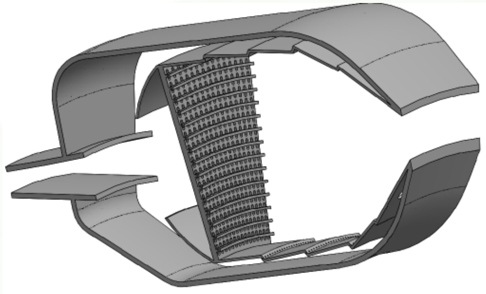


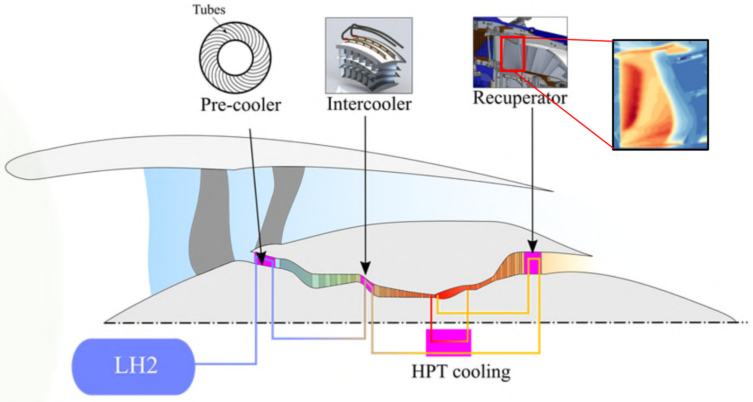
- Fewer emissions of particulates
- Appropriate mission management (persistent contrail avoidance trajectories)
- Less aggressive cycles?

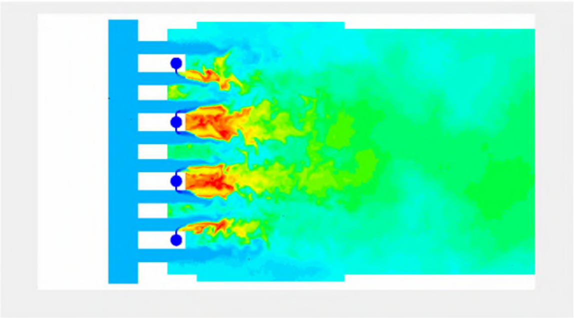
Ref: D.S. Lee, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.R. De León, L.L. Lim, M.T. Lund, R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, R. Sausen, L.J. Wilcox, “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018”. Atmospheric Environment, Volume 244, 2021, 117834, ISSN 1352-231

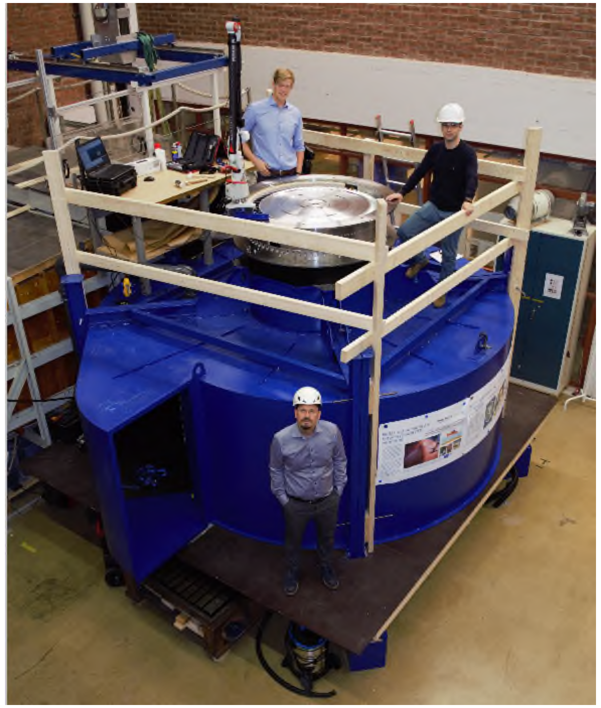
ENABLEH2
Project Overview

- EU H2020 Project ~4M€, 20+ 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









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ENABLEH2 – **A World Class Team**

ENABLE·H2

Project Consortium

Cranfield University

CHALMERS

EST 1892 LSBU

SAFRAN

GKN AEROSPACE

EHA EUROPEAN HYDROGEN ASSOCIATION

Heathrow

ARTTIC

Industry Advisory Board

AIRBUS

ROLLS ROYCE

MTU Aero Engines

IAG INTERNATIONAL AIRLINES GROUP

Lufthansa Technik

IATA

ICAO • OACI • ИКАО

REACTION ENGINES

DASSAULT AVIATION

Infosys® Navigate your next

Air Liquide

TOTAL

GEXCON

SIEMENS

ABENGOA

MHPS

ACI AIRPORTS COUNCIL INTERNATIONAL

HyEnergy

Clean Sky 2 JOINT UNDERTAKING

FLY ZERO AEROSPACE TECHNOLOGY INSTITUTE

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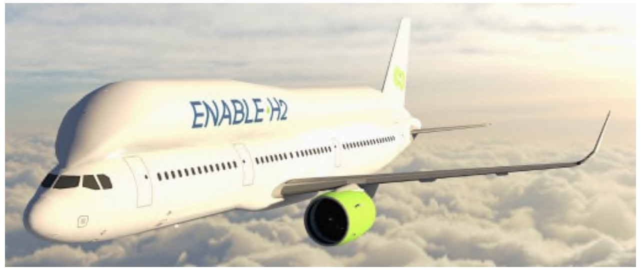
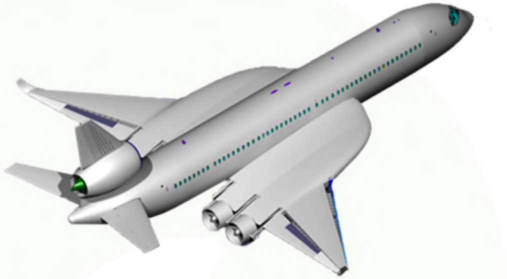
ENABLEH2 Project Overview
Technology Evaluation (WP1)





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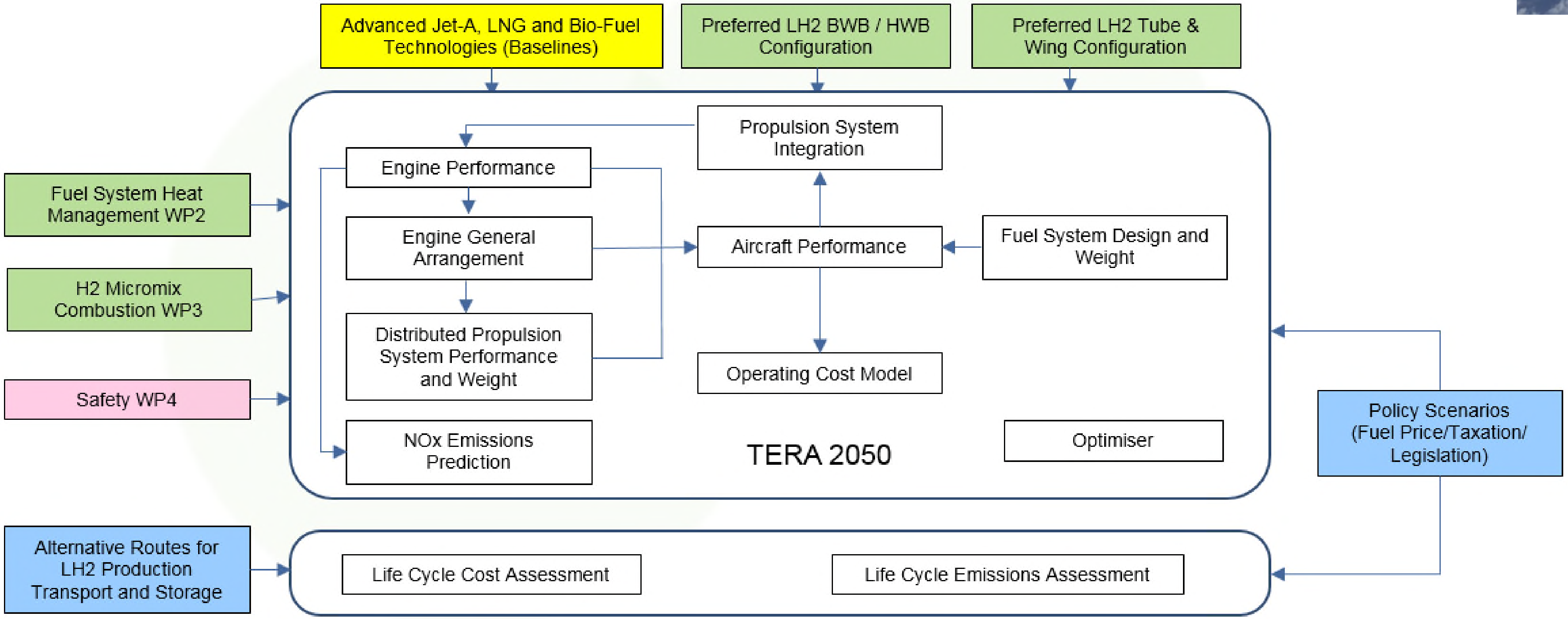
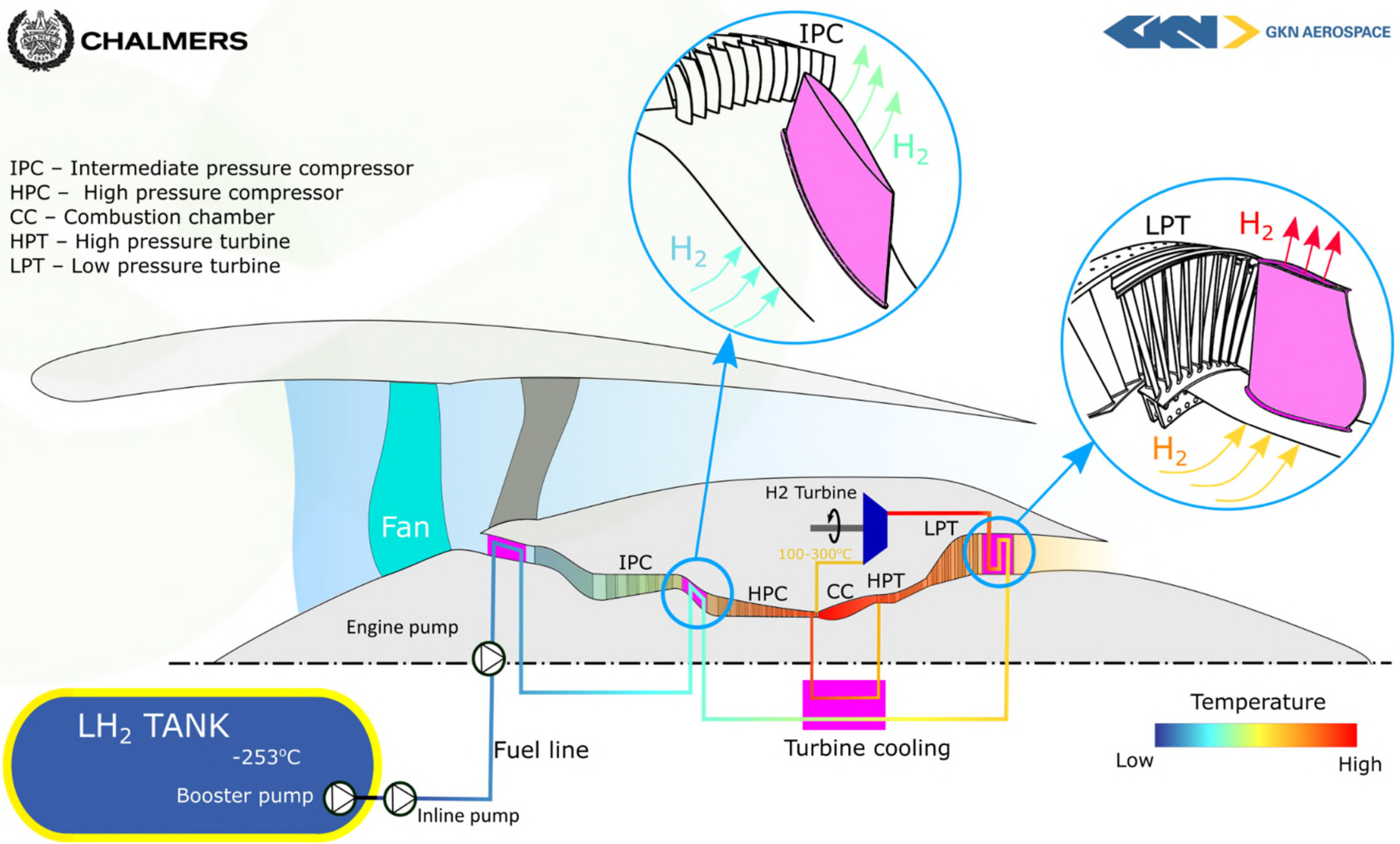


