# Progress in heat management for hydrogen combustion aircraft

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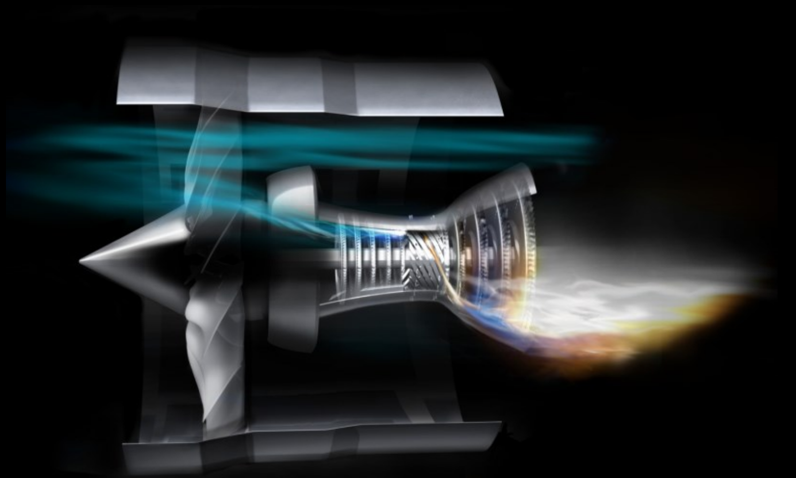
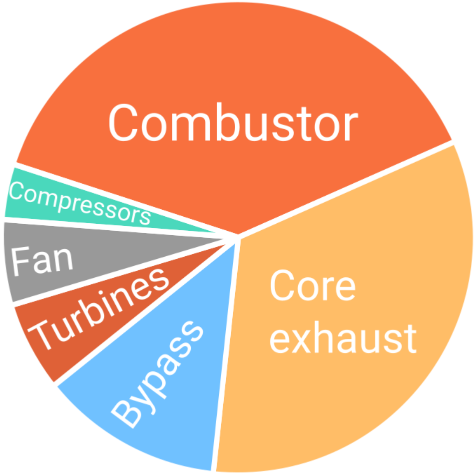
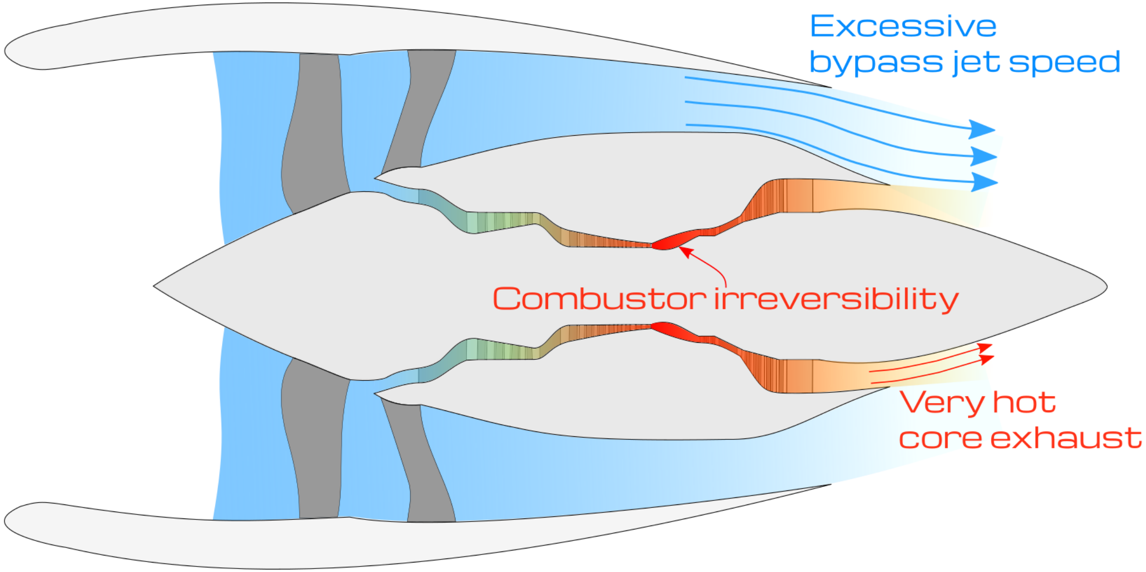
Major contributions also by: Carlos Xisto, Isak Jonsson, Alexandre Capitao-Patrao



# ULTIMATE (EU project - 2015 – 2018)

## Ultra Low emission Technology Innovations for Mid-century Aircraft Turbine Engines





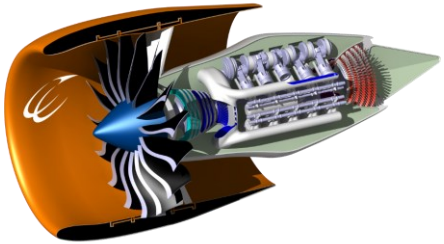
Grönstedt, Tomas, Carlos Xisto, Vishal Sethi, Andrew Rolt, Nicolás García Rosa, Arne Seitz, Kyros Yakinthos et al. "Ultra low emission technology innovations for mid-century aircraft turbine engines." *Turbo Expo: Power for Land, Sea, and Air*, vol. 49743, p. V003T06A001. American Society of Mechanical Engineers, 2016.

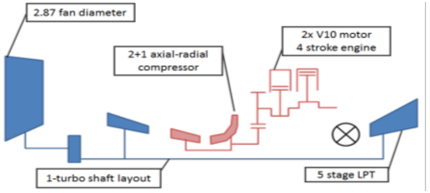
# Efficiency improvement potential

## Pressure gain combustion

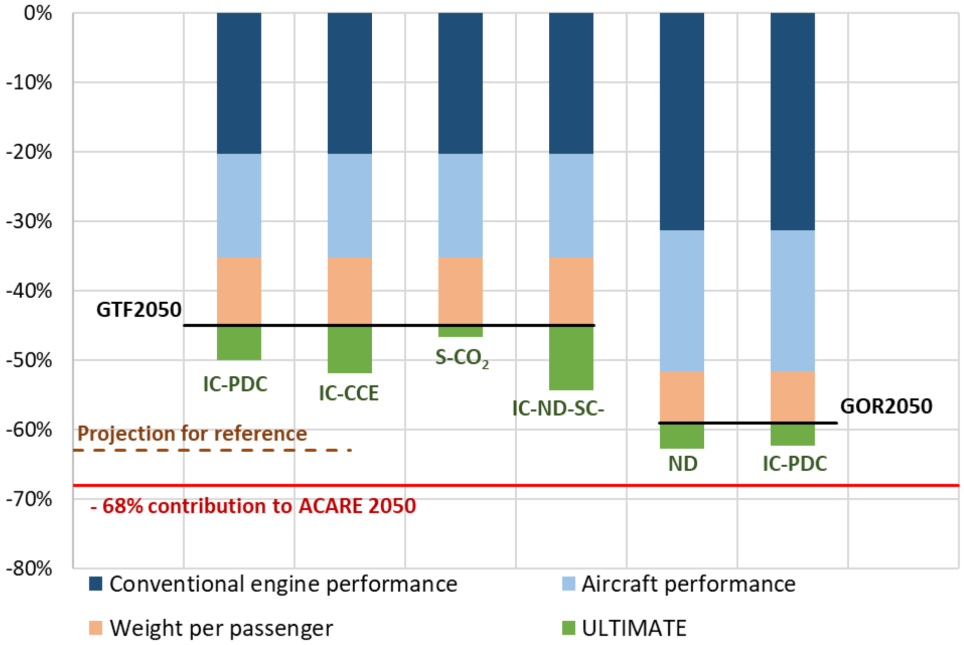
Bauhaus Luftfahrt
Neue Wege.

