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A new propulsion architecture for a hydrogen aircraft

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Problem 1: Carbon emissions

CO_2

915 million ton

4.5bil

2019

Source: atag.org

Problem 2: Long flight hours

Non-stop madness: How long-haul flights affect your mind

[1]

A321 XLR

Flying 11 hours (4,700nm) non-stop [2]

Requirements for 2050 zero-carbon emission

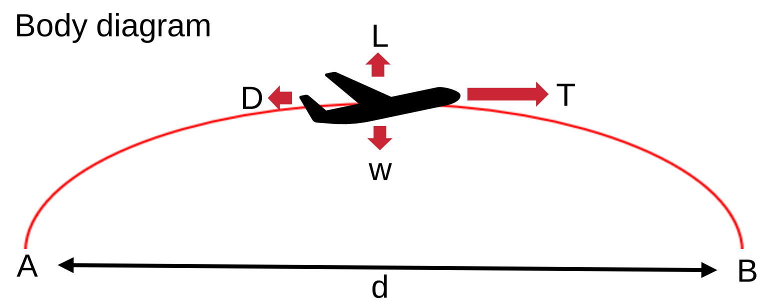
[3]

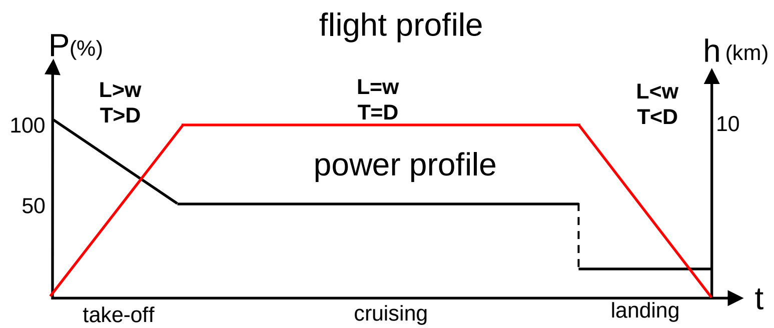
Regional aircraft
GI = 0.35

International aircraft
GI = 0.5

***GI = Gravimetrix index**

Theory and fundamental





Energy = area under the graph of power profile
Energy parameter = **thrust**, **speed** and **flight time**

Design trade-off

- **Low gravimetric index**
- **Low boil-off**
- **Low speed**
- **High *Isp***
- **Low volume efficiency**

Regional/air cargo

International/ transatlantic aircraft

- **High gravimetric index**
- **High boil-off**
- **High speed**
- **Low *Isp***
- **High volume efficiency**

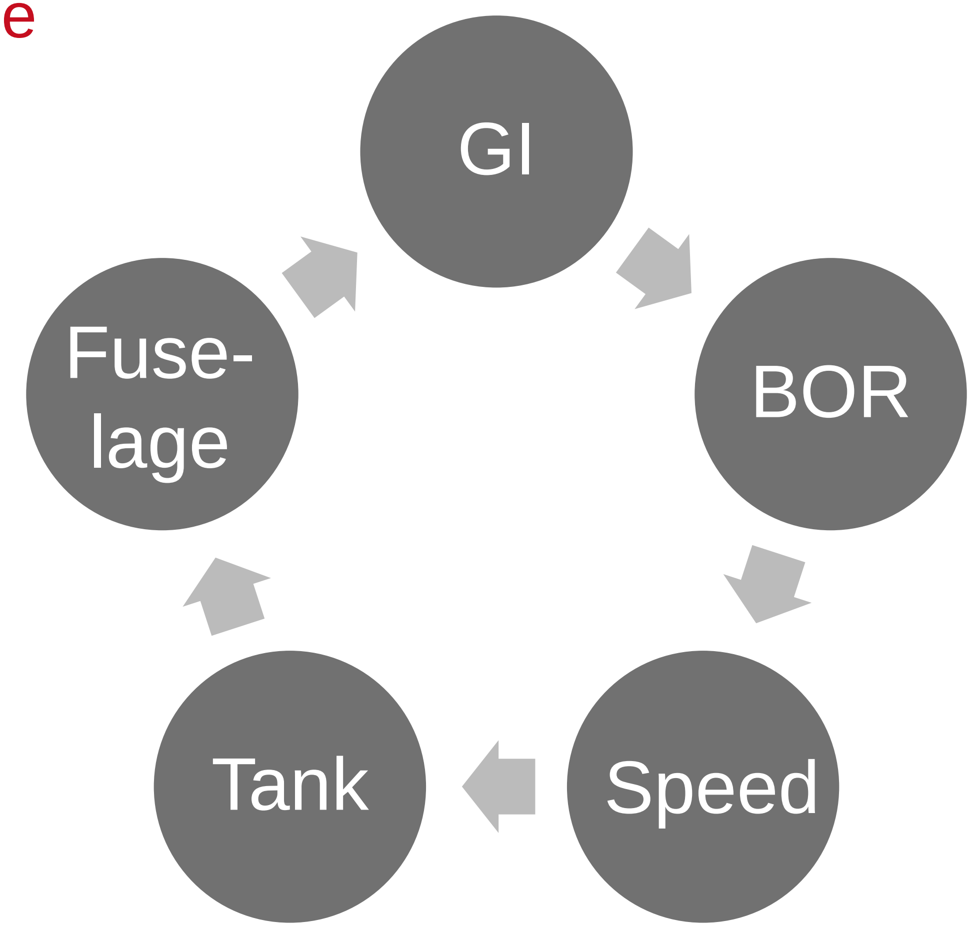
[4]

[5]

[6]

[7]

Design cycle

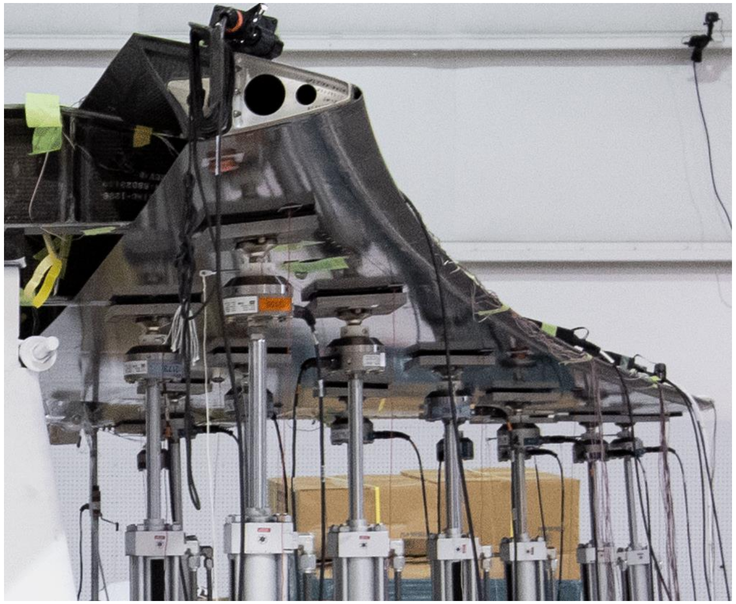


***GI = Gravimetrix index**

***BOR= Boil-off rate**

Design challenges

1. A high GI allows a complex geometry of a tank (e.g. wing)



[8]