ENABLEH2 Project Overview
Fuel System heat Management (WP2)

Develop heat management concepts

Explore synergies

Investigate the integrated performance



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ENABLEH2 Project Overview
Fuel System heat Management (WP2)

Phase 1: Conceptual Design

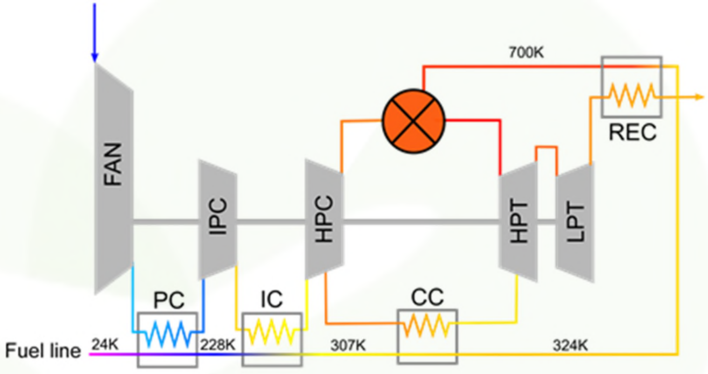
- System Model: Adaptation of components for cryogenic fuel simulation
- Parametric Studies

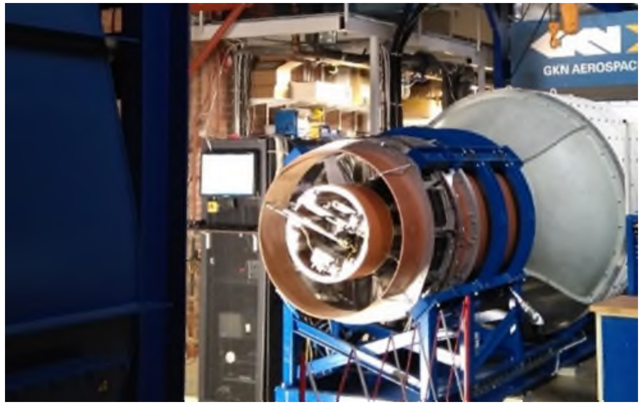
Phase 2: Preliminary design and validation

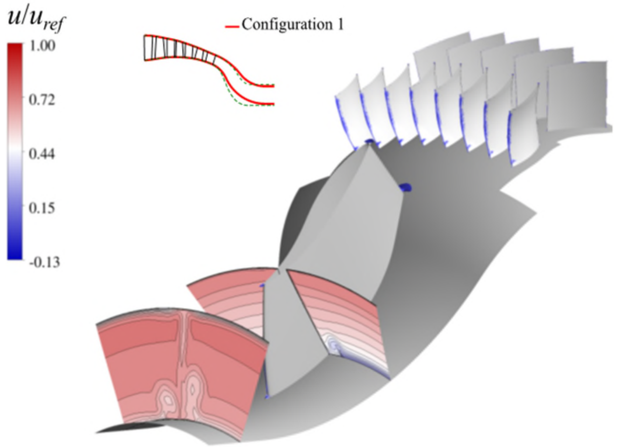
- Heat transfer, flow turning at representative conditions
- Core exhaust heat rejection
- Core flow cooling
- Low speed high Reynolds number annular test facilities

Phase 3: Heat Management System

- Final heat management system to be down-selected
- Optimize solutions applicable to the ENABLEH2 aircraft concepts
- TRL 2 achieved