MTU Aero Engines

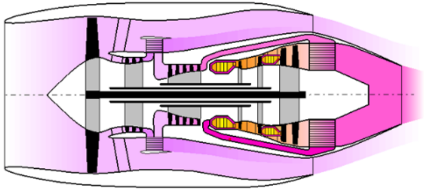




CO$_2$ reduction relative to year 2000



## Core exhaust heat recovery



MTU Aero Engines

ARISTOTLE UNIVERSITY OF THESSALONIKI

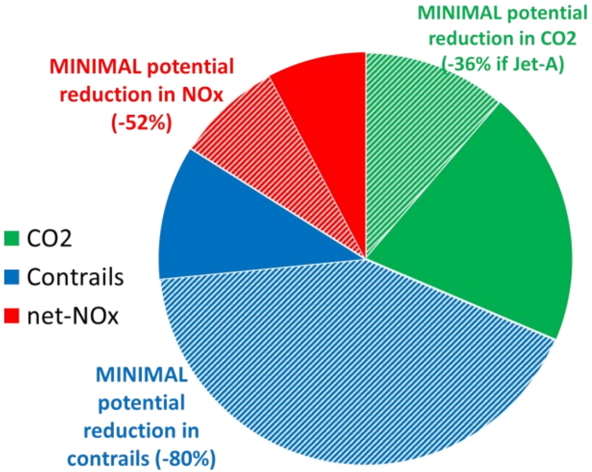
## Ultra low specific thrust

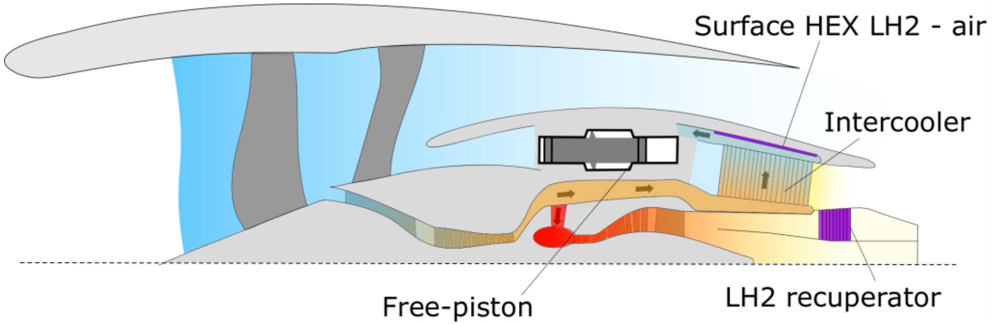
Boxprop

Grönstedt, Tomas, Carlos Xisto, Vishal Sethi, Andrew Rolt, N. G. Roas, Arne Seitz, D. Misirlis, John Whurr, Nicolas Tantot, and Martin Dietz. "Conceptual design of ultra-efficient cores for mid-century aircraft turbine engines." In *Proceedings of the 24th ISABE Conference, Canberra, Australia*, pp. 22-27. 2019.

# MINIMAL (2022-2026)

- Step improvement in thermal efficiency.
- Operational flexibility
- Heavy-duty proven NOx mitigation technology
- Attack in all fronts





CHALMERS UNIVERSITY OF TECHNOLOGY

Cranfield University

ARTTIC

GKN AEROSPACE

REACTION ENGINES

MTU Aero Engines

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Rolls-Royce

TU Delft Delft University of Technology

Bauhaus Luftfahrt Neue Wege.

# Climate impact of targets

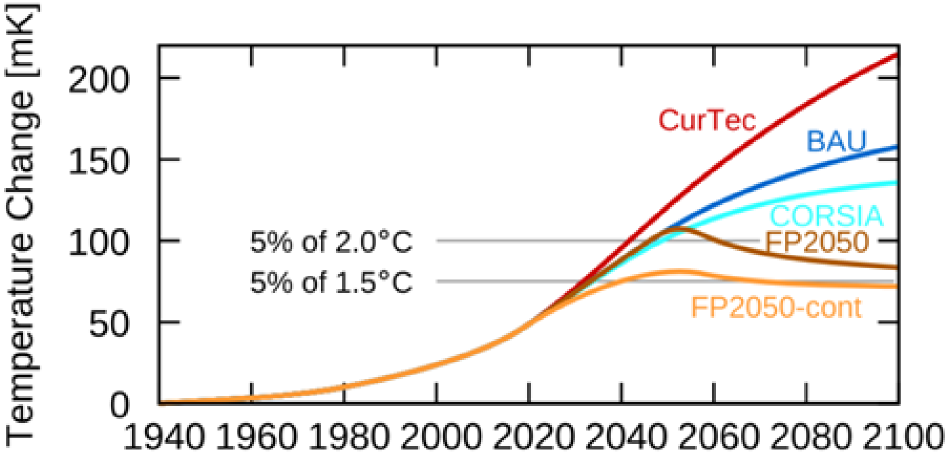

**Fig. 2 Near-surface temperature change of five scenarios including $CO_2$ and non-$CO_2$-effects.**

Grewe, V., Gangoli Rao, A., Grönstedt, T. *et al.* Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects. *Nat Commun* **12,** 3841 (2021). https://doi.org/10.1038/s41467-021-24091-y

# Impact vs efficiency of hydrogen

Efficiency

Batteries

~ 5% (up to 500 km)[1]

Hydrogen

~ 52% (up to 3000 km)[1]

Synfuels

All ranges flown today

Range

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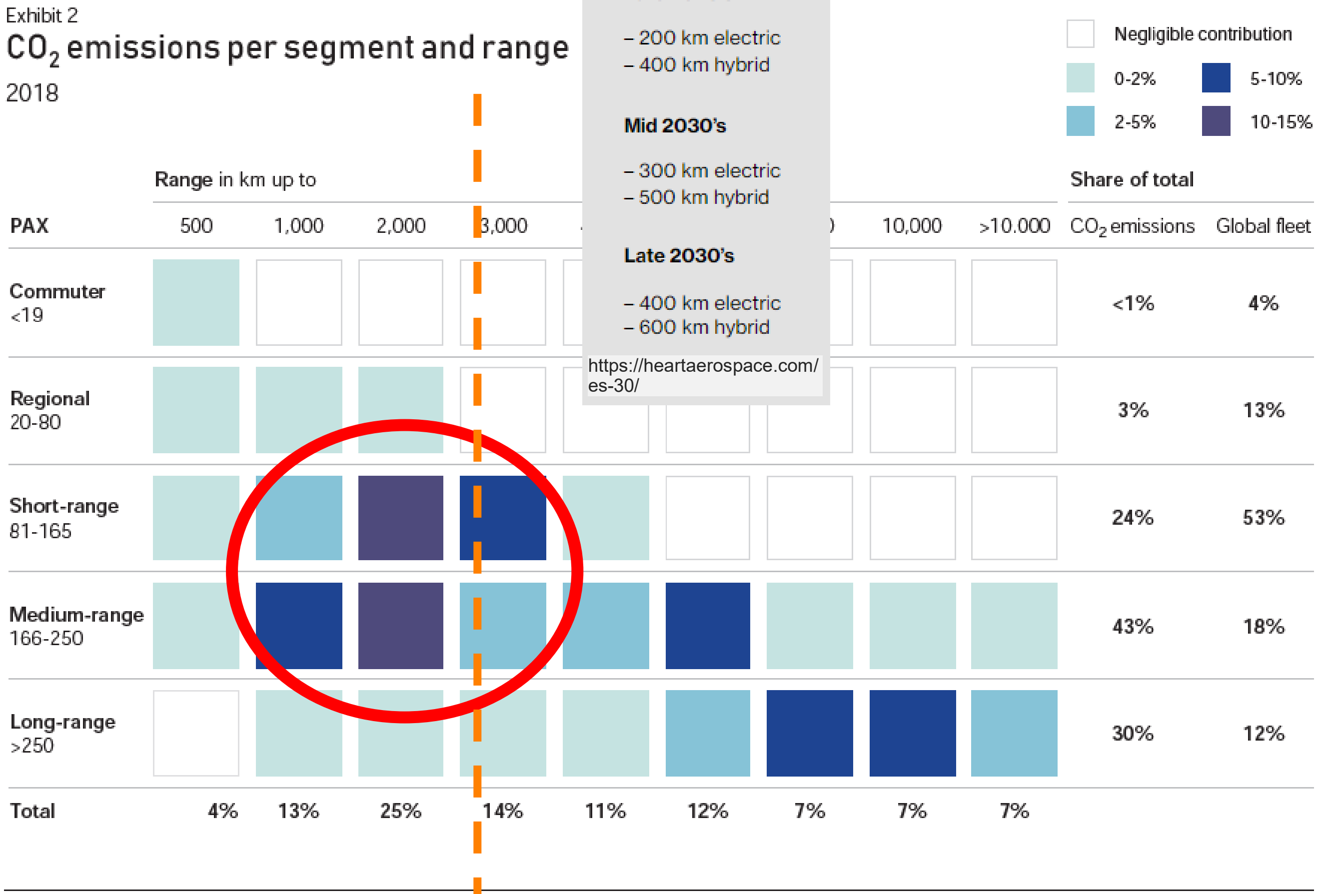
[1] Graver, Brandon, Kevin Zhang, and Dan Rutherford. "emissions from commercial aviation, 2018." ICCT, 2019.