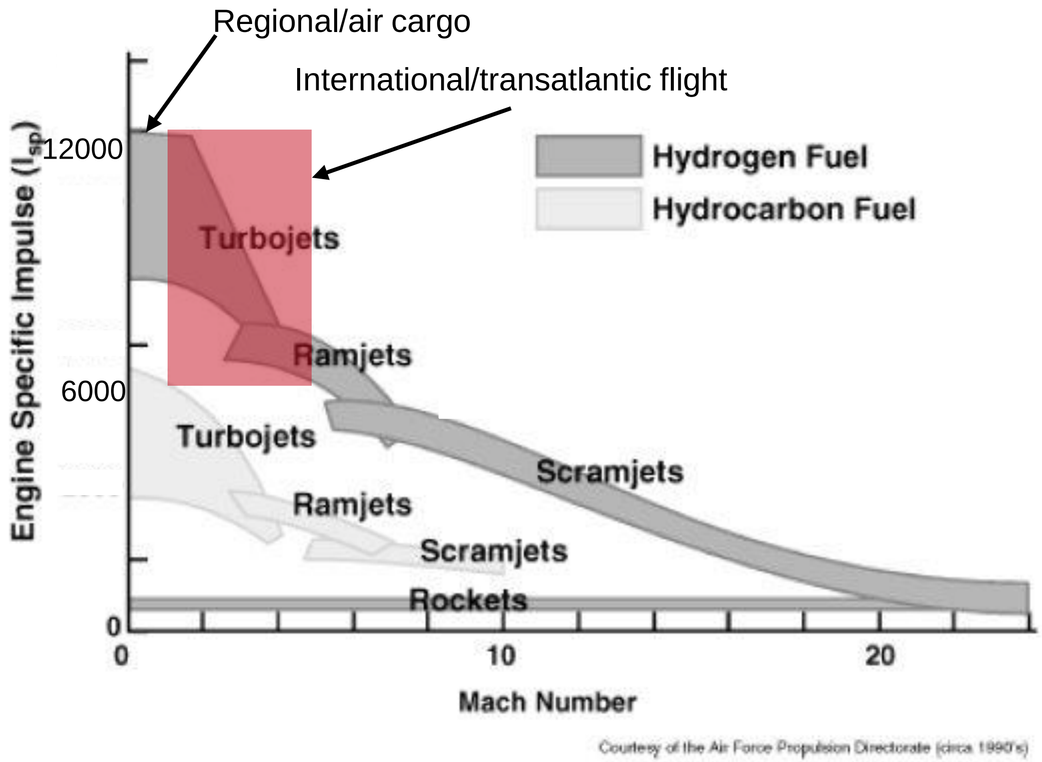
***GI = Gravimetrix index**

Propulsion architecture

[9]

- **Safety**
- **Reliability**

Engine

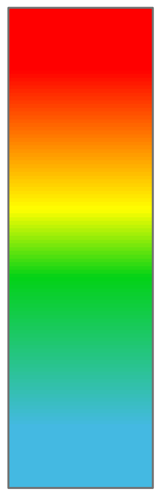

Regional/air cargo
International/transatlantic flight
Engine Specific Impulse (I_{sp})
12000
6000
0
Hydrogen Fuel
Hydrocarbon Fuel
Turbojets
Ramjets
Scramjets
Turbojets
Ramjets
Scramjets
Rockets
0
10
20
Mach Number
Courtesy of the Air Force Propulsion Directorate (circa 1990's)

[10]

LH_2 Tank

C-C	Li-Al	Mg-Alloy
• Small • High pressure	• Big • Lightweight	• Huge • High strength

Thermal range



Gas turbine **3500 ±500 K**

Aero thermal **400 ±15 K**

FC **310 ±10 K**

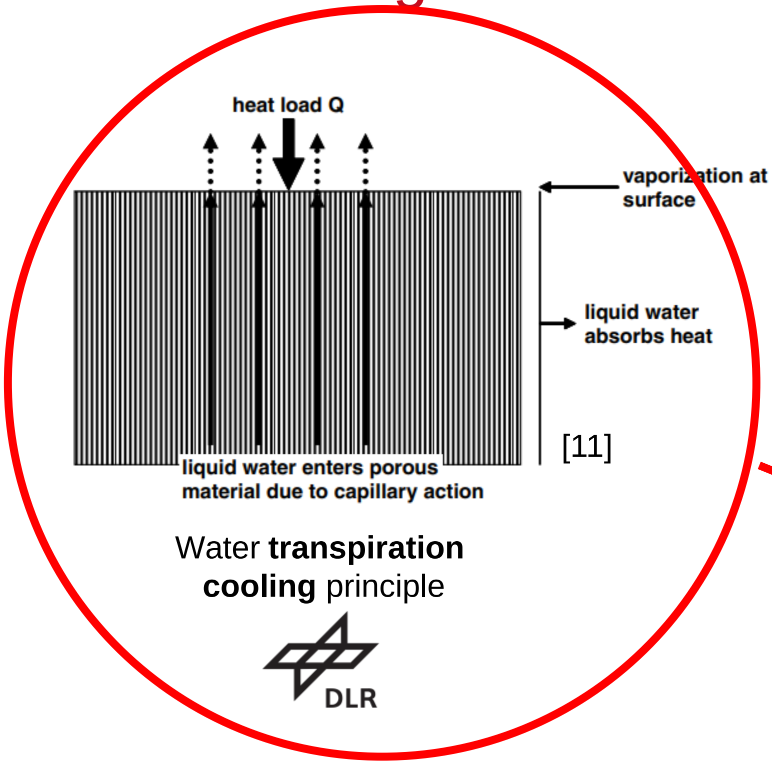
Insulator **290 ±10 K**

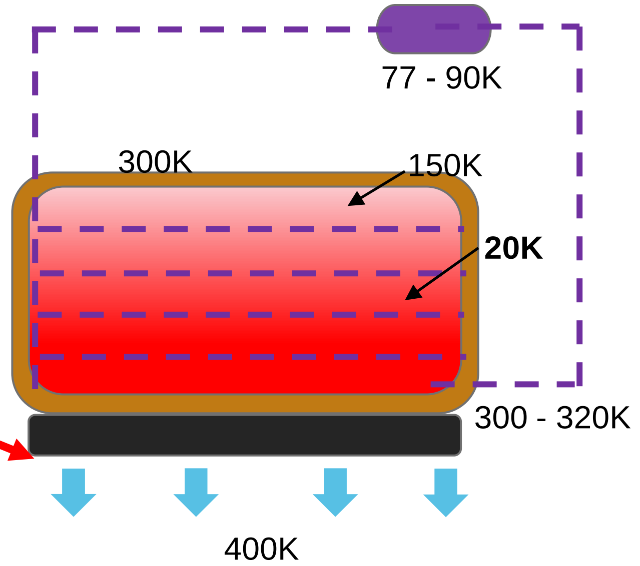
GH2 **150 ±10 K**

LN2 **77 - 90 K**

LH2 **22 ±2 K**

Thermal design





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Safety: Hydrogen dumping

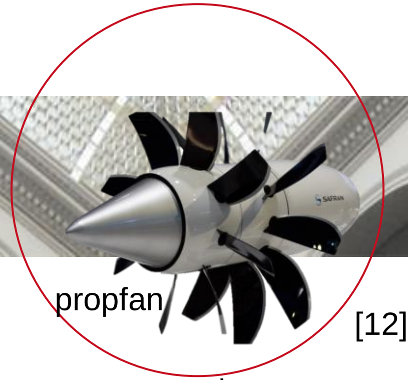
1. Emergency landing
2. Built-up pressure
3. Electrostatic charge around the aircraft body