Formation of Thermal NO_x: The Zeldovich Mechanism

Zeldovich Mechanism

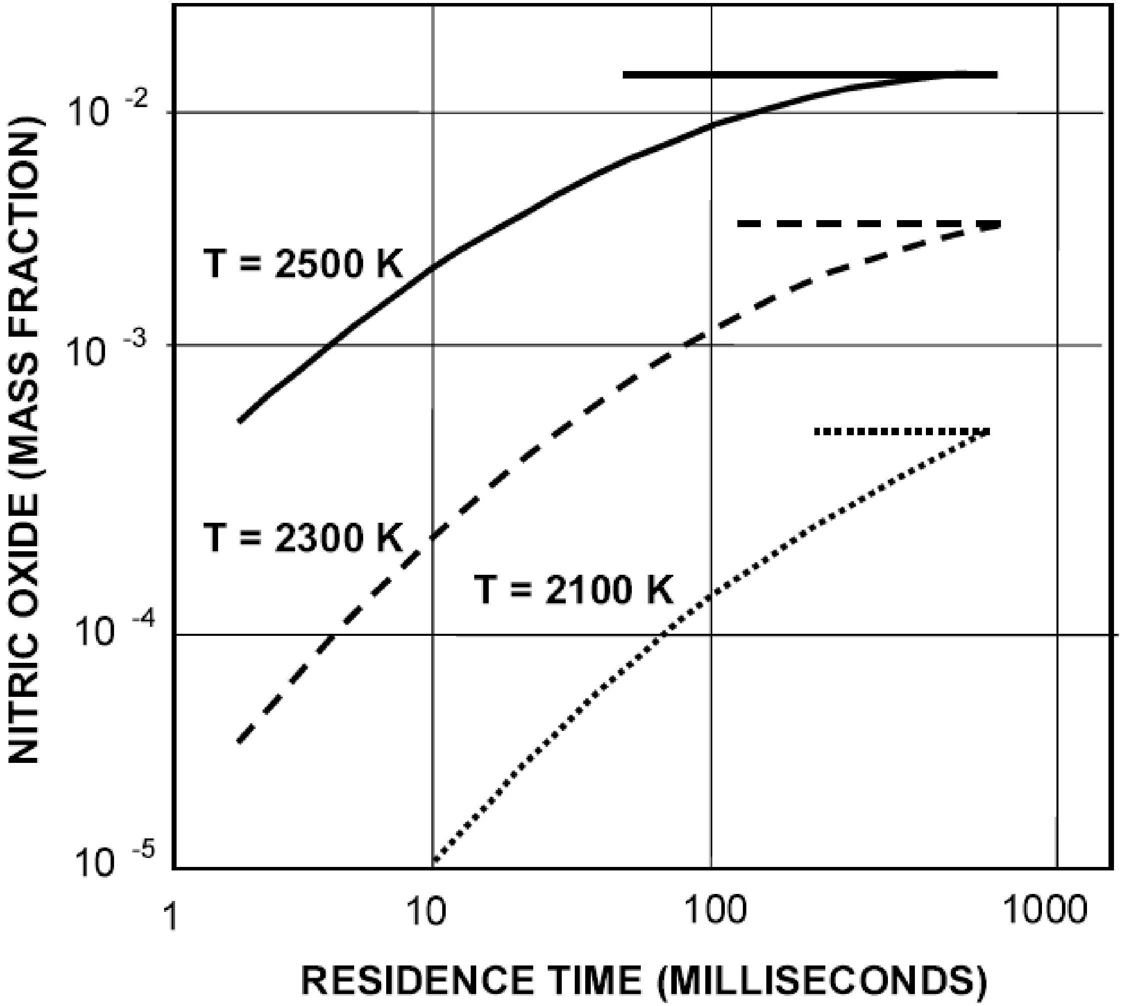
$$O_2 \rightleftharpoons 2O$$

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

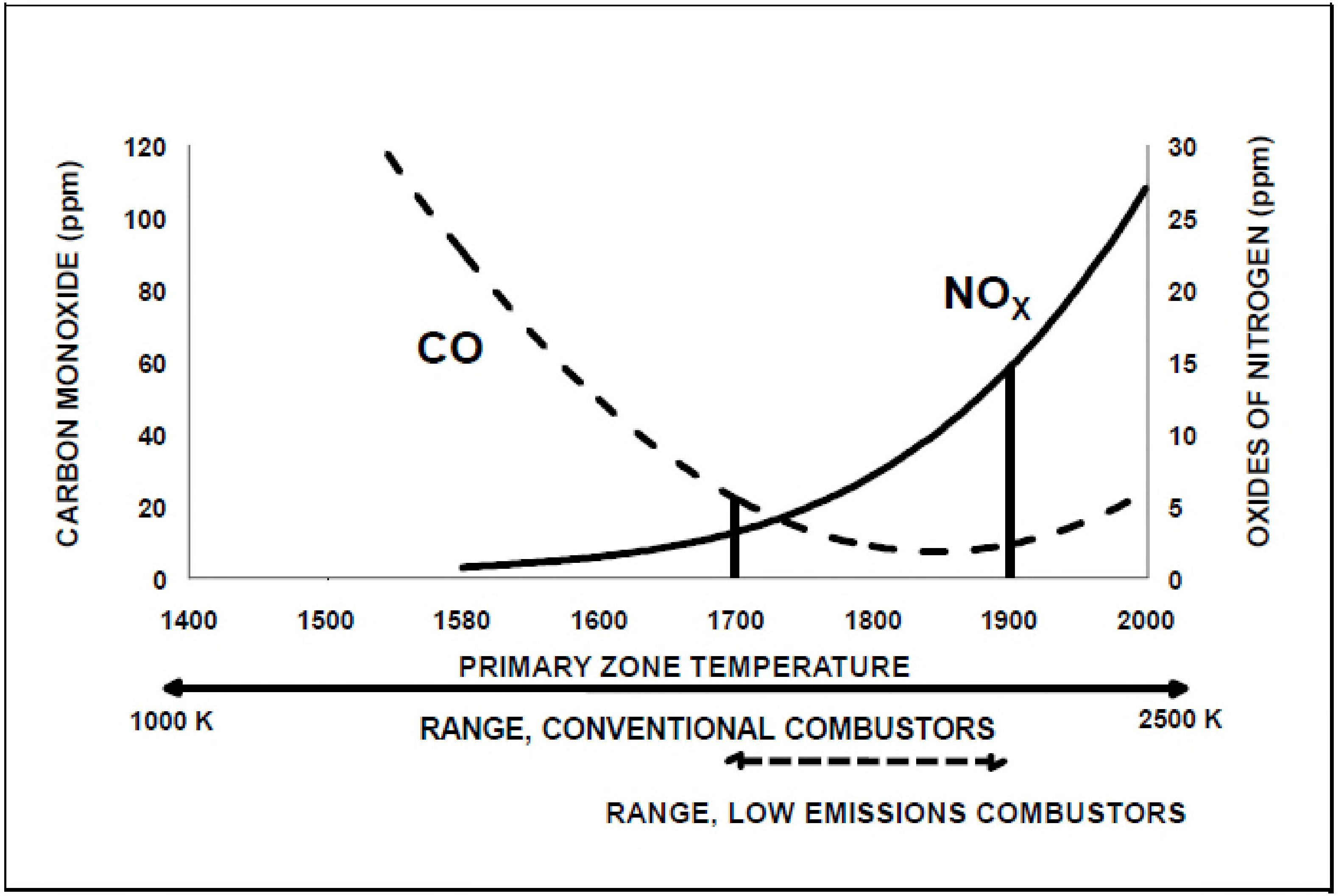
$$N + O_2 \rightleftharpoons NO + O$$

At Lower Temperatures

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



Effect of Primary Zone Temperature: NO_x and CO



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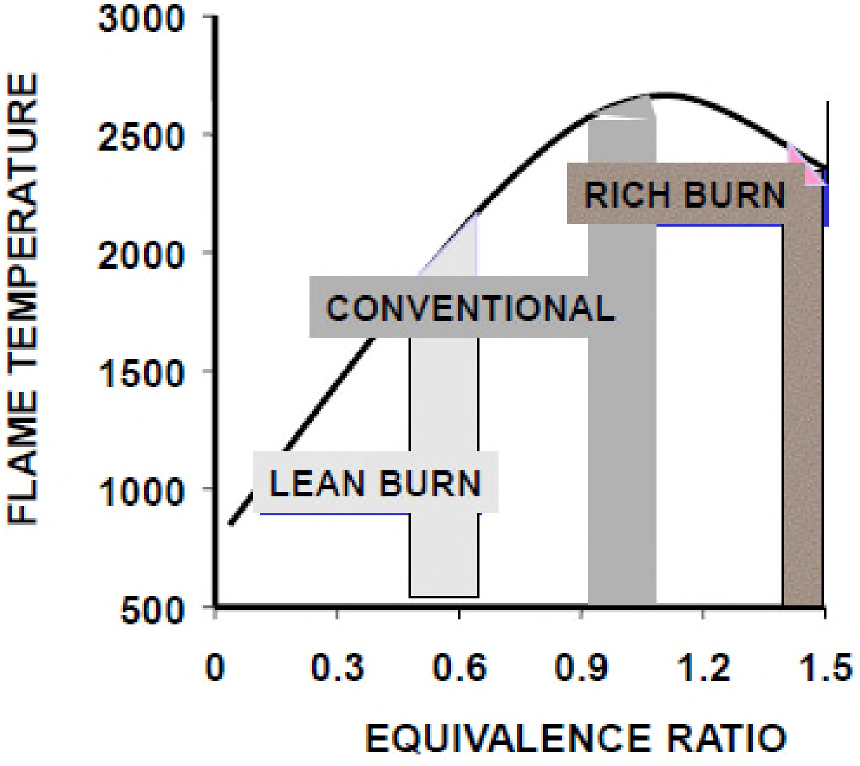
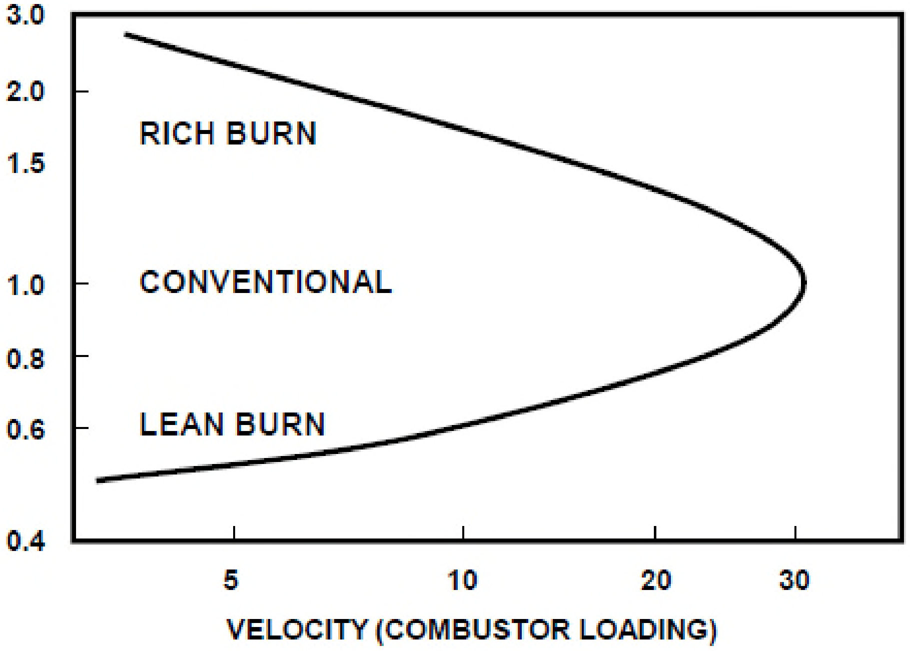
Effect of ϕ on Flame Temperature and Stability



Effect of ϕ on Flame Temperature

Effect of ϕ on Stability



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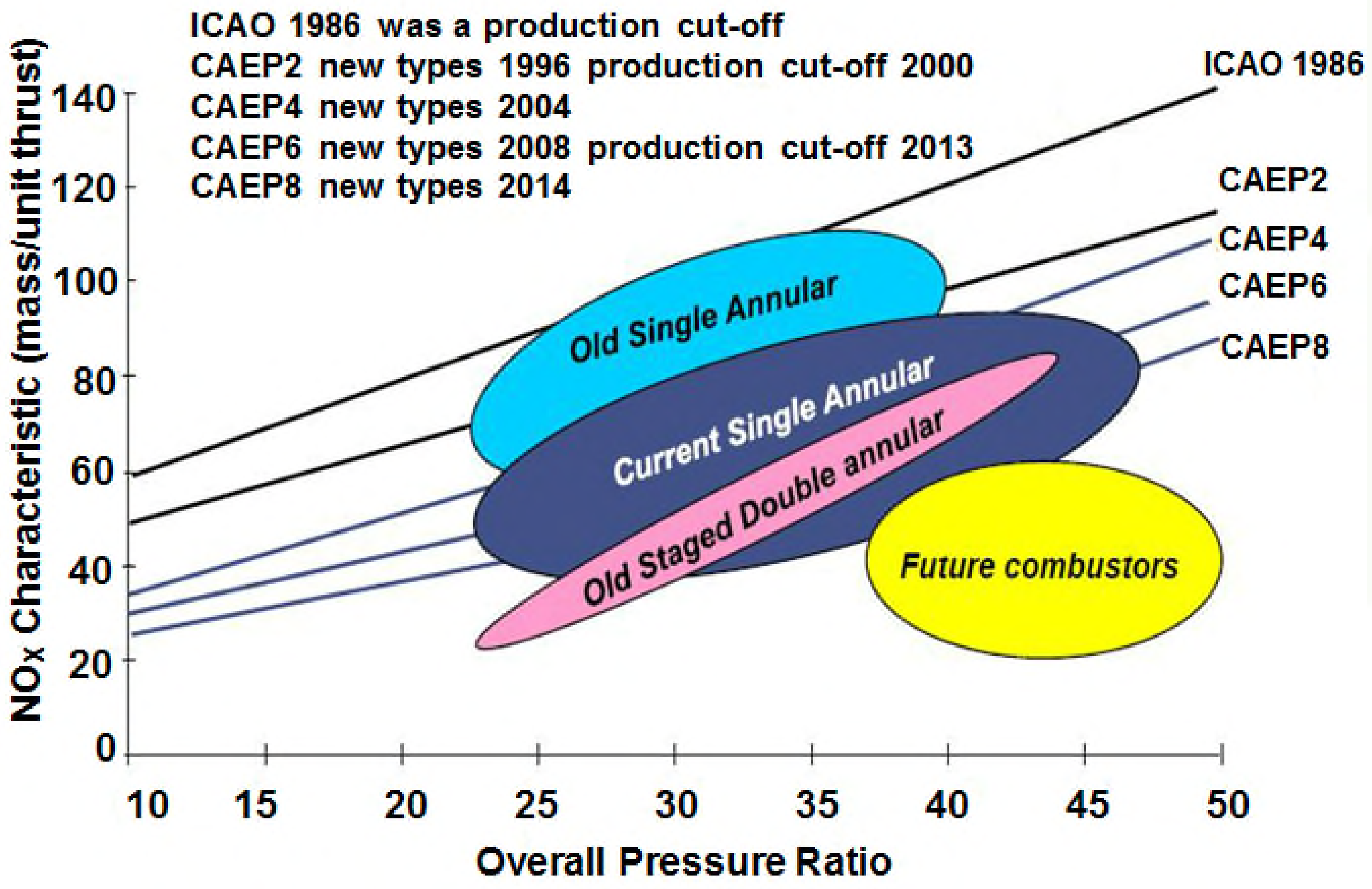
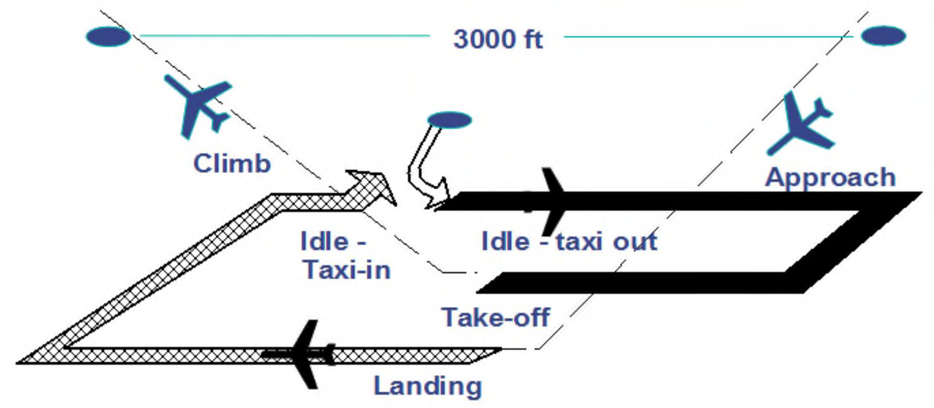
Technology Goals and Challenges for NO_x