Exhibit 2

## $CO_2$ emissions per segment and range

2018



- ⬜ Negligible contribution
- 0-2%
- 2-5%
- 5-10%
- 10-15%

Range in km up to

Share of total

| PAX | 500 | 1,000 | 2,000 | 3,000 | | | | 10,000 | >10.000 | $CO_2$ emissions | Global fleet |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Commuter**<br><19 | | | | | | | | | | <1% | 4% |
| **Regional**<br>20-80 | | | | | | | | | | 3% | 13% |
| **Short-range**<br>81-165 | | | | | | | | | | 24% | 53% |
| **Medium-range**<br>166-250 | | | | | | | | | | 43% | 18% |
| **Long-range**<br>>250 | | | | | | | | | | 30% | 12% |
| **Total** | 4% | 13% | 25% | 14% | 11% | 12% | 7% | 7% | 7% | | |

**Late 2020's**

– 200 km electric
– 400 km hybrid

**Mid 2030's**

– 300 km electric
– 500 km hybrid

**Late 2030's**

– 400 km electric
– 600 km hybrid

https://heartaerospace.com/es-30/

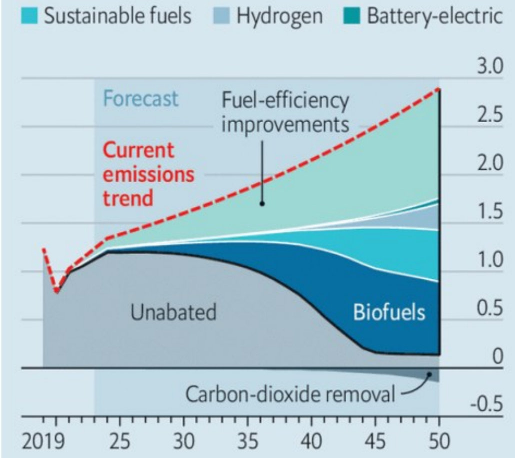
## Hydrogen-powered aviation

A fact-based study of hydrogen technology, economics, and climate impact by 2050

**Operating beyond distances of 2,222 km in a single-stage flight would require a battery pack specific energy of at least 1,600 Wh/kg**

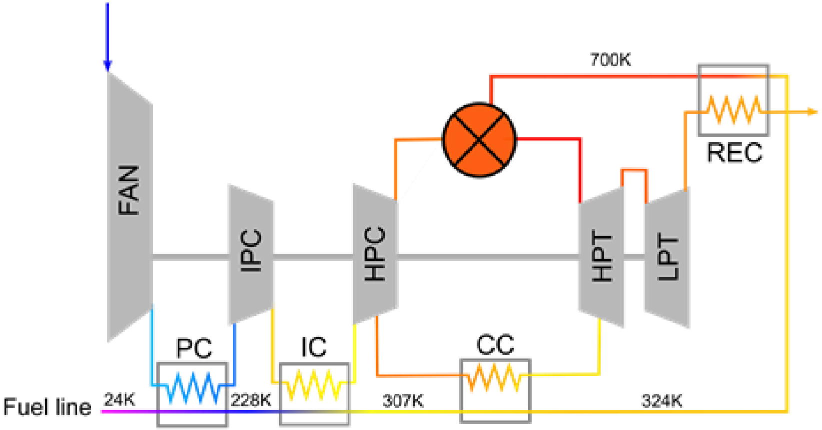
Gnadt, A. R. Technical and Environmental Assessment of All-Electric 180-Passenger Commercial Aircraft. SM thesis, MIT, 2018

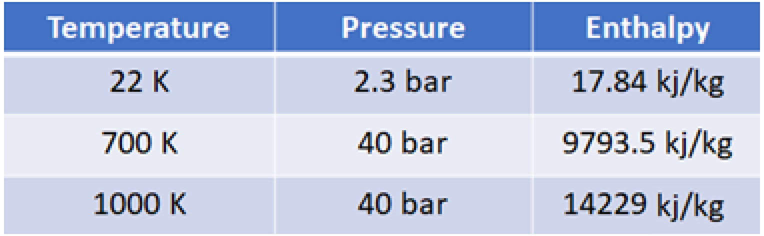
*The economist, 30 May, 2023*



# Heat management

# Cryogenic hydrogen
# Heat management research





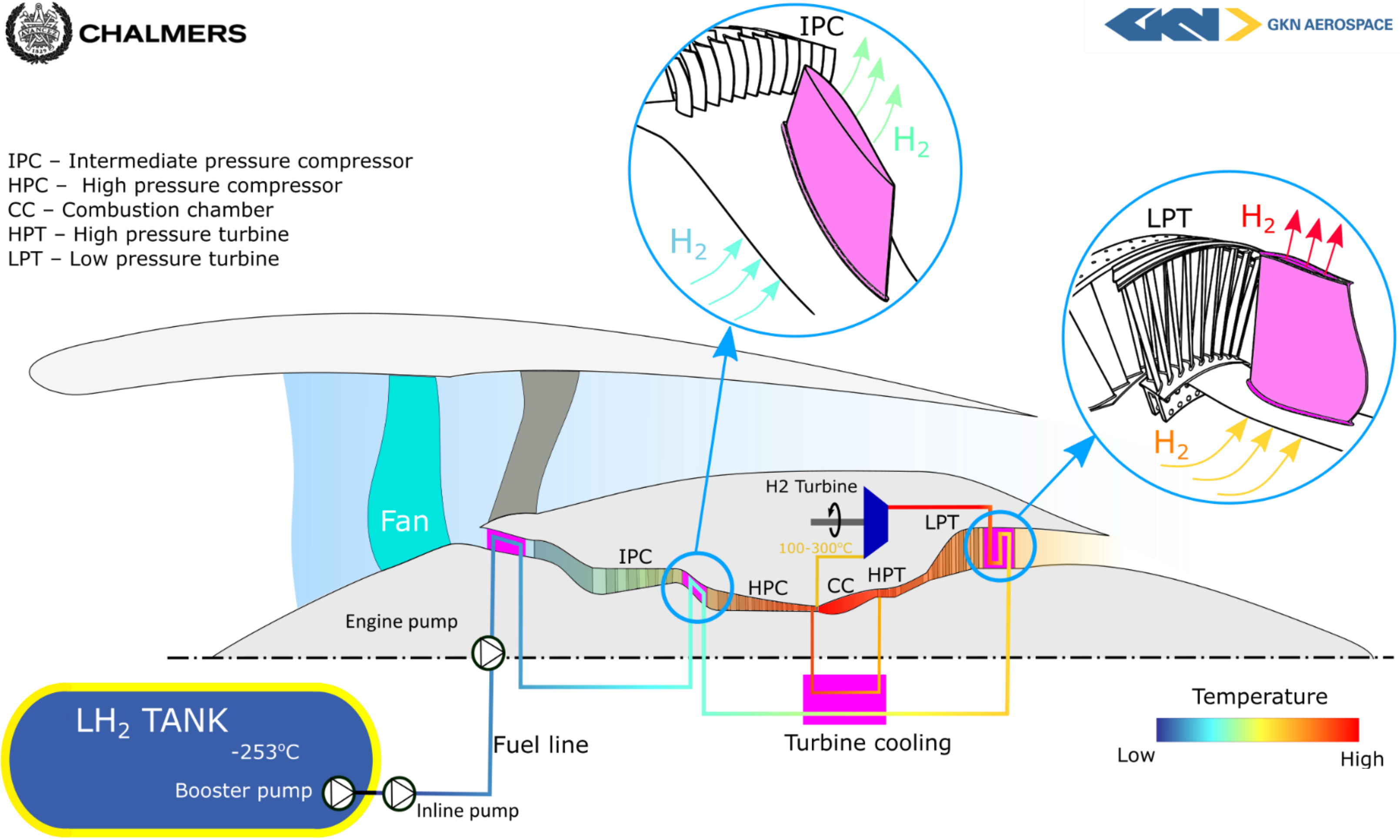
| Temperature | Pressure | Enthalpy |
|---|---|---|
| 22 K | 2.3 bar | 17.84 kj/kg |
| 700 K | 40 bar | 9793.5 kj/kg |
| 1000 K | 40 bar | 14229 kj/kg |

- Heat addition to fuel could easily be 10% of fuel heat value
  - theoretically ~ 10% SFC!
- Advanced engine integration may allow further improvement

**CHALMERS**

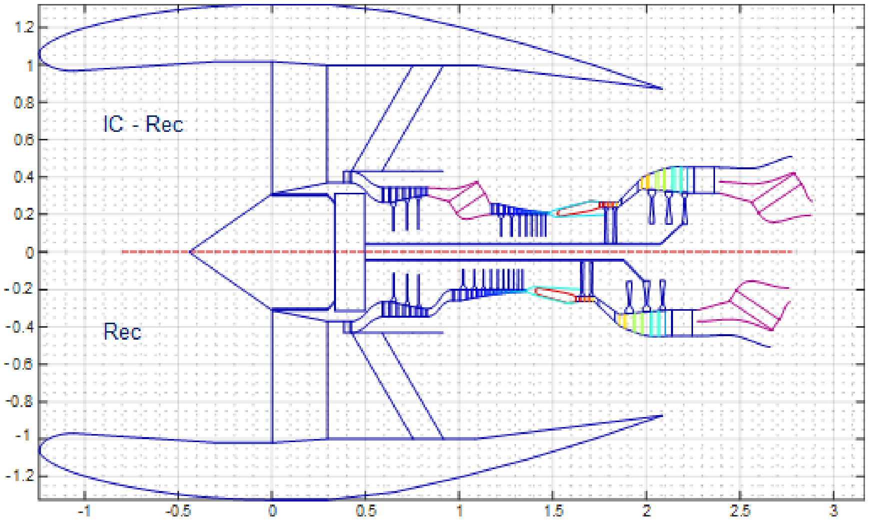
**GKN AEROSPACE**

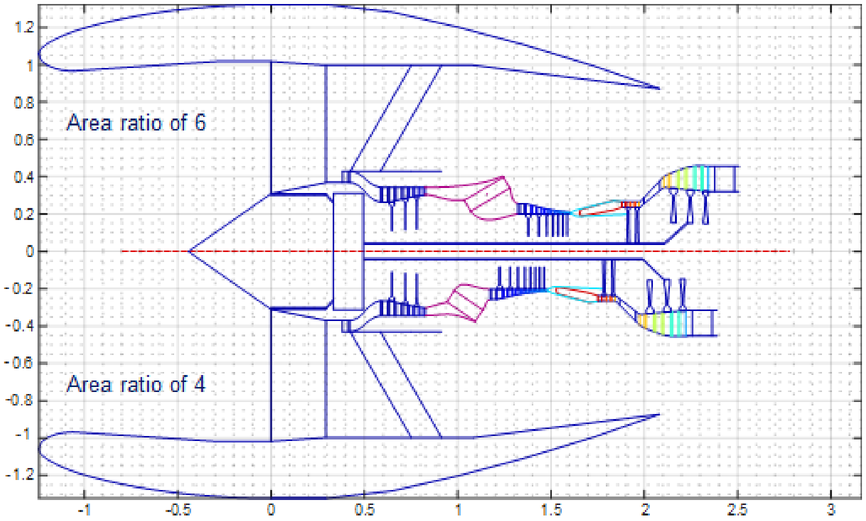
IPC – Intermediate pressure compressor
HPC – High pressure compressor
CC – Combustion chamber
HPT – High pressure turbine
LPT – Low pressure turbine