Combustion w/o thrust

Combustion w/o flame

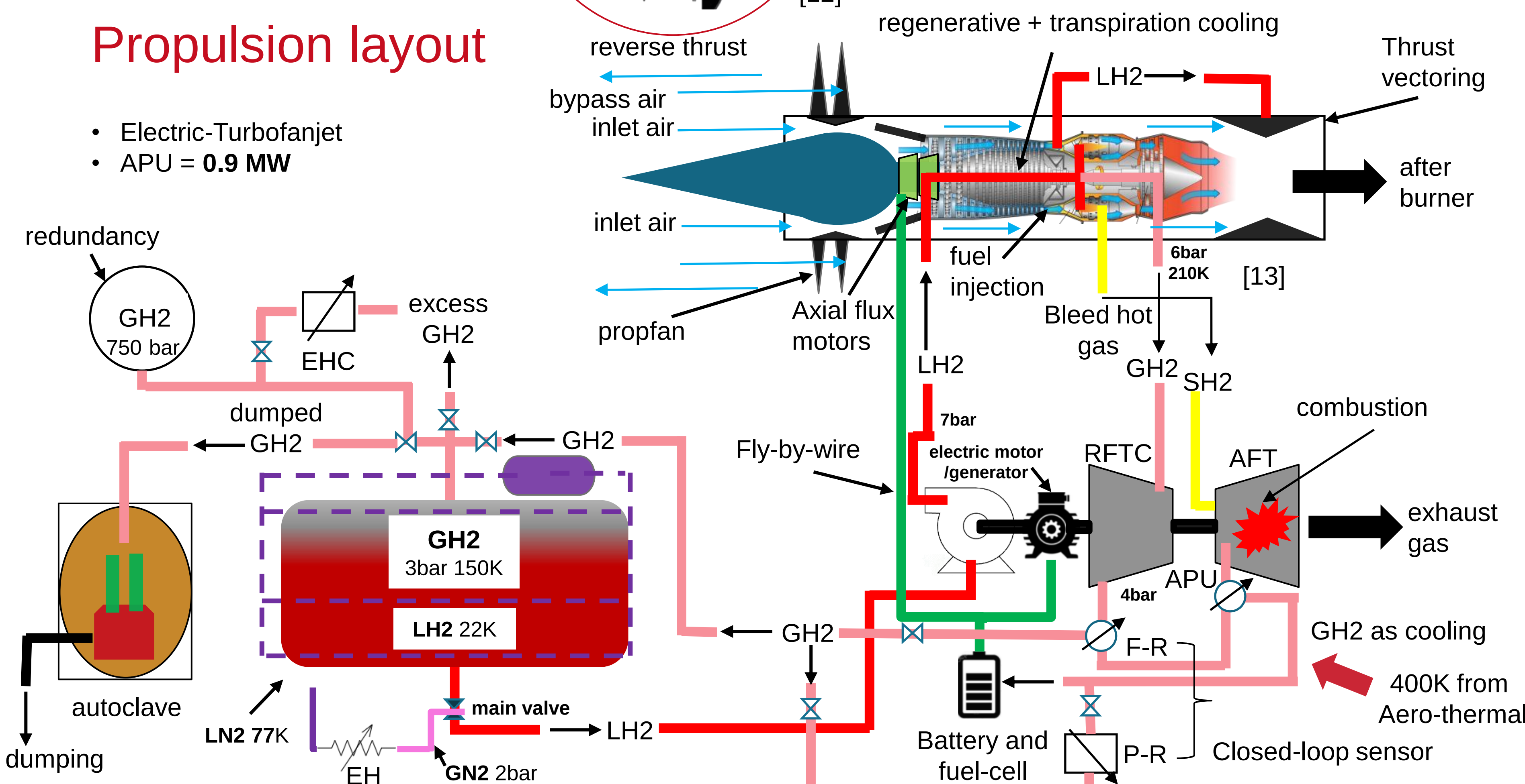
Hydrogenation

*w/o = without

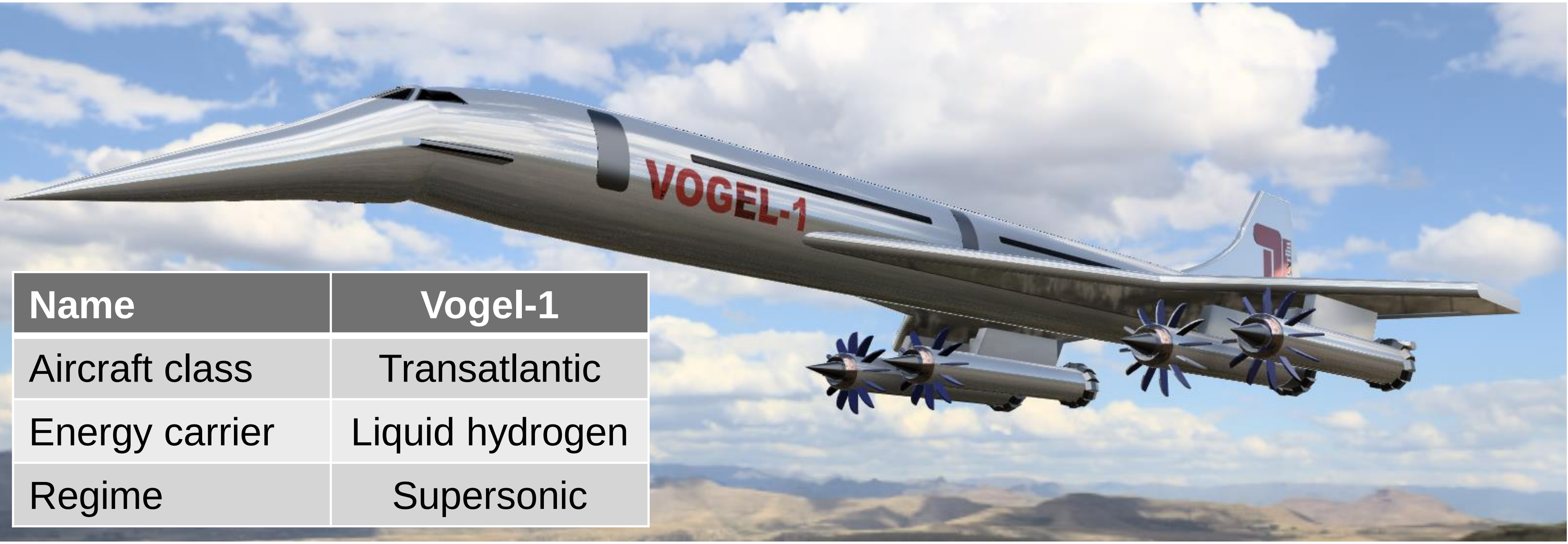


Propulsion layout

- Electric-Turbofanjet
- APU = **0.9 MW**

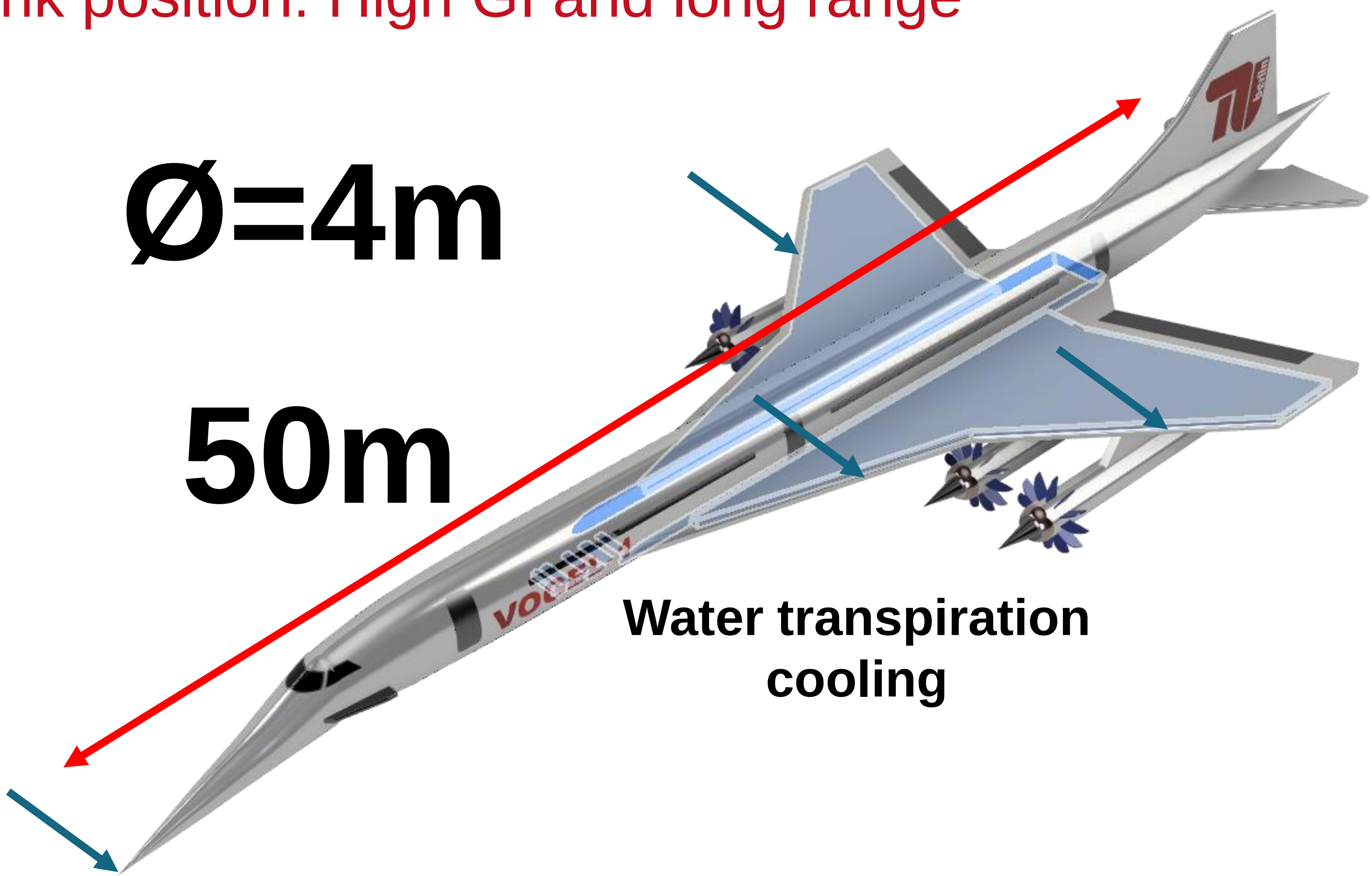


Tank position: High GI and long range



Name	Vogel-1
Aircraft class	Transatlantic
Energy carrier	Liquid hydrogen
Regime	Supersonic