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



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

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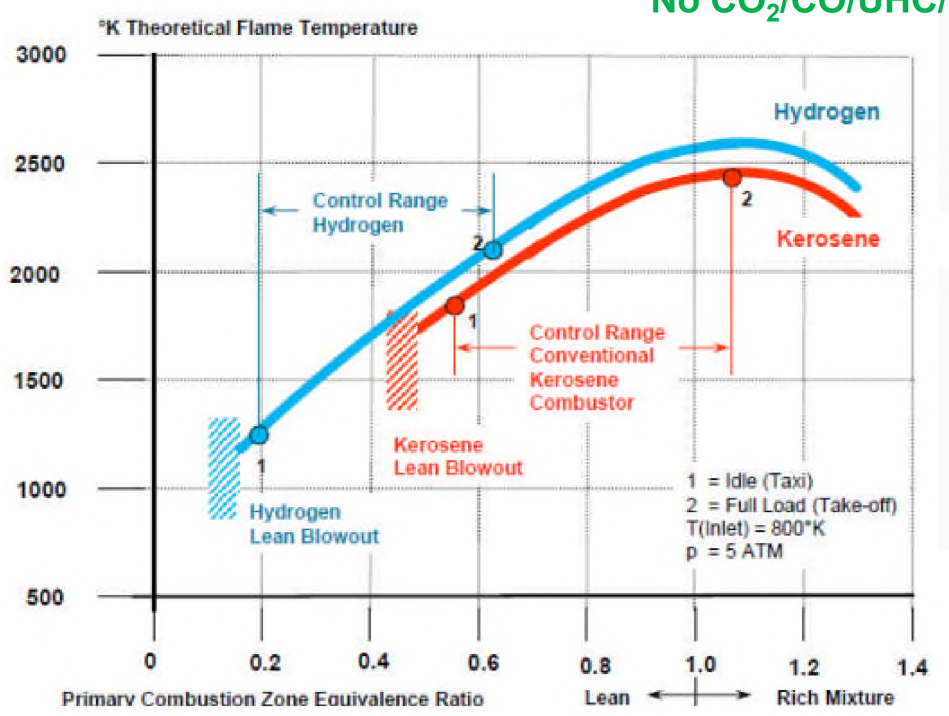
Hydrogen Micromix Combustion
Why Hydrogen?



No Carbon → No CO_2/CO/UHC/Soot; Less Luminous Radiation → **Better liner durability**

Wider stability limits → Leaner combustion → Lower flame temperature → **Lower thermal NOx**

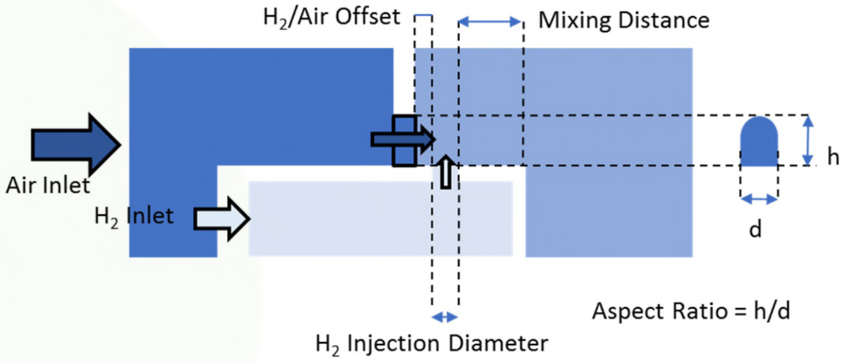
Higher burning velocity → Higher reaction rate → Lower residence time → **Lower thermal NOx**; **Shorter combustor**

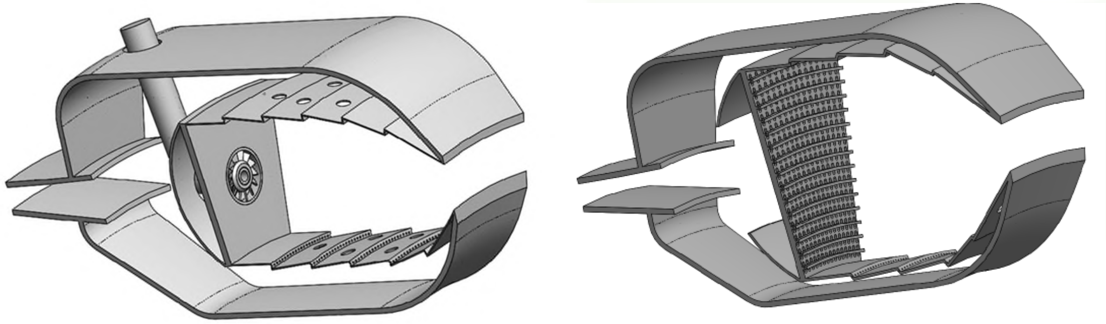
Higher diffusivity → Faster mixing → Higher reaction rate

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).

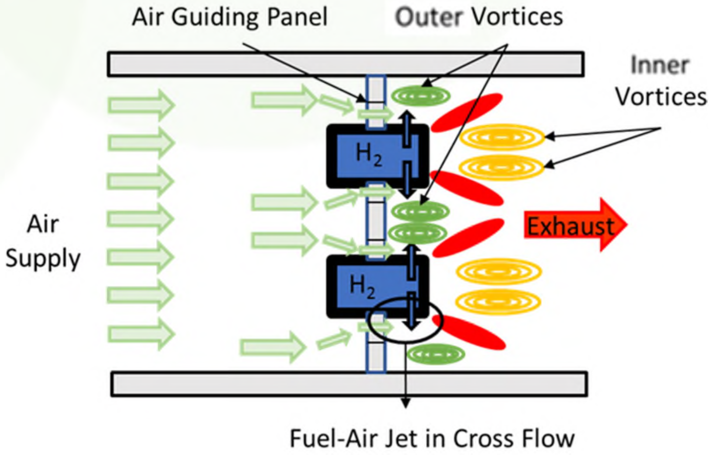
Hydrogen Micromix Combustion
Why Micromix?

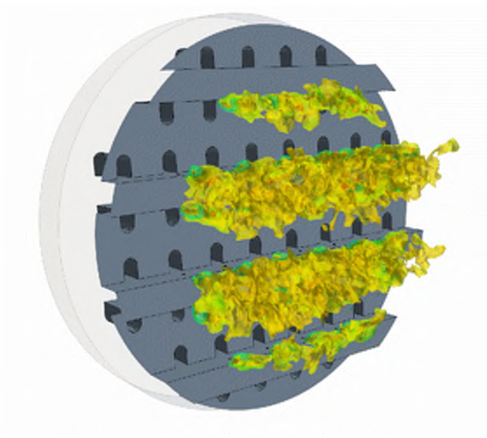
- Mixing length scale minimised while mixing intensity maximised
- Diffusion flame - reduces risk of flashback
- More flexibility for customised fuel scheduling:
  - Tailor outlet temperature distribution (without dilution zone)
  - Control of thermoacoustic instabilities



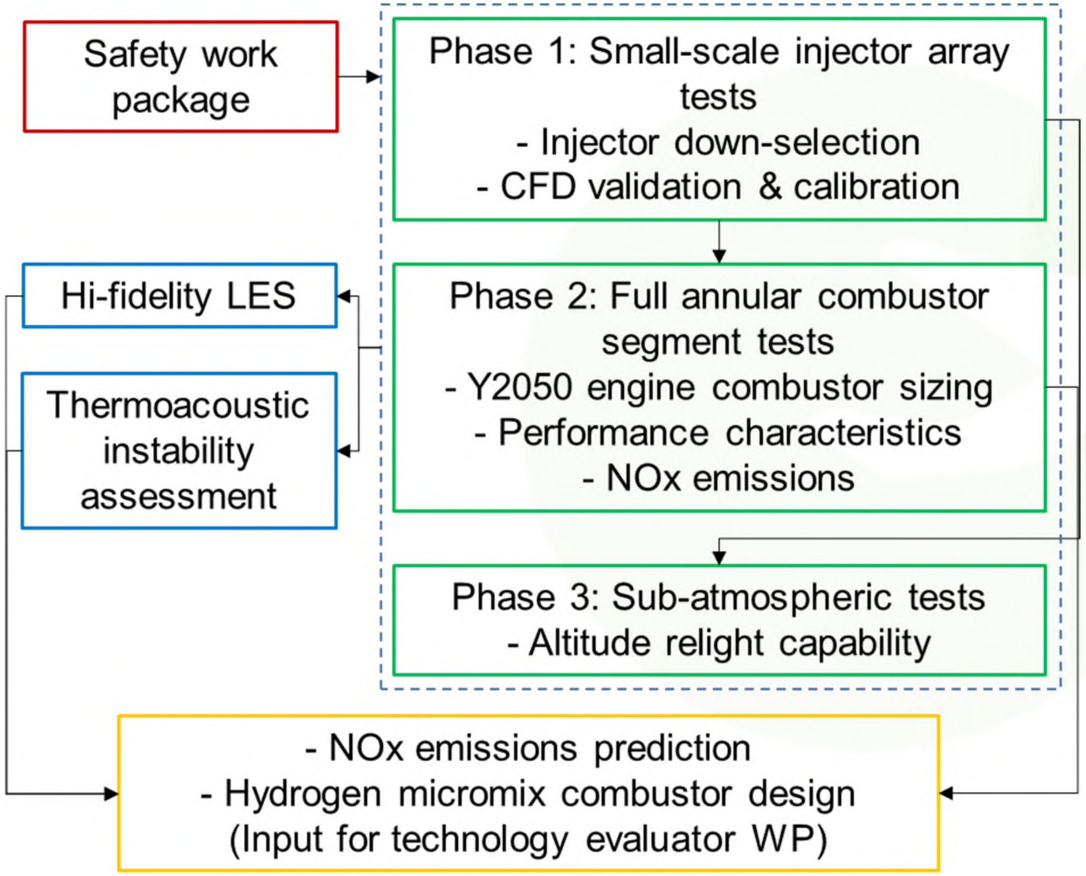


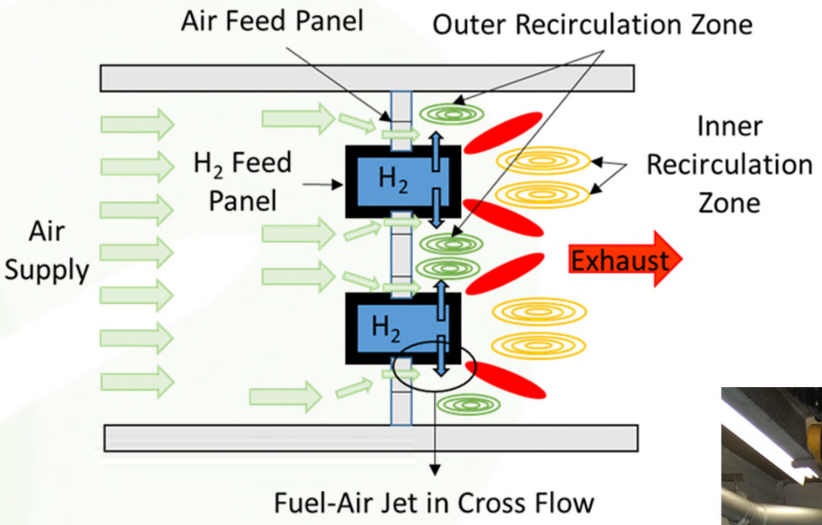
Conventional annular kerosene ***vs*** micromix combustor (conceptual)