# Propulsion system integration (IPC/LPT)

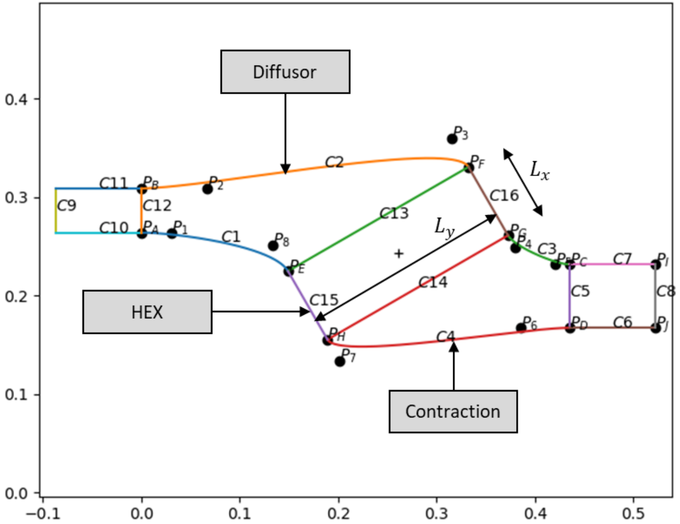
AR4/AR6 – area ratio
of diffuser

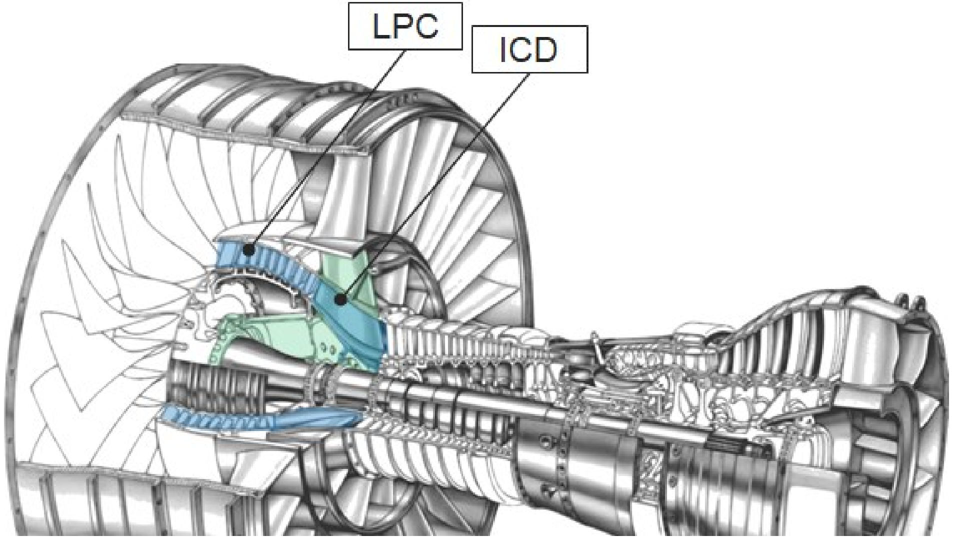




# Hydrogen heat recovery system – compression side (IPC)

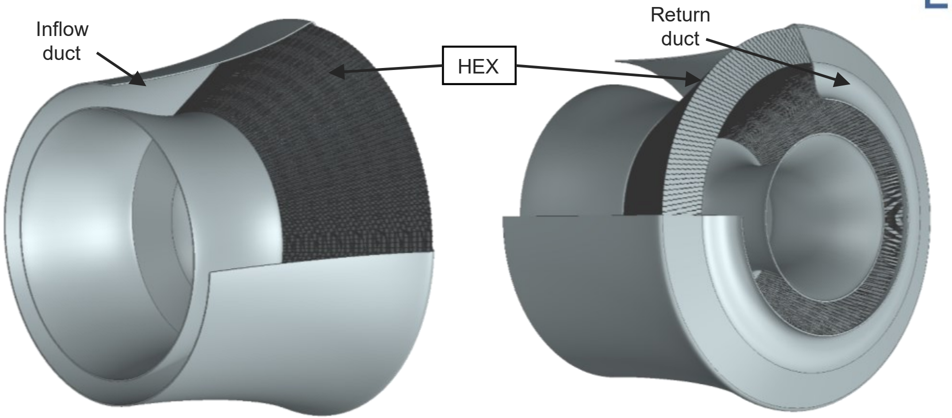
- Finned tube design
- Optimization of diffuser and contraction ducts
- 19 design parameters

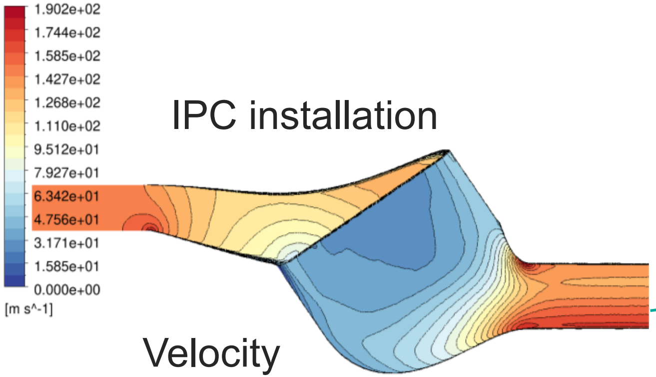




# IPC installation

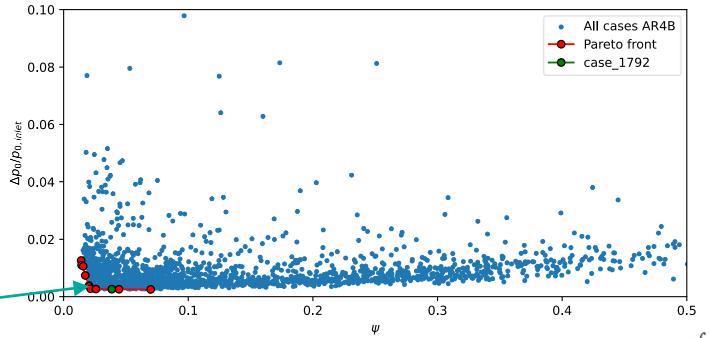
- Achieve low pressure loss and good flow uniformity





IPC installation

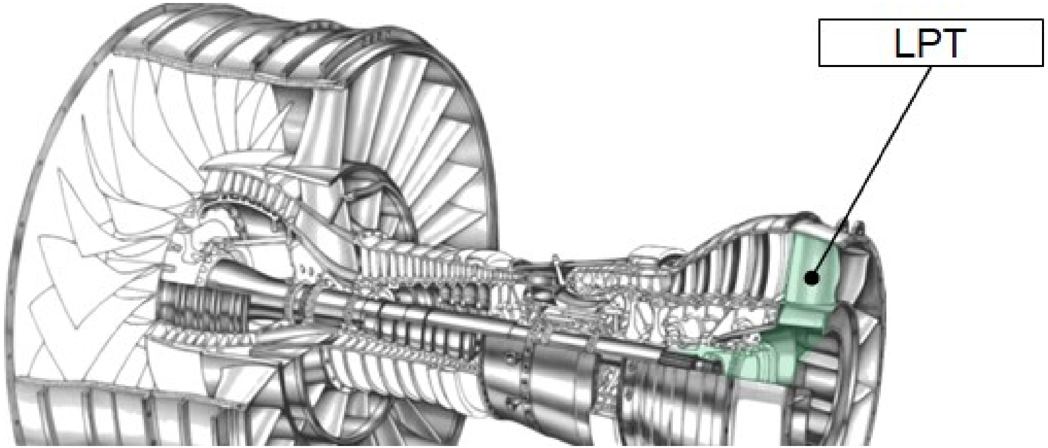
Velocity distribution



$$\psi = \int_{A_{inlet}} \frac{1}{2} v'^2 dA \Big/ \int_{A_{inlet}} \frac{1}{2} V^2 dA$$

