香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Hydrogen-Powered Aircraft

Sustainable Future Takes Flight

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HYDROGEN-POWERED AIRCRAFT:

SUSTAINABLE FUTURE TAKES FLIGHT

MAR 23

ROOM **4621**

near lifts 31/32

5:00 PM

Registration and mingling session

4:30 PM

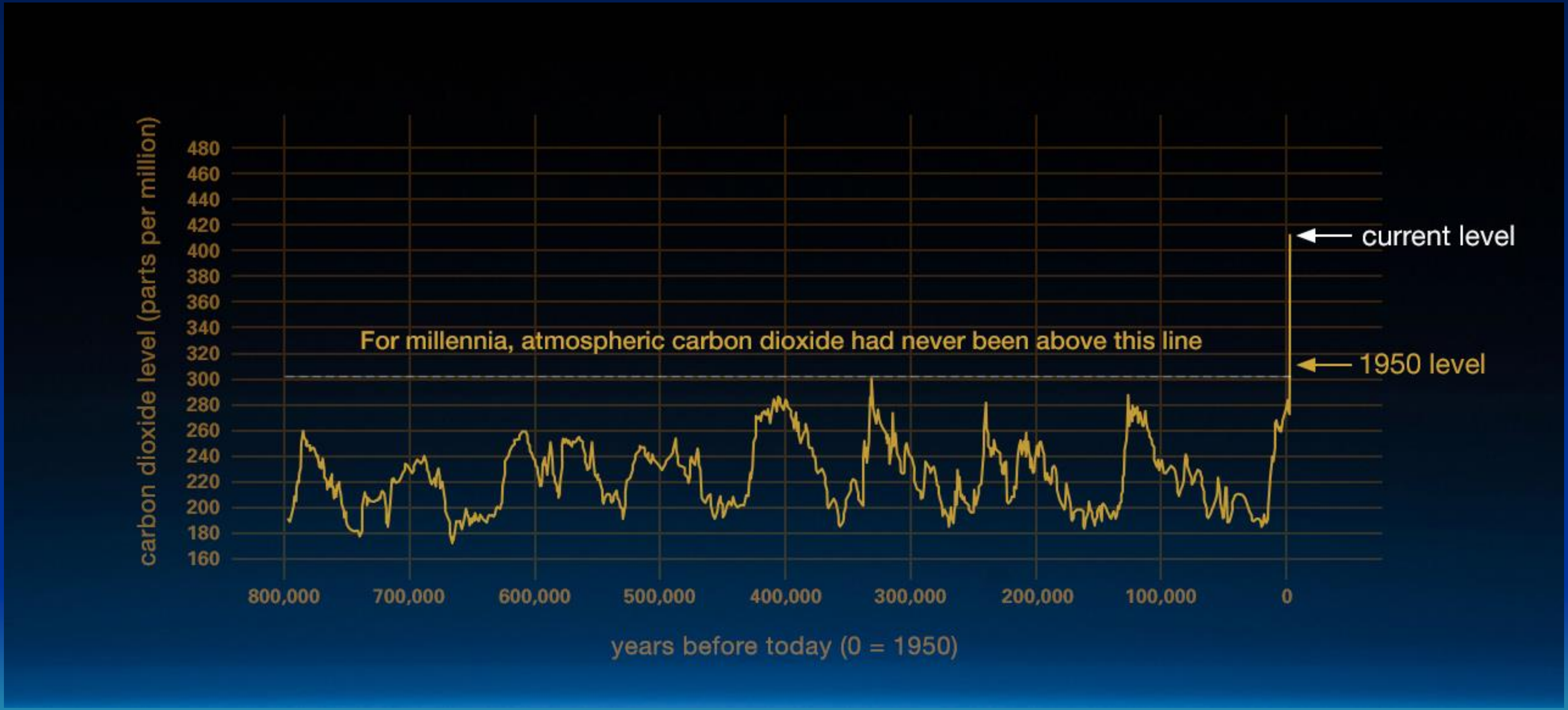
Refreshment will be provided

Tony Hays

Tony has 50 years of experience working in the aerospace industry -- with 30 years spent at Lockheed in aircraft conceptual design

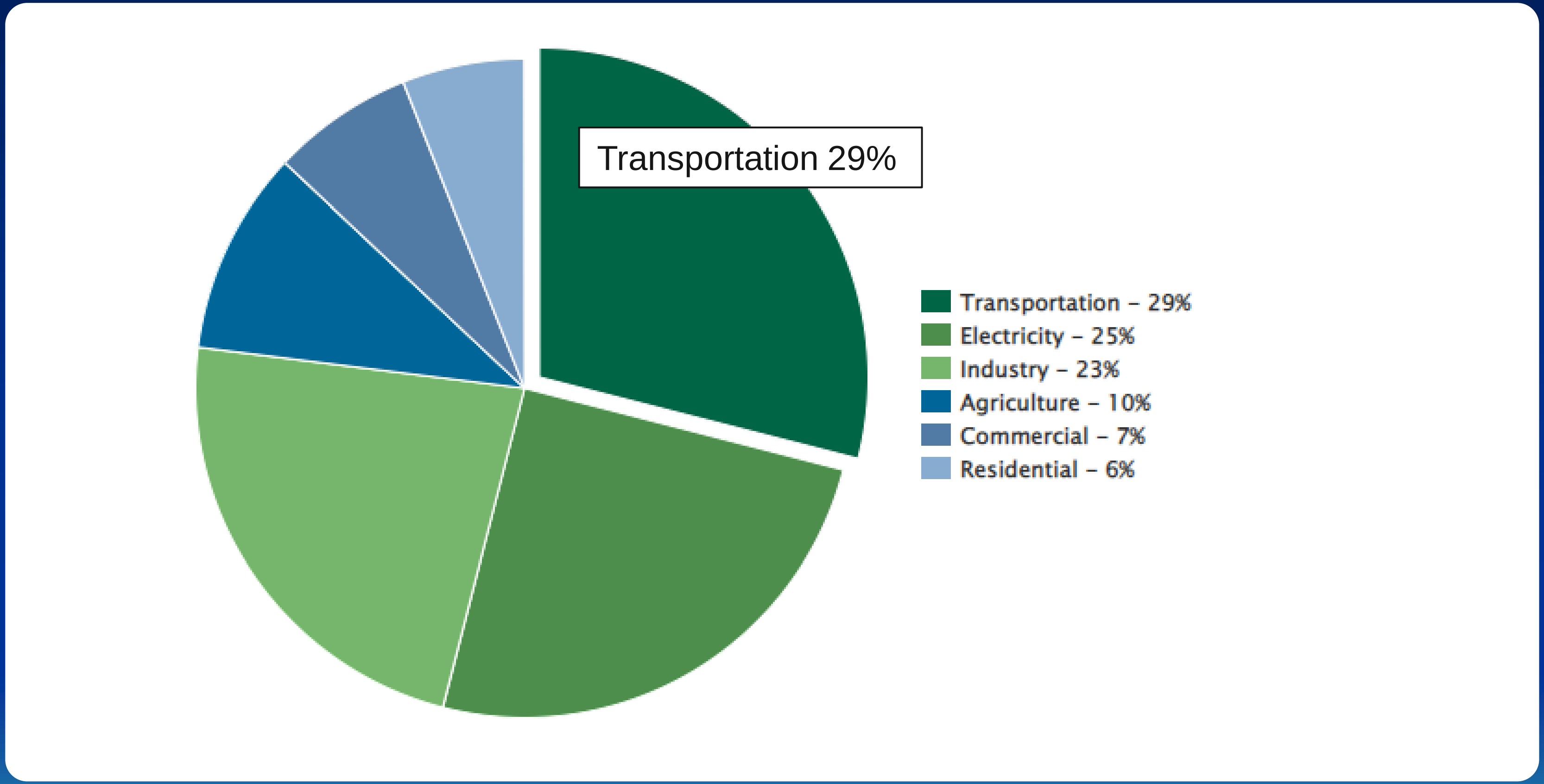
- Need for Zero-Carbon Economy
- Hydrogen vs. Batteries
- History of Hydrogen-powered Propulsion
- Hydrogen Generation and Distribution
- Applications of Hydrogen Energy
- The Future of Hydrogen
- Contrails
- Conclusions

The Relentless Rise of CO_2

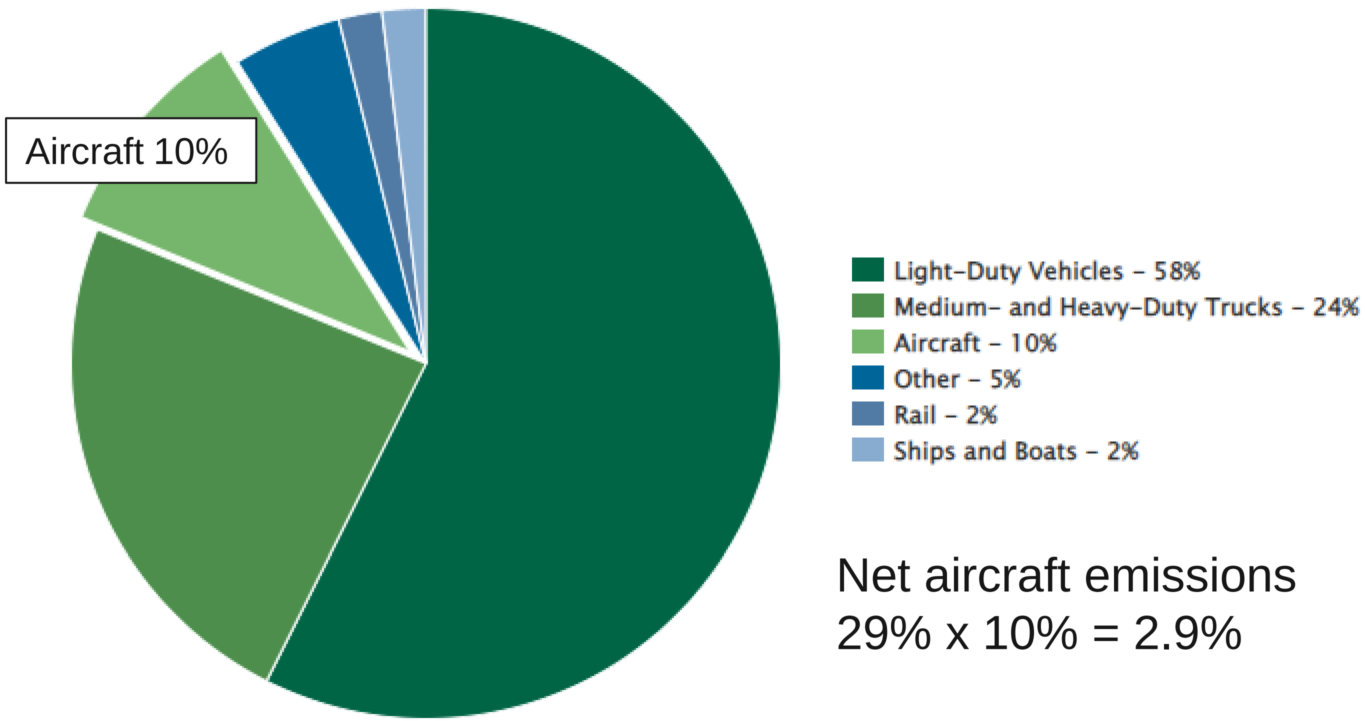


https://climate.nasa.gov/climate_resources/24/graphic-the-relentless-rise-of-carbon-dioxide/

2019 U.S. GHG Emissions by Sector



2019 U.S. Transportation Sector GHG Emissions by Source



Net aircraft emissions
29% x 10% = 2.9%

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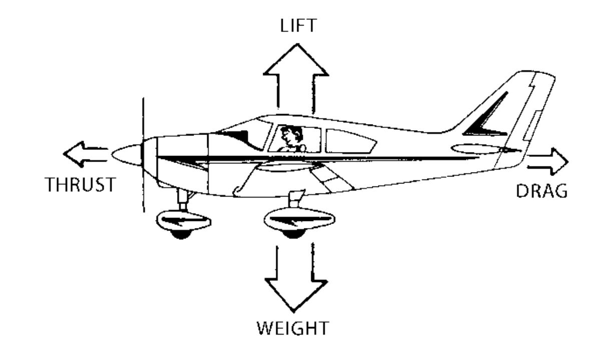
Drag Polar

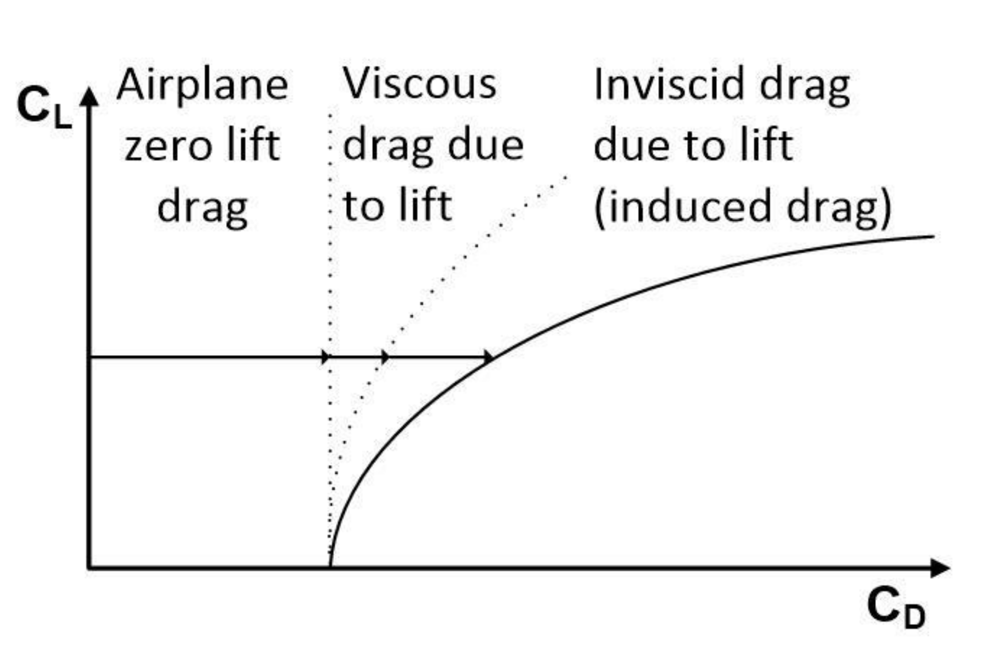
For an airplane, almost half the drag is directly dependent on weight



$$C_D = C_{D_0} + K C_L^{\,2}$$

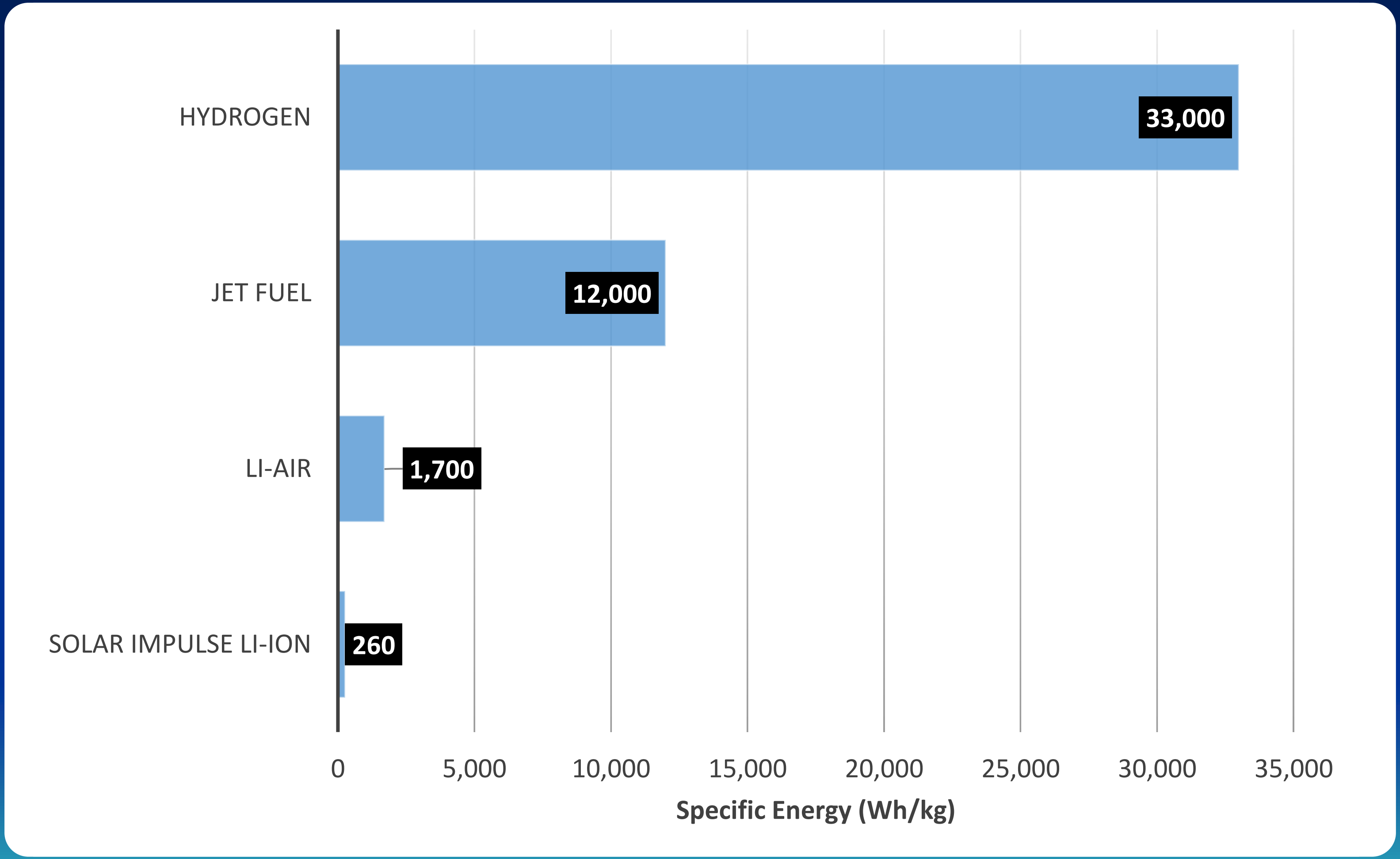
$$where \quad C_L = \frac{L}{\frac{1}{2}\rho V^2 S}$$

$$and \quad L = W$$

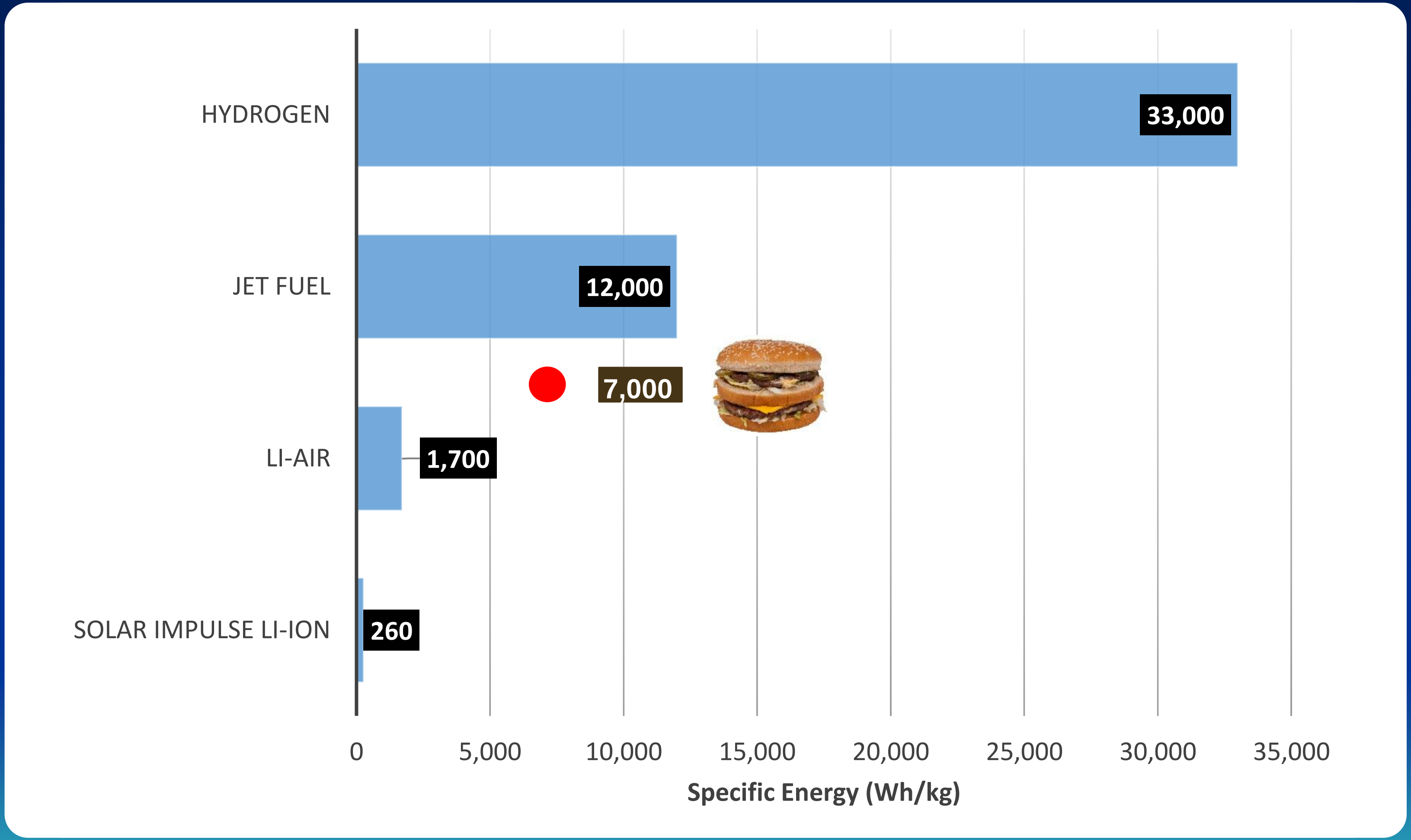


More weight > more lift req'd > more drag > more thrust req'd > more power req'd > more energy req'd > more battery weight

Energy/Unit Weight is Important



Energy/Unit Weight is Important



https://en.wikipedia.org/wiki/Big_Mac

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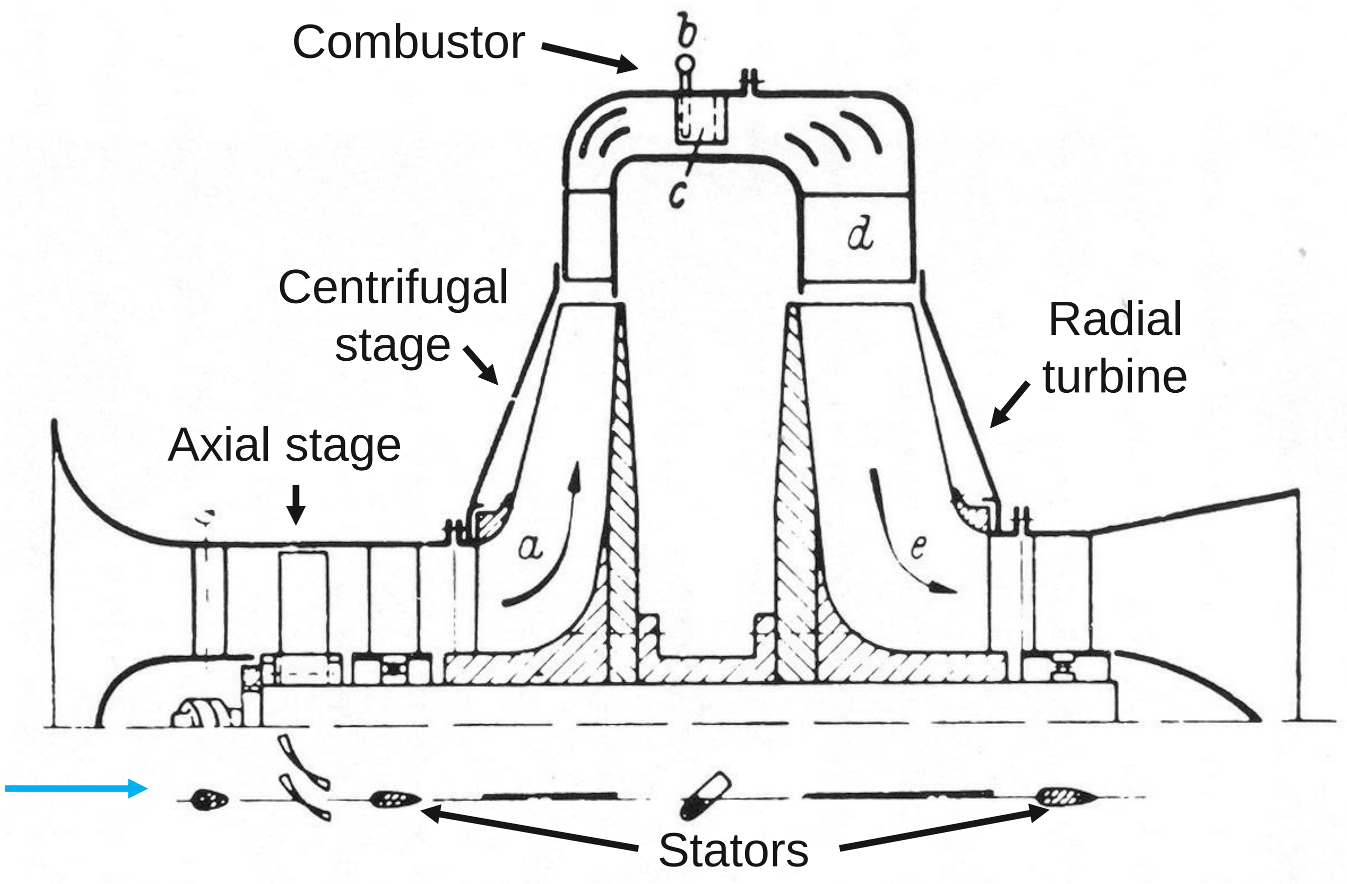
He S-1 Turbojet