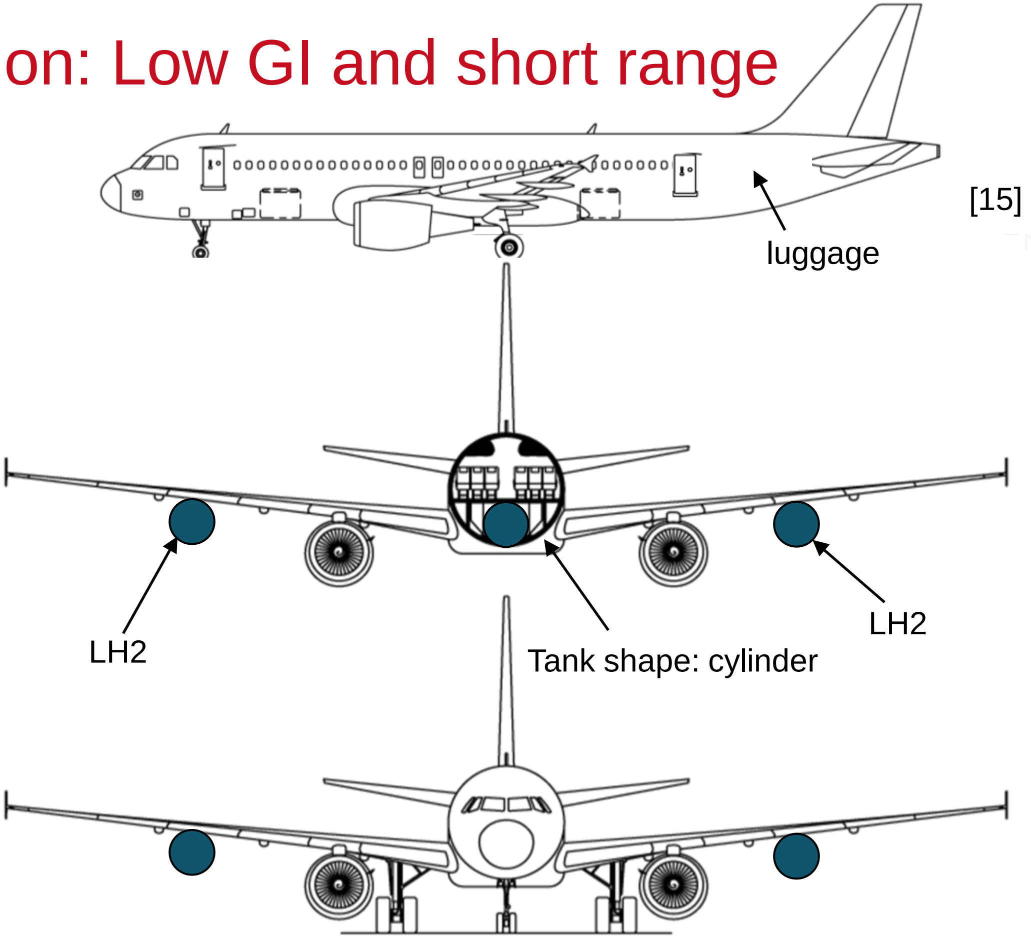
Tank position: High GI and long range



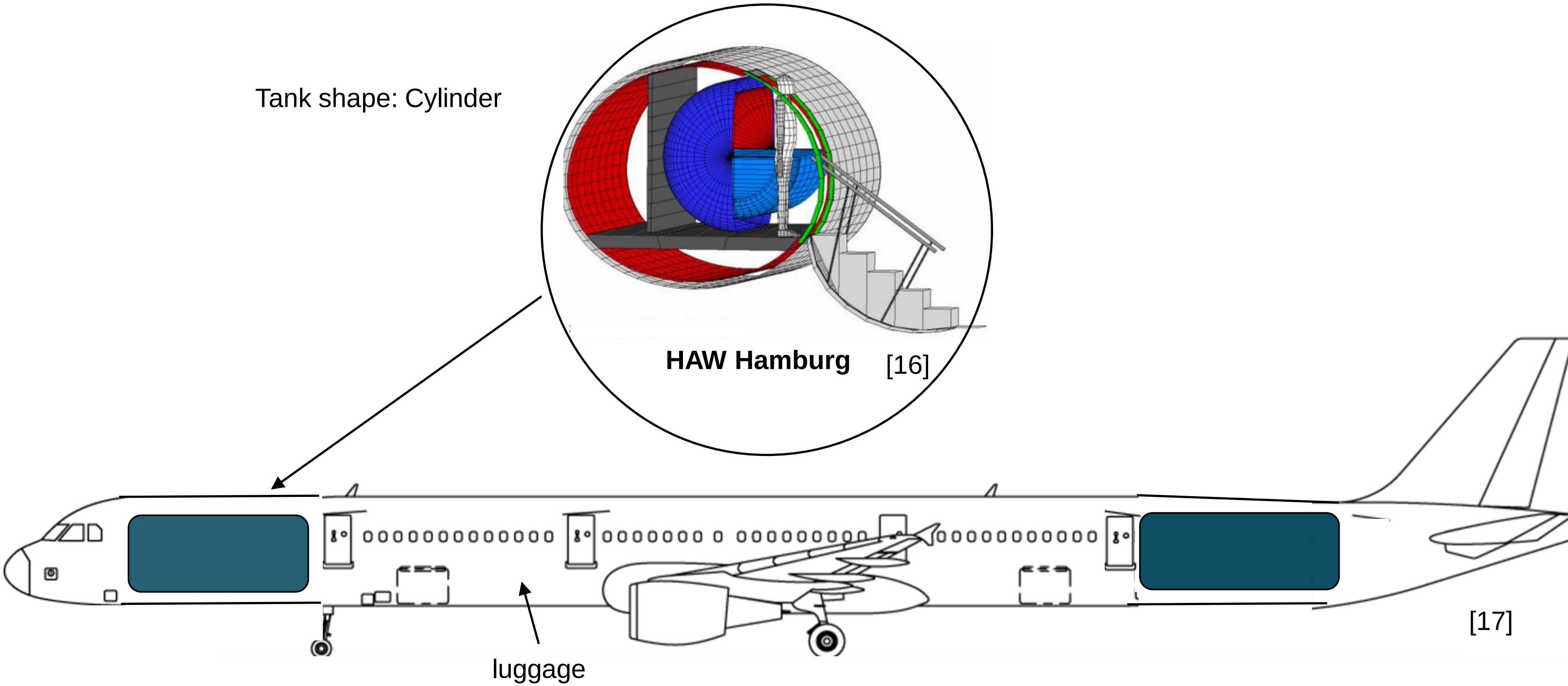
Vogel-1

Specifications	Unit	Figures
Passenger capacity	PAX	200-240
Gravimetric index	GI	0.8
Range	km	10000
OEW	ton	63
Fuel tank	m^3	370
Heat flux (maximum)	W/m^2	150
Wing thickness	m	0.85 (average)
Wing surface area	m^2	400
Propulsion	-	hybrid-turbojet
Engine power (1unit)	MW	27.4
Engine thrust (1unit)	kN	40