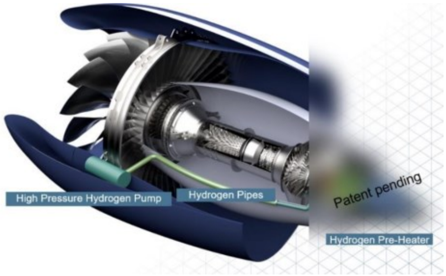
$$v' = V - \int_{A_{inlet}} V dA$$

# LPT installation



- Work close with GKN Aerospace
- Successful testing and demonstration of new pre-heater concept

H2JET



System predictions

| Variant | Mass (kg) | Architecture | $\Delta_{FB,SFC}$ | $\Delta_{FB,W}$ | $\Delta_{FB}$ (3000 NM) |
|---|---|---|---|---|---|
| Baseline | 3185 | 1+3+10+2+3 | datum | datum | datum |
| Intercooled AR4 | 3127 | 1+3+8+2+3 | -2.06% | -0.26% | -2.3% |
| Intercooled AR6 | 3159 | 1+3+7+2+3 | -2.96% | -0.12% | -3.1% |
| Intercooler AR4 Recuperated AR4 | 3440 | 1+3+8+2+3 | -5.94% | 1.17% | -4.8% |
| Recuperated AR4 | 3390 | 1+3+10+2+3 | -5.94% | 0.93% | -5.1% |

# Low-Pressure Compressor Facility At Chalmers

## 2.5 Stage Compressor

1.2 m diameter, 2.5 stage low-pressure compressor provides representative operation

## Wide operation Space

Reynolds numbers up to $Re_c = 600{,}000$

## Stable Operation

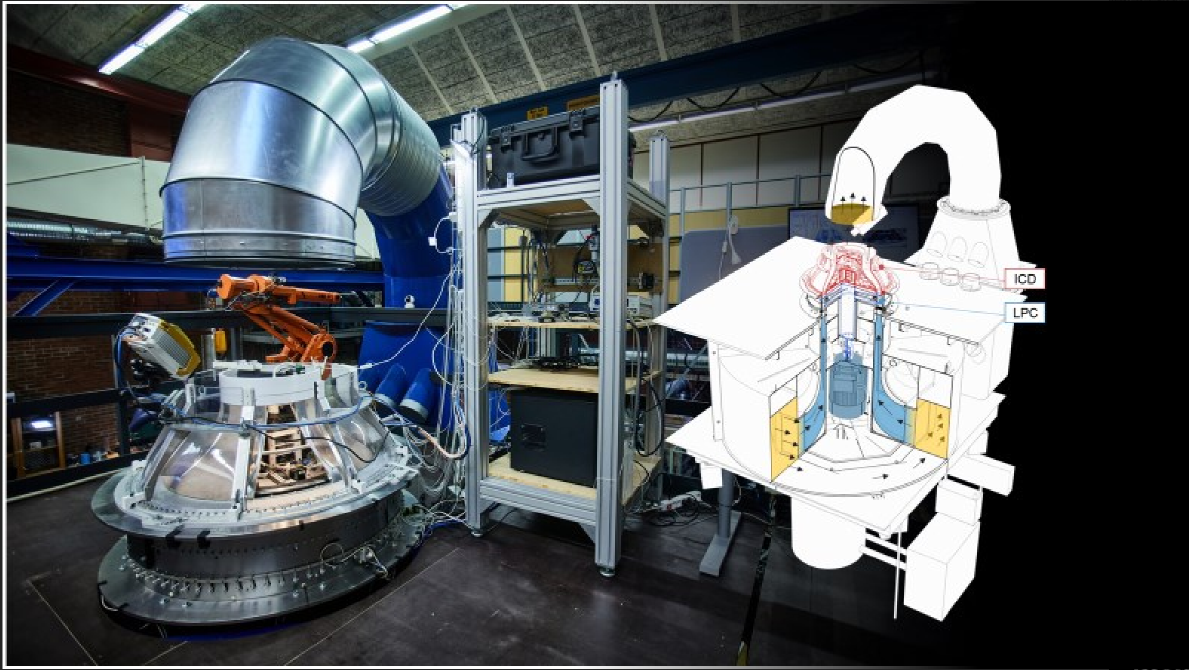
Continuous operation near stall up to 16 hour allows for detailed studies.

## Aerothermal Investigation

Build for advanced measurement with; several Multi-hole probes, PIV, IR-thermography, Hot-wire, Pressure taps…

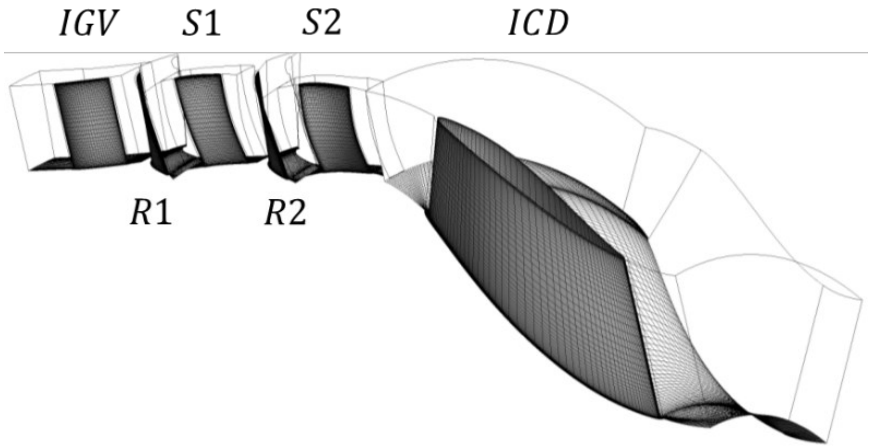
## Excellent Access and Modularity

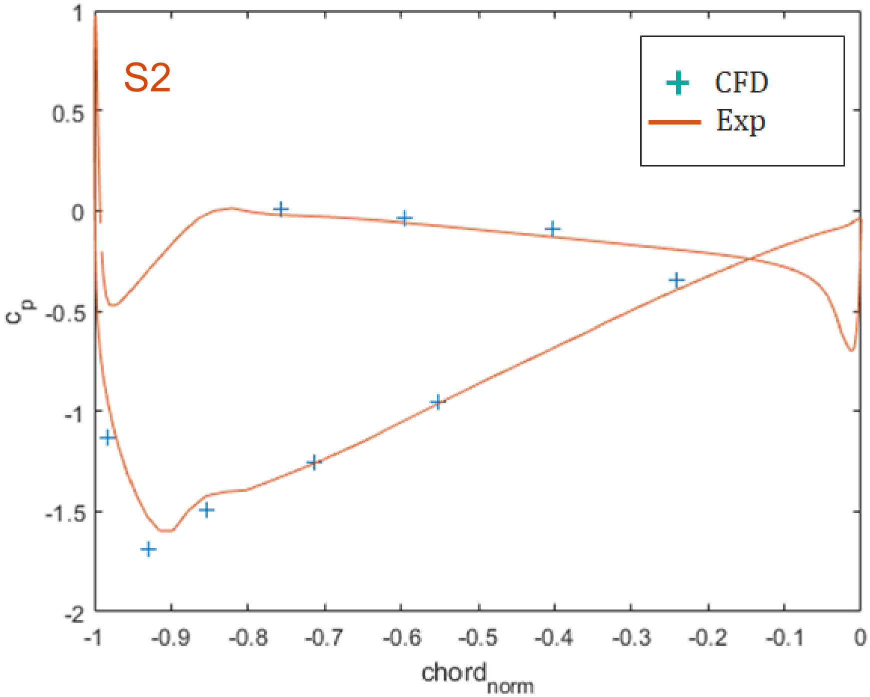
Build for modularity and access and an entire ICD can be changed with less than 20 min downtime.



Grant agreement ID: 769241

# Validation with CFD

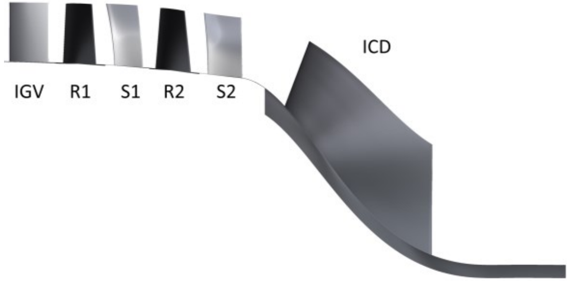




- ANSYS - CFX
- $k-\omega$ SST
- $\gamma - \theta$ transition model
- Semi-perfect gas

- 100% speed tests
- Good flow uniformity

# Validation



| ENABLEH2 Compressor | |
|---|---|
| Rotational Speed | 1920 rpm |
| Mass flow | 17 kg/s |
| Pressure ratio | 1.07 |
| Tip Speed | 100 m/s |
| Axial Velocity | 70 m/s |
| Rotor $Re_c$ | 600 000 |
| Avg Tip radius | 620 mm |
| Avg Hub radius | 540 mm |
| N. stator Blades (IGV, S1, OGV, ICD) | 75, 126, 124, 8 |
| N. rotor Blades (R1, R2) | 61, 69 |
| Avg Aspect Ratio | 2.157 |
| Avg Tip Clearance | 0.75 mm |

- Heat transfer and flow uniformity validations on-going
- So far so good.
- Work on regularizing conditions, currently S2 ICD (wake transition)