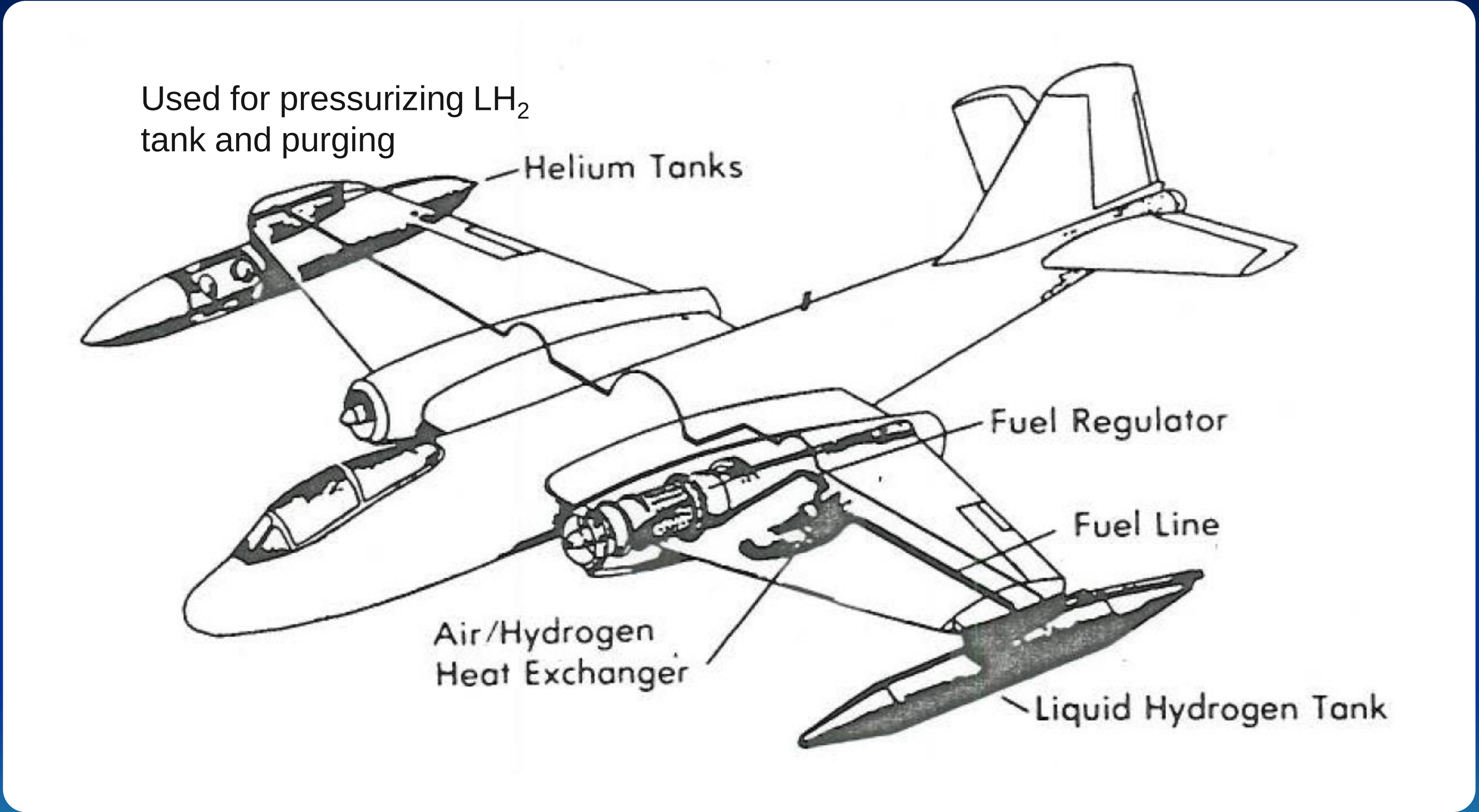
- Built in 1936, tested in April 1937
- Manufacturer: Heinkel-Hirth Mortorenbau
- Designer: Hans von Ohain
- Axial + centrifugal compressor
- Gaseous hydrogen-powered
- Rotor radius: ~ 30 cm (1 ft)
- Thrust: ~1,100 N (250 lb)

IGV/blade/stator/injector sections



ADA505106 AMCs Future - Sustainable Air Mobility. A.D. Reiman.pdf

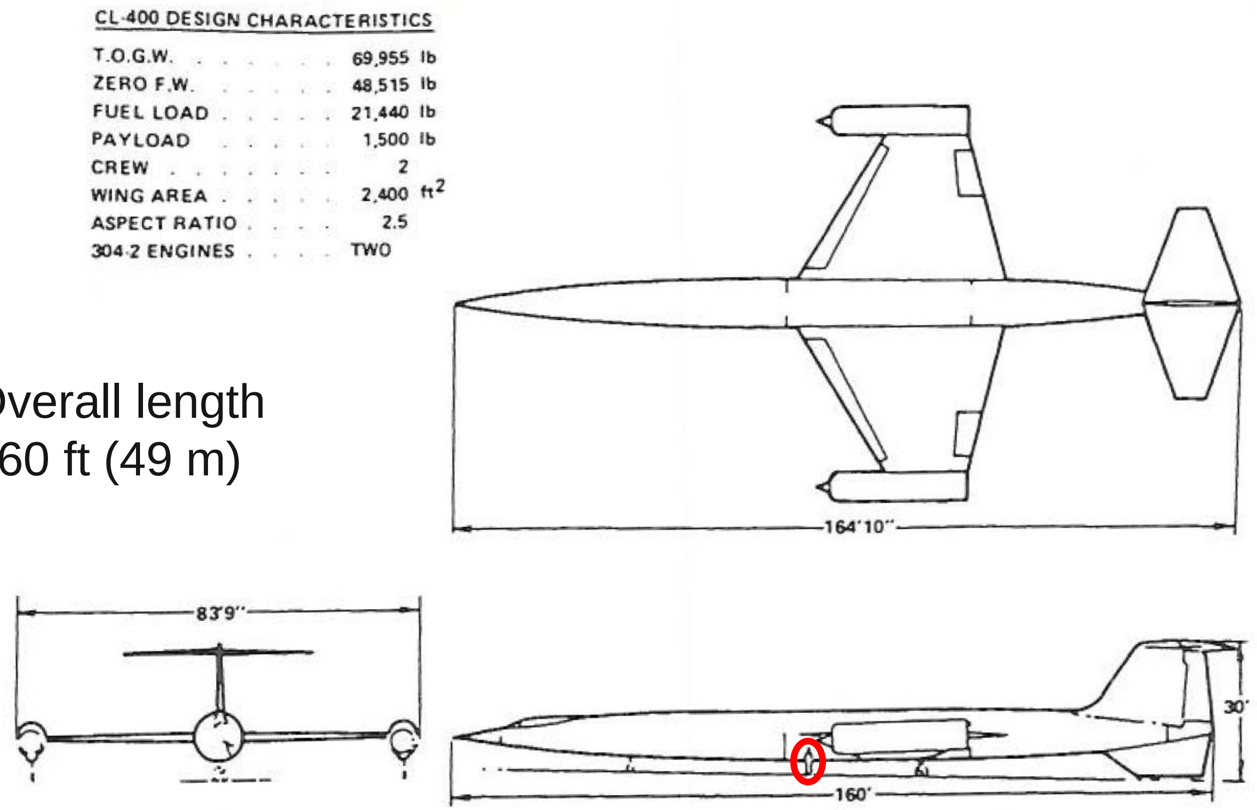
Martin B-57 Canberra



ADA505106 AMCs Future - Sustainable Air Mobility. A.D. Reiman.pdf

- First flight 1955
- NACA Lewis Flight Propulsion Laboratory
- Standard B-57 with Wright J65 engine
- Mach 0.75 @ 50,000 ft
- Switched from JP-4 to H_2
- 21 minutes on H_2
- Switched back to JP-4

Lockheed CL-400



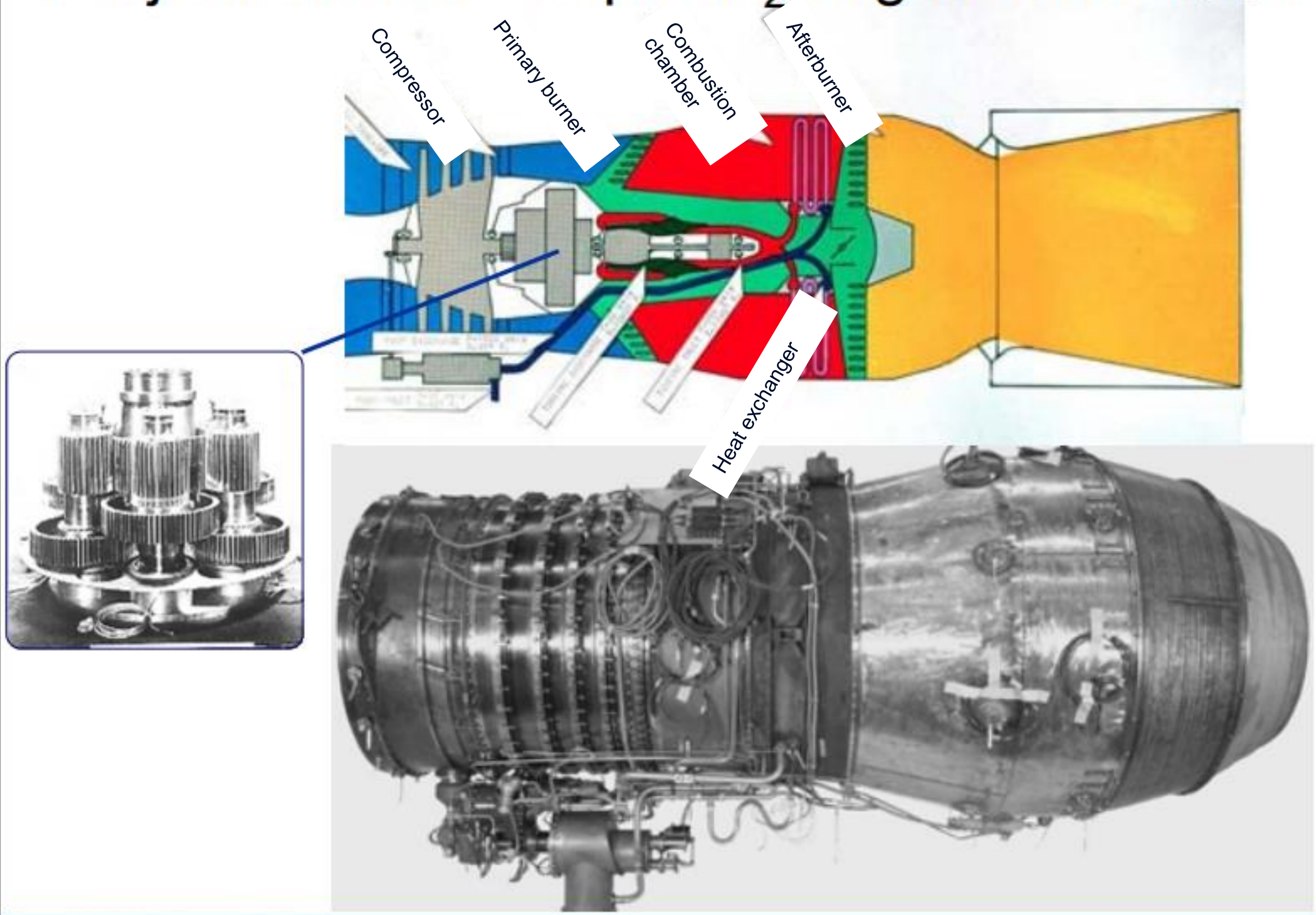
Overall length
160 ft (49 m)

- 1956-1958
- Design Mach 2.5 @ 100,000 ft
- Engines placed on wingtips to vaporize LH_2 as it passed though hot wings
- Demonstrated that H_2 could be handled as safely and easily as hydrocarbon fuel
- Not built, in part because of lack of H_2 infrastructure

ADA505106 AMCs Future - Sustainable Air Mobility. A.D. Reiman.pdf

P&W Hydrogen Fueled Aircraft Engine

Project Suntan – Liquid H_2 engine circa 1957-58

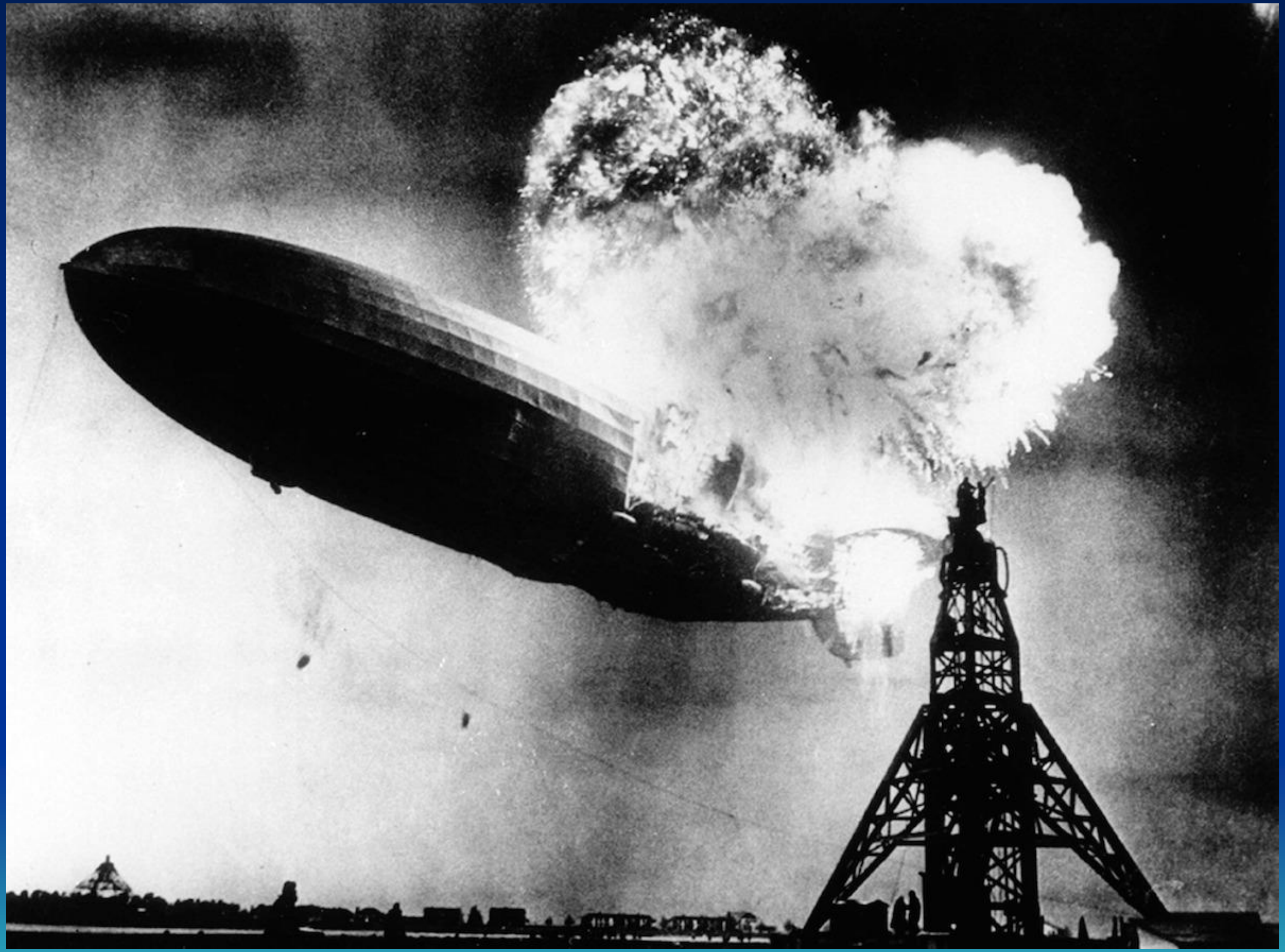


Pratt & Whitney
A United Technologies Company

Hindenberg Disaster

Trenton, New Jersey 1937-05-06
Of 97 pax and crew, 62 survived

Visible flames are from burning cotton skin and protective ‘doping’ (butyrate or cellulose nitrate)



Safety of Hydrogen vs. JP-8

For most issues of practical importance, hydrogen is safer than JP-8

Source: Reiman, A.D., “AMC’s Hydrogen Future: Sustainable Air Mobility”, Air Force Institute of Technology, AFIT/IMO/ENS/09-13, June 2009

Hydrogen vs JP-8

Safety

Item	Information	Advantage
Detonation	Gun shot tests into liquid hydrogen tanks failed to result in detonation. Heavy impact tests of liquid hydrogen tanks failed to result in detonation. Detonation of a perfect mixture of hydrogen and air only takes place with a strong detonator, but it is improbable that a perfect mixture of hydrogen and air will occur at the time of a strong detonation. JP-8 has a lower detonability limit in air as a percentage of volume than hydrogen. (Brewer, 1991)	Hydrogen
Emissivity	Hydrogen has a lower emissivity than JP-8 making the thermal radiation during a fire less. If a large hydrogen spill occurs outside an aircraft, remain inside for the heat will not be likely to enter the fuselage due to the low emissivity. (Brewer, 1991)	Hydrogen
Frost Bite	Contact with minute amounts of liquid hydrogen can lead to severe frost bite, while JP-8 poses no frostbite hazard. (Praxair, 2007)	JP-8
Fuel Spills	Hydrogen evaporates much more rapidly than JP-8 and if ignited burns quicker than JP-8. A 12,600 kg hydrogen fuel spill will dissipate in 32 seconds, while a similar volume of JP-8 would take closer to 13 minutes. (Brewer, 1990)	Hydrogen
Ignition Temperature	Hydrogen has a higher autoignition temperature than JP-8, but a lower temperature in an air mixture. A lit cigarette will not ignite in pure hydrogen although it could light a hydrogen-air mixture. A lit cigarette could ignite JP-8. (Brewer, 1991)	JP-8
Invisible Flame	Hydrogen can be a burn hazard due to invisible flame, while JP-8 has a visible flame. (Praxair, 2007)	JP-8
Suffocation	The high diffusion rate of hydrogen can rapidly replace the oxygen in an unventilated room leading to possible suffocation, while JP-8 poses a lesser suffocation hazard. (Praxair, 2007)	JP-8
Toxicity	JP-8 is a liver toxin, kidney toxin, nerve toxin, blood toxin, lung aspiration hazard and a reproductive fetotoxin, while hydrogen is not toxic. (Dfdl, 2001).	Hydrogen

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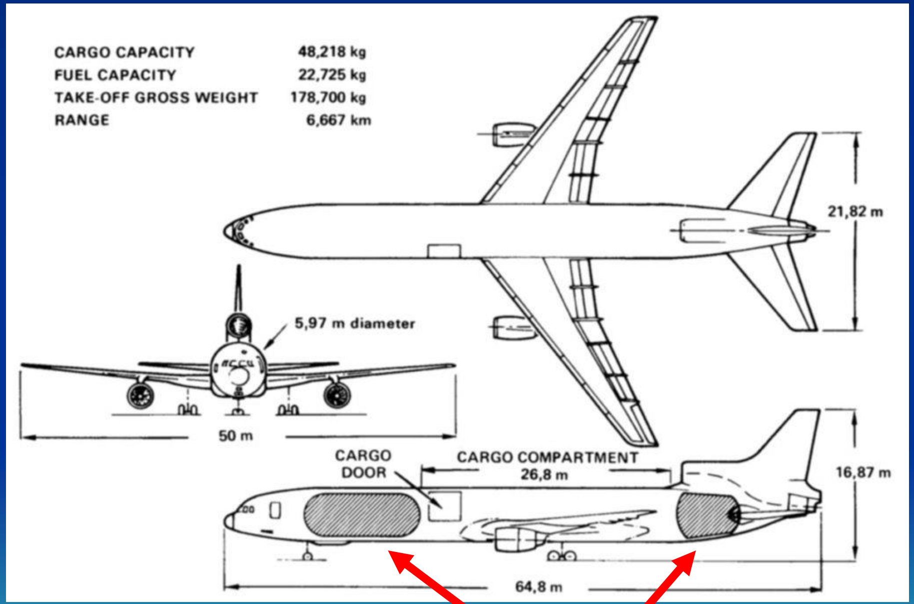
LH_2-powered L1011

Lockheed L1011-500 with 40 ft stretch to fuselage for fore and aft cryogenic tanks

- Circa 1976
- No carbon footprint
- Energy/unit weight (specific energy) of H_2 about 3 x that of jet fuel (excluding weight of cryogenic tank)
- Requires about 4.2 x volume for same energy
- Problems are mostly institutional



LH_2 tanks

Source: Lockheed

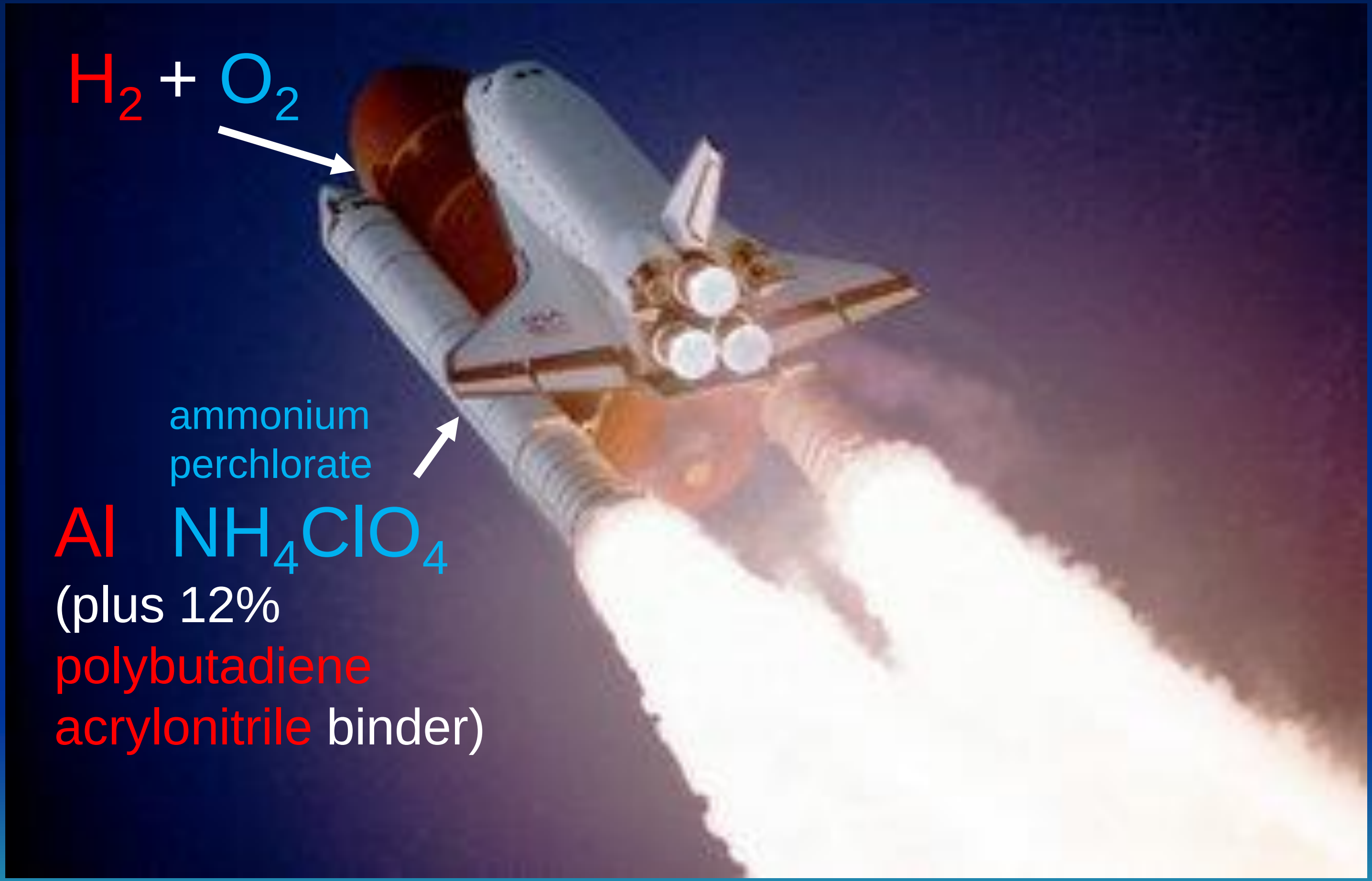
For infrastructure study by Dan Brewer see https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770003090.pdf

Space Shuttle Initial Ascent

First operational flight 1981-04-12

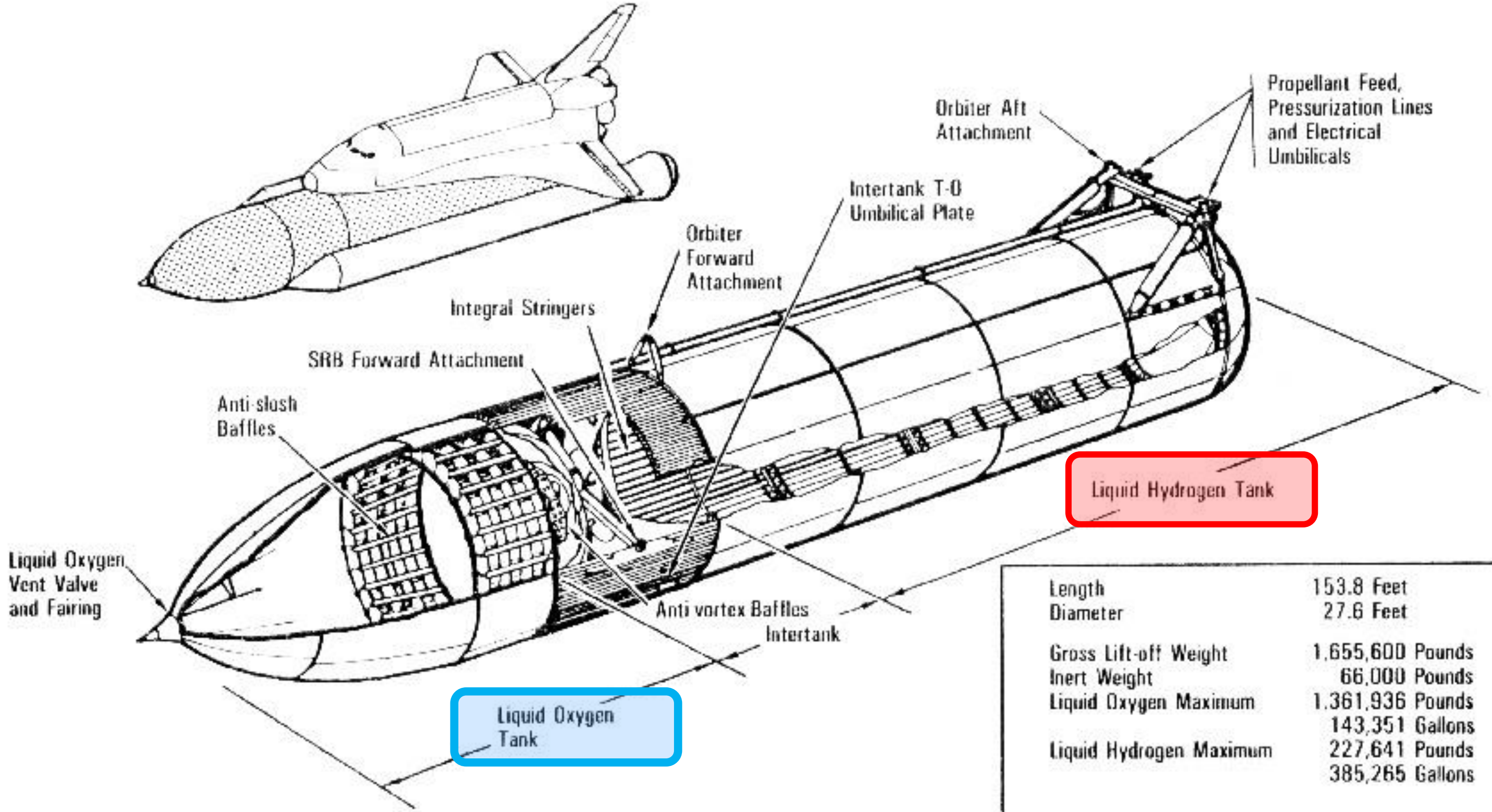
Products of combustion:
Main engines
- H_20

Solid Rocket Boosters (SRBs)
- Al_2O_3 (aluminium oxide)
- $AlCl_3$ (aluminium chloride, anti-perspirant)
- H_20
- N_2