Tank position: Low GI and short range



Tank position: Low GI and long range



Trade-off results

Parameter	Unit/Symbol	SAF	H_2 sub	H_2 super
Range	km	10000	10000	10000
Passenger	PAX	200	200	200
Grav index	GI	0.9	0.38	0.8
Glide ratio	L/D	18	18	7
Boil-off-rate	%	0.01	0.1	18.0
Speed	Mach	0.78	0.85	2.0
Fuel tank	ton	2.9	36.3	5.5
Isp	s	6040	12600	10000
Fuselage	m	44.8	58.2	50.0
Carried fuel	ton	34.7	24.3	26.5

Trade-off summary

Low GI short range

- Medium size
- Moderate flight hours
- Fuel saving

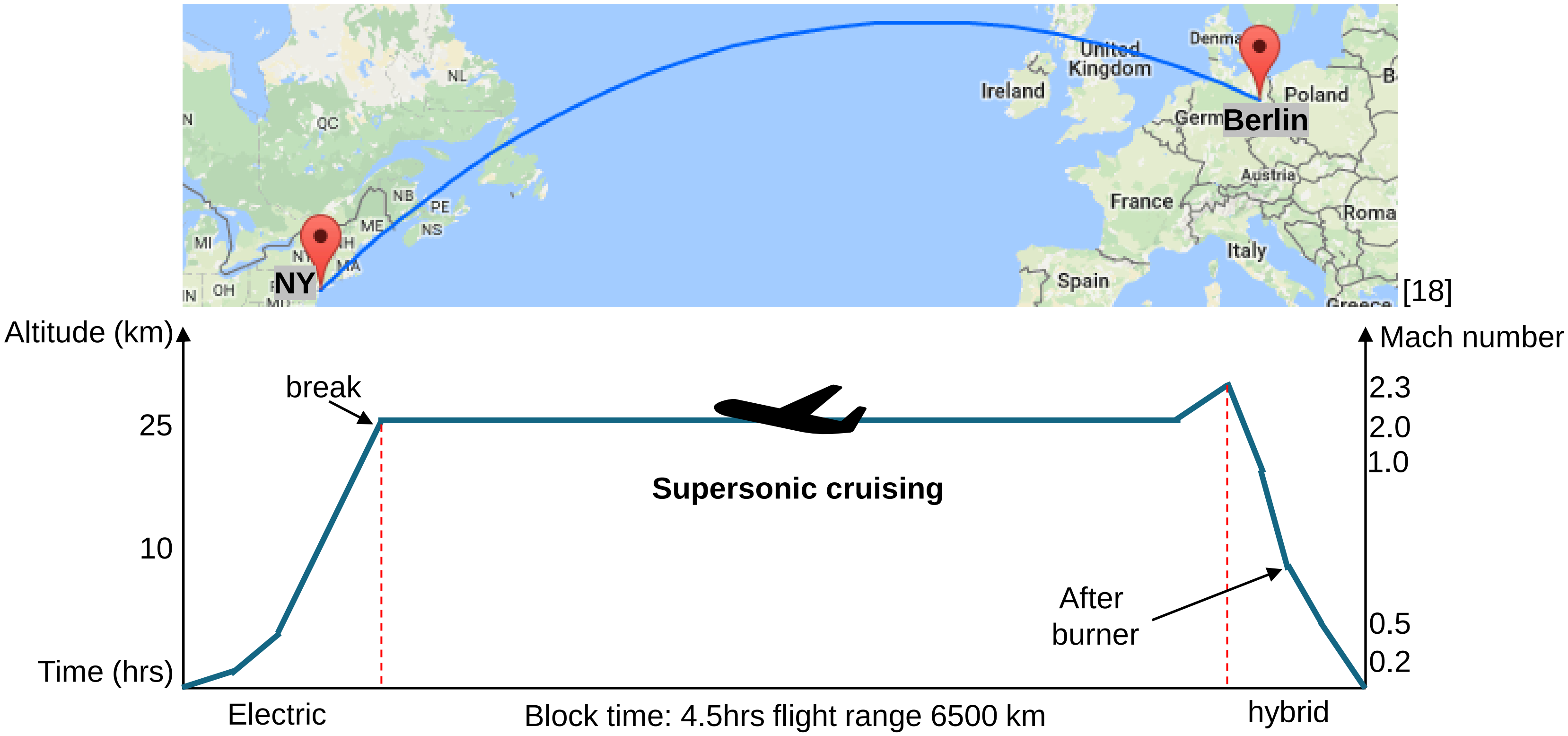