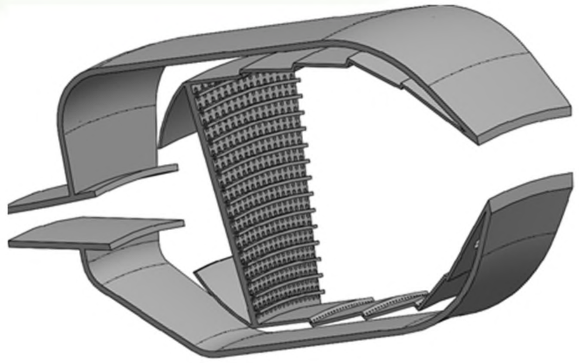




ENABLEH2 Project Overview
Hydrogen Micromix Combustion (WP3)







Aero engine H_2 micromix combustor concept

High Pressure air heater

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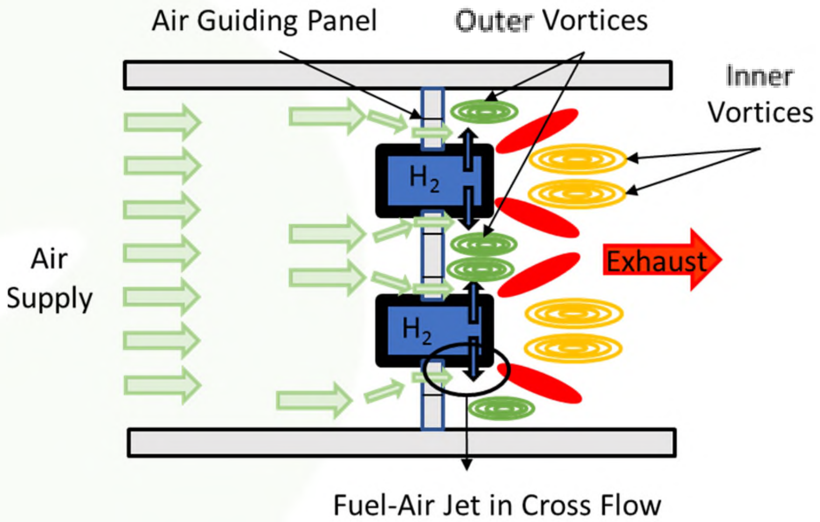
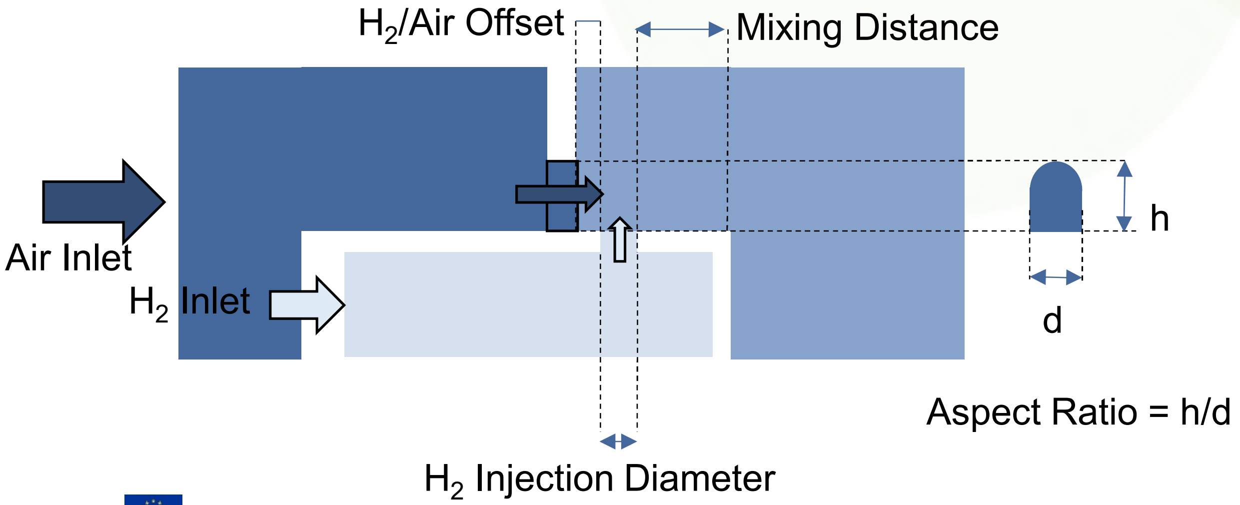
Hydrogen Micromix Combustion (WP3)
Micromix Injector Design

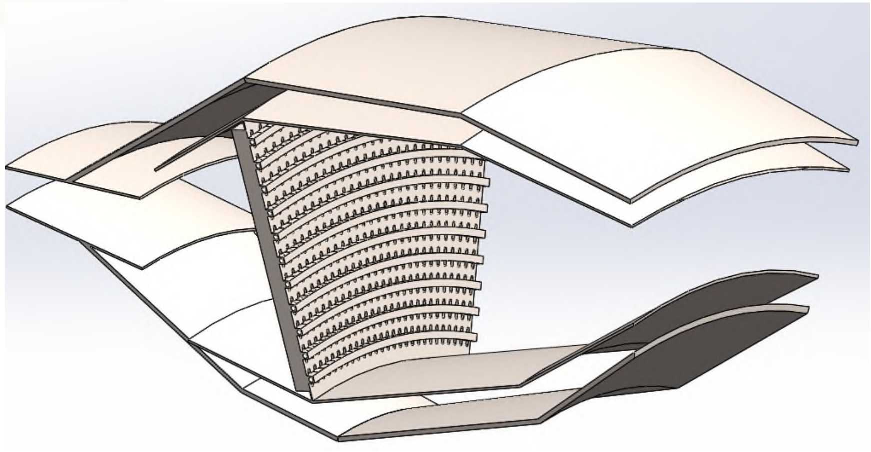
- Hydrogen Offset Distance (0.5mm – 5mm)
- Mixing Distance (0.5mm –2.5mm)
- Hydrogen Inlet Diameter (0.3mm)
- Air Feed Dimensions
  - Air Feed Height (1mm – 2.4mm)
  - Air Feed Diameter (1mm -2.5mm)
  - Aspect Ratio (1- 2)

Momentum Flux Ratio ~ 0.85 - 40

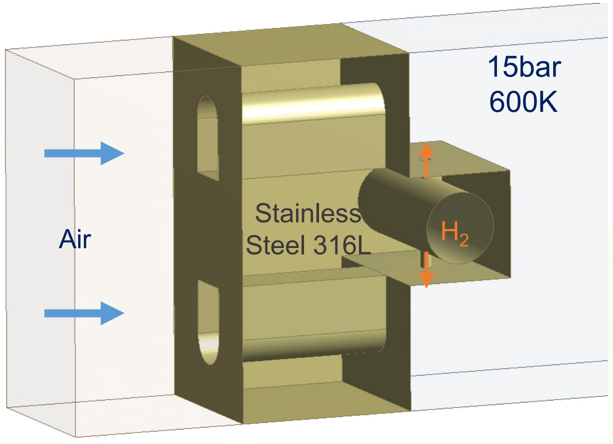


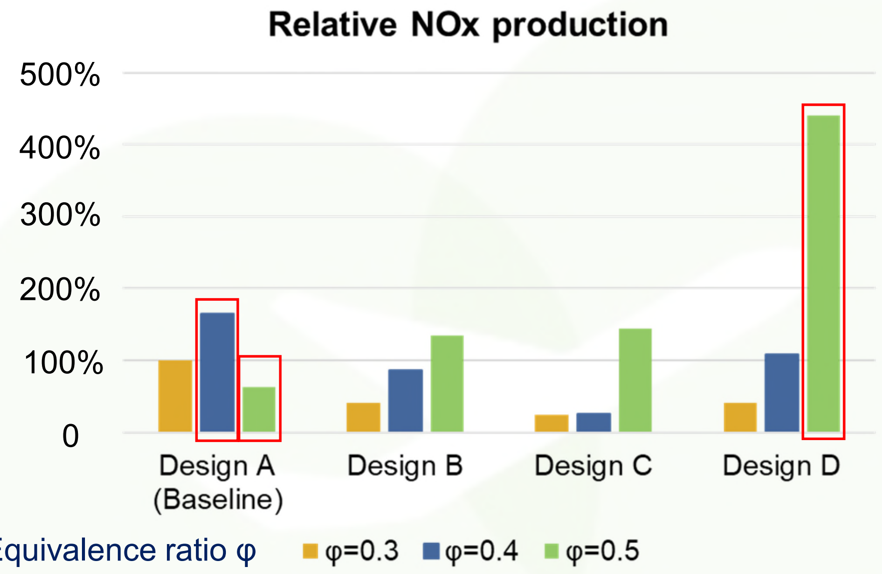


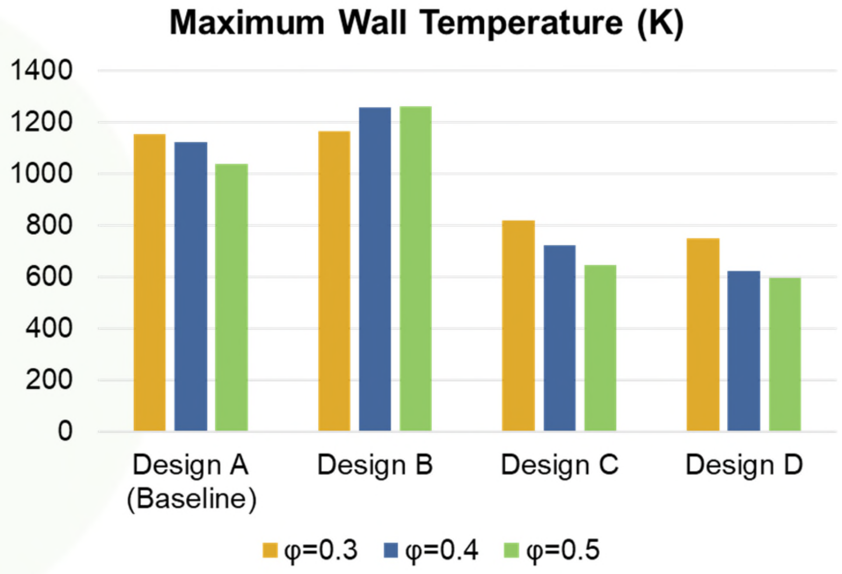
Annular combustor with micromix injector array



