Hydrogen Aviation Technology: Benefits, Challenges, and Opportunities

WSAS Sustainable Aviation Symposium

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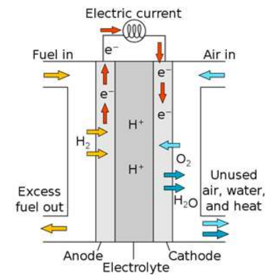
Hydrogen Aircraft