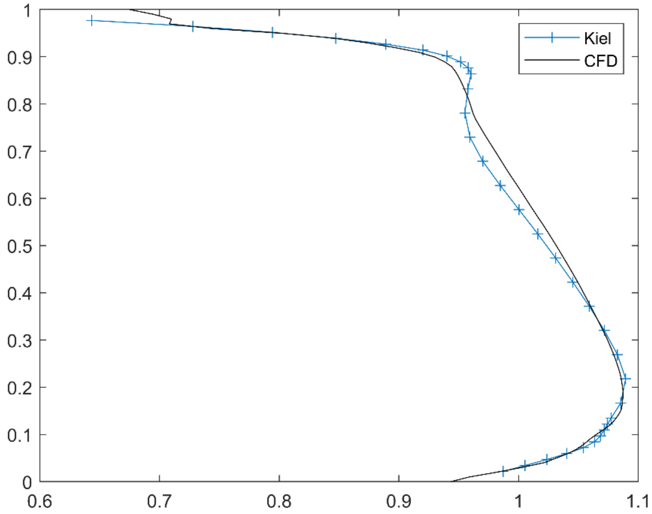
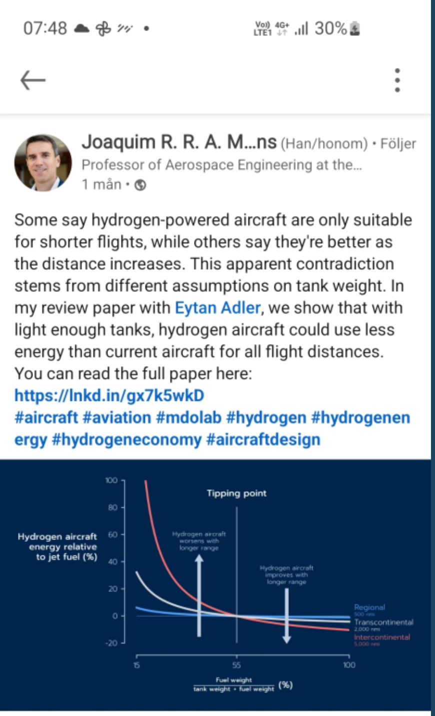


*Figure 6-5 Normalised total pressure at the inlet of S2 for Keil probe measurements and numerical simulations (sector integrated, 2000 pts in 15 deg.)*

# Cryo-tanks



**Joaquim R. R. A. M...ns** (Han/honom) • Följer
Professor of Aerospace Engineering at the...
1 mån •

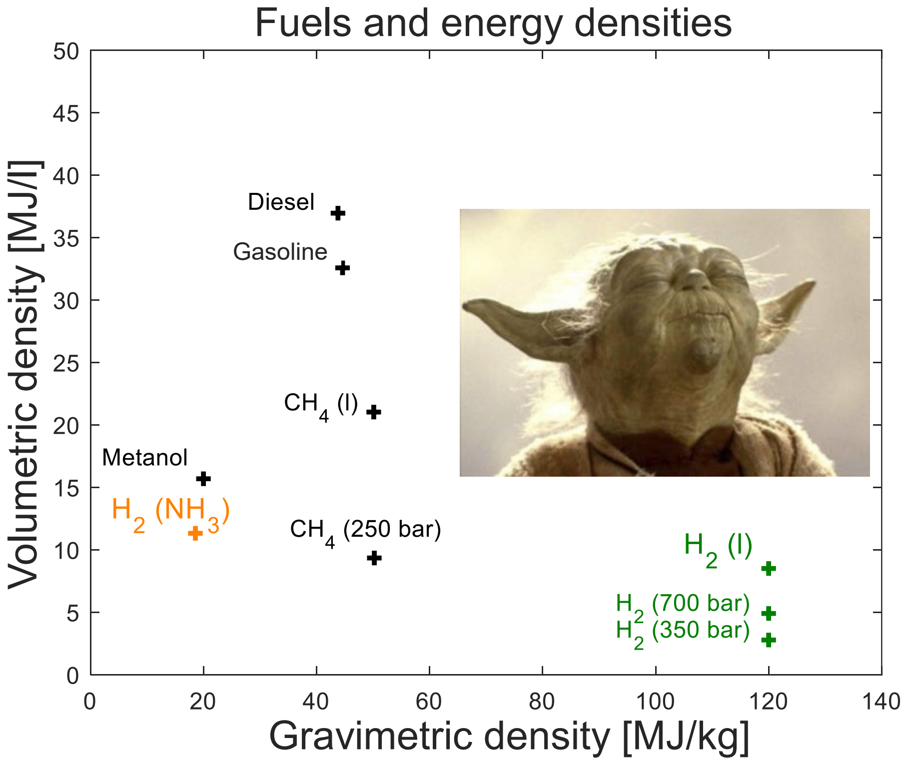
Some say hydrogen-powered aircraft are only suitable for shorter flights, while others say they're better as the distance increases. This apparent contradiction stems from different assumptions on tank weight. In my review paper with Eytan Adler, we show that with light enough tanks, hydrogen aircraft could use less energy than current aircraft for all flight distances. You can read the full paper here:
https://lnkd.in/gx7k5wkD
#aircraft #aviation #mdolab #hydrogen #hydrogenenergy #hydrogeneconomy #aircraftdesign

**Misconception:** Hydrogen aircraft actually get better at longer range - Potentially – relative to jet fuel.
(R. Miller, Cambridge, 2023-04-26, ETC conference

# Hydrogen – storage properties

$q_{grav} = heat\ content\ per\ mass\ [kWh/kg]$
$q_{vol} = heat\ content\ per\ volume\ [kWh/litre]$

- Hydrogen has extremely high energy density per kg
- But it has low energy density per volume
- Transportation in form of ammonia may be attractive

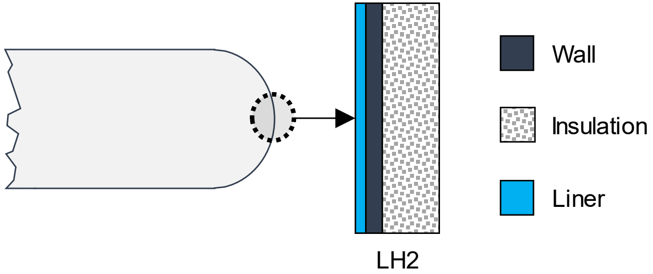


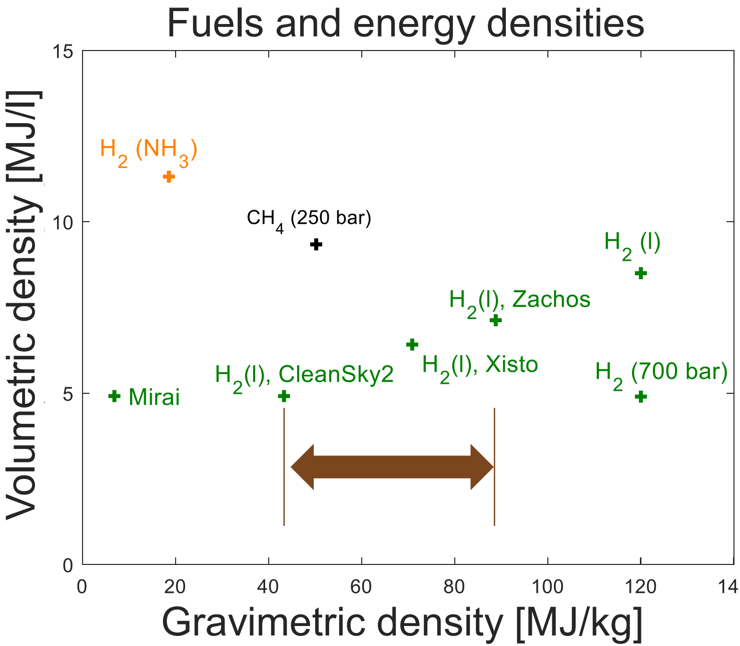
# Installed cryo densities

- Clean Sky 2 estimates
  - Resulting in close to Jet A densities
  - Double wall vacuum tank
- Single wall, external isolation

Hydrogen-powered aviation
A fact-based study of hydrogen technology, economics, and climate impact by 2050
May 2020

K. Dahal, S. Brynolf, C. Xisto, J. Hansson, M. Grahn, T. Grönstedt, M. Lehtveer,
Techno-economic review of alternative fuels and propulsion systems for the aviation sector, Renewable and Sustainable Energy Reviews, Volume 151,
2021, 111564, ISSN 1364-0321,