High GI long range

- Compact size
- Short flight hours
- Fuel economy

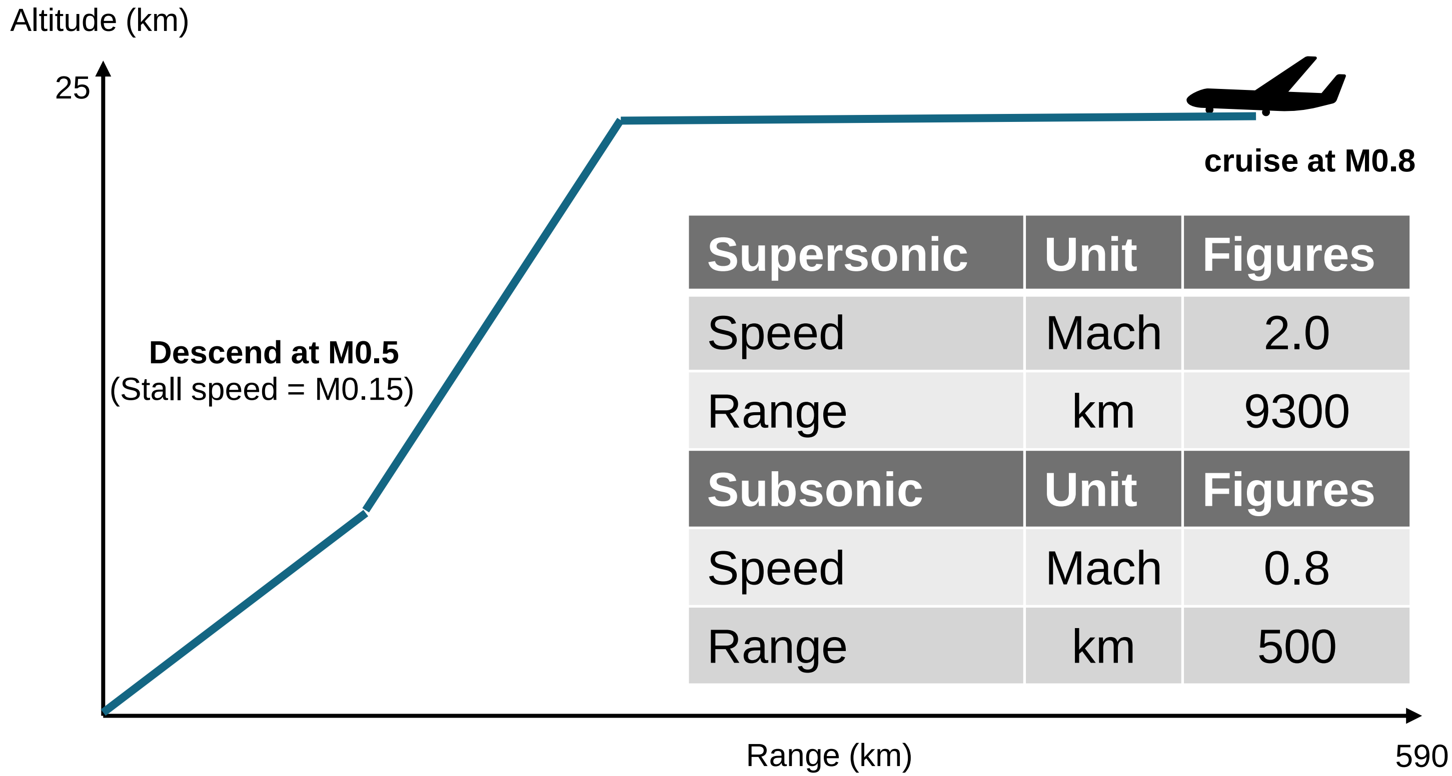
Low GI long range

- Bulky size
- Long flight hours
- Fuel saving

Berlin-New York



Supersonic to subsonic flight



Supersonic	Unit	Figures
Speed	Mach	2.0
Range	km	9300
Subsonic	**Unit**	**Figures**
Speed	Mach	0.8
Range	km	500

Berlin-New York : edge of space flight at 25km altitude

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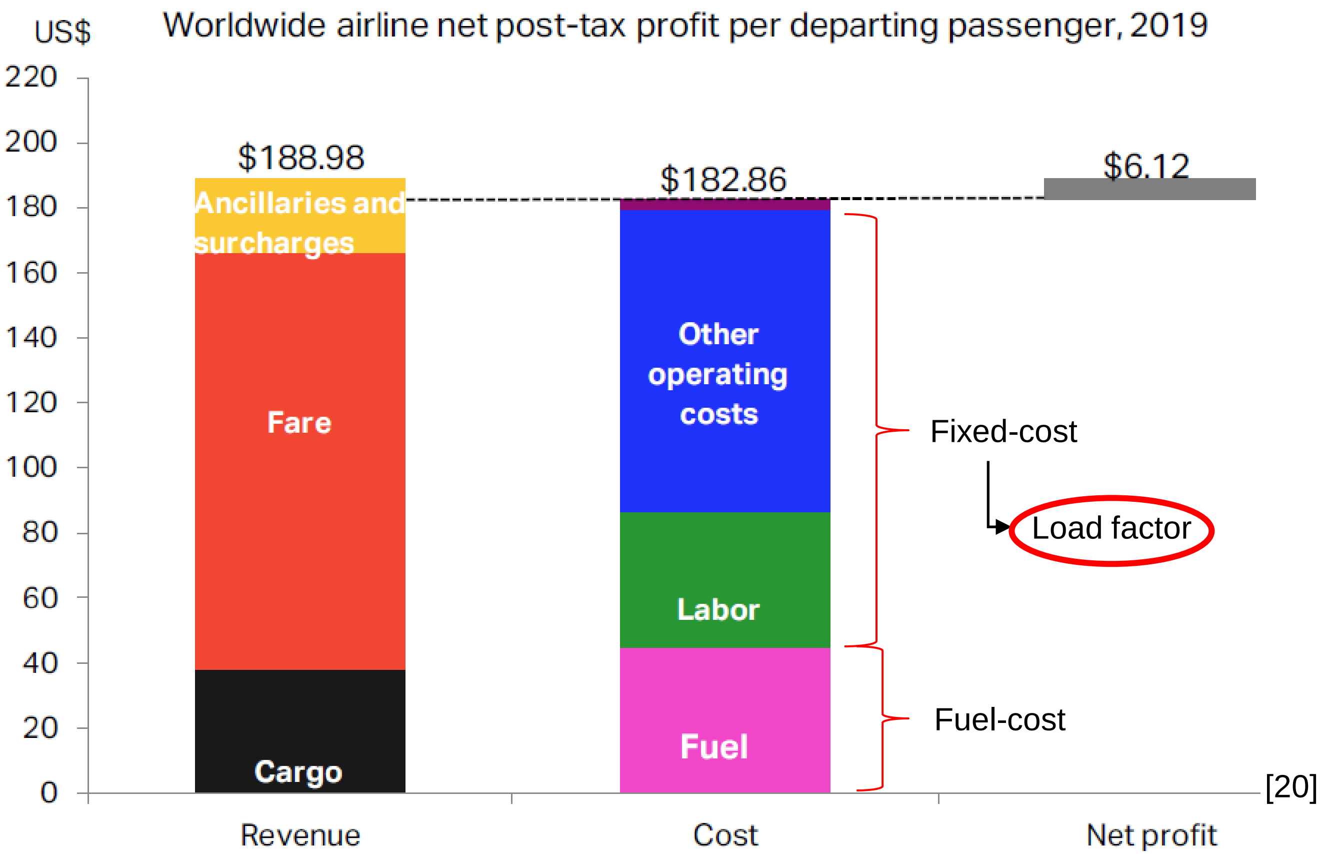
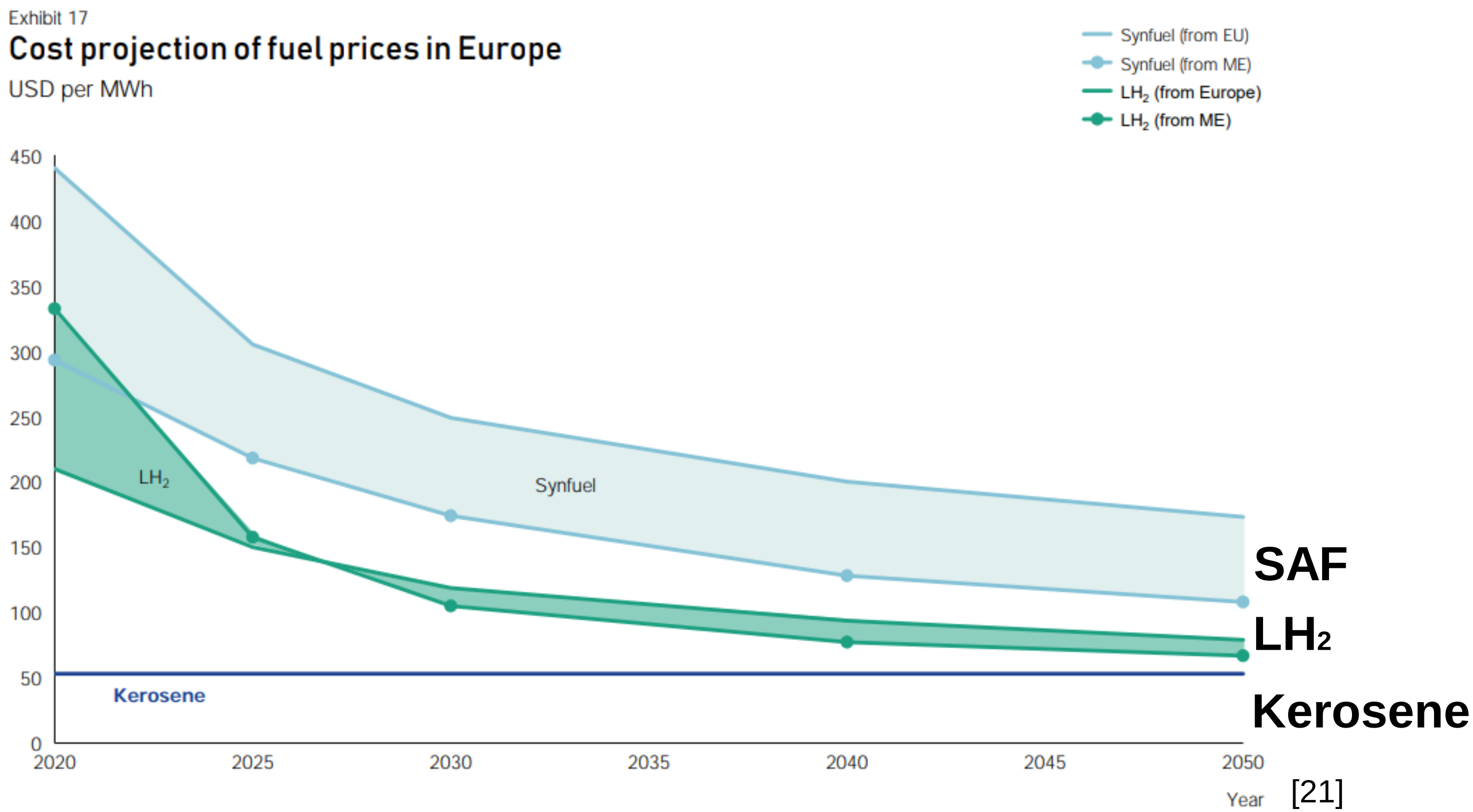
Fuel economy