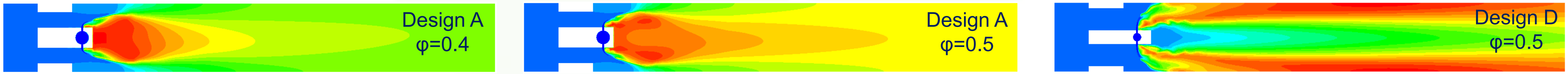
Hydrogen Penetration: Effect on Emissions and Wall Temperature







Temperature contour



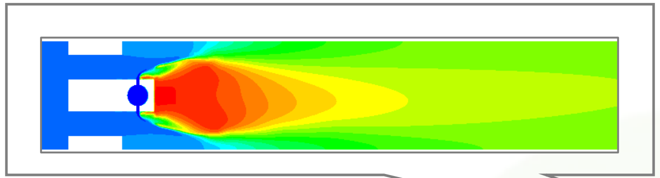
Mass fraction NOx contour

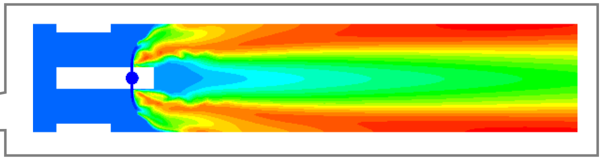
- High wall temperature at low penetration (low momentum flux ratio) due to flame attachment
- NOx strongly dependent on flame interaction and recirculation of hot products

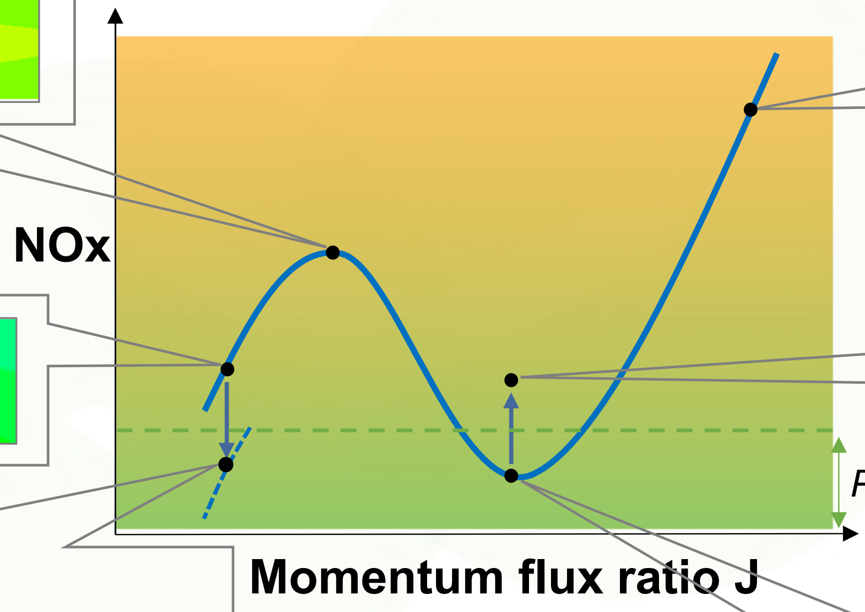
Hydrogen Micromix Combustion (WP3)

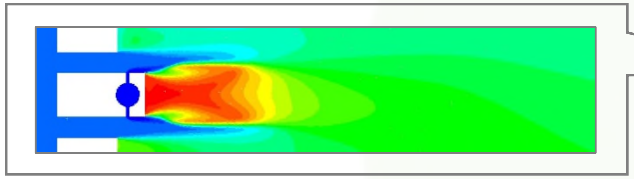
Micromix injector design space

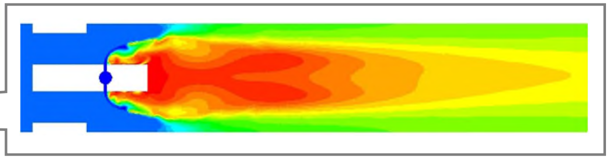
Temperature contours from RANS FGM simulations



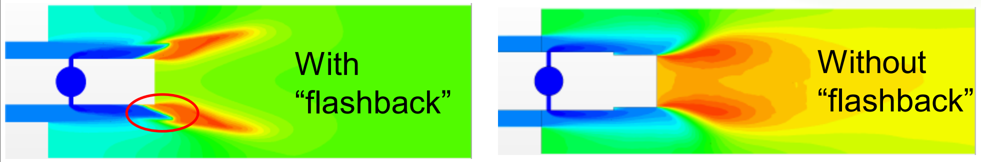




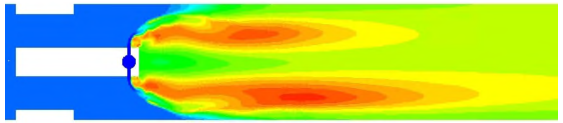




- Partial premixing
- Flame “isolation” by vertical injector distance



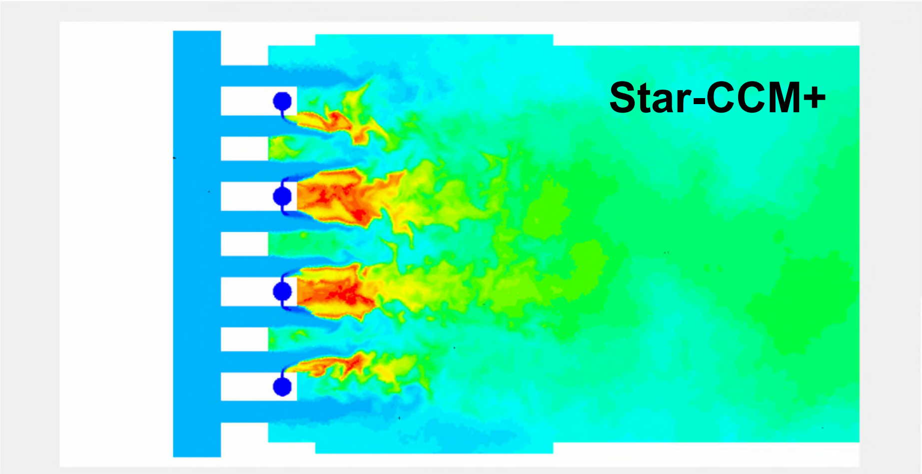
Beyond ENABLEH2 - Clean Aviation



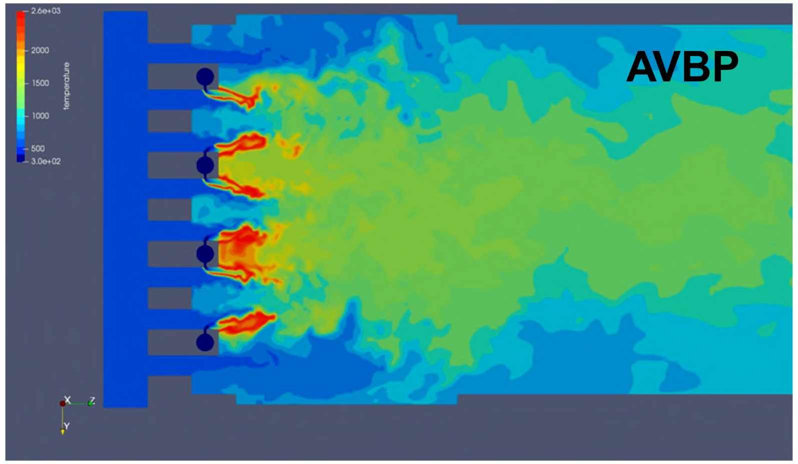
- Purely diffusion
- Flame “isolation” by high jet penetration

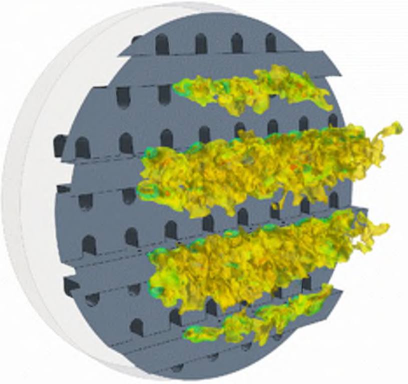
Hydrogen Micromix Combustion (WP3)

Small-Scale injector array design and modelling



Temperature

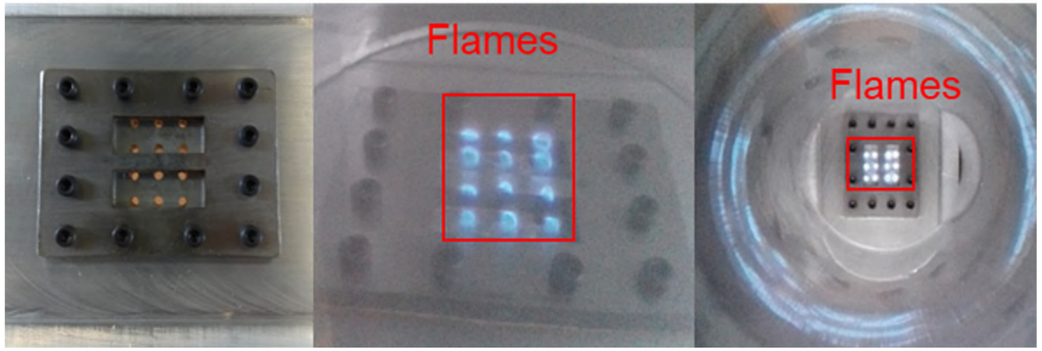




Several discrepancies between S-O-A CFD modelling software tools!