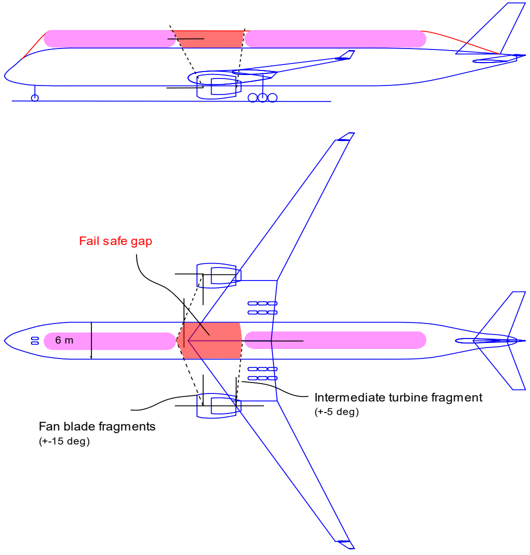


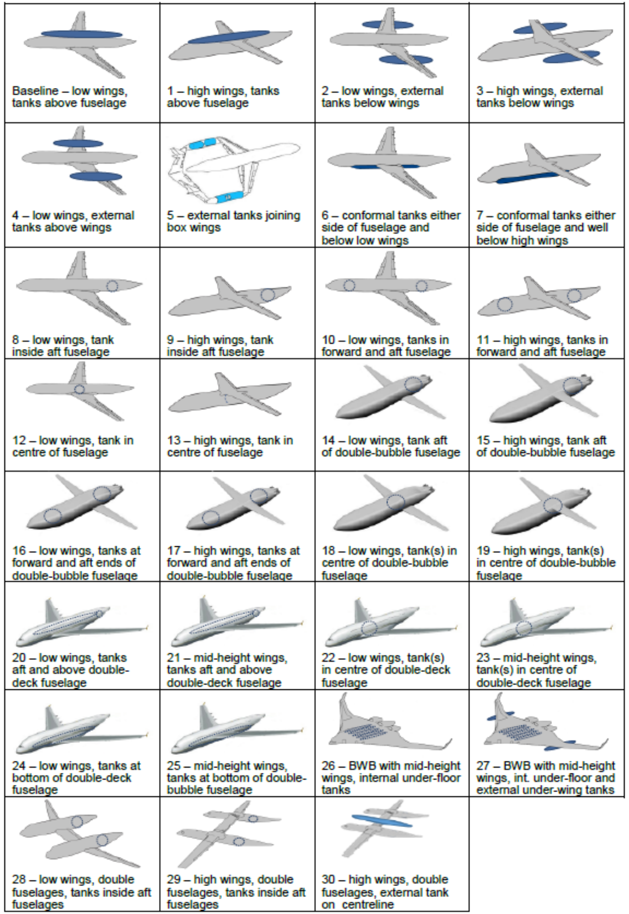


- We can conclude that there is a large uncertainty in gravimetric density

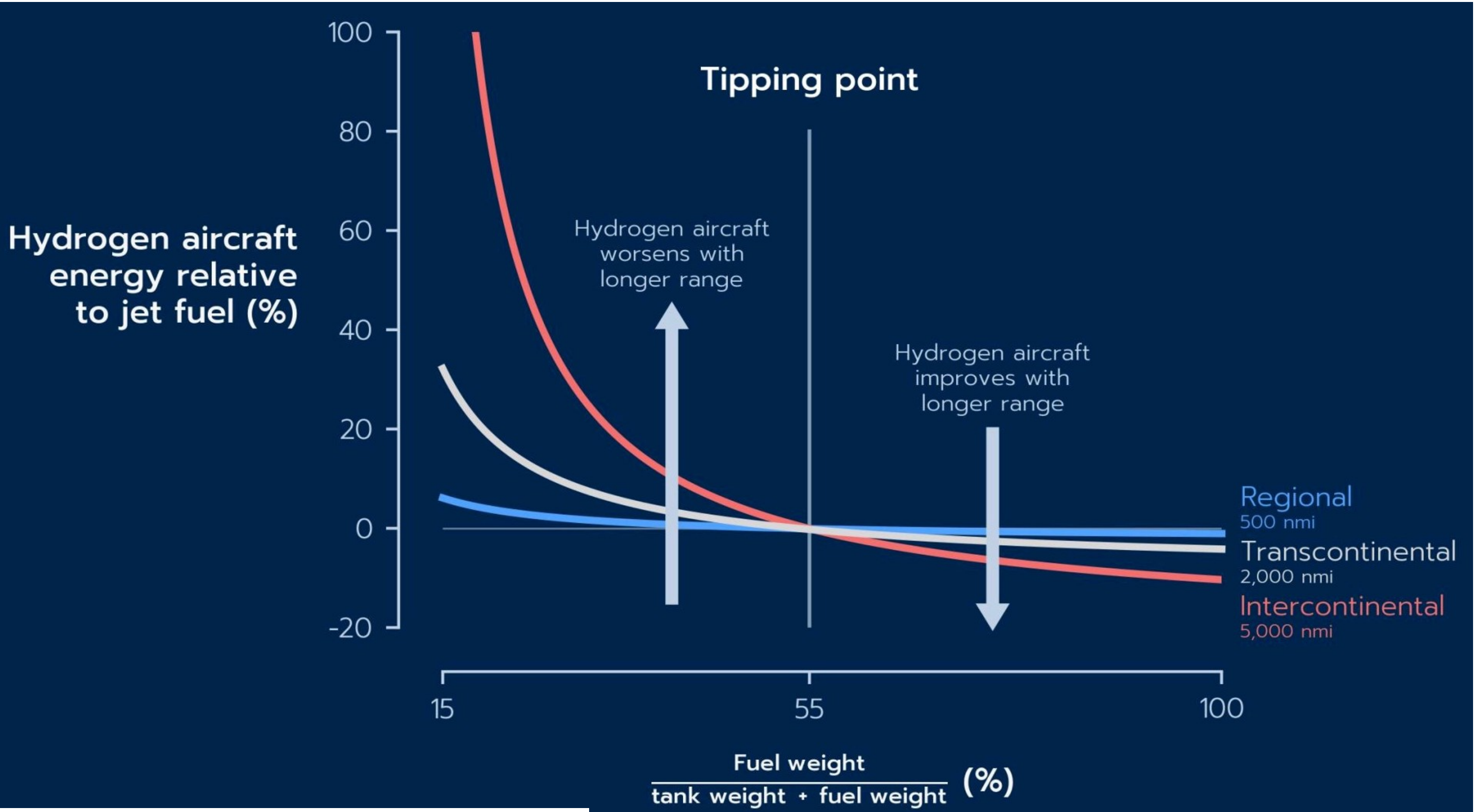
# Cryogenic hydrogen storage

- ENABLEH2 (EU project)
  - One project goal was to “revitalize interest in hydrogen for aviation”
- Insulated foam tanks are low TRL
- Double walled vacuum tanks are heavy (difficult with longer ranges)





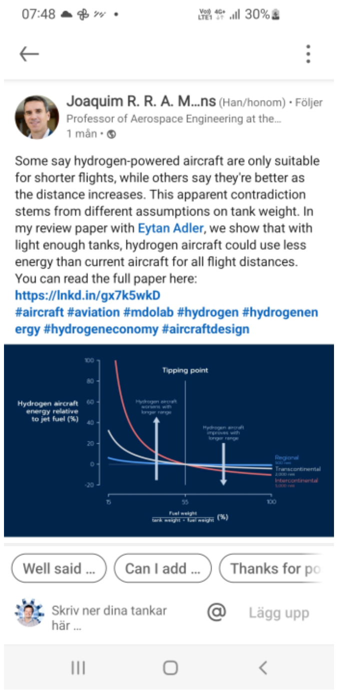
Rompokos, P, Rolt A, Nalianda D, Isekveren A T, Senné C, Grönstedt T., Hamidreza A., Synergistic technology combinations for future commercial aircraft using liquid hydrogen”, Journal of Engineering for Gas Turbines and Power, Volume143, Issue, 7, 2021



# Hydrogen-Powered Aircraft: Fundamental Concepts, Key Technologies, and Environmental Impacts

Eytan J. Adler* and Joaquim R. R. A. Martins
Department of Aerospace Engineering, University of Michigan, Ann Arbor, United States

Version: December 11, 2022



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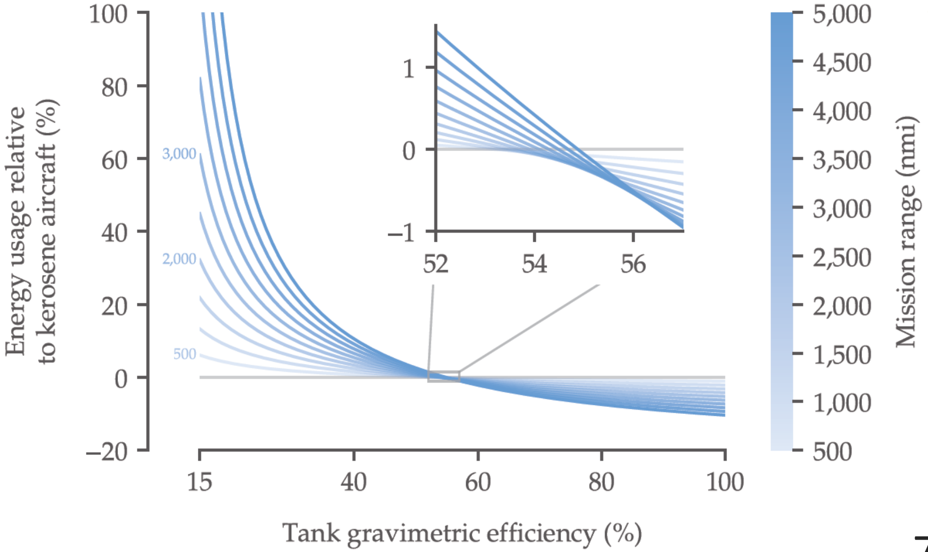

# Hydrogen-Powered Aircraft: Fundamental Concepts, Key Technologies, and Environmental Impacts

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Department of Aerospace Engineering, University of Michigan, Ann Arbor, United States

Version: December 11, 2022

777-200LR

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[†] Data is based on the Breguet range equation. It assumes a thrust-specific energy consumption based on the GE90 [48] and a cruise condition of Mach 0.8 at 35,000 ft. The lift-to-drag ratio is assumed to be 18. Tank weight is added to the base zero fuel weight. We found that the tipping point of 55% is insensitive to these parameter values.