Source: nasa

Space Shuttle Main Tank



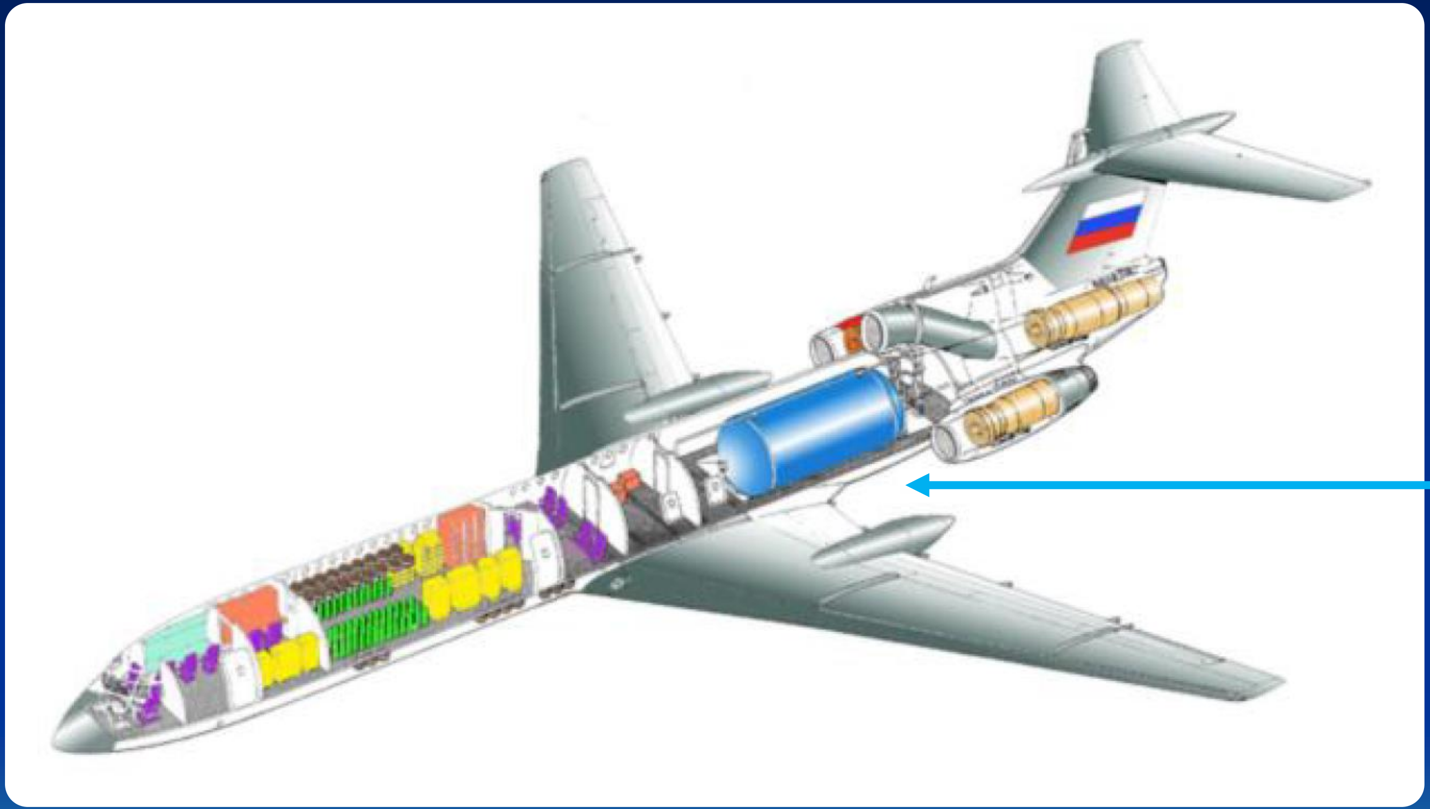
Length	153.8 Feet
Diameter	27.6 Feet
Gross Lift-off Weight	1,655,600 Pounds
Inert Weight	66,000 Pounds
Liquid Oxygen Maximum	1,361,936 Pounds
	143,351 Gallons
Liquid Hydrogen Maximum	227,641 Pounds
	385,265 Gallons

(All Weights Approximate)

Lightweight External Tank

Source:science.ksc.nasa.gov

LH_2-powered Tu-155



- First flight: 1988-04-15
- Fuel: LH_2 (later LNG for #3 engine only)
- Propulsion: 3 x Kuznetsov NK-8-2 (later replaced #3 with NK-88)
- NK-8-2 can also burn jet fuel
- LH_2 tank diameter 3.1 m (10 ft 2 in), length 5.4 m (17 ft 8 in), AMG6 Al alloy
- 50 mm (2 in) foamed polyurethane lagging

https://leehamnews.com/2020/07/24/bjorns-corner-the-challenges-of-hydrogen-part-1-background/

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Hydrogen Challenges

- Production
  - Either methane reformation
    - Cost of methane
    - Cost of reformation
    - Cost of disposal of CO_2
  - Or electrolysis
    - Cost of electricity
    - Cost of electrolysis
- Cost of H_2 distribution and storage
- Cost and energy of H_2 liquefaction
- No existing infrastructure

Typical Hydrogen Production

Step 1 Steam-methane reforming reaction

$CH_4 + H_2O$ (+ heat) $\rightarrow$ $CO + 3H_2$

Or partial oxidation of methane reaction (produces less H_2)

$2CH_4 + O_2 \rightarrow 2CO + 2H_2$ (+ heat)

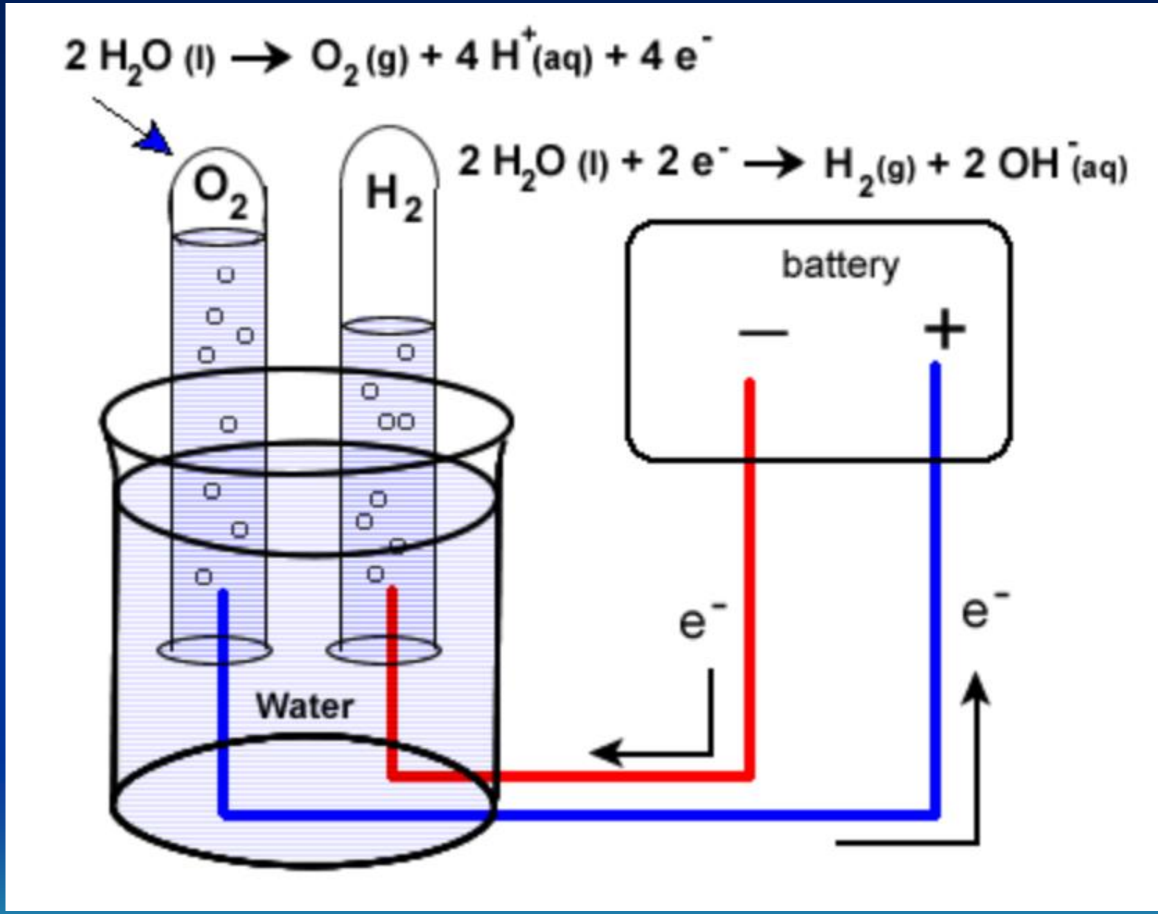
Step 2 Water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2$ (+ small heat)

CO_2 is captured and either converted into a solid chemical or buried

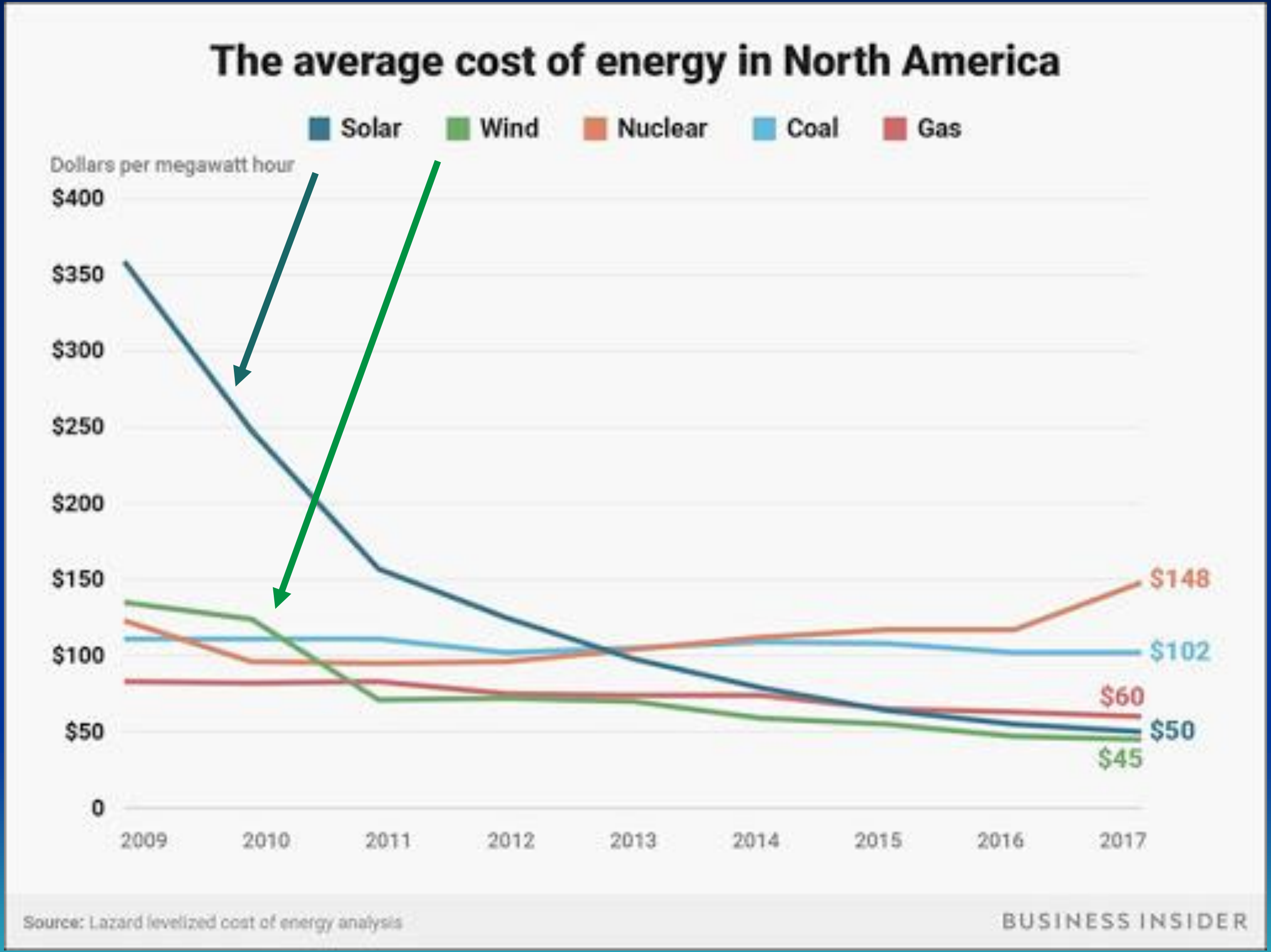
https://energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

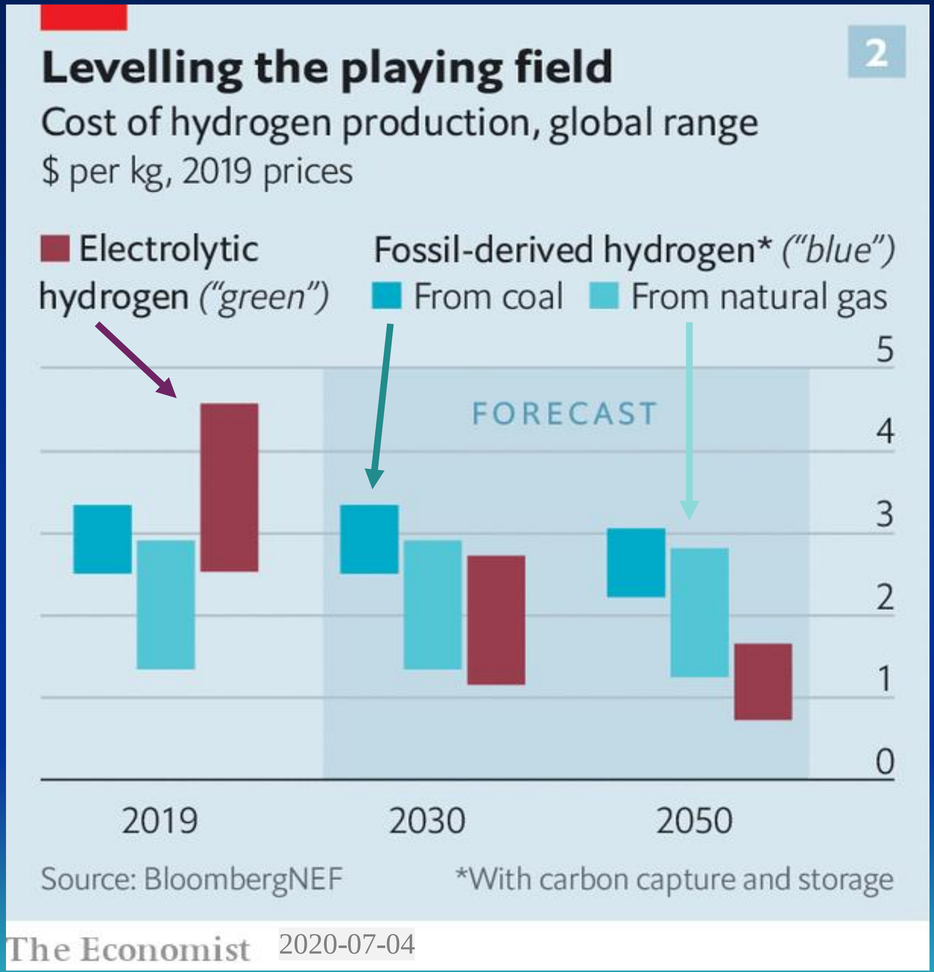
Electrolysis of Water

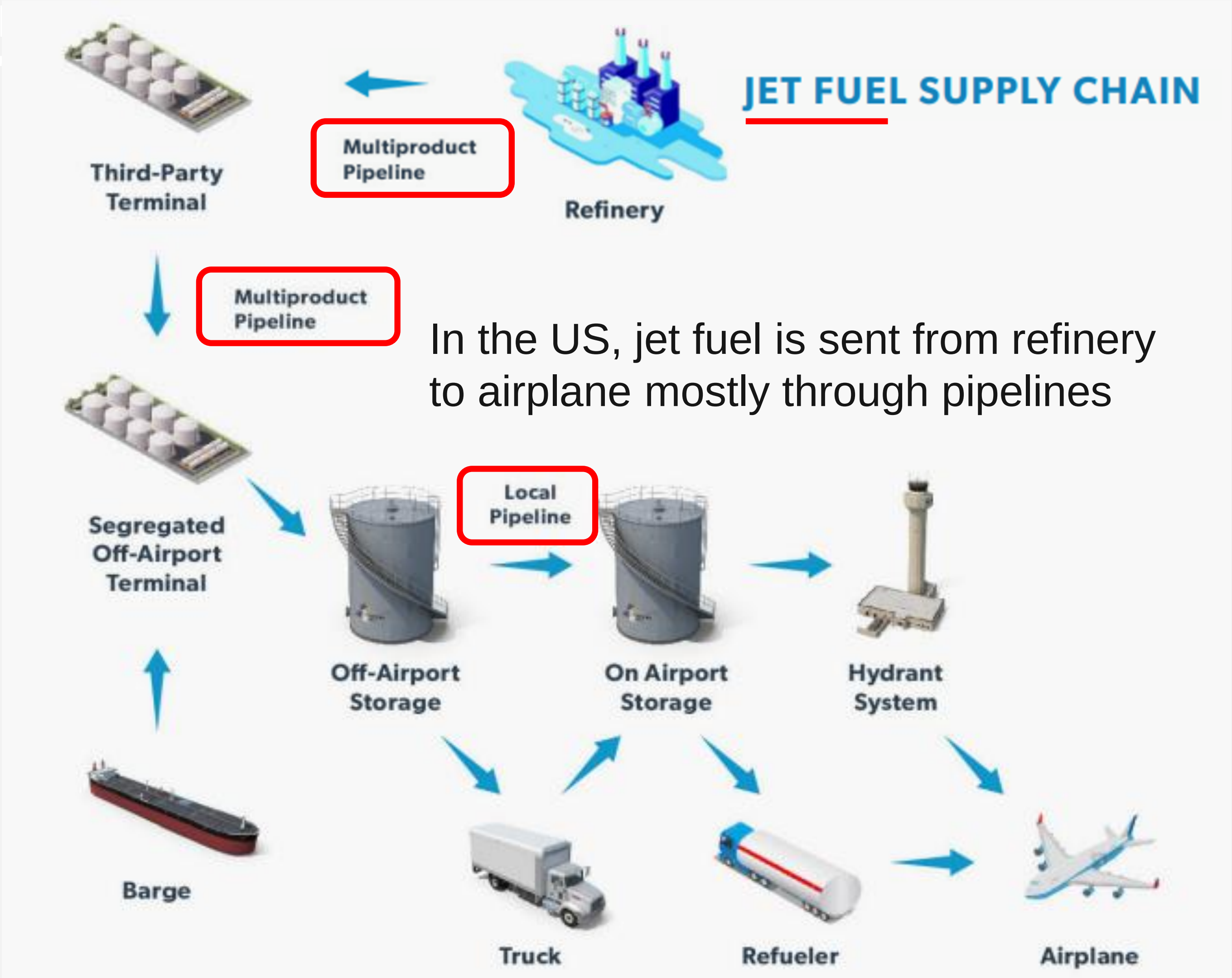


https://sites.prairiesouth.ca/legacy/chemistry/chem30/6_redox/redox3_3.htm

Electrolytic Hydrogen will get Cheaper







In the US, jet fuel is sent from refinery to airplane mostly through pipelines

https://www.airlines.org/wp-content/uploads/2018/01/jet-fuel-1.pdf

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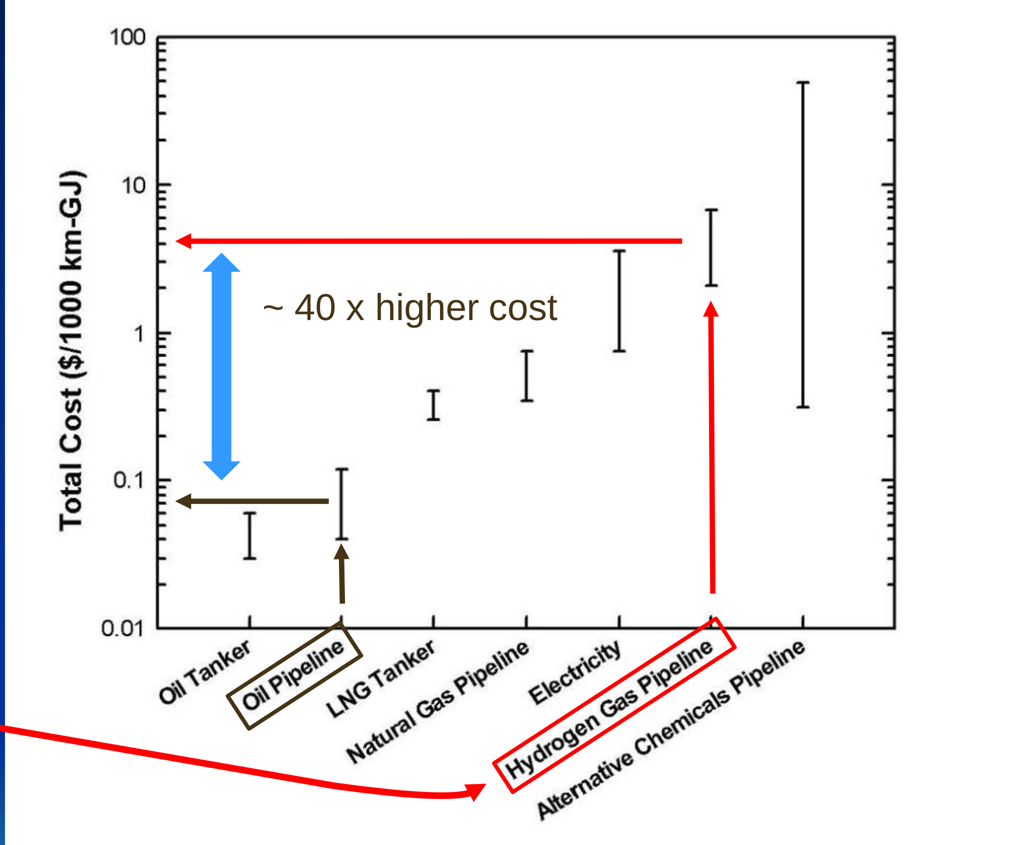
- Production
  - Either methane reformation
    - Cost of methane
    - Cost of reformation
    - Cost of disposal of CO_2
  - Or electrolysis
    - Cost of electricity
    - Cost of electrolysis
- Cost of H_2 transportation and storage
- Cost and energy of H_2 liquefaction
  - About 30% of H_2 energy
- No existing infrastructure



Can you use jet fuel pipelines for hydrogen?

- In theory, yes – but
  - If sent at low pressure above atmospheric, then it won't leak significantly*, but energy flow rate is too small
  - If sent at high pressure above atmospheric, hydrogen is likely to leak
  - If sent as liquid, then pipes would have to be thermally insulated

*In the UK, "town gas" (used up until 1967)
made from coal was 50% H_2, 35% CH_4, 10% CO, 5% C_2H_4

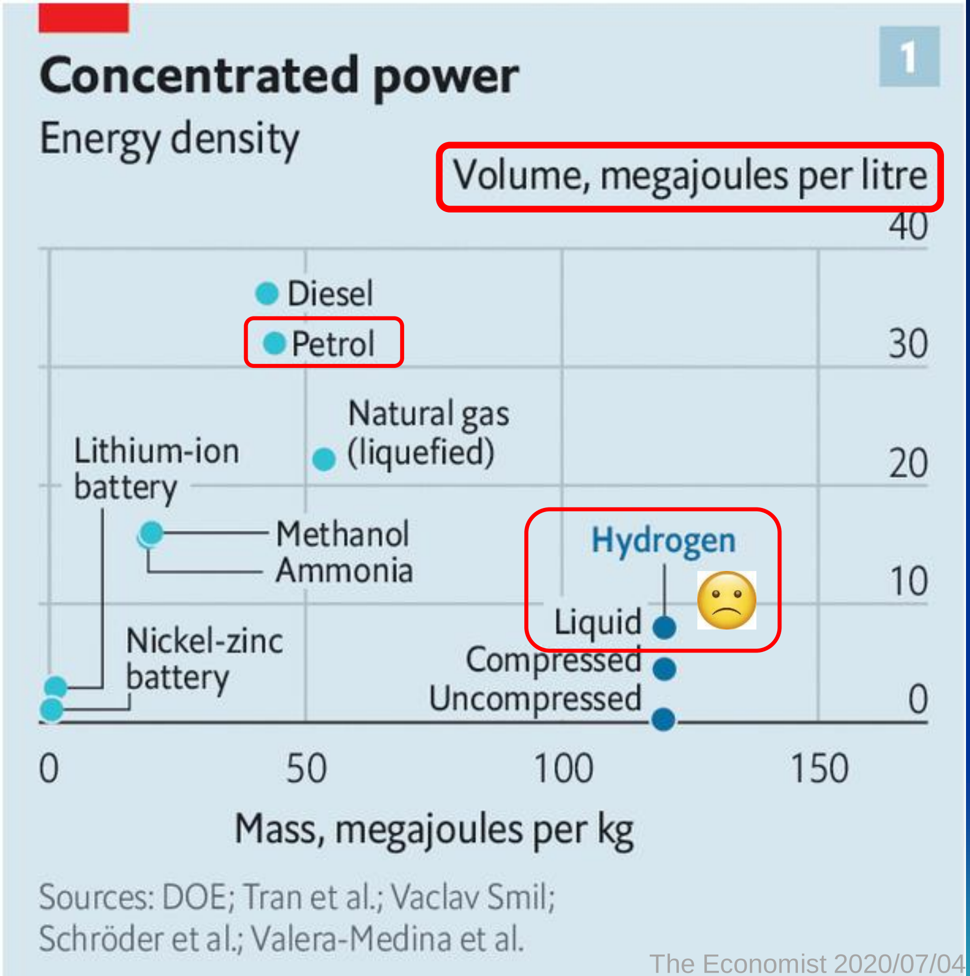
The Economist 2020/07/04

Hydrogen Transmission

Even if liquified, for same flow velocity, energy flow rate of hydrogen (MJ/L x L/s)* is about 1/4 that of petrol