Source: IATA Economics - Economic Performance of the Airline Industry, Mid-Year 2019

Fuel economy



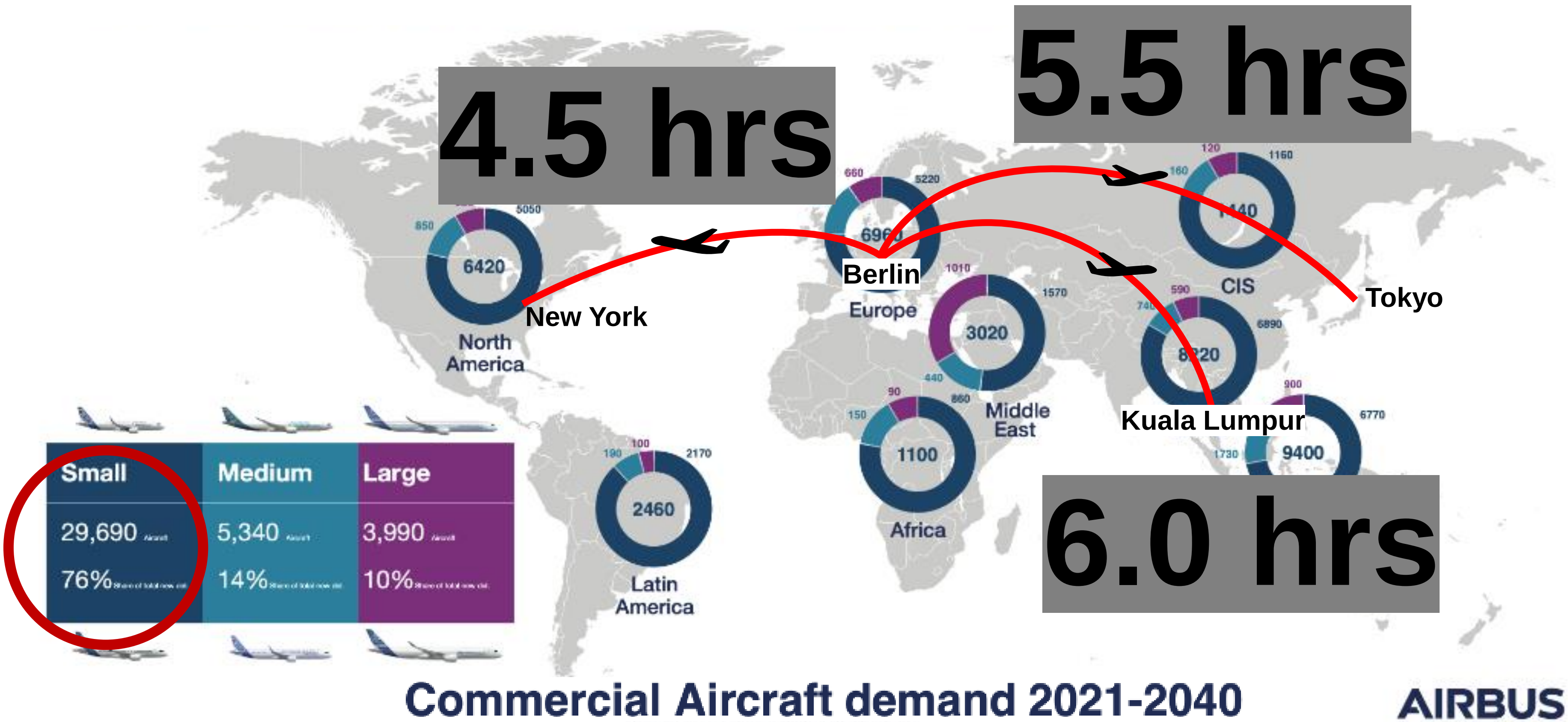
[21]

Fuel Economy: Berlin-New York in 2050

Parameter	Unit/Symbol	Kerosene	SAF	H_2 sub	H_2 super
€/kg	€/kg	0.60	1.56	2.00	2.00
Energy	MWh	0.4	0.4	0.8	0.9
Frequency	flight/day	1	1	1	2
Fixed cost	€	140.86	140.86	140.86	93.91
Fuel cost	€	45.00	117.00	111.00	114.00
Ticket	€	185.86	257.86	251.86	207.91

*tax and profit are not included

Air passenger: travel in half of the time



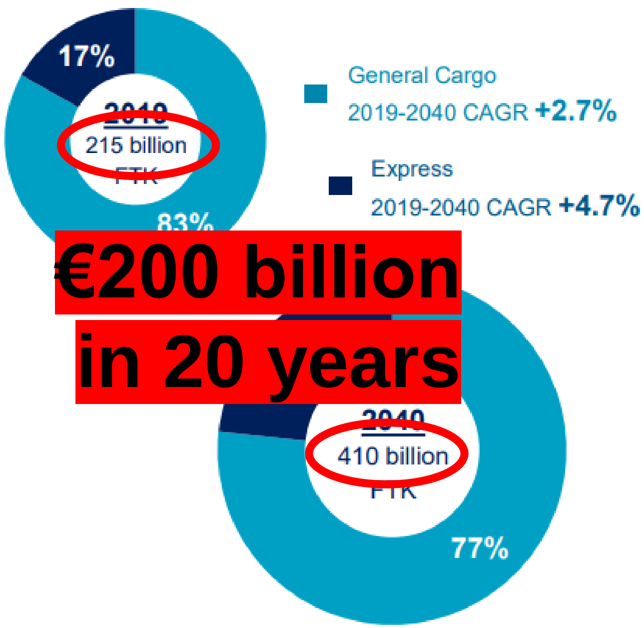
[22]

A new era of supersonic flight

0% carbon emissions at M2.0

Air cargo: Bulky but cheap

World air cargo traffic



€200 billion in 20 years

AIRBUS [23]

[24]

Summary

GI 0.8

Range 9800 km

Time 4.5 hrs

Mass 31 ton

Key-point

1. A **high-speed** is the solution to get a high GI (GI>0.5)
2. A **high GI** is a key to store the LH2 within the wings and fuselage
3. **APU** will play a vital role for cryogenic management of hydrogen aircraft

GI = Gravimetric Index
APU = Auxiliary Power Unit

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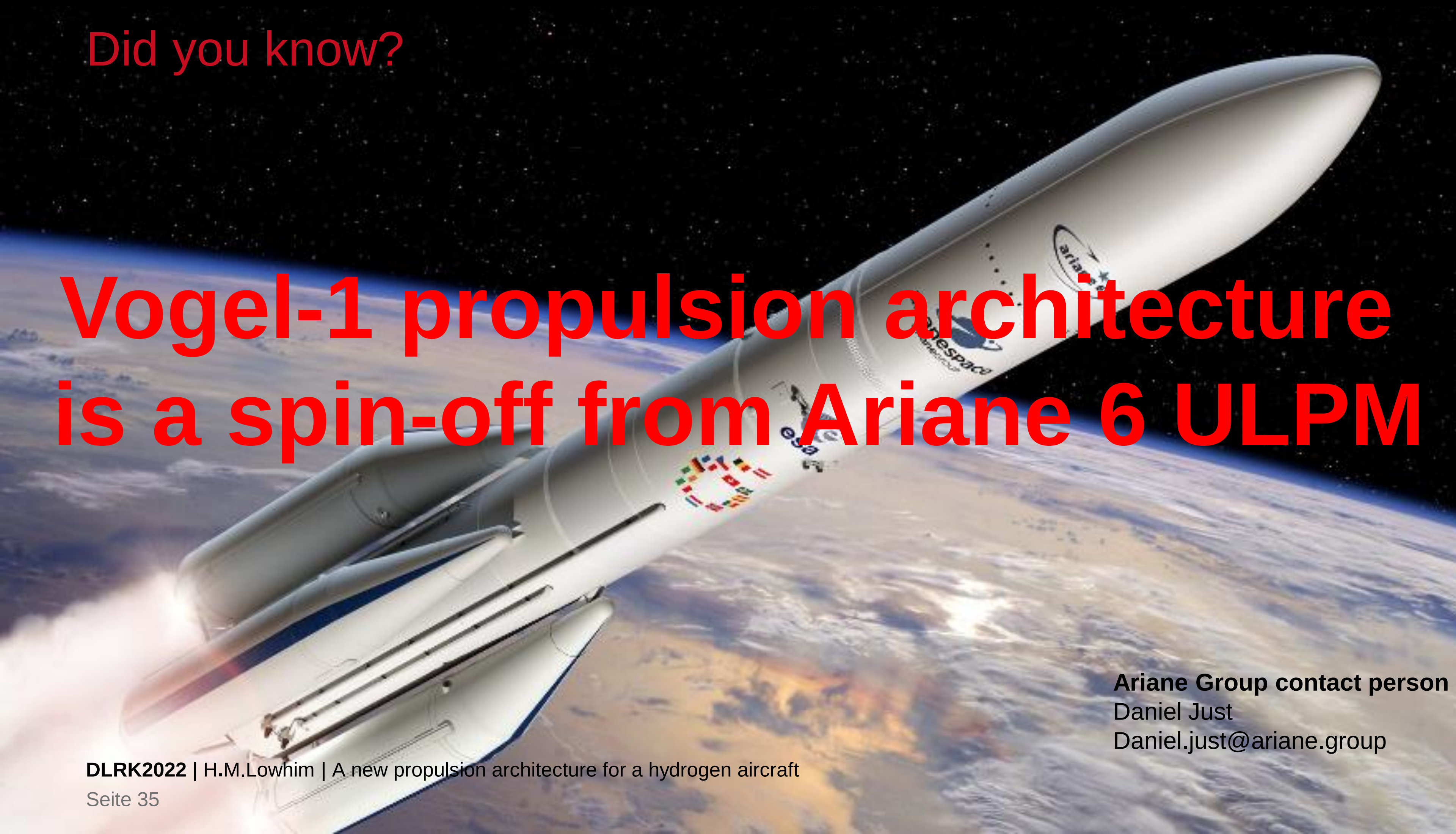
Key-point

4. Usability of supersonic LH_2 is **98%**
5. Transpiration cooling is a key technology for **oxygen-rich** of a H_2 gas turbine
6. Market entry time is 10-15 years (**2035**)

Did you know?

Vogel-1 propulsion architecture is a spin-off from Ariane 6 ULPM



Ariane Group contact person
Daniel Just
Daniel.just@ariane.group

Thank you!
Q&A

Main formulas

1. Braguet range equation

$$\Delta R = I_{sp} V \frac{L}{D} \ln \frac{m_0}{m_f}$$

2. Thermal exchange

$$Q = m c_p \Delta T$$

$$Q = \varepsilon \sigma A T^4$$

$$Q = -k \nabla T$$

$$Q = h A \Delta T$$

3. APU power

$$P = \frac{\Delta \mathrm{P} \dot{m}}{\rho}$$

4. Heat exchanger

$$\Delta h = c_p \Delta T$$

5. Density

$$\rho = \frac{m}{v}$$

6. Gravimetrix index

$$GI = \frac{m_{fuel}}{m_{fuel} + tank + fuel\ system}$$

7. Cabin length

$$L_{Cabin} = s_P \left| \frac{\mathrm{PAX}}{s_A} \right| + L_{\mathrm{galley}}$$

Image index

1. https://www.dw.com/en/ultra-long-haul-flights-your-body-and-mental-health/a-61714702
2. https://aircraft.airbus.com/en/aircraft/a320/a321xlr
3. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3854
4. https://www.toyota.com/mirai/
5. https://www.rolls-royce.com/innovation/accel.aspx
6. https://www.airbus.com/en/products-services/commercial-aircraft/passenger-aircraft
7. https://www.esa.int/Enabling_Support/Space_Transportation/Launch_vehicles/Ariane_6
8. https://boomsupersonic.com/flyby/post/what-are-wing-bend-tests-and-how-are-they-performed
9. https://aircraft.airbus.com/en/aircraft/a320/a321xlr
10. https://www.researchgate.net/figure/Specific-Impulse-and-Mach-Number-for-Various-Engine-Types-5_fig17_263808170
11. https://elib.dlr.de/62969/1/VanForeest_AIAA-39070-373%5B1%5D.pdf
12. https://en.wikipedia.org/wiki/Propfan#/media/File:Safran_Open_Rotor.png
13. https://energyeducation.ca/encyclopedia/Gas_turbine

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14. https://upload.wikimedia.org/wikipedia/commons/thumb/4/45/Concorde_fuel_trim.svg/1154px-Concorde_fuel_trim.svg.png
15.https://www.fzt.hawhamburg.de/pers/Scholz/dglr/hh/text_2020_11_19_HydrogenAircraft.pdf
16. https://www.the-blueprints.com/vectordrawings/show/2795/airbus_a320-200w/
17. https://www.the-blueprints.com/vectordrawings/show/2795/airbus_a320-200w/
18. https://www.google.com/search?q=Berlin+to+New+York+route&sxsrf=ALiCzsZ-N-y9UNRzGhxV84KvrbzH7v5j9g:1662970106019&source=lnms&tbm=isch&sa=X&ved=2ahUKEwj6wMOz5o76AhX7XfEDHaVNB5sQ_AUoAnoECAEQBA&biw=1600&bih=757&dpr=1#imgrc=1ROJx6TWxSc8JM
19. https://www.dpreview.com/news/3193636407/video-admire-earth-from-nearly-25-000-meters
20. https://www.iata.org/
21. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3854
22. https://www.airbus.com/en/products-services/commercial-aircraft/market/global-market-forecast
23. https://www.airbus.com/en/products-services/commercial-aircraft/market/global-market-forecast
24. https://aircraft.airbus.com/en/aircraft/freighters/belugaxl

References

1. Rocket Propulsion Elements, Seventh Edition, George P. Sutton, & Oscar Biblarz, John Wiley & Sons, Inc. 2001
2. Fundamentals of aircraft and rocket propulsion, Ahmed F. El-Sayed, Springer, 2000
3. Thermal Control of the Cryogenic Upper Stage of Ariane 6, Ariane Group Bremen , 49th International Conference on Environmental Systems, 2019

Glossary

1. MLI = Multi Layer Insulator
2. NGS = Nitrogen Generation System
3. RAT = Ram Air Turbine
4. APU = Auxiliary Power Unit
5. GH2 = Gaseous Hydrogen
6. LH2 = Liquid Hydrogen
7. LN2 = Liquid Nitrogen
8. GN2 = Gaseous Nitrogen
9. SH2 = Saturated Hydrogen
10. EHC = Electrochemical Hydrogen Compressor
11. P-R = Pressure Regulator
12. F-R = Flow Regulator
13. EH = Electrical Heater
14. RFTC = Radial Flow Turbine Compressor
15. AFT = Axial Flow Turbine