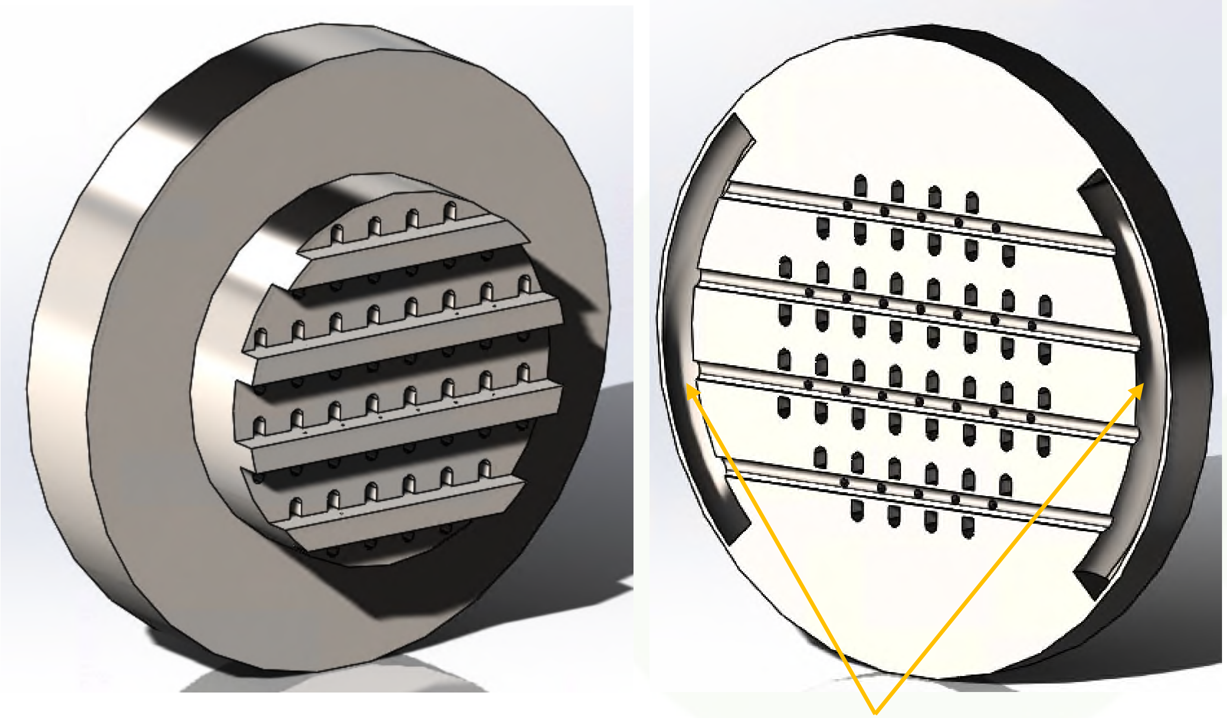
Data generated to be used to evaluate, validate and calibrate CFD models

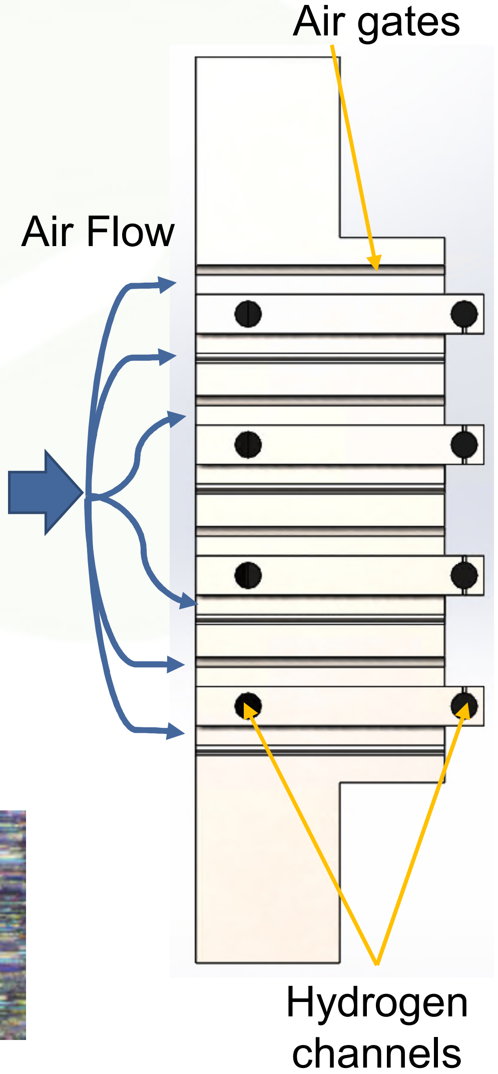
Initial test plate burning with propane

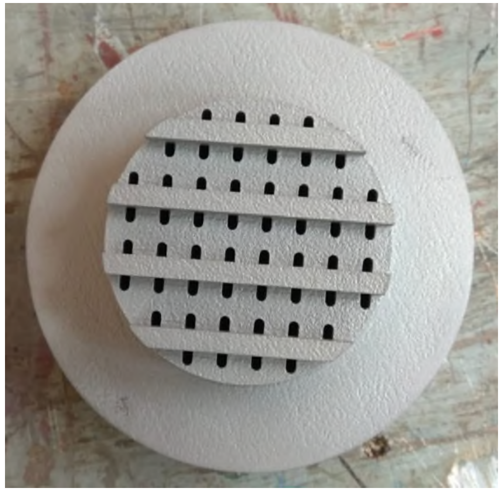


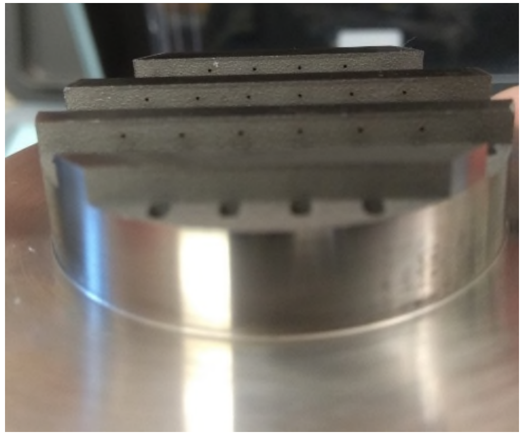
Hydrogen Micromix Combustion (WP3)

Final injector design & manufacturing

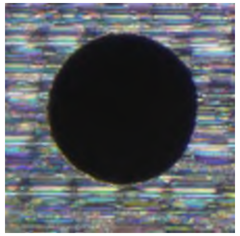




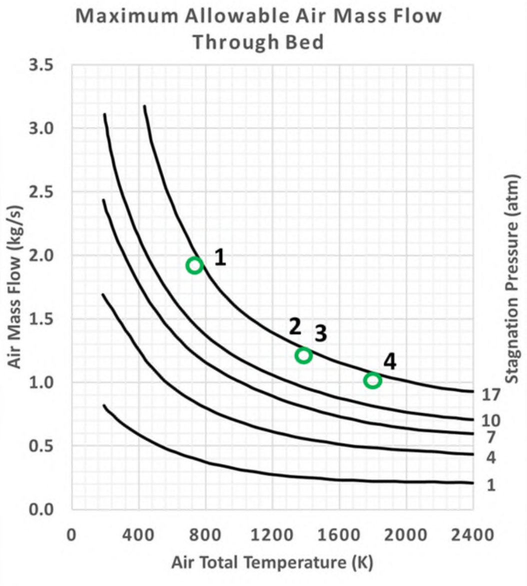




Hybrid manufacturing
3D printed plates (compromise on air gate)
Micro EDM hole drilling (D±10 microns , concentricity 10-15 microns)



Pebble Bed Facility: Low Emissions Combustion Research



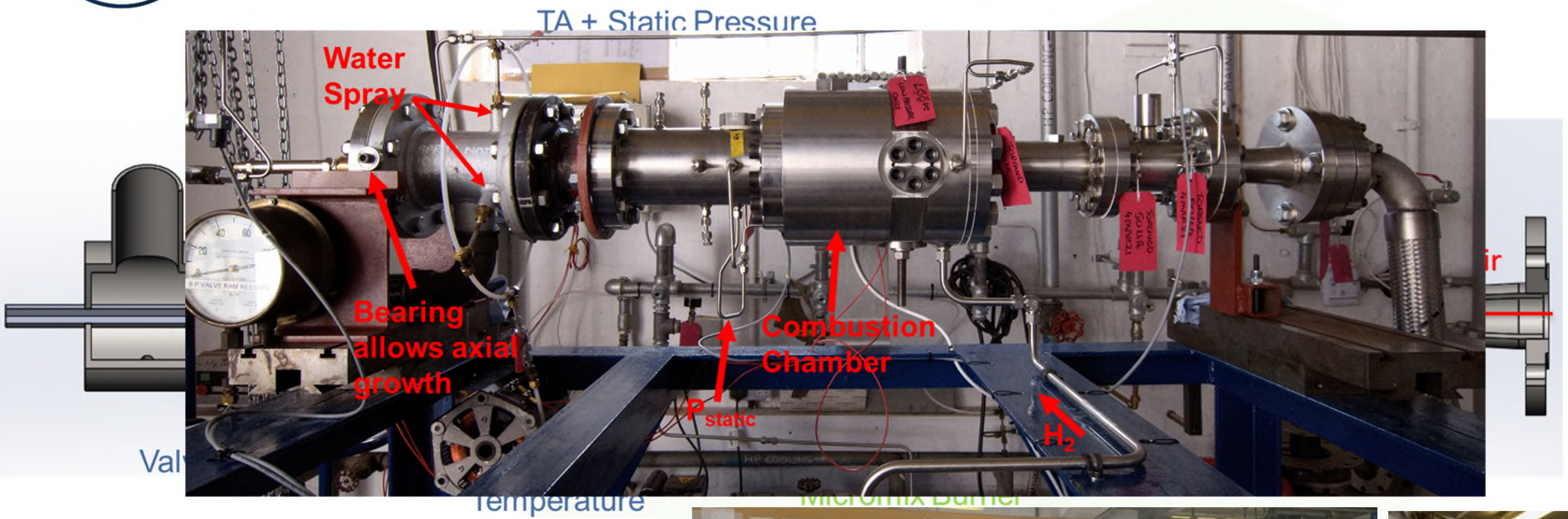
Condition No.	1	2	3	4
Pressure (bar)	15	15	15	15
Bed air temperature (K)	725	1400	1400	1800
Bed air mass flow (kg/s)	1.90	1.17	1.17	1.05
Dilution air mass flow (kg/s)	0.00	2.43	1.83	1.80
Test section inlet mass flow (kg/s)	1.90	3.60	3.00	2.85
Test section inlet temperature (K)	725	660	725	850

- The facility is able to provide high mass flow of non-vitiated air at high pressures (fed by a compressor) and high temperatures to reproduce representative gas turbine combustor inlet conditions (cruise for aero engines)
- By varying the combination of pebble bed and dilution air flow a wide range of test section inlet mass flows & temperatures can be produced
- 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 (STAR-CCM+ and ANSYS-Fluent)

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

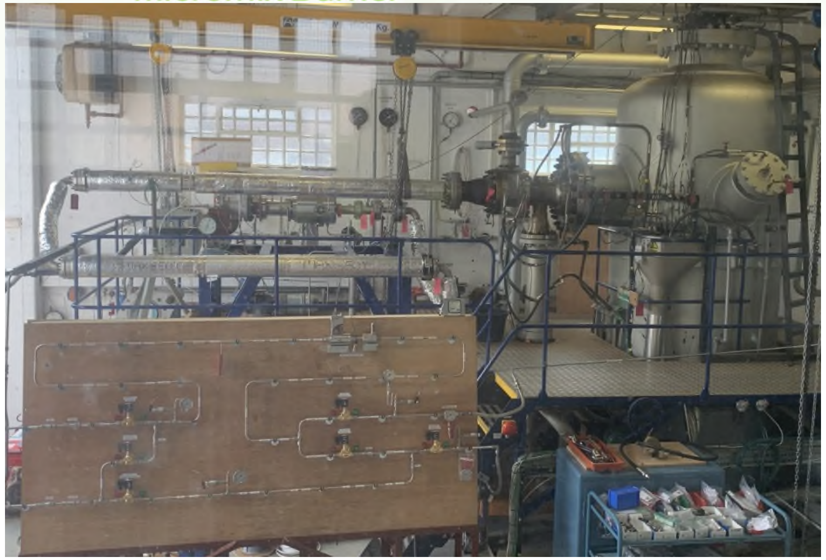
Hydrogen Micromix Combustion (WP3)