* i.e. MW

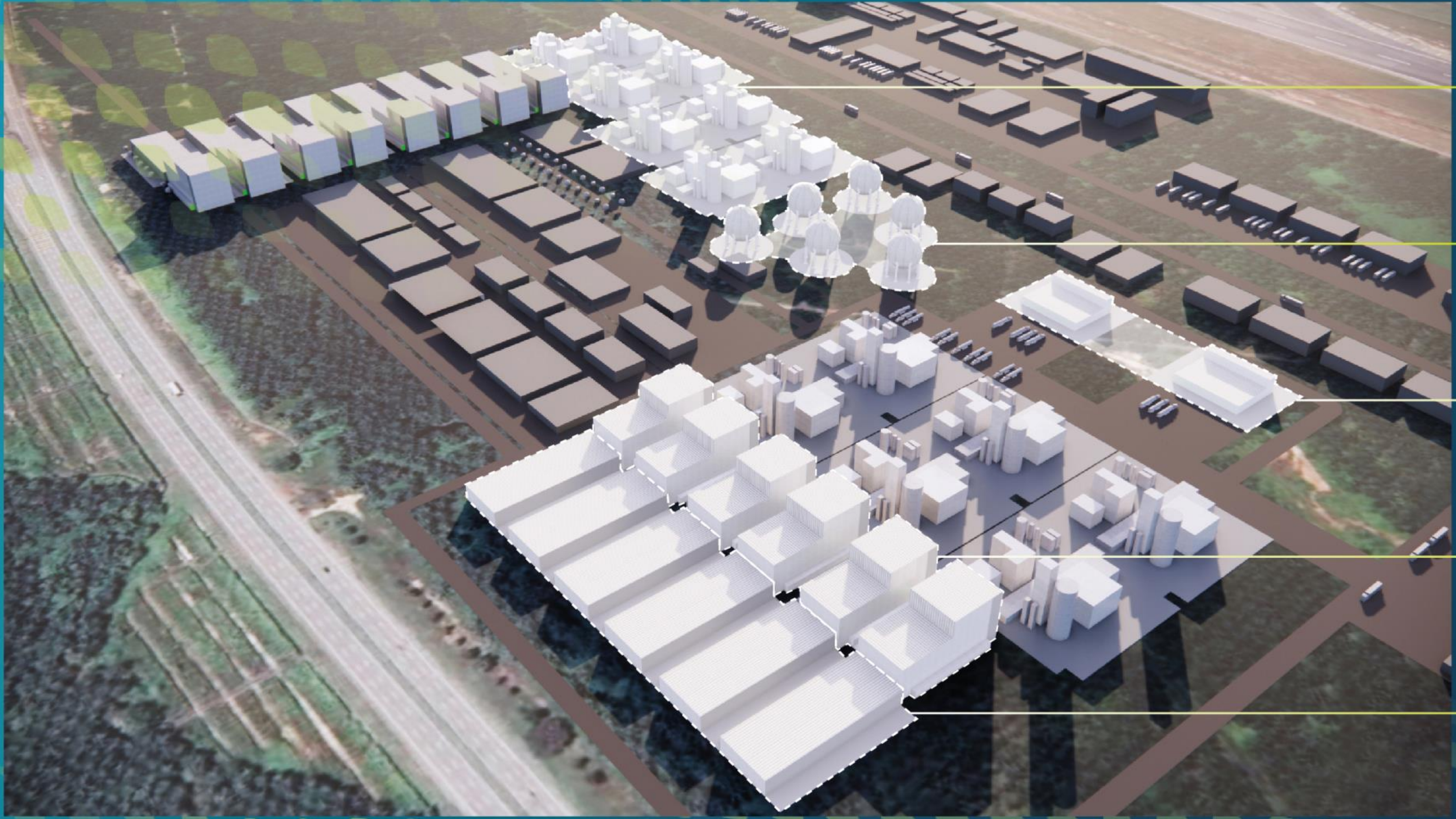
Probably better to produce H_2 locally using electrolysis



The Economist 2020/07/04

ZEROe

Liquid hydrogen production at large airport



Air Liquide GROUPE ADP AIRBUS

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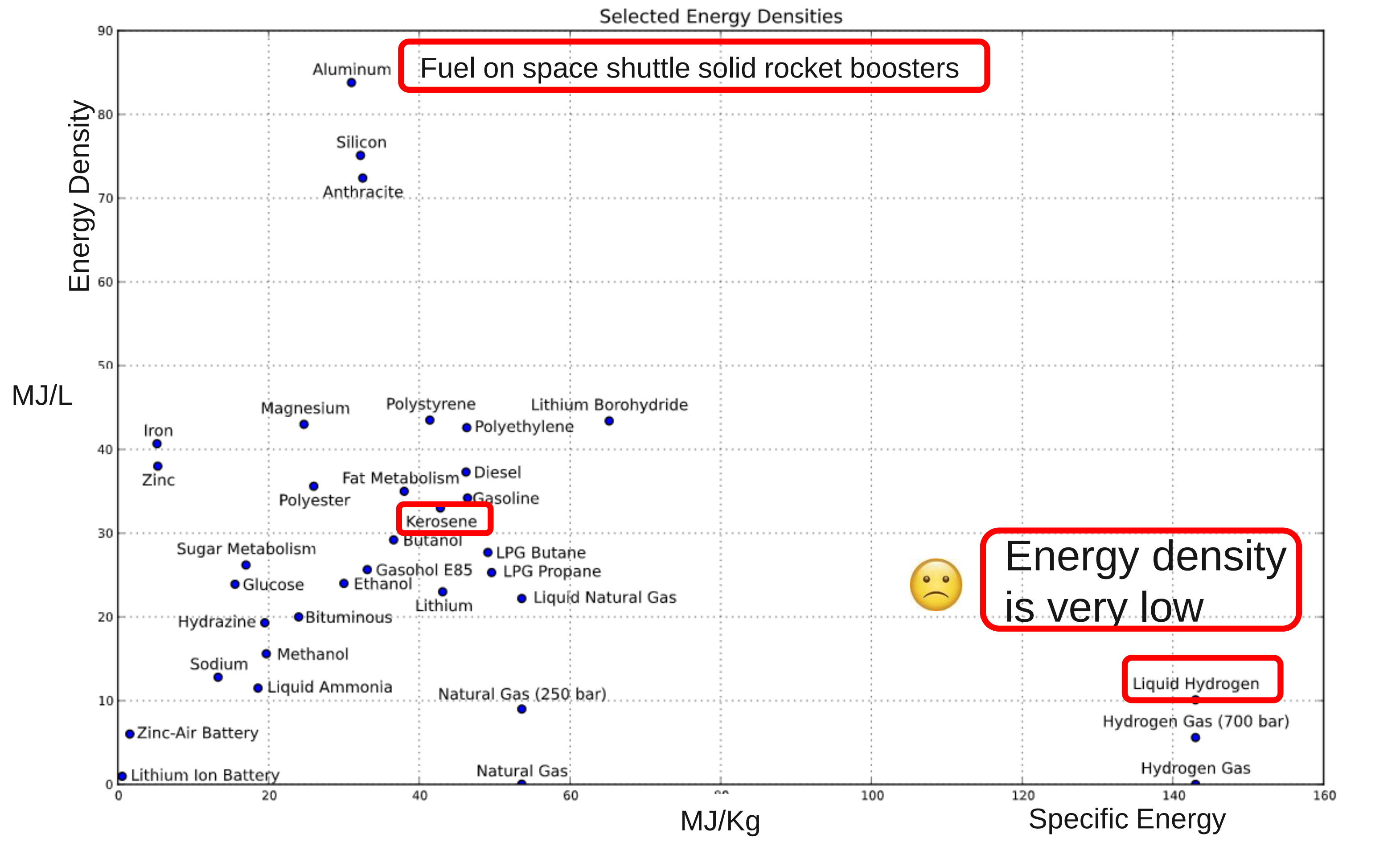
  - Energy conversion

Energy Storage



https://en.wikipedia.org/wiki/Hydrogen-powered_aircraft

Reducing Distribution Cost

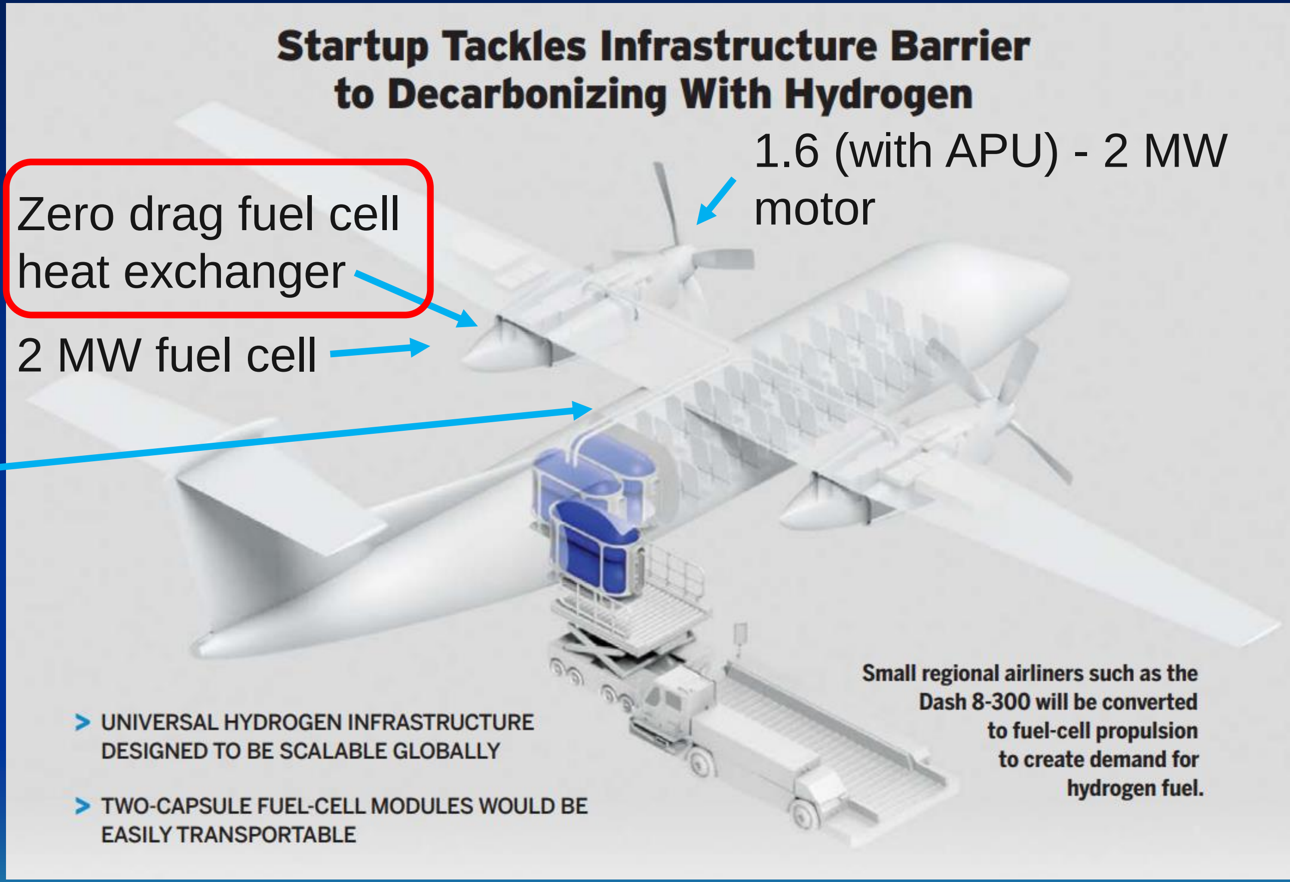
- 2020-09 Startup company Universal Hydrogen
  - 850 bar high pressure gas tanks, or
  - LH_2 tanks (40 hour dwell time between production and consumption)

Interchangeable gaseous or liquid-hydrogen capsules will be transported and stored on aircraft in easy-to-handle modules.

https://aviationweek.com/sites/default/files/2020-09/AWST_200914.pdf

Universal Hydrogen

- For De Havilland Dash 8-300
  - 400 nmi range with gaseous H_2 tanks
  - 550 nmi range with LH_2 tanks
  - (Fleet average currently 300 nmi)
  - Fuel tank lines through dorsal fin, external to pressure hull
- Pax seats reduced from 50 to 40
- Maintenance costs 25% lower



https://aviationweek.com/sites/default/files/2020-09/AWST_200914.pdf

Dash 8 H_2 Fuel Cell Testbed

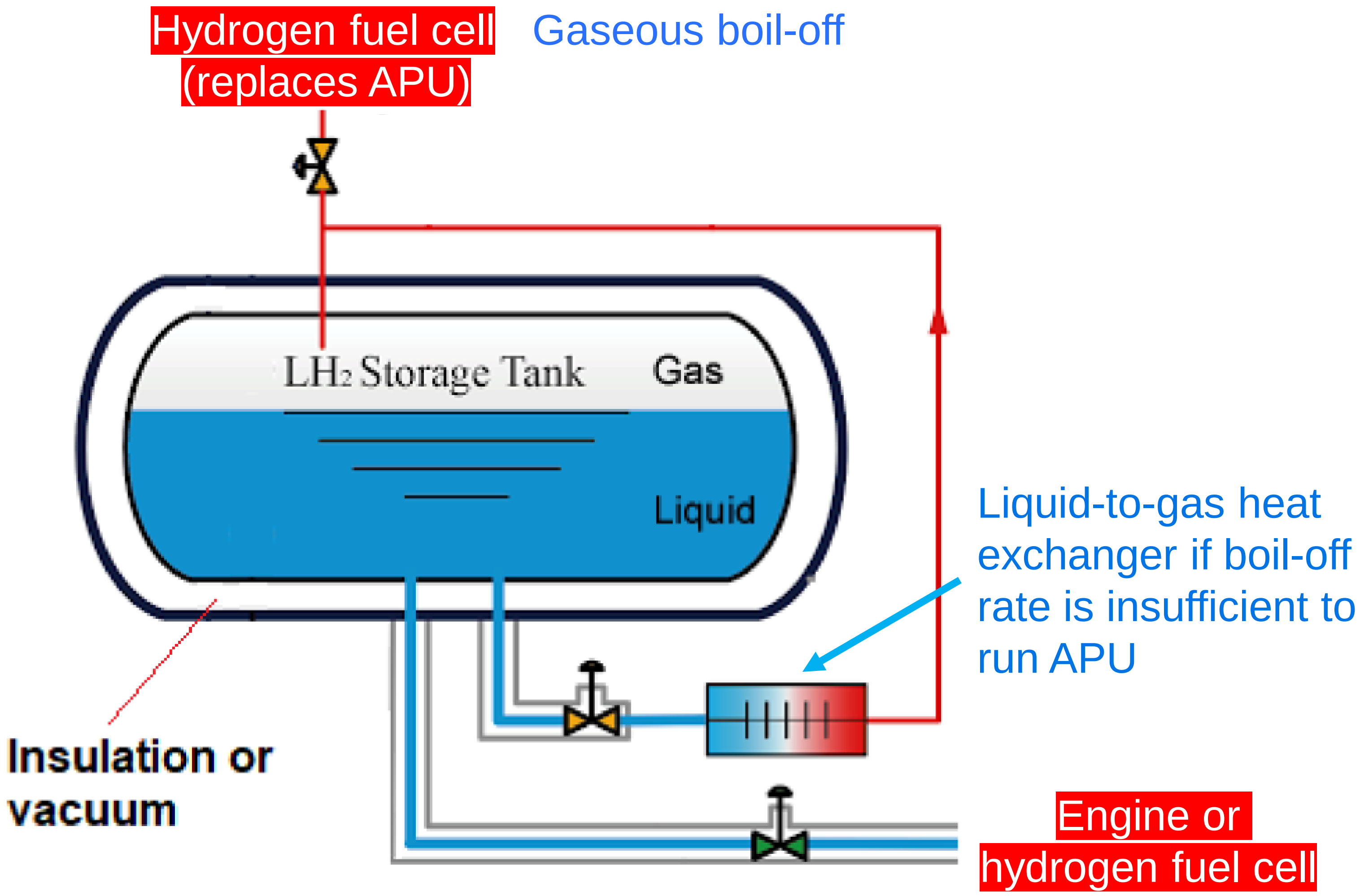
- #2 engine only.
- First flight 2023-03-02.
- Flight duration 15 minutes

- Inlets either side of nacelle for fuel cell cooling
- 560-640KW MagniX 650 motor

- Hartzell 91” propeller
- Orders for 247 conversions from 16 customers

The Economist 2020/07/04

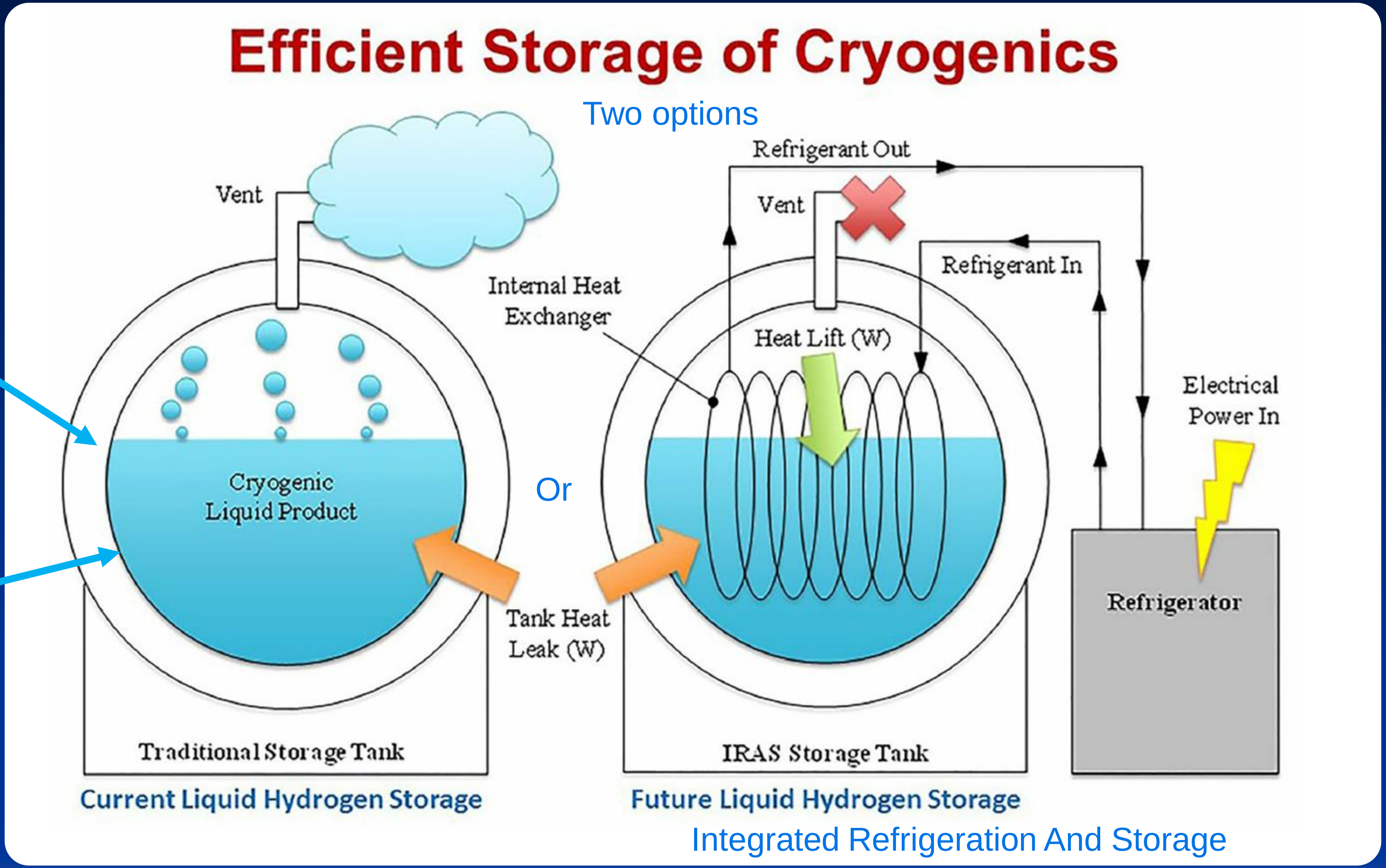
Typical Airplane LH_2 Tank



Vacuum and/or foam insulation

Aluminium tank

Maintain temp < 20 K



IRAS system complexity and weight only pays off for missions > 15 hours

H_2-powered Britten-Norman Islander

Low-cost application of H_2 propulsion

https://www.greencarcongress.com/2021/03/20210330-fresson.html

https://www.greencarcongress.com/2021/03/20210330-fresson.html

- Pods contain compressed H_2 tanks
- Fuel cells in rear of engine nacelles

- Project of Cranfield Aerospace
- First flight planned 2023
- Entry into service: early 2026

- Endurance: 1 hour, with 45 minutes reserves
- Projected use by Loganair (includes world's shortest scheduled flight of 1.5 minutes)

Scottish islands have cheap electricity for electrolysis of water, thanks to wind farms

Nacelles with Integrated Fuel Tanks

- Removable pods include
  - Propeller
  - Electric Motor
  - Power electronics
  - LH_2 tank
  - Cooling system
  - Auxiliary equipment

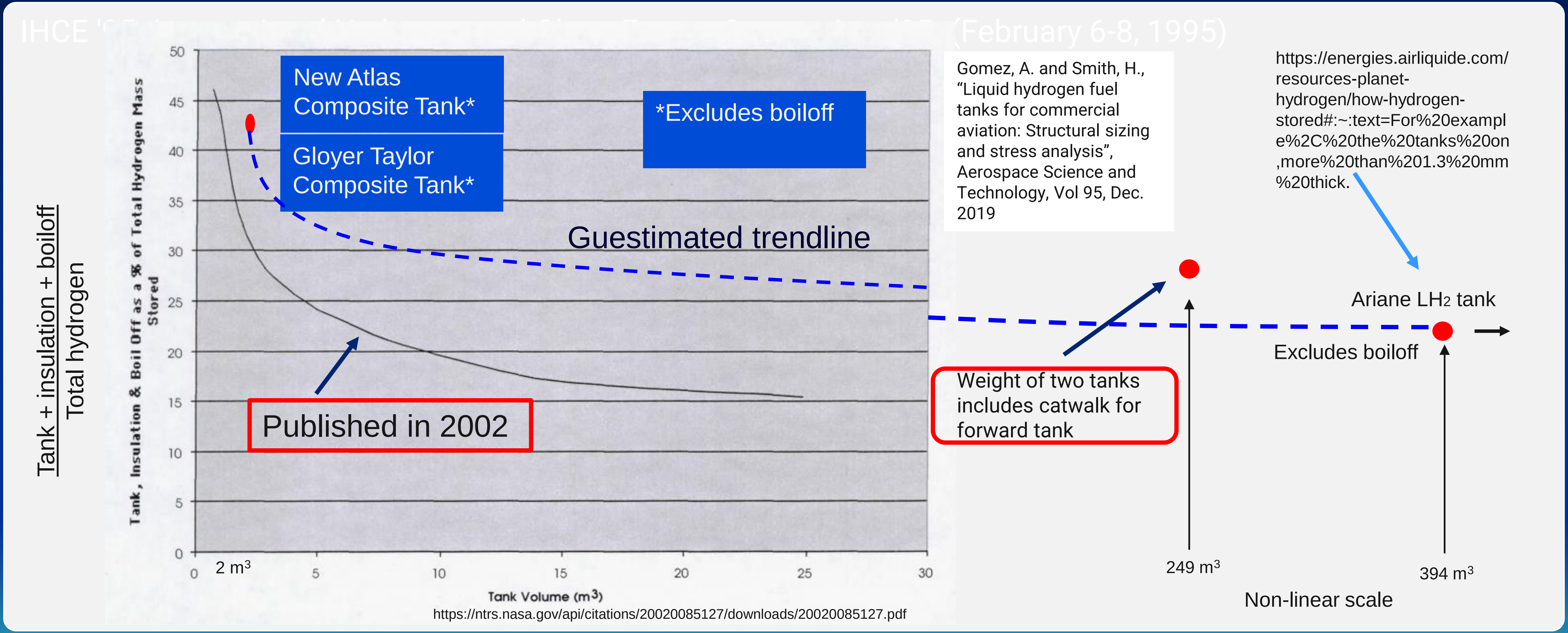
Source: Leeham Company LLC

Gloyer-Taylor Labs Composite Tank

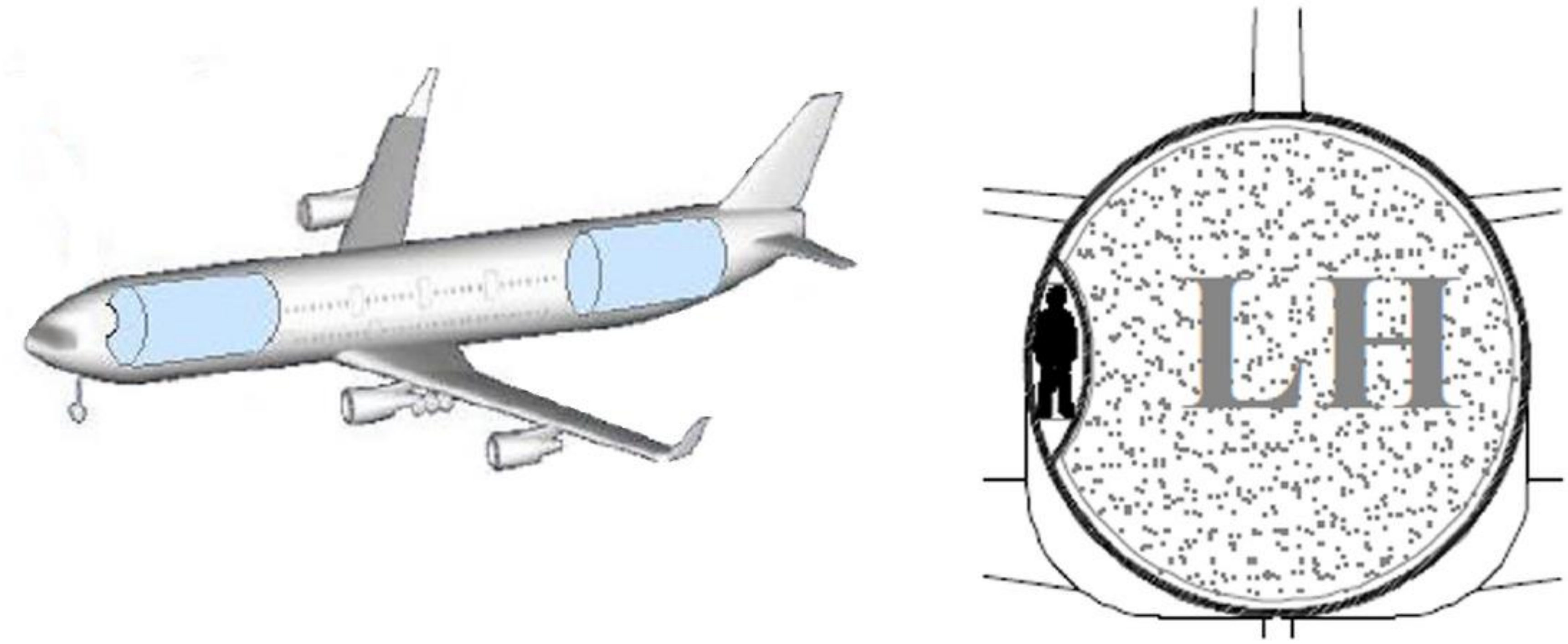
- Double-walled vacuum
- Length: 2.4 m
- Weight: 12 kg
- Capacity: 150 kg LH_2
- Weight/Capacity: 0.08