For Martins data (in original paper) we repeat the chart. Where the gravimetric efficiency $\eta$ is defined as:

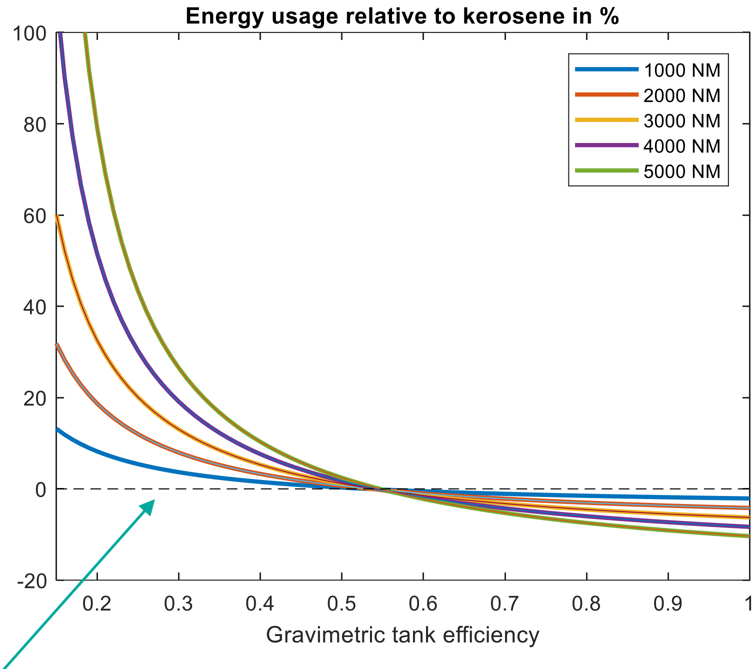
$$\eta = \frac{m_{fuel,H2}}{m_{fuel,H2} + m_{Tank,H2}}$$

Analytic solution for problem exist:

$$\alpha = \frac{\dfrac{Q_{H2} m_0 \left(1 - e^{\frac{g \cdot R \cdot SFC_{H2}}{V \cdot \frac{L}{D}}}\right)}{Q_{JET-A} \cdot m_{fuel,JET-A}} + 1}{e^{\frac{g \cdot R \cdot SFC_{H2}}{V \cdot \frac{L}{D}}} - 1}$$

Where the gravimetric efficiency relates to $\alpha$ as (easily derived from definition):

$$\eta = \frac{1}{1 + \alpha}$$

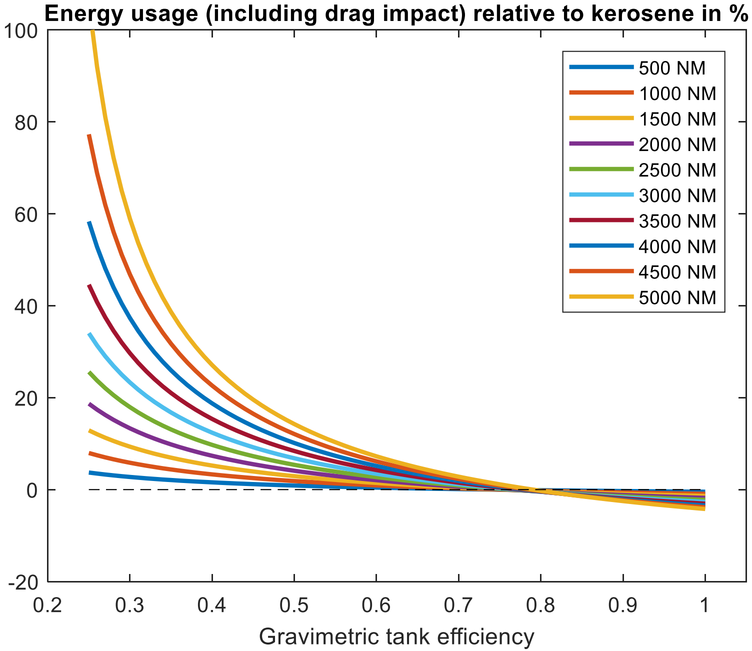


Nominal kerosene level

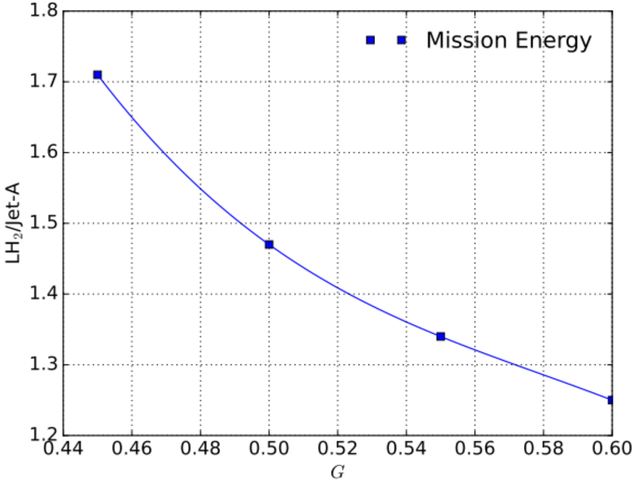
For the 5000 NM we get:

$$\alpha = 0.8289 \; and \; \eta = 0.5468$$

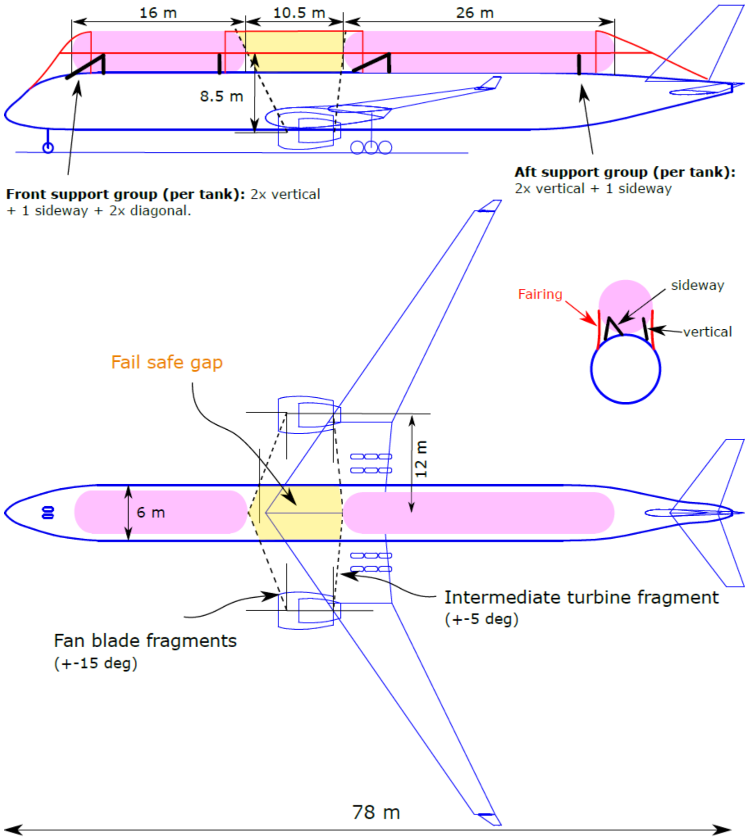
- Now repeating with drag included (Raymer, Eq. 3.12)



- When added structural weight is considered NO cross over is found (always more energy need for H2)



Xisto, C., Lundbladh, A., “Design and Performance of Liquid Hydrogen Fuelled Aircraft for Year 2050 EIS”, ICAS, 2022



| | Jet-A (2020) | Jet-A (2050) | LH2 (2050) | LH2 versus Jet- A (rel.) |
|---|---|---|---|---|
| MTOW (kg) | 338,500 | 294,500 | 284,800 | 0.97 |
| L/D | 19.1 | 20.6 | 17.9 | 0.87 |
| Wetted area fuselage ($m^2$) | 1300 | 1300 | 1970 | 1.52 |
| $LH_2$ tank volume ($m^3$) | - | - | 714 | - |
| $LH_2$ tank weight (kg) + structures and Fairing | - | - | 26,500 | - |
| Energy use (rel. to 2020) | Datum | -28% | -11% | - |

*Gravimetric 65%*
*Foam insulated*

K. Dahal, S. Brynolf, C. Xisto, J. Hansson, M. Grahn, T. Grönstedt, M. Lehtveer,

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