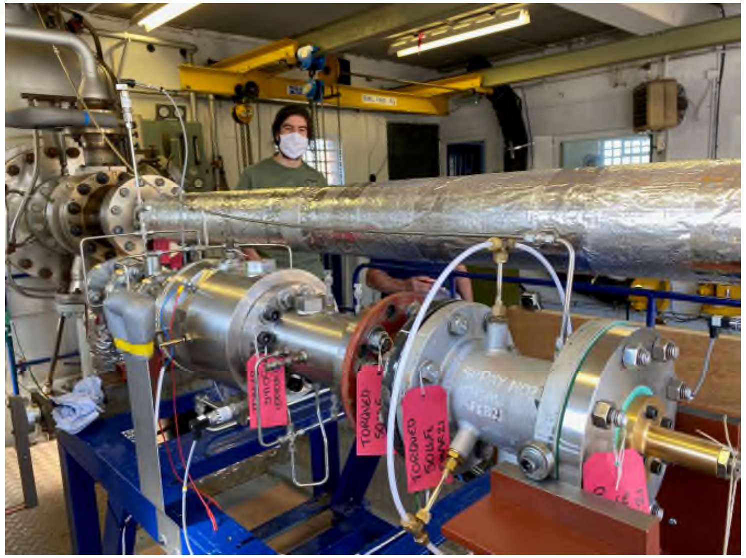
Phase 1 Experimental rig



- OH-PLIF
- Pressure loss
- NOx emissions
- Flame Transfer Functions

	Range of test conditions	
Pressure (bar)	1	15
Air Temperature (K)	300	600
Equivalence Ratio (-)	Lean Blow-out limit	0.5
Heat Release rate(kW)	5	150





ENABLEH2 Project Overview
Safety (WP4)

- Dispersion LH_2 clouds
  - Hazardous distance study
- RE test facility: LH_2 tank leak
  - LH_2 Leak – Dispersion
  - Explosion overpressure
- Aircraft crash scenarios
  - Pool Fire simulations
  - LH_2 vs LNG vs JET A
- Aircraft refuelling study
  - LH_2 leak + explosion o/p

ENABLEH2 Project Overview
Safety (WP4)

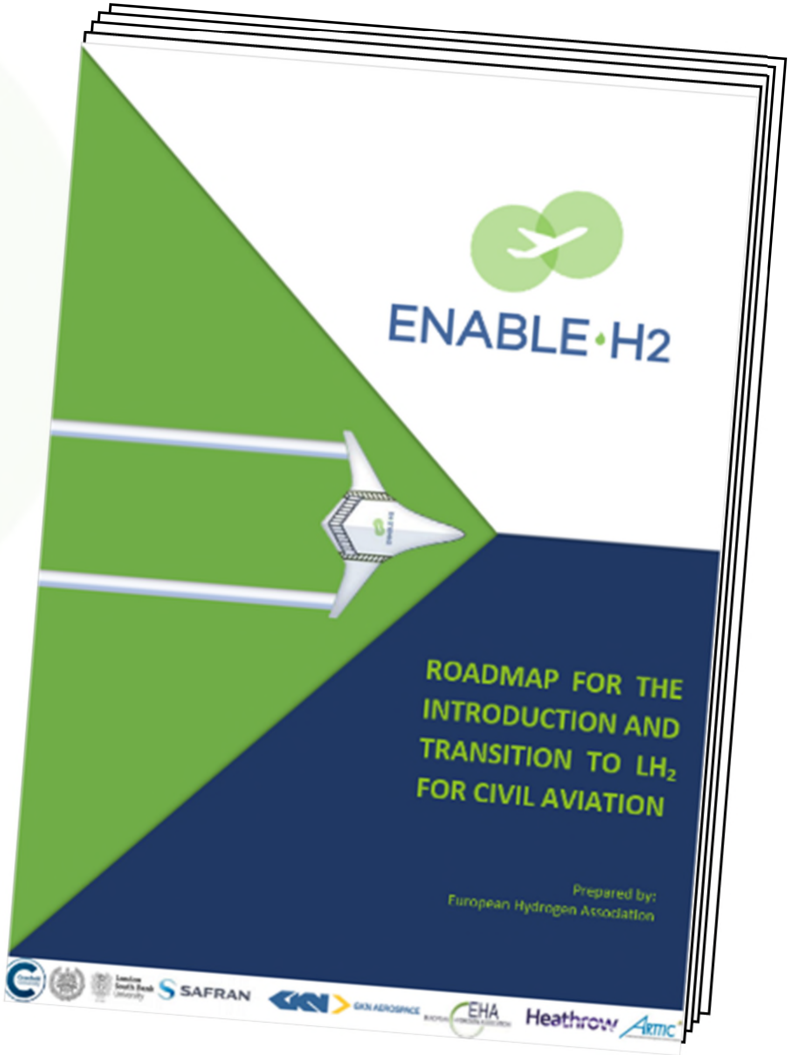
- PHA at Heathrow: Aircraft manufacturers, Airline, fire service
- New hazards examined or increases in severity and/or likelihood of harm
- Overall pragmatic & positive
- Moving forwards will use FLACS data for future risk assessment

Storage, on-site generation	Fuelling (and ground transport)	Taxiing, take off, landing	Firefighting
• Scale & location • Explosion • Existing mitigation	• Underground/ vehicle/ robot supply • Cryogenic/ fire hazards • Many unknowns	• Fuel leaks • Runway excursion • Similar hazards and prevention to Jet A	• Largescale change • Protocols & standards • Training & equipment • Whole fire service

[6,7,8]

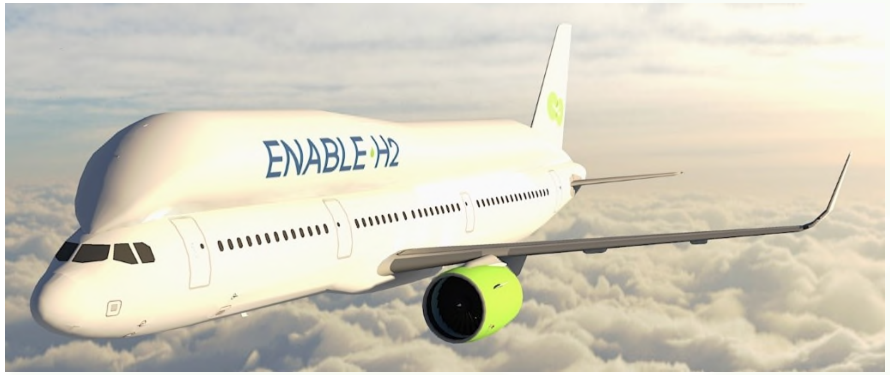
Enabling research strands for LH2
ENABLEH2 Roadmapping (WP5)

- Ensuring safety with hydrogen-fuelled aviation
- Decarbonisation of power generation
- Hydrogen production, liquefaction and distribution
- Airport infrastructure and aircraft fuelling systems for LH_2
- Design of aircraft fuel systems for LH_2
- Propulsion systems using hydrogen as fuel (including distributed propulsion options)
- Combustor design and emissions reduction with hydrogen
- New commercial aircraft designs for LH_2
- Aircraft operation and maintenance with LH_2 fuel
- Aircraft economics with LH_2 v. alternative fuels
- Environmental impact research, and assessment of hydrogen v. alternative fuels
- Integration of research funding and timeframes for the introduction of LH_2 fuelled aircraft



ENABLEH2

Roadmapping – Presented at ICAO 2020 CO_2 Stocktaking Seminar



Main Challenges

Costs

- LH_2 production and liquefaction
- Design and manufacturing of new LH_2-fuelled aircraft
- Airport infrastructure development

Technical

- Ultra-low NOx combustor design
- Design of aircraft fuel systems for LH_2
- Propulsion systems using hydrogen as fuel
- New commercial aircraft designs for LH_2

CO_2 reductions per flight	100%
Level of finance required	↑↑*1
Timeframe	~2040*2
Main challenges	(see left)

[1] Justified considering the environmental and employment benefits

[2] Not fully optimised

GA no. 769241

ENABLEH2 Thought Leadership and Impact for Decarbonisation – LH_2

ENABLEH2 Features in Key Publications

- ICAO:
  - 2019 Environmental Report
  - 2020 CO_2 Stocktaking Seminar
- European Commission:
  - Hydrogen Powered Aviation (Clean Sky)
  - Towards Climate Neutral Aviation (H2020)
- Aviation Week Magazine "H_2 in Aviation"
- RAeS Aerospace Magazine
- UK Parl. POSTNOTE "Low Carbon Aviation Fuels"
- Forbes Magazine "Aviation is the Driving Force for H_2"
- Airport World Magazine "LH_2 Powered Aircraft"
- The Times "Hydrogen-powered planes to clean up skies"

Prestigious Invitations

- Invitation to participate in UK Gov. Jet Zero Council
- Invited to serve on EUROCAE and SAE Working Group – Fuel Cells/H_2 for aeronautical applications
- Invited by Safran for "Clean Aviation" H_2-pillar bid
- Invited by CS2 CSO for "Low Emissions Workshop"
- Invited to serve on "Freedom Flight Prize" Tech. Panel
- Chairing H_2 sessions at EASN, ASME and ISABE
- Invited to contribute to AIAA "H_2 Aircraft" Panel
- Invitation for Hamburg Aviation Lecture Series

ROYAL AERONAUTICAL SOCIETY HAMBURG BRANCH e.V.

easn

TURBO EXPO

Freedom Flight

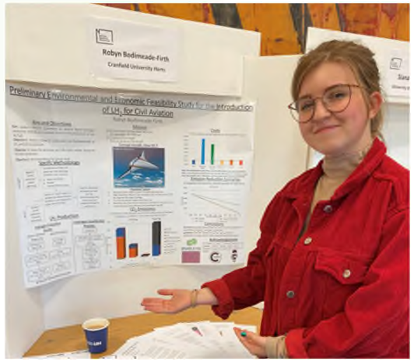
ISABE

International Society for Air Breathing Engines

GA no. 769241

Wider Community Engagement Examples:

Inauguration of the CU Low NOx H_2 Combustion experimental facility at the 2019 "CU Aviation and Environment Conf."



Encouraging young and diverse high school students to consider university degrees and careers in STEM related to "Zero Emissions" (Nuffield Scheme)

PHA workshop at Heathrow for alleviating public concerns about LH_2 safety

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!

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