Source: Leeham Company LLL

Square-Cube Law in effect

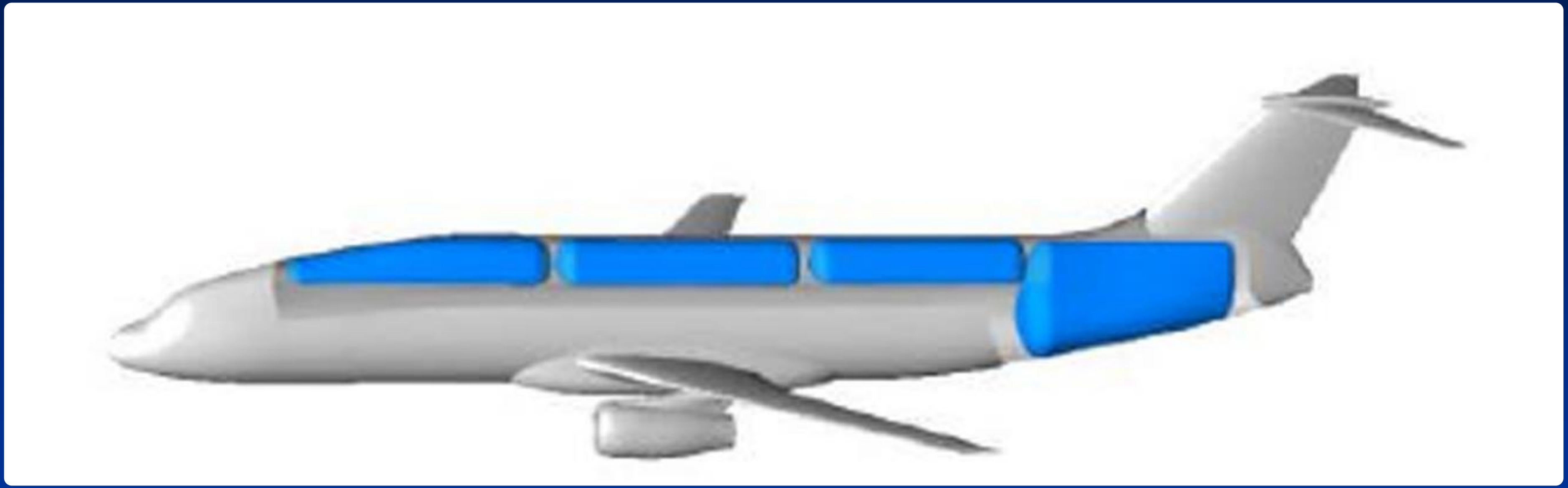


Tank Location – Long Range



Forward and aft tanks with passageway for flight deck crew

Tank Location – Short/Medium Range



© Leehamnews.com-Bjorns Corner The challenges of Hydrogen Pat 6 Tank placement.pdf

Combine aft tank with expanded fuselage crown

Tank Location – Short/Medium Haul

For relatively low fuel fraction, ok to put tanks in aft location

© Leehamnews.com-Bjorns Corner The challenges of Hydrogen Pat 6 Tank placement.pdf

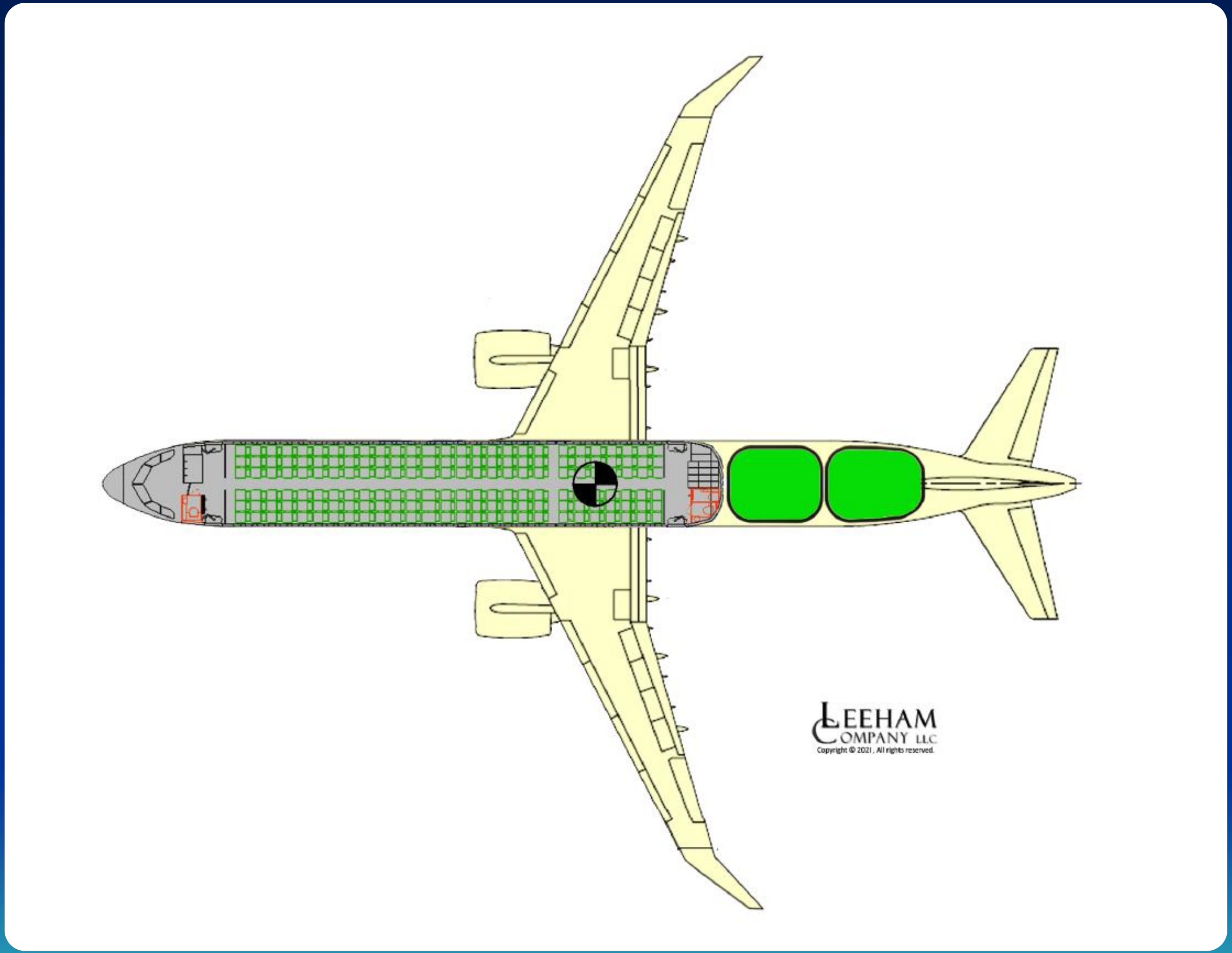
Airbus ZEROe Program

Credit: Airbus

LH_2-powered A320

6-abreast, single aisle
160 seats, high density

Assume typical 800 nm
(1,482 km) flight segment

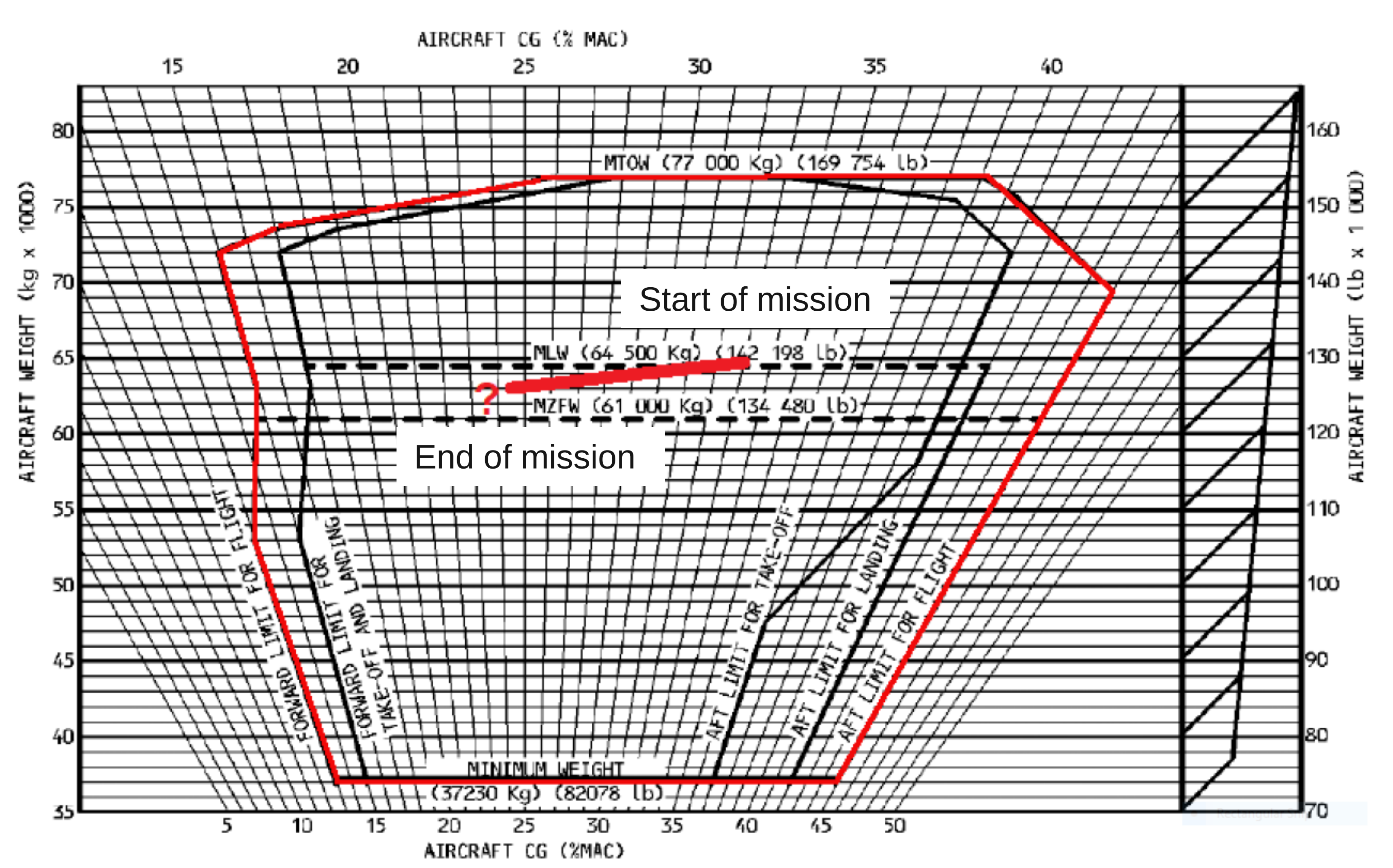


Source: leehamnews.com – Bjorn's Corner
"The Challenges of Hydrogen Part 18"

Source: © Leeham Company LLC

LH_2-powered A320 c.g. travel

- Direct combustion of H_2
- C.g. envelope for A320 →
- Assume 800 nmi stage length
- From forward tank, assume 1.4 t of LH_2 consumed during flight
- Assume c.g. at 33% MAC at start of flight
- C.g. moves forward as fuel is burned
    - Increases trim drag



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Credit: Airbus

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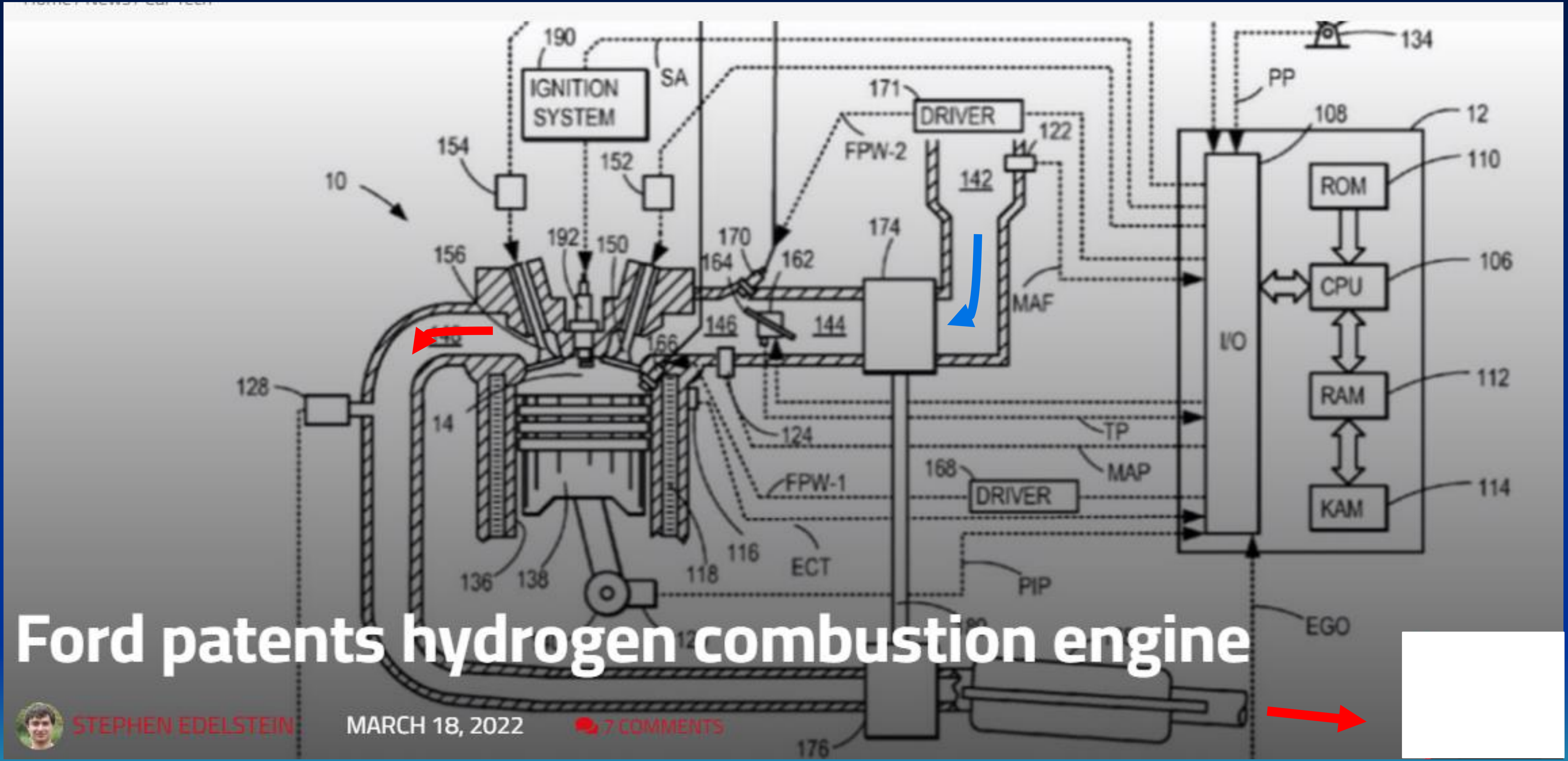
  - Energy conversion

- Energy conversion
  - Burn it directly with atmospheric O_2 (or LO_2) (reciprocating engine, gas turbine, or rocket)
  - Combine it with atmospheric O_2 (or LO_2) in fuel cell to generate electricity
  - Hybrid of direct burn and fuel cell
  - Hybrid of battery and fuel cell


IGNITION SYSTEM
SA
DRIVER
FPW-2
PP
ROM
CPU
RAM
KAM
I/O
MAF
TP
MAP
FPW-1
DRIVER
ECT
PIP
EGO
Ford patents hydrogen combustion engine
STEPHEN EDELSTEIN
MARCH 18, 2022
7 COMMENTS

Boeing Phantom Eye

Source: ainonline.com

- LH_2 fuel
- 2 x Ford 2.3 litre gasoline engines
- Multiple turbochargers
- First flight June 2012
- Program terminated Aug 2016

- Claimed performance up to 4 days at up to 65,000 ft
- Payload 450 lb
- Cruise speed 150 kt
- Possibly did not meet performance goals

LH_2-powered Airbus A310

- 2000-2002 study by consortium led by Airbus
- Larger wetted area: energy consumption increases 9% -12%
- OWE increases ~ 23%
- MTOGW varies from –ve 14.8% to +ve 4.4% depending on config.
- Increase in DOC of 4%-5% due to fuel only
- No fundamental technical roadblocks

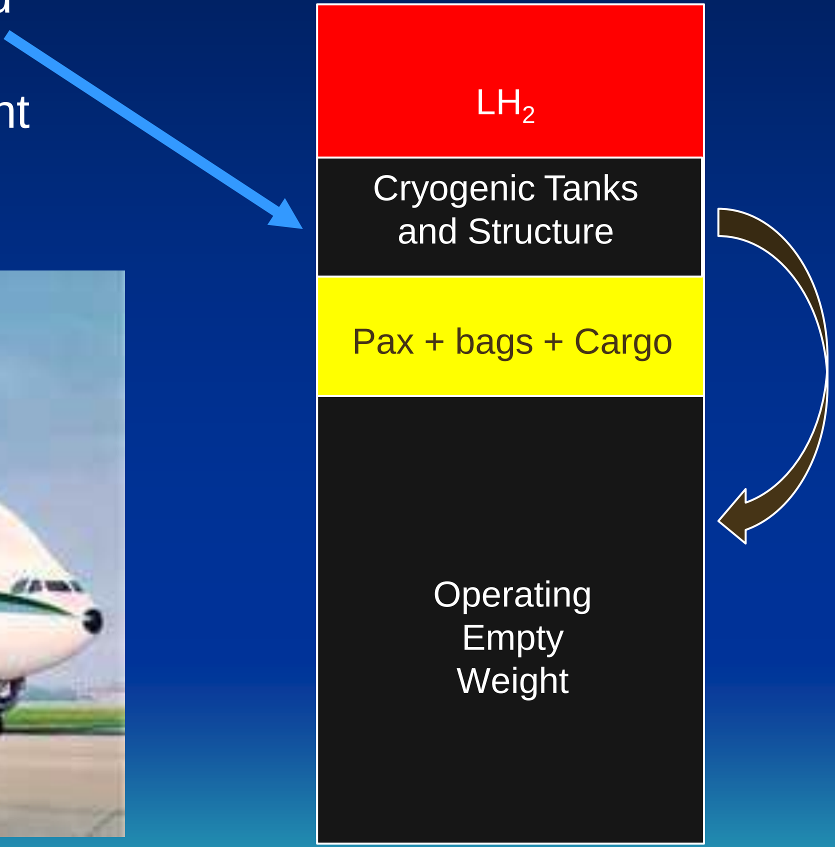
http://planetforlife.com/h2/h2vehicle.html

Airbus A310 H_2 Cryoplane Concept

LH_2-powered Airbus A310

- Trade reduced LH_2 weight for increased cryogenic tank and structural weight
- Not so much change in weight on long range flights

http://planetforlife.com/h2/h2vehicle.html




ZEROe Hydrogen combustion demonstrator
A380 multimodal test platform
with its capacity to store large hydrogen tanks
Hydrogen combustion engine
located along the rear fuselage
4 liquid hydrogen tanks
stored in a caudal position
Liquid hydrogen distribution system
flightlab
ZEROe demonstrator
AIRBUS

Airbus ZEROe Program

- CFM (GE + Safran) will modify GE Passport engine
  - 79-84 kN thrust
  - OPR 45
  - BPR 5.6
  - Twin shaft
- 4 x 100 kg tanks of LH_2

FlyZero – Direct Burn Test Requirements

Major tests

Hydrogen gas turbine architectures are applicable to all market segments considered in FlyZero: regional, narrowbody and midsize.

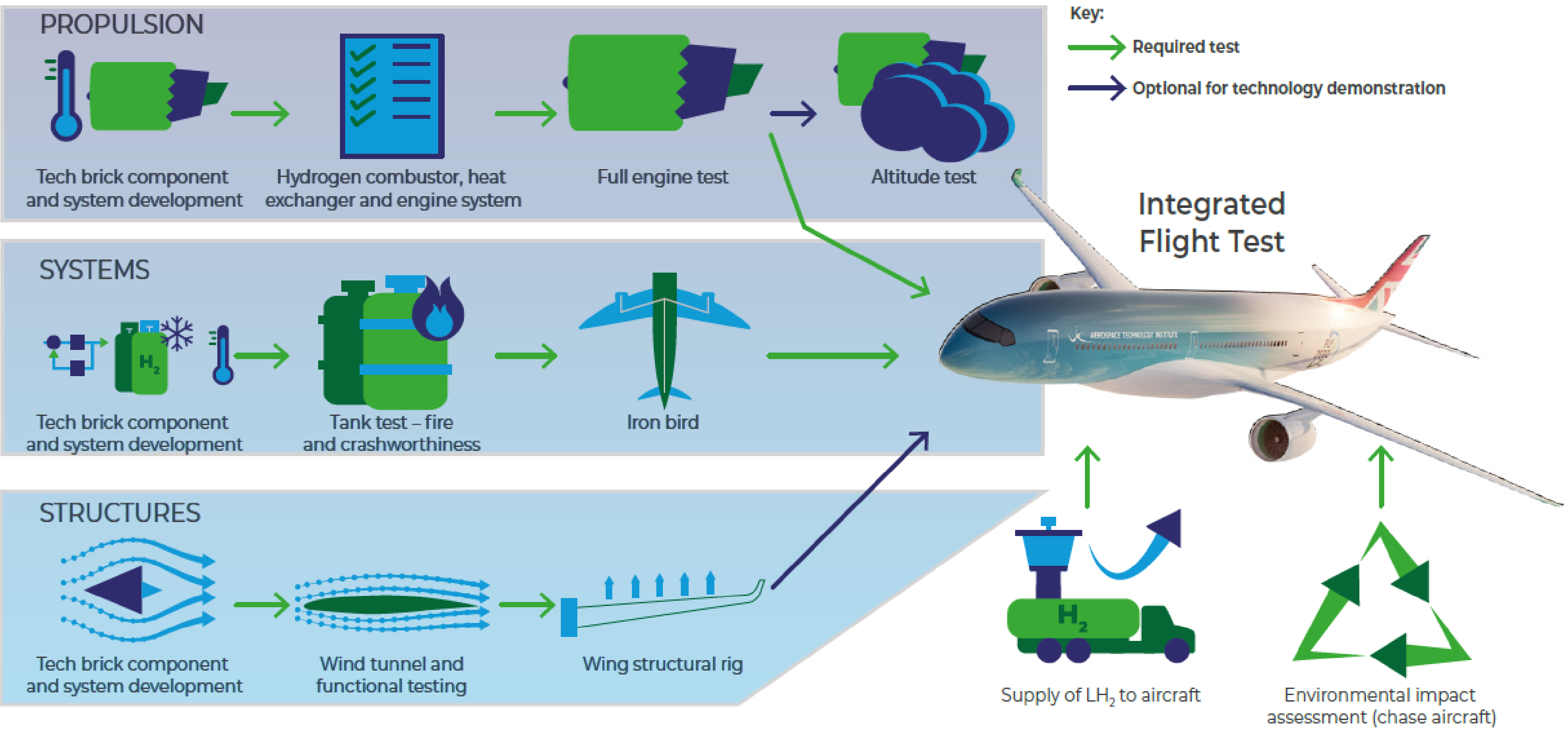
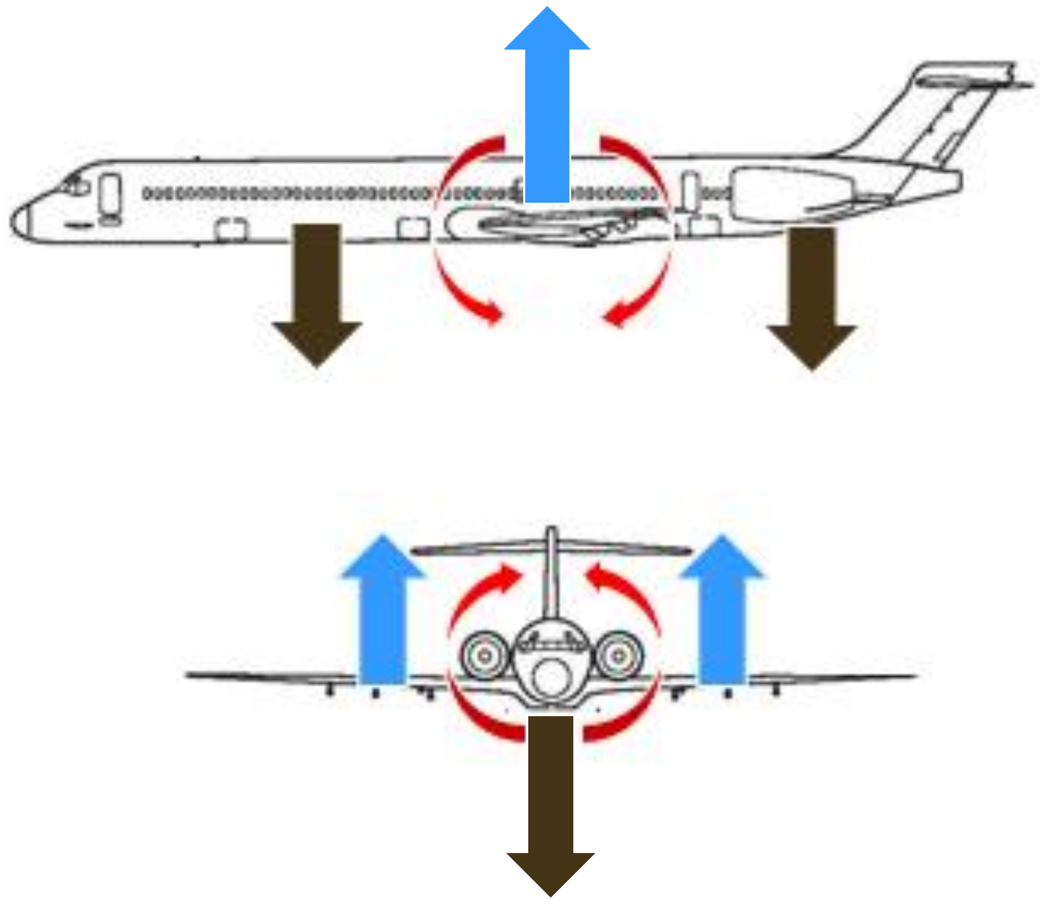


Figure 9 – Hydrogen gas turbine aircraft architecture - major tests.

Fuselage And Wing Root Bending

- Engines mounted on rear fuselage induce additional fuselage and wing bending
- Made worse by
  - Stretched fuselage
  - Heavier engines

- Number of DC-9s and MD-80s still operating ~ 126
- Number of 737 and A320s operating ~ 11,000



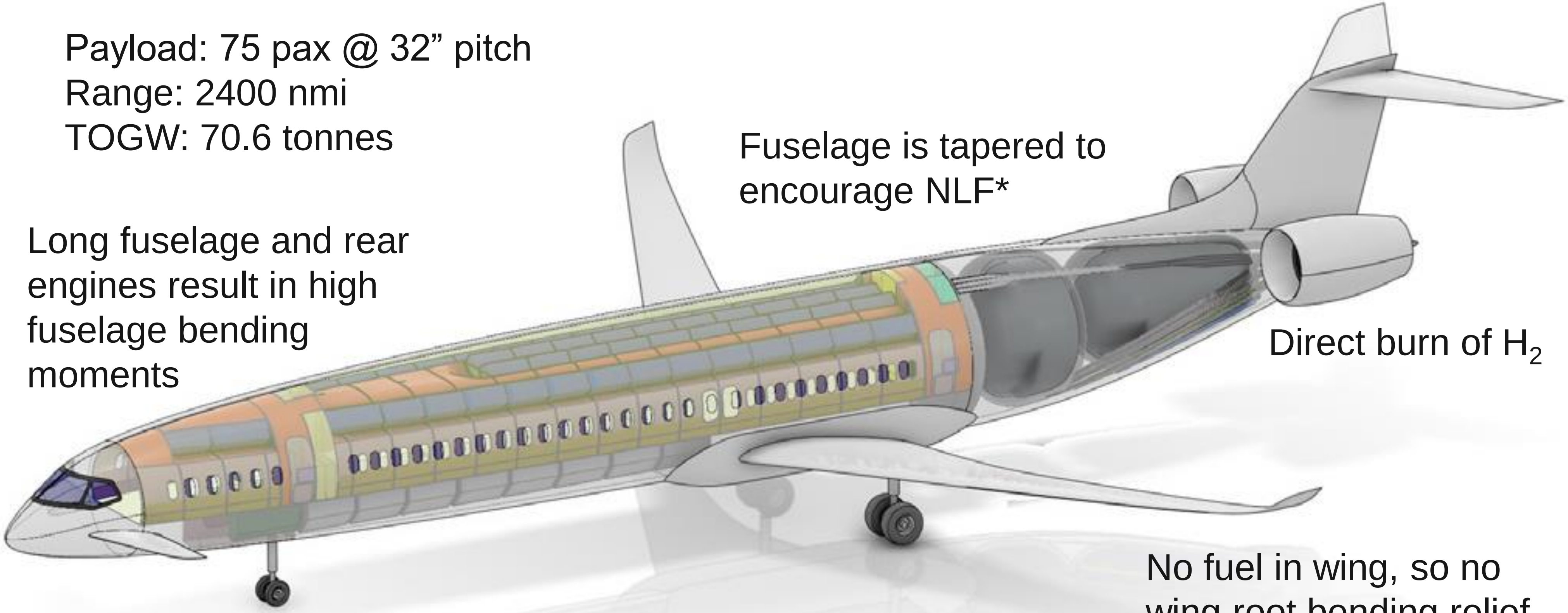
FlyZero – A320 Replacement

*NASA report CR3970 'Design of Fuselage Shapes for Natural Laminar Flow'

Payload: 75 pax @ 32" pitch
Range: 2400 nmi
TOGW: 70.6 tonnes

Long fuselage and rear engines result in high fuselage bending moments

Fuselage is tapered to encourage NLF*



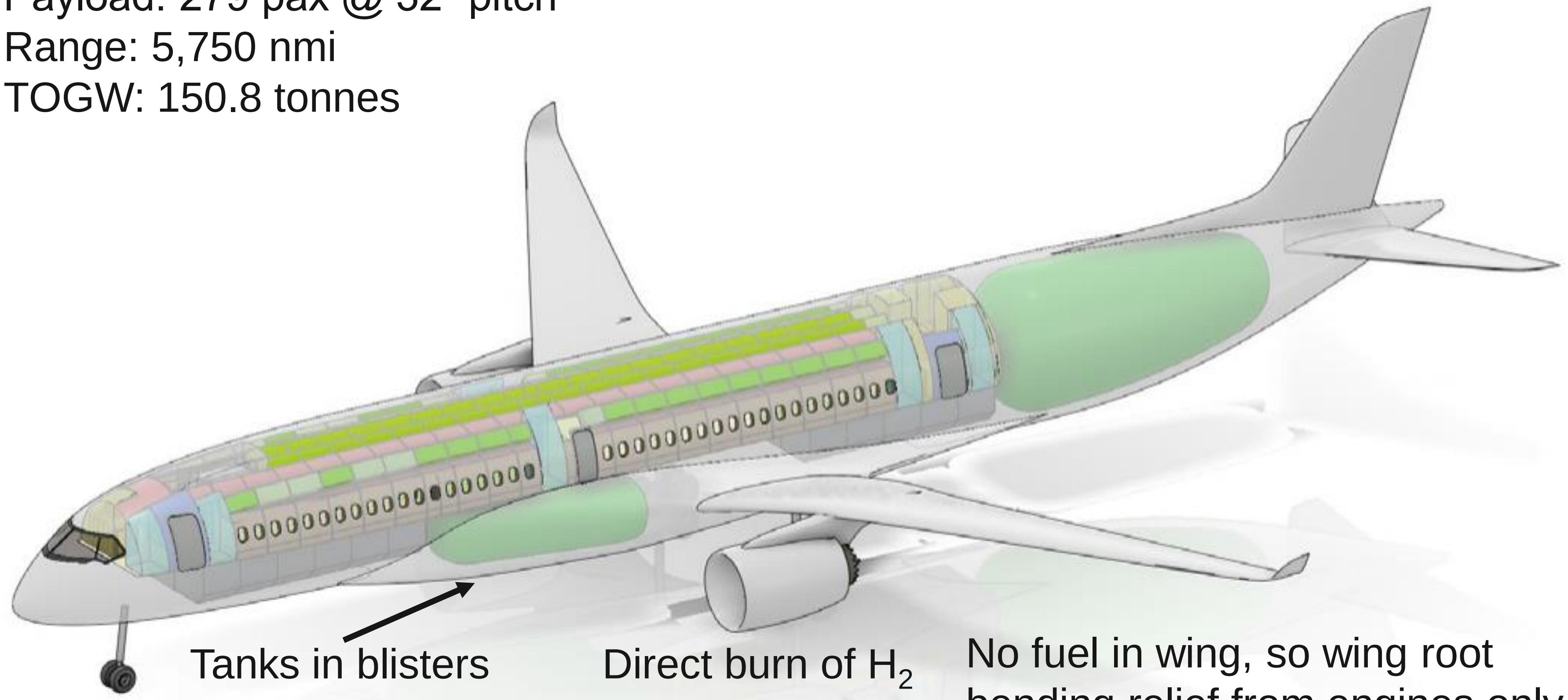
Direct burn of H_2

No fuel in wing, so no wing root bending relief

https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

FlyZero – 767-200ER Replacement

Payload: 279 pax @ 32” pitch
Range: 5,750 nmi
TOGW: 150.8 tonnes



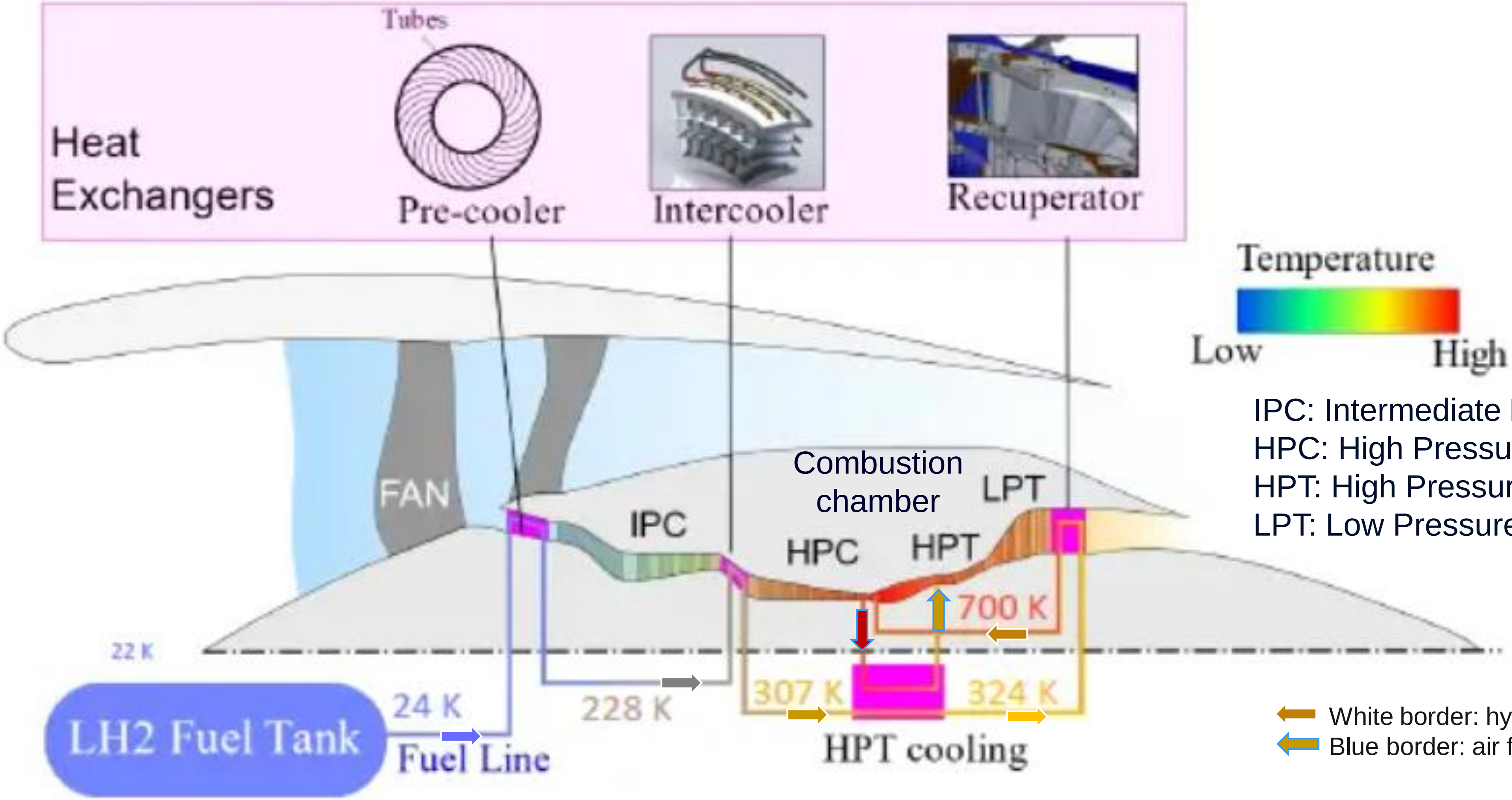
Tanks in blisters

Direct burn of H_2

No fuel in wing, so wing root bending relief from engines only

https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

EU ENABLEH2 Intercooled Turbine



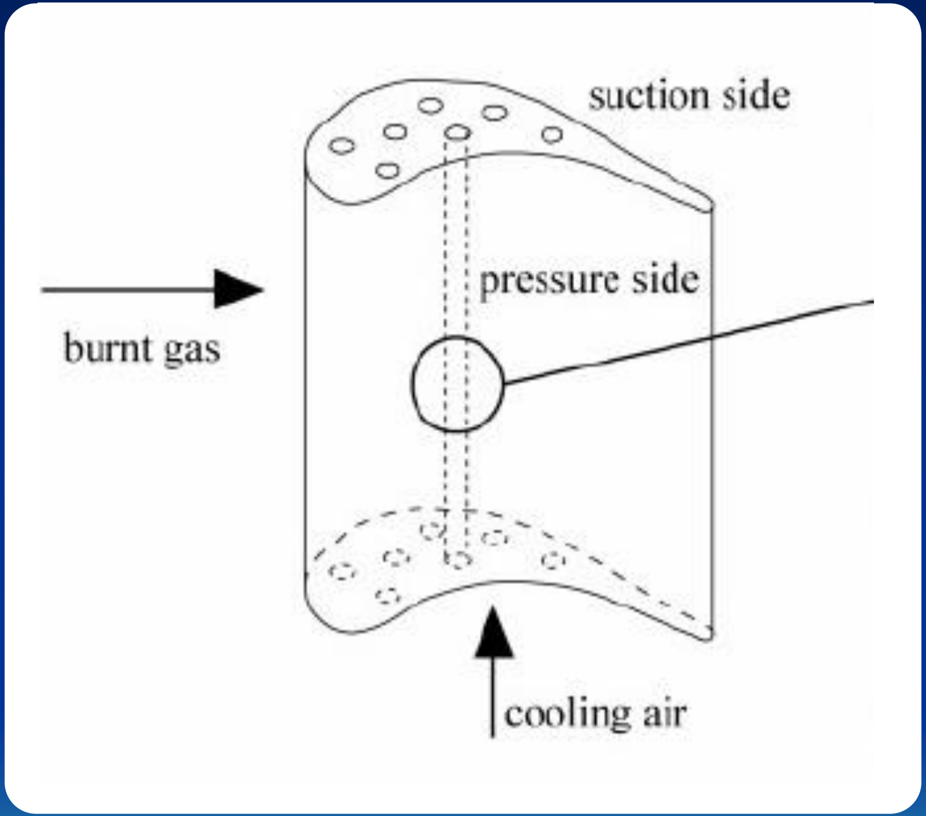
IPC: Intermediate Pressure Compressor
HPC: High Pressure Compressor
HPT: High Pressure Turbine
LPT: Low Pressure Turbine

White border: hydrogen
Blue border: air for HP turbine blade cooling

https://leehamnews.com/2022/05/06/bjorns-corner-sustainable-air-transport-part-18-advanced-hydrogen-gas-turbines/

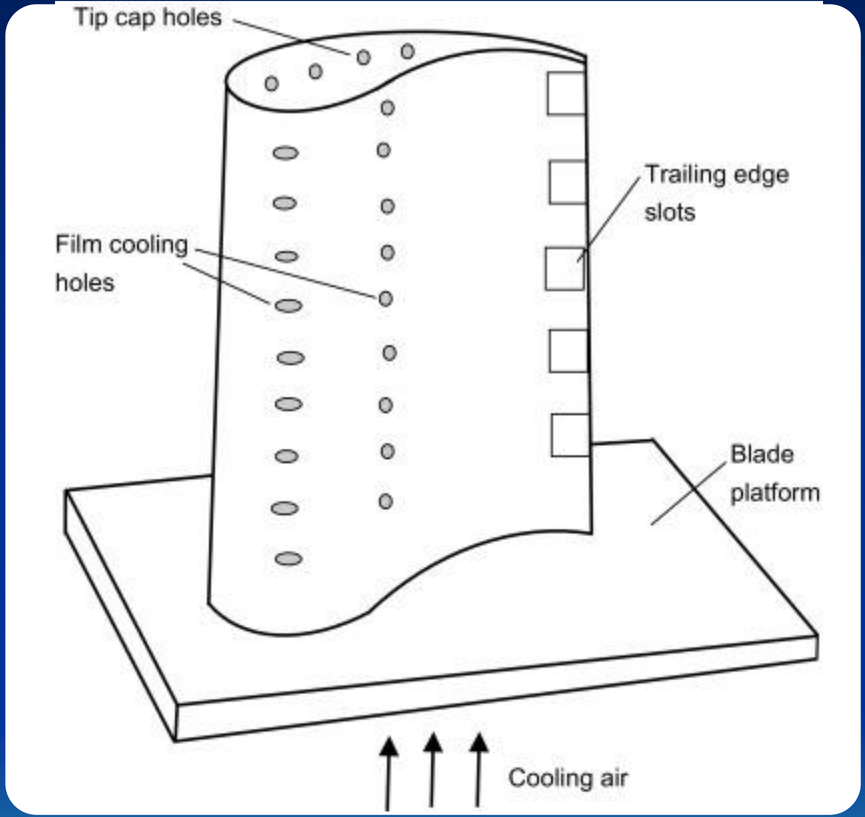
Turbine Blade Cooling

Cooling holes – early configuration



https://www.researchgate.net/figure/Turbine-blade-with-cooling-holes_fig1_225496222

Cooling holes with film cooling

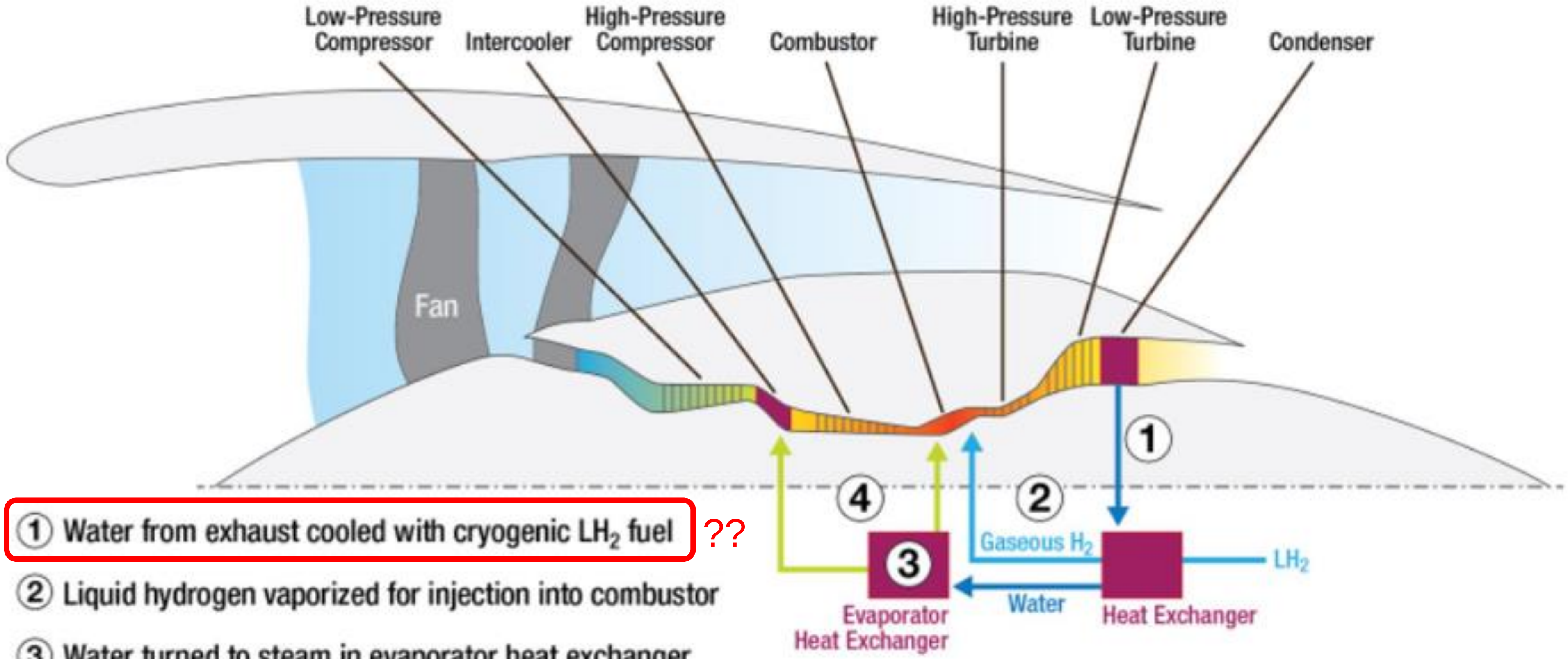



External and Internal Cooling Techniques in a Gas Turbine Blade - An Overview

Karthik Krishnaswamy
Research Scholar
National Institute of Technology
Tiruchirappalli, India

Dr. Srikanth Salyan
Assistant Professor
Department of Aeronautical Engineering
Dayananda Sagar College of Engineering, Bengaluru, India

Notional Hydrogen Steam-Injected, Intercooled Turbine Engine (HySIITE) Cycle



① Water from exhaust cooled with cryogenic LH_2 fuel ??

② Liquid hydrogen vaporized for injection into combustor

③ Water turned to steam in evaporator heat exchanger

④ Steam fed to intercooler and injected into combustor

Source: Guy Norris/AW&ST

For more info https://airinsight.com/pratt-whitney-hysiite/
Or https://newsroom.prattwhitney.com/2022-02-21-Pratt-Whitney-Awarded-Department-of-Energy-Project-to-Develop-Hydrogen-Propulsion-Technology

SWITCH Engine Concept

Sustainable Water Injection Turbofan Comprising Hybrid-Electric

The hybrid-electric GTF powertrain will enable greater efficiency across all phases of flight by leveraging megawatt class electric motor generators, power electronics, and batteries to optimize the performance of the fuel-burning gas turbine. The WET concept recovers water vapor from the engine exhaust and re-injects it into the combustion chamber to significantly improve fuel efficiency, reduce NOx emissions, and lessen contrail forming emissions. These revolutionary technologies are designed to work together to deliver a step change reduction in emissions and energy use across the full operating system, while maintaining world class reliability and operability.

https://www.militaryaerospace.com/commercial-aerospace/article/14286346/switch-project-aims-to-advance-hybrid-electric-and-water-enhanced-turbofan-tech

- Applications of Hydrogen Energy
  - Burn it directly with atmospheric O_2 (or LO_2) (rocket, gas turbine, or reciprocating engine)
  - Combine it with atmospheric O_2 (or LO_2) in fuel cell to generate electricity
  - Hybrid of direct burn and fuel cell
  - Hybrid of battery and fuel cell

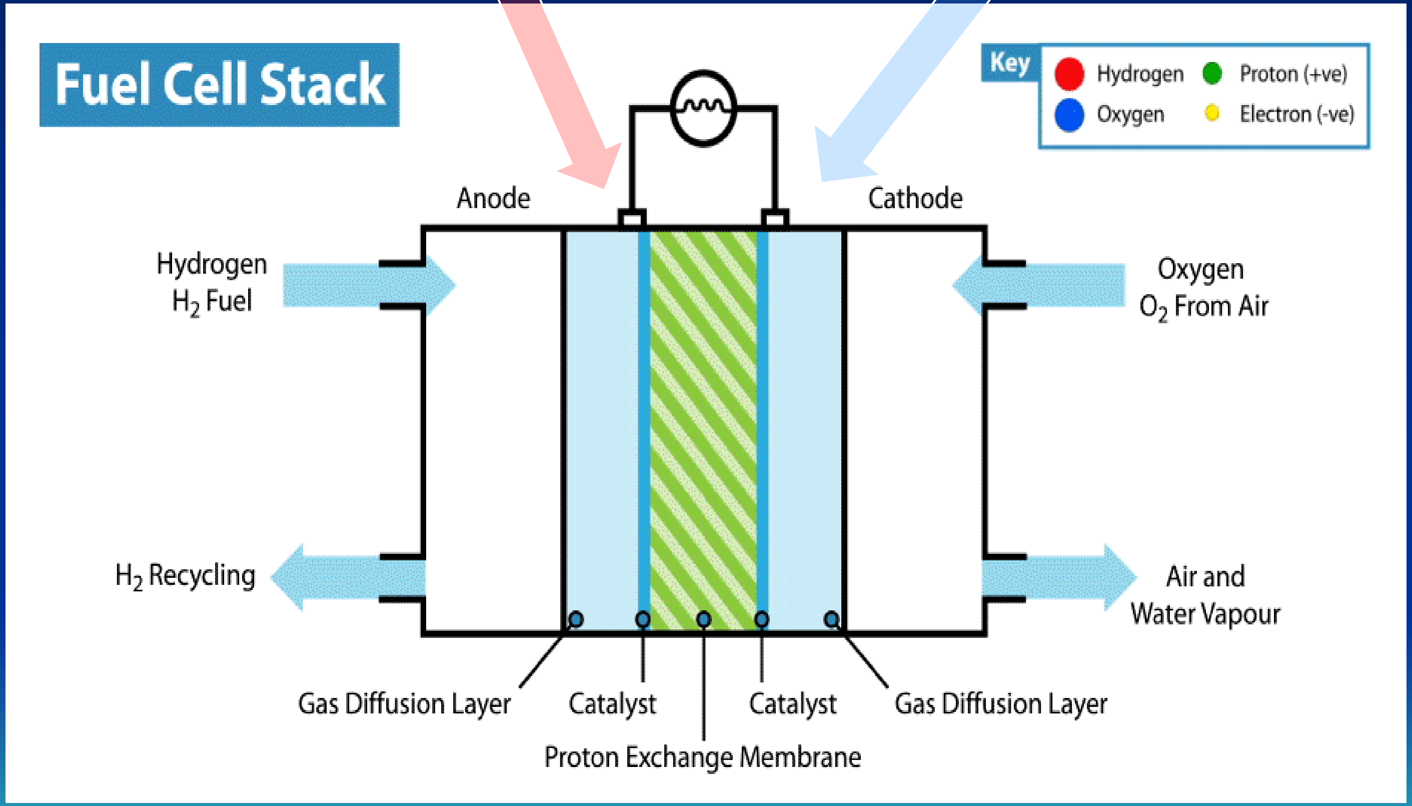
- Applications of Hydrogen Energy
  - Burn it directly with atmospheric O_2 (or LO_2) (rocket, gas turbine, or reciprocating engine)
  - Combine it with atmospheric O_2 (or LO_2) in fuel cell to generate electricity
  - Hybrid of direct burn and fuel cell
  - Hybrid of battery and fuel cell

- Areas where direct burn may be inferior
  - When multiple propulsors can be used for lift augmentation, drag reduction, or S&C
  - For short-haul turboprops flying at lower Mach numbers and shorter field length requirements
  - When propulsors are small and become very inefficient due to Reynolds Number effects (e.g., light aircraft)
  - When higher efficiency of electric motors outweighs weight of fuel cell* and inverter for long range aircraft

*can expect significant decrease in fuel cell weight in future

Fuel Cell Operation

$2H_2 + O_2 \rightarrow 4H + 2O \rightarrow 4p^+ + 4e^- + 2O \rightarrow 2H_2O$

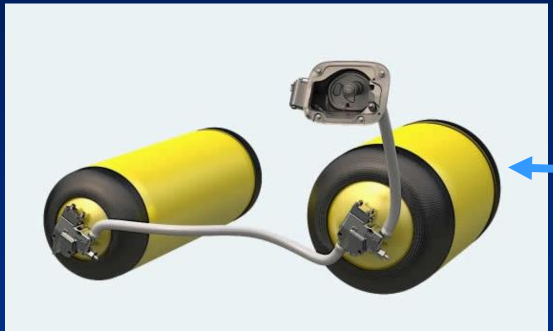


40-60% energy efficient (compared with i.c. engine efficiency of ~ 25%)

Source: www.intelligent-energy.com/technology/technology-faq/

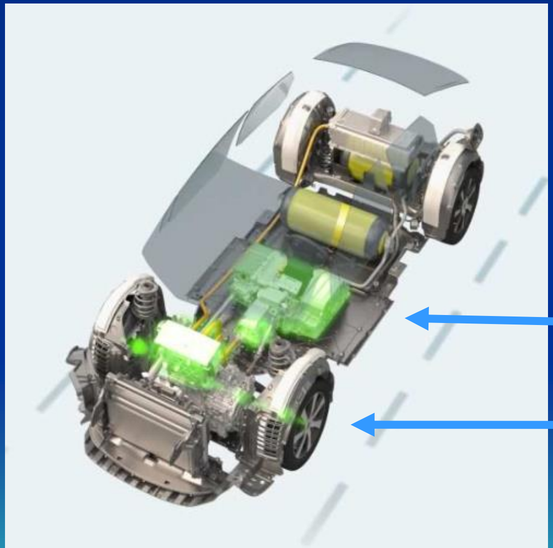
ADAC
Aircraft Design & Consulting

Toyota Mirai



Tanks with H_2
at 70 MPa
(10,000 psi)

Starting price ~ $50,100
(excluding $7,500 rebate)
Range (2023 model) 400 mi
(644 km)



Source:ssl.Toyota.com

Fuel cell

Electric motor

Cost of H_2 ~ 17 ¢/mile
Cost of gasoline ~ 17.2 ¢/mile
at $6/gal

Alaka'i Technologies LH_2 fuel cell-powered VTOL

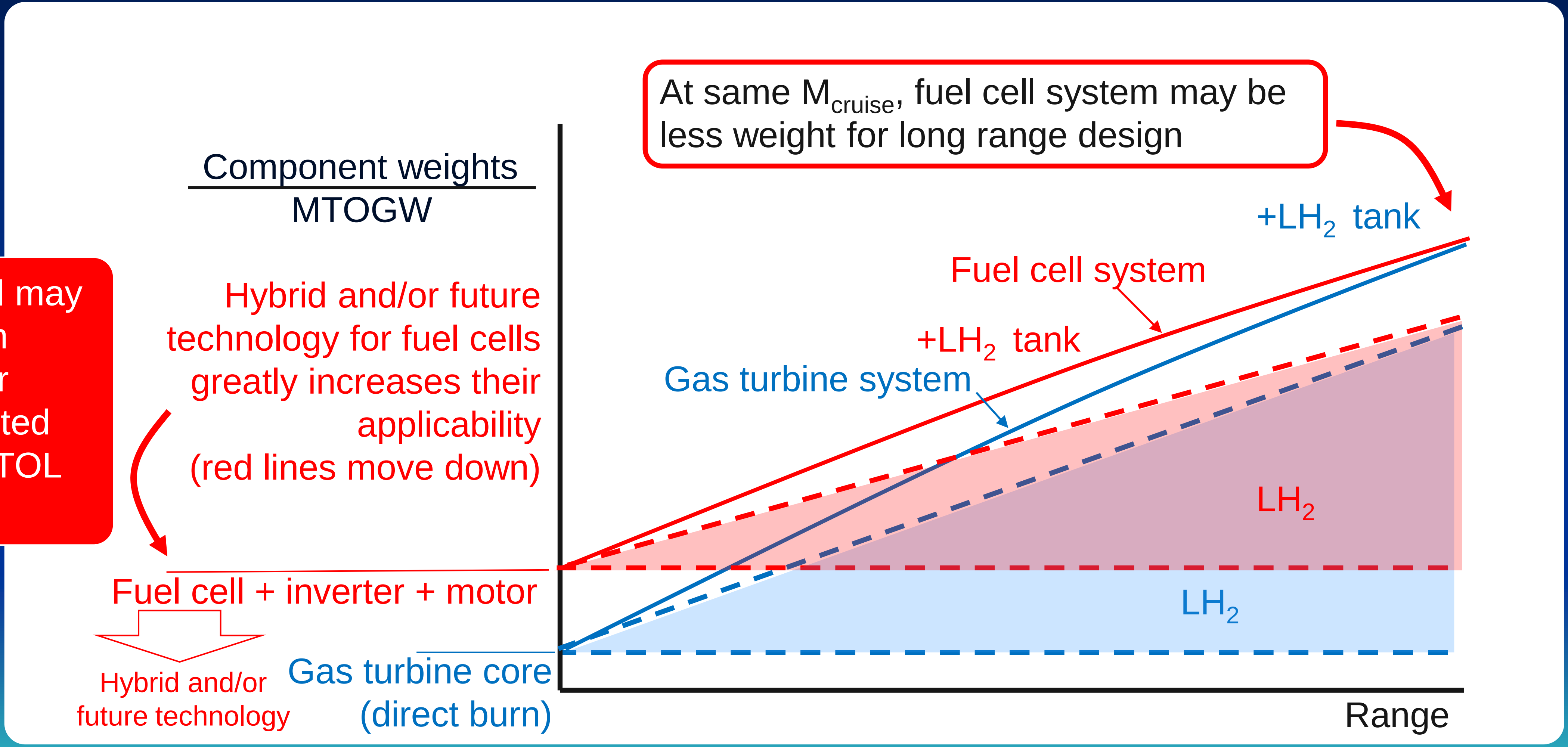
- MA-based (30 employees)
- Codesigned by BMW-owned Designworks
- 3 x LH_2 fuel cells
- 6 x 100 kW electric motors
- Payload: 456 kg (1000 lb)
- Range: up to 644 km (348 nmi)
- Endurance: up to 4 hours
- Speed: up to 190 km/h (103 kt)
- < 10 minute refueling time

https://www.designboom.com/technology/alakai-technologies-skai-evtol-hydrogen-fuel-cell-flying-car-03-20-2019/
Courtesy of alakai'I technologies

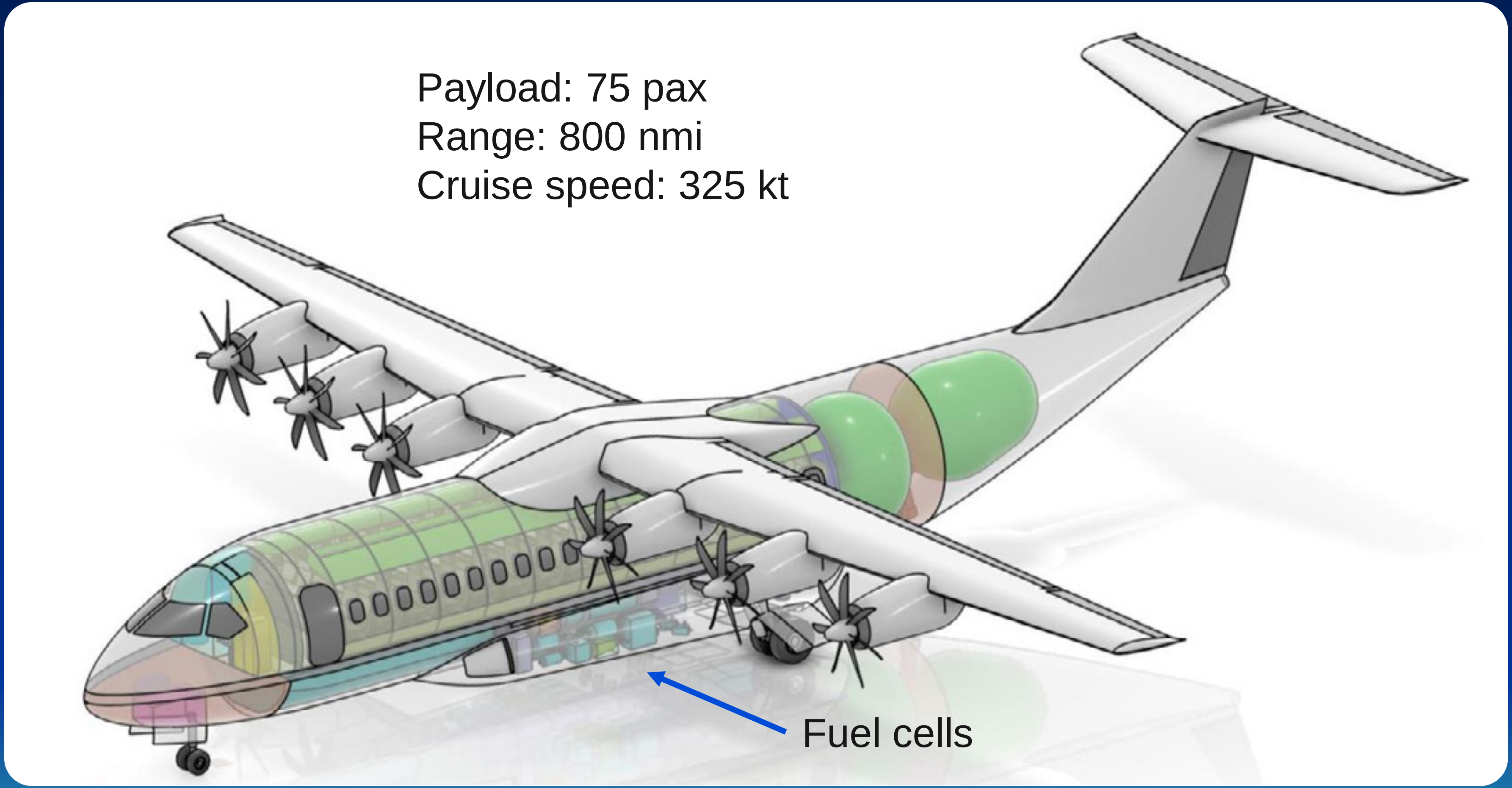
Skai H_2-powered flying taxi

Jet Propulsion Relative Weights

Fuel cell may be worth using for augmented lift for STOL aircraft



FlyZero - Regional Airliner

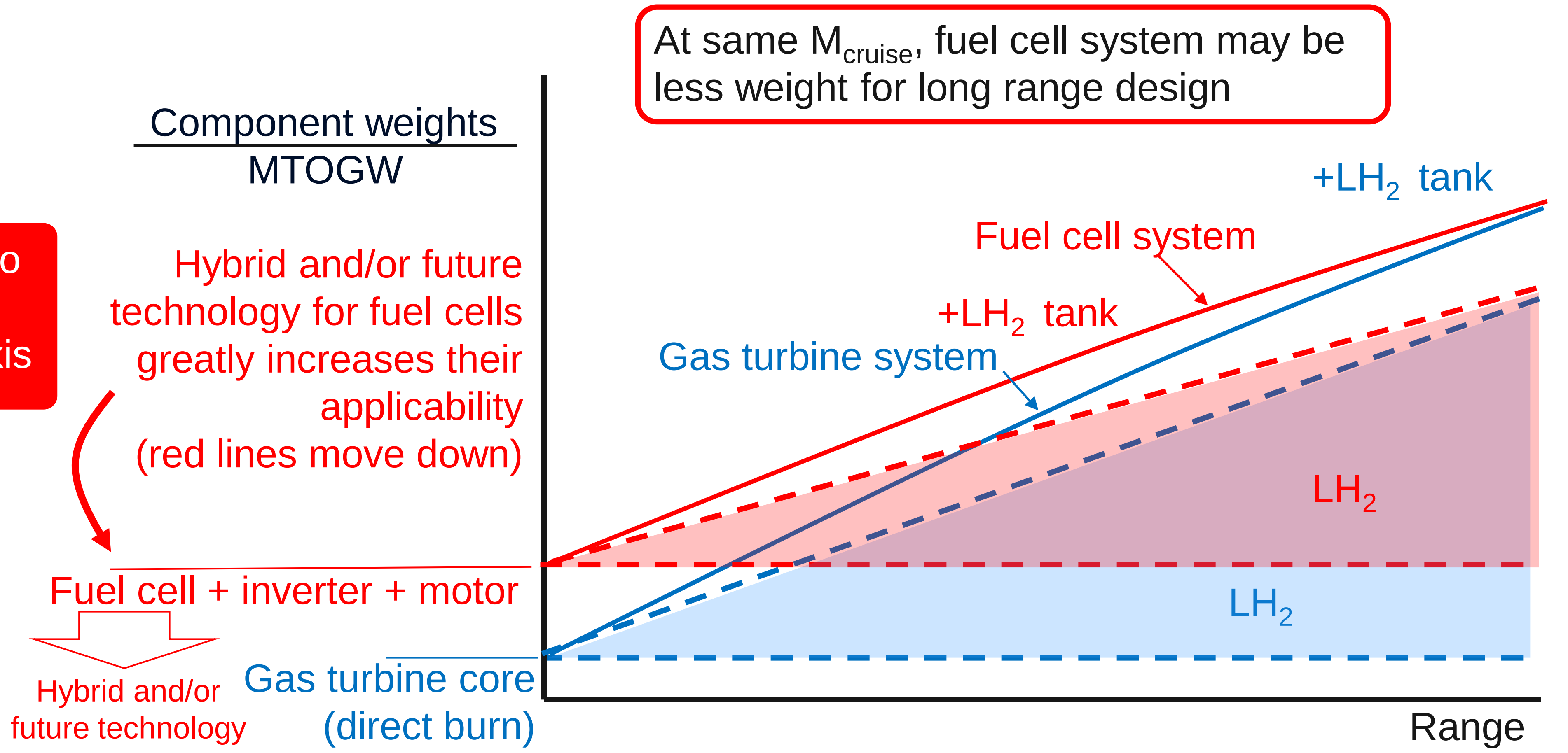


https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

- Applications of Hydrogen Energy
  - Burn it directly with atmospheric O_2 (or LO_2) (rocket, gas turbine, or reciprocating engine)
  - Combine it with atmospheric O_2 (or LO_2) in fuel cell to generate electricity
  - Hybrid of direct burn and fuel cell
  - Hybrid of battery and fuel cell

Jet Propulsion Relative Weights

Following two charts apply to vertical axis



H_2 Propulsion Options – Current Technology

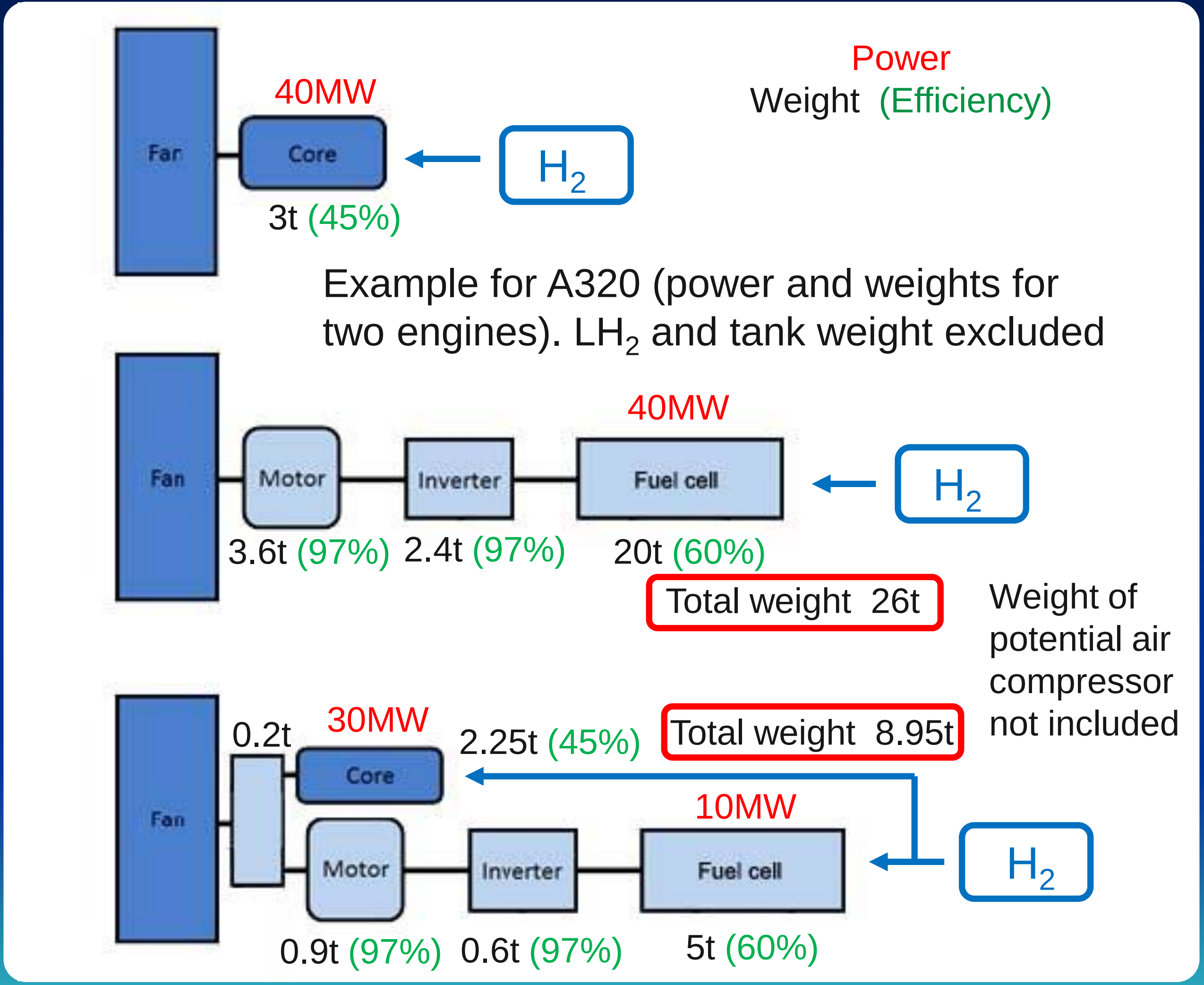
Direct combustion of H_2 in conventional gas turbine

Weights for A320-sized aircraft

Combine H_2 with atmospheric O_2 in fuel cells to generate electrical power

(maybe works for very long range)

Size electric power train for cruise, size core for extra power at takeoff



Inverter weight (2 MW/ton) from Bjorn’s Corner; Fuel cell and motor kW/kg from Bjorn’s Corner

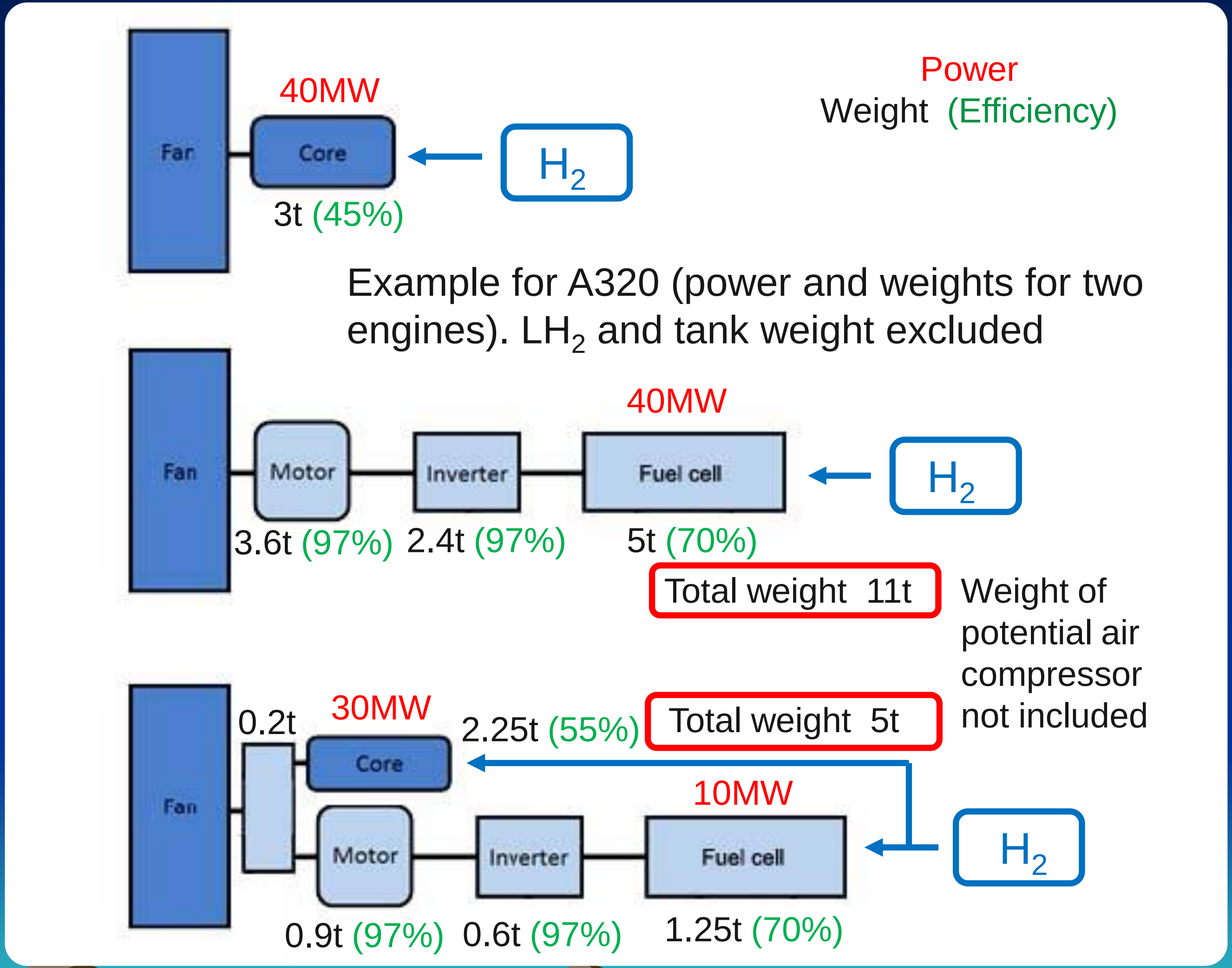
H_2 Propulsion Options – Future Technology

Direct combustion of H_2 in conventional gas turbine

Combine H_2 with atmospheric O_2 in fuel cells to generate electrical power

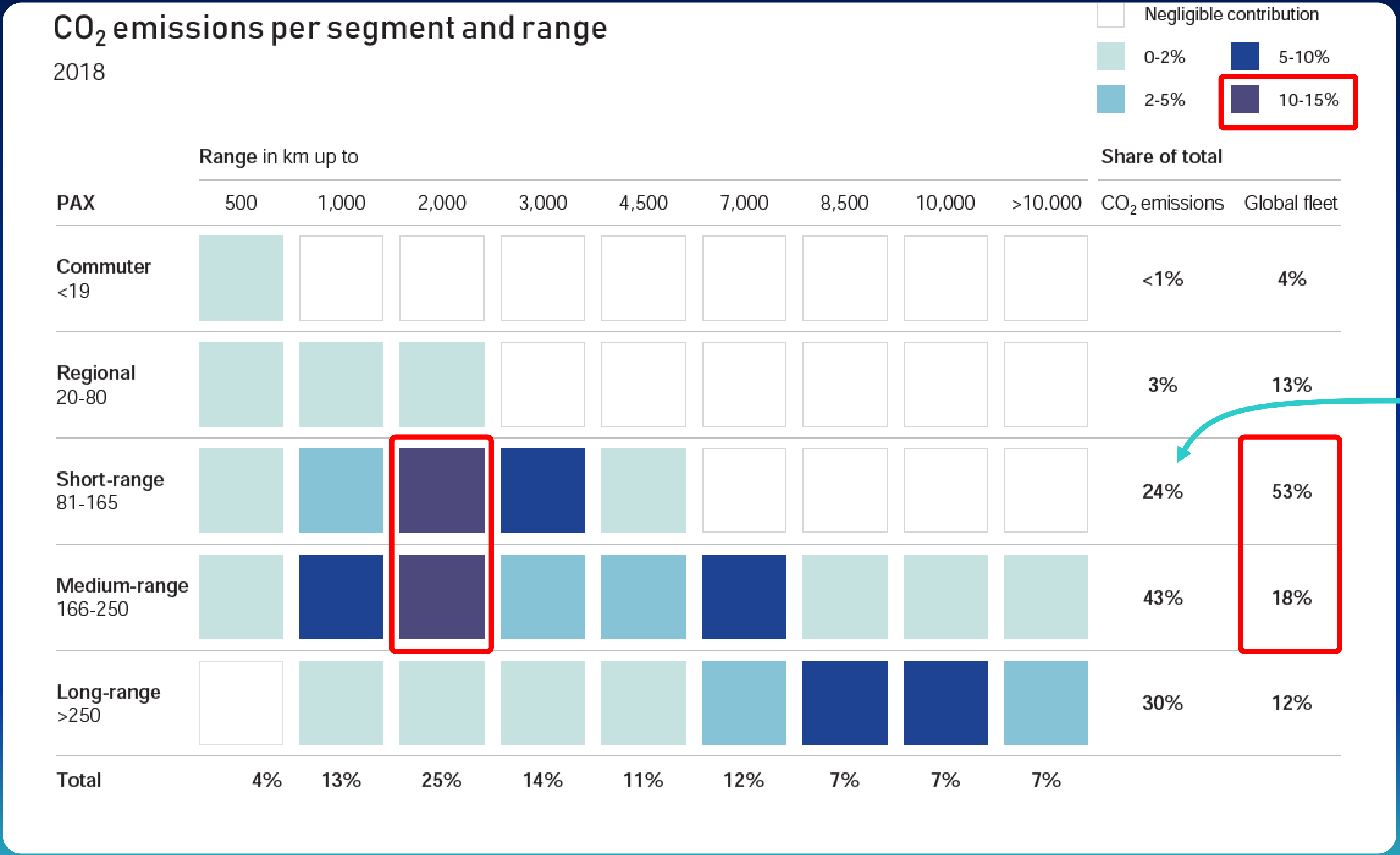
(maybe best for very long range)

Size electric power train for cruise, then size core for extra power at takeoff



Fuel cell kW/kg from Kadyk, et al., “Analysis and Design of Fuel Cell Systems for Aviation”, Energies 2018,11,375, 6 Feb 2018

Summary of EU-commissioned report



- Range up to 2000 km and 81-250 pax create 67% of CO_2 emissions

Source: EU Hydrogen Powered Aviaition.

Exhibit 8

Short-range aircraft powered by hybrid H_2 propulsion

Revolutionary aircraft

Design mission: 165 PAX, 2,000 km range, cruise speed Mach 0.72

- **2 LH_2 tanks** behind PAX cabin -added weight: 4 tons
- **Fuel cell system (11 MW)** powering electric motors
- **Electric motor** driving main turbine fan shaft during cruise, while H_2 turbine is turned off

Fuel cells justified because of lower M_{cruise}, less sweep, smaller engines

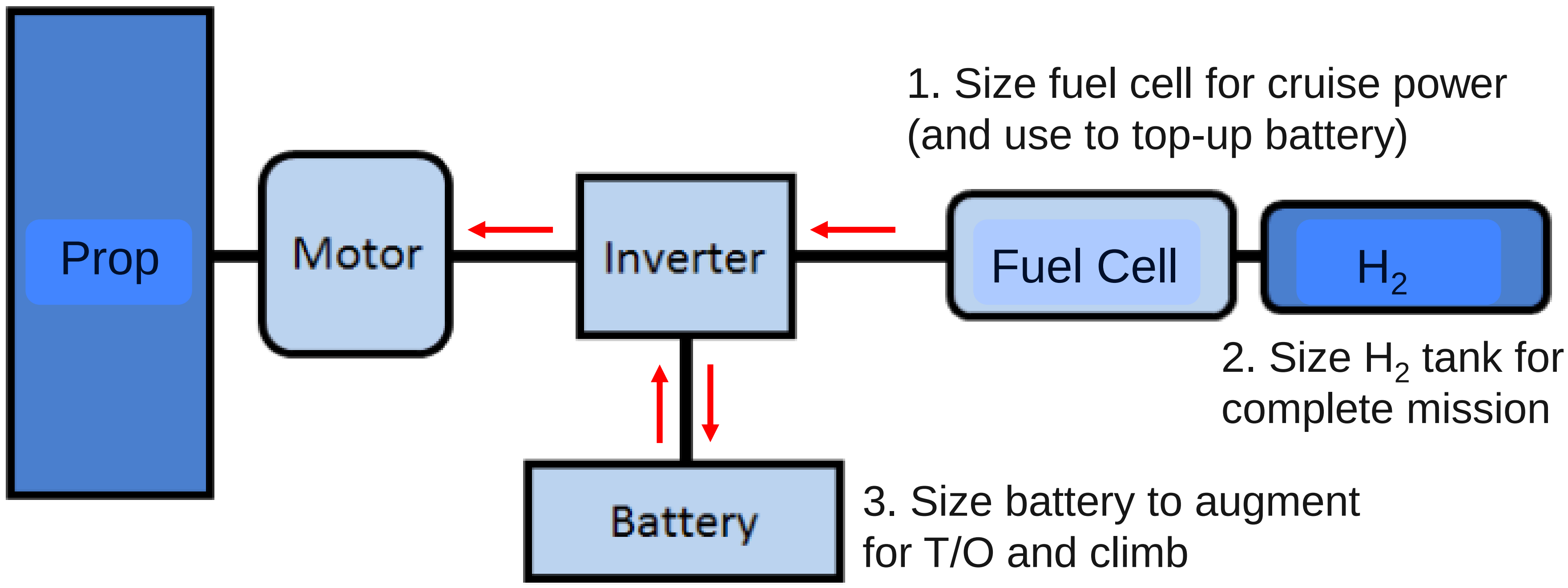
Energy demand[1]	-4%
CO_2 reduction	100%
Climate impact reduction	70-80%
Additional cost	20-30% CASK[2]
Entry into service	15 years
Propulsion power	Hybrid
MTOW[3]	+14%

1. Major assumptions: 35% gravimetric index of LH_2 tank, 91% useable LH_2 fuel, FCS mass 2 kW/kg (incl. cooling) and 60% peak efficiency (LHV), e-motors and PMAD with 97% efficiency, battery with 0.6 kWh/kg, H_2-turbine with 45% cruise efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

McKinsey, Hydrogen-powered aviation, A fact-based study of the hydrogen technology, economics, and climate impact by 2050, 2020-05

- Applications of Hydrogen Energy
  - Burn it directly with atmospheric O_2 (or LO_2) (rocket, gas turbine, or reciprocating engine)
  - Combine it with atmospheric O_2 (or LO_2) in fuel cell to generate electricity
  - Hybrid of direct burn and fuel cell
  - Hybrid of battery and fuel cell

Hybrid Battery and Fuel Cell



Source: Wikipedia

Weight of battery more than offset by reduction in weight of fuel cell

Boeing R&T Europe Dimona (Modified)

- Powered by hydrogen fuel cell and Li batteries (2008)
- Climb: Li battery + fuel cell
- Cruise: 20 minutes on fuel cell
- Cruise at 27 m/sec (51 kt)
- Paris Air Show 2009

Source: Wikipedia

Liaoning Ruixiang GA Co. RX1E-A

辽宁锐翔通用飞机制造有限公司

- Developed at Liaoning General Aviation Academy at Shenyang Aerospace University
- In 2016 tested with combined hydrogen and battery power
- First flight of all-electric advanced config.: 2017-11-01
- Characteristics
  - Endurance: 60 minutes
  - TOGW: 600 kg (1,320 lb)
  - Two seats
  - Max speed: 165 km/h (90 kt)
  - Cost of electricity: ¥10/flight

Source: http://www.telegraph.co.uk/news/world/china-watch/technology/new-electric-aircraft/

First flight of RX1E-A

Liaoning Ruixiang GA Co. RX1E-A

辽宁锐翔通用飞机制造有限公司

RX1E
Fuel cell + battery

RX1E-A
Battery power only

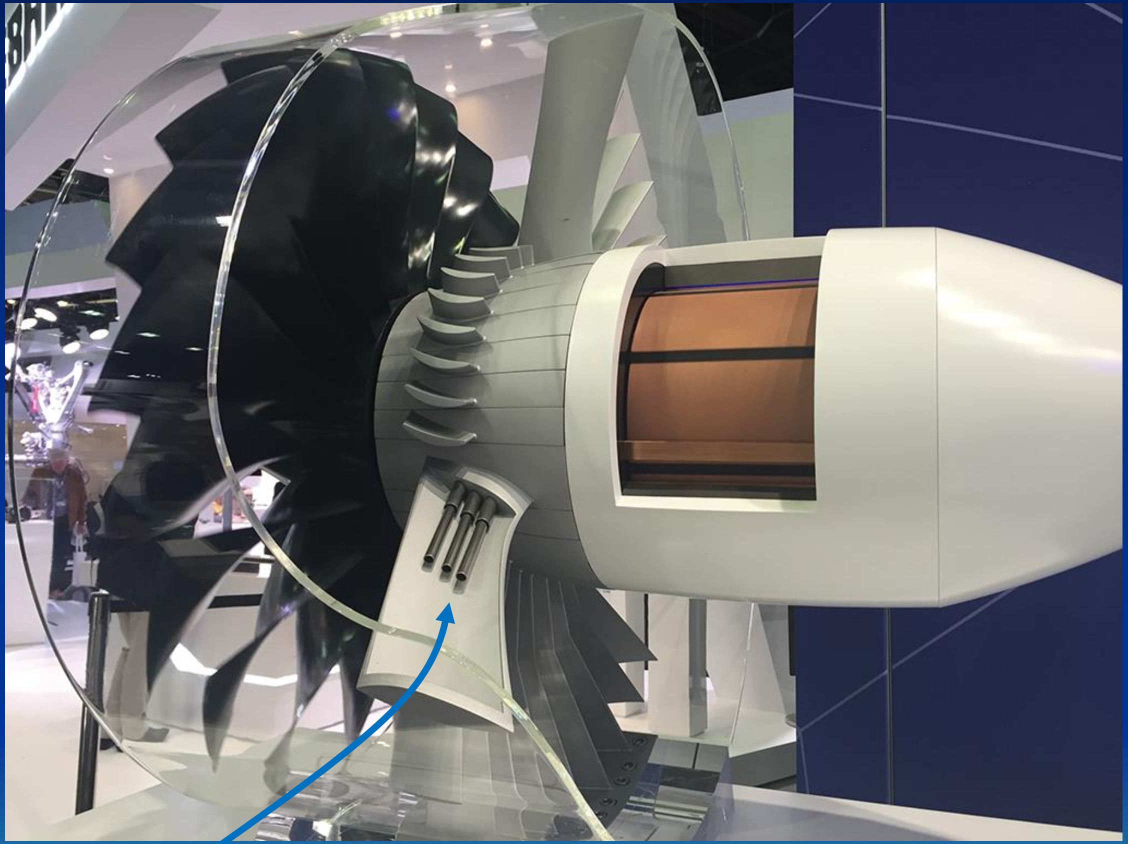
- Need for Zero-Carbon Economy
- Hydrogen vs. Batteries
- History of Hydrogen-powered Propulsion
- Hydrogen Generation and Distribution
- Applications of Hydrogen Energy
- The Future of Hydrogen
- Contrails
- Conclusions

- The Future of Hydrogen
  - Technology
  - Reduction in Emissions

ASuMED Superconducting Motor

- Advanced Superconducting Motor Experimental Demonstrator
- Developed by Oswald Electromotoren
- High temperature superconductor @ 23 K (- 418 F)
- 1 mW output @ 6,000 rpm
- Specific power 20 kW/kg* — Biggest benefit
- Overall η 99.9% — Additional benefit

* Compare with 5-6 kW/kg for conventional



LH_2 lines

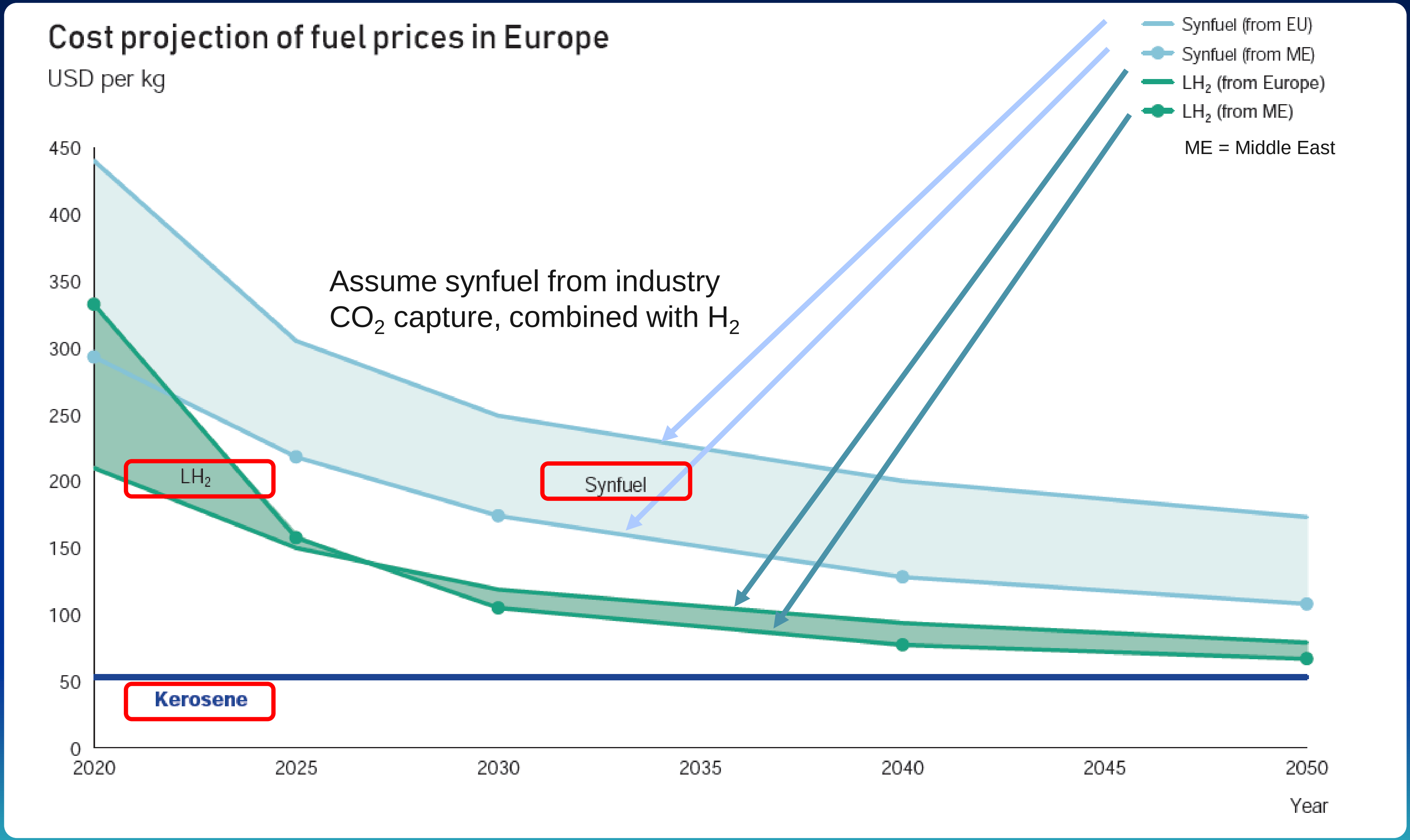
https://aviationweek.com/future-aerospace/full-superconducting-motor-readied-tests

- The Future of Hydrogen
  - Technology
  - Reduction in Emissions

Summary of EU-commissioned report

- Prepared by McKinsey & Company
- Commissioned by Clean Sky 2 Joint Undertaking and Fuel Cells and Hydrogen 2 Joint Undertaking
- Published 2020-05
- H_2 combustion could reduce climate impact by 50–75%
- Fuel cell propulsion by 75-90%

Comparative Cost of Synfuel and LH_2



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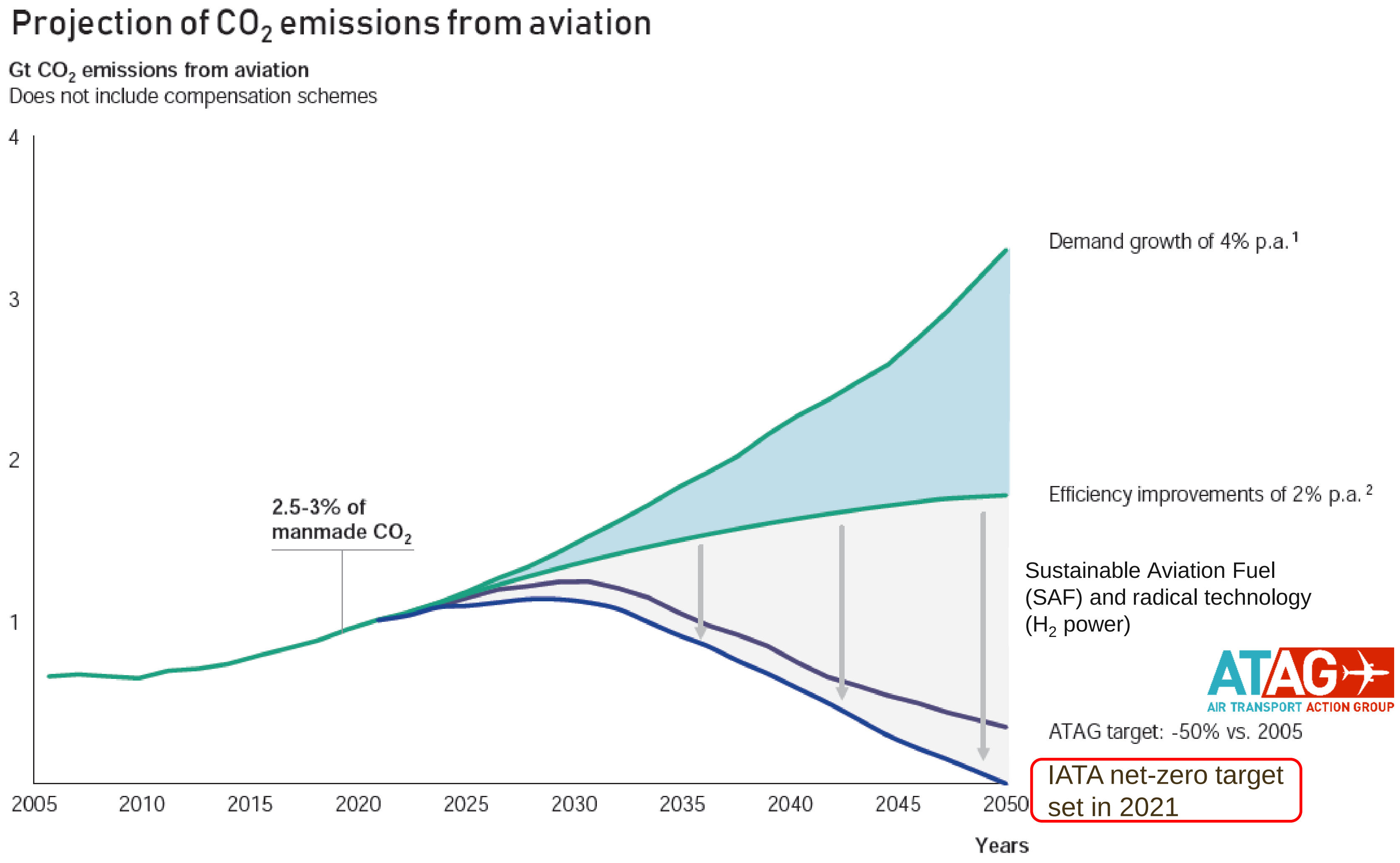
Summary of EU-commissioned report



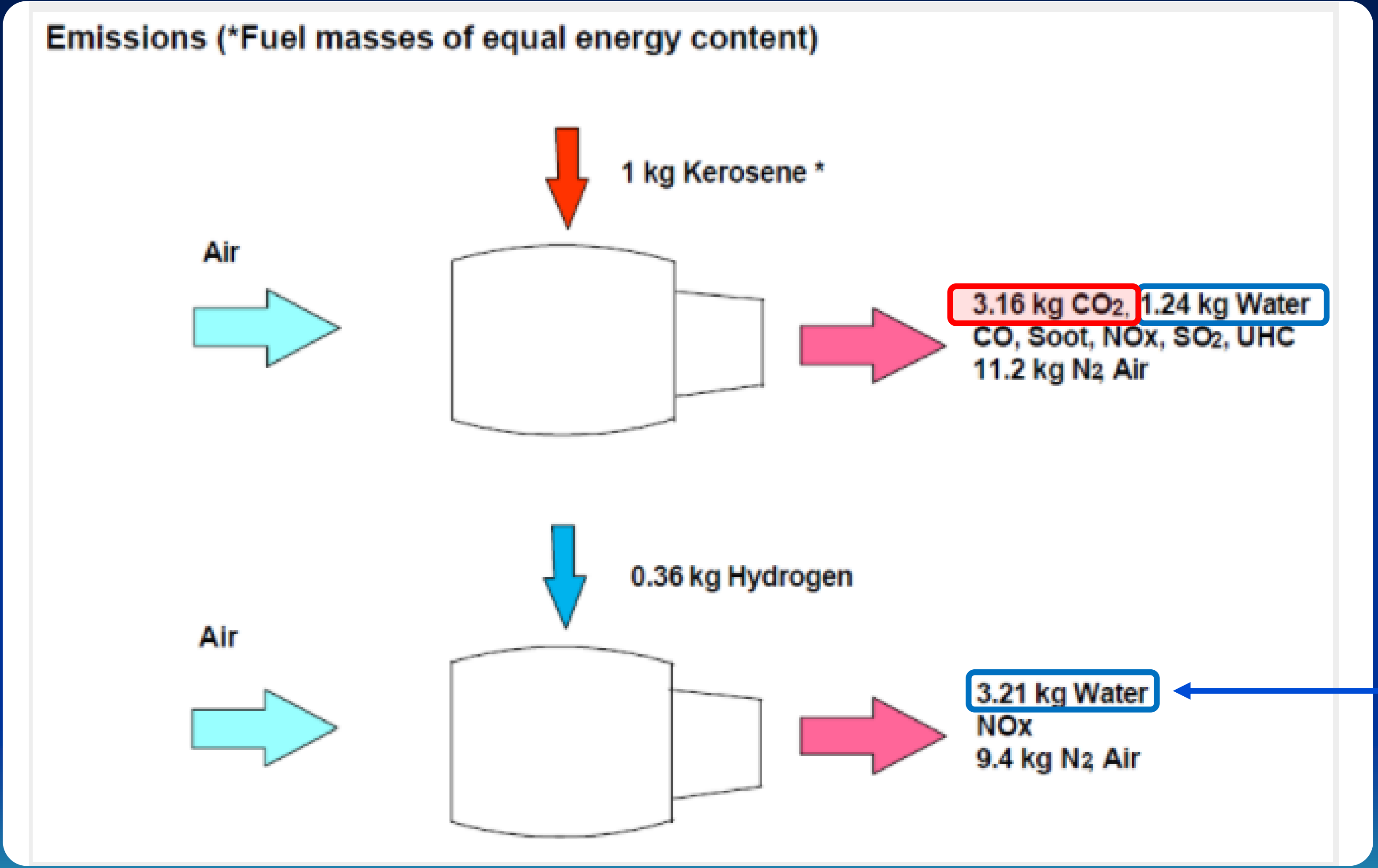
IATA = International Air Transport Association

1. Assumption based on growth projections from ATAG, IATA, ICCT, WWF, UN
2. ICAO ambition incl. efficiency improvements in aircraft technology, operations and infrastructure

McKinsey, Hydrogen-powered aviation, A fact-based study of the hydrogen technology, economics, and climate impact by 2050, 2020-05

- Need for Zero-Carbon Economy
- Hydrogen vs. Batteries
- History of Hydrogen-powered Propulsion
- Hydrogen Generation and Distribution
- Applications of Hydrogen Energy
- The Future of Hydrogen
- Contrails
- Conclusions

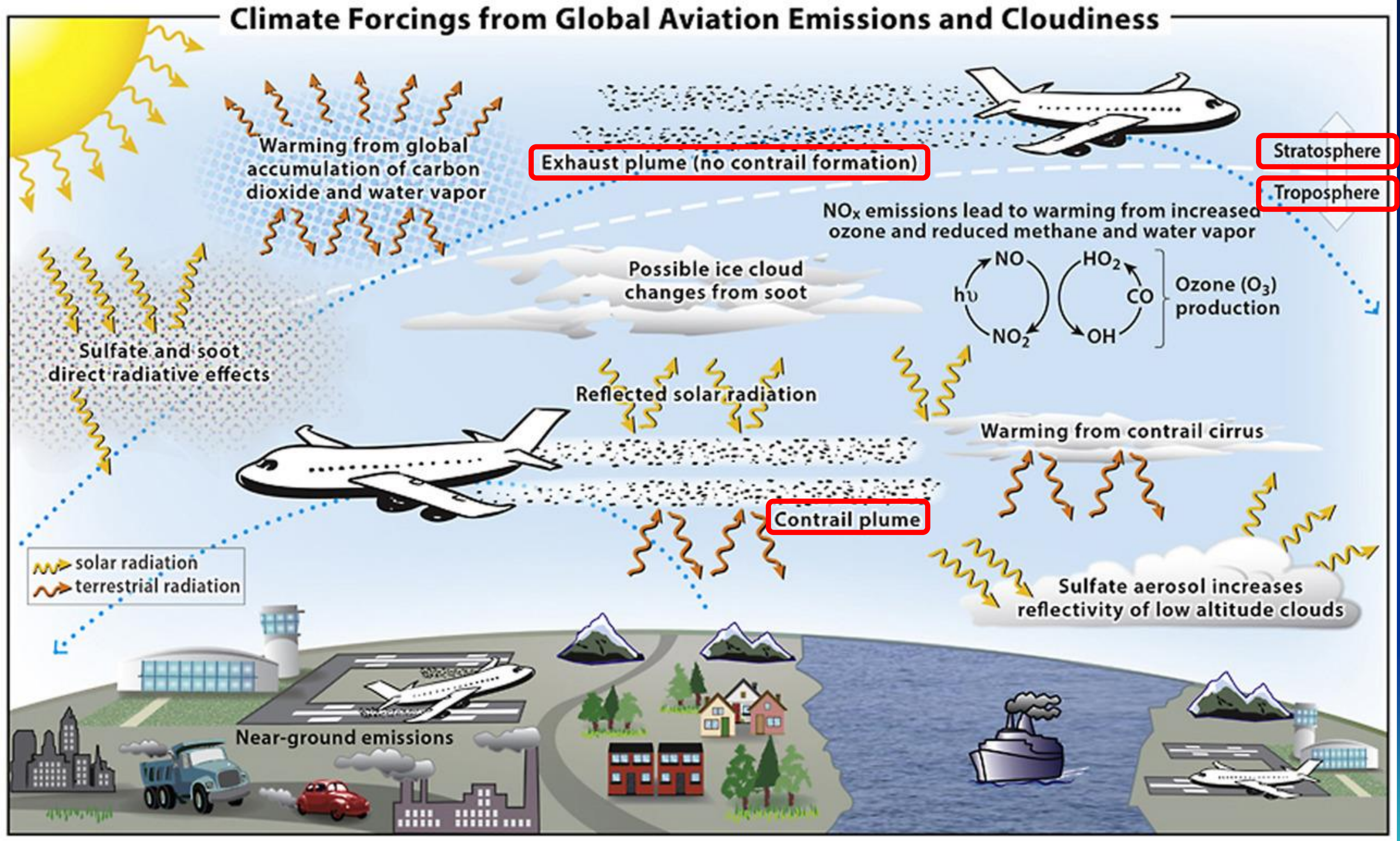
Jet fuel vs. H_2 Emissions



Compared with jet-fueled engine:
- No CO_2
- 2.6 x water vapor results in increased condensation trails, which contribute to increased global warming

Source: Airbus Cryoplane study

Condensation Trails from Kerosene Fuel



https://ars.els-cdn.com/content/image/1-s2.0-S1352231020305689-fx1_lrg.jpg

Understanding Condensation Trails

A NASA DC-8 with a fast forward scattering spectrometer probe followed a DLR A320 ATRA on nine flights over Germany in 2018 to measure ice particle concentrations.

Credit: DLR/NASA/Florian Friz

Keith Button, Curbing Contrails, AIAA Aerospace America 2021-05

Condensation Trails from Jet Fuel

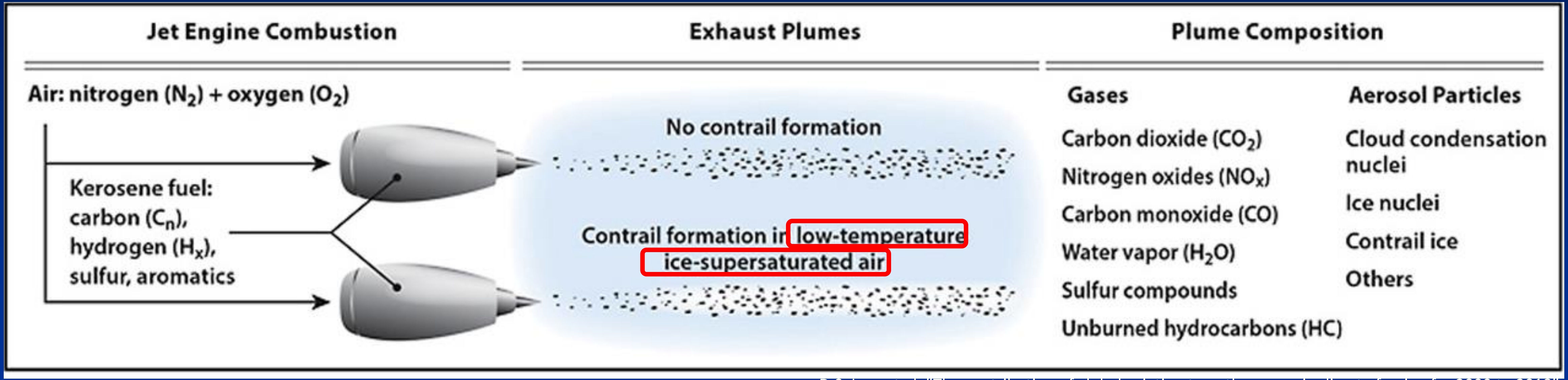
The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018

Dedication: This paper is dedicated to the memory of Professor Ivar S. A. Isaksen of the University of Oslo, whose scientific excellence, friendship, and mentorship is sorely missed.

D.S. Lee [a], D.W. Fahey [b], A. Skowron [a], M.R. Allen [c, n], U. Burkhardt [d], Q. Chen [e], S.J. Doherty [f], S. Freeman [a], P.M. Forster [g], J. Fuglestvedt [h], A. Gettelman [i], R.R. De León [a], L.L. Lim [a], M.T. Lund [h], R.J. Millar [c, o], B. Owen [a], J.E. Penner [j], G. Pitari [l] ... L.J. Wilcox [m]

Published in 'Atmospheric Environment', Elsevier, 2021-01-01

Condensation Trails from Jet Fuel



D.S. Lee, et al. "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018"

Contrail formation depends on atmospheric conditions

Condensation Trails from Jet Fuel

Highlights

- Global aviation warms Earth's surface through both CO_2 and net non-CO_2 contributions.
- Global aviation contributes a few percent to anthropogenic radiative forcing.
- Non-CO_2 impacts comprise about 2/3 of the net radiative forcing. !!
- Comprehensive and quantitative calculations of aviation effects are presented.
- Data are made available to analyze past, present and future aviation climate forcing.

D.S. Lee, et al. "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018"

Condensation Trails from Jet Fuel

NOVEMBER 24, 2020

Airline contrails warm the planet twice as much as CO2, EU study finds

While airline contrails have featured less in our skies during the pandemic, an EU study published today finds they are among the non-CO2 emissions which contribute twice as much to global warming as aircraft CO2.[1] The research, by leading scientists, finds that jet engine emissions of nitrogen oxides, water vapor, soot and black carbon were responsible for two-thirds of aviation's climate impact in 2018. Transport & Environment (T&E) said it is an acknowledgement by the European Commission that contrails finally need to be addressed.

https://www.transportenvironment.org/discover/airline-contrails-warm-planet-twice-much-co2-eu-study-finds/

Measuring Contrail Properties

Funded by German Aerospace Center (DLR)

https://www.bbc.com/news/business-5876

Prof. Christiane Voigt at Mainz U. claims aircraft can avoid 80% of contrail-producing airspace with little cost

Airbus/DLR to Evaluate Hydrogen Combustion Emissions

Photo credit: James Darcy via Airbus

Purchased two Arcus J jet gliders, one with kerosene-fueled jet, other hydrogen-fueled jet

Airbus/DLR to Evaluate Hydrogen Combustion Emissions

Grob G 520:

- PT-6 powered long-endurance high-altitude reconnaissance (service ceiling: 50,000 ft)
- will tow gliders to altitude and carry equipment to measure jet contrail composition

- Need for Zero-Carbon Economy
- Hydrogen vs. Batteries
- History of Hydrogen-powered Propulsion
- Hydrogen Generation and Distribution
- Applications of Hydrogen Energy
- The Future of Hydrogen
- Contrails
- Conclusions

Conclusions

- For VTOL and very short-range aircraft (i.e., small fuel mass fraction), batteries may be preferred
- For H_2, hybrid turboprop + fuel cell may offer lightest weight for short haul, lower M_{cruise} operations
- For medium and long range, H_2 direct burn (i.e., gas turbine) is currently best solution
- If fuel cell weight can be reduced, hybrid gas turbine + fuel cell may be preferable for long haul aircraft
- Zero net CO_2 must be achieved by 2050
- Contrail formation may be as important as emissions
- There are still many unknowns

香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Thanks for your interest

Presentation will be posted at
https://www.adac.aero/class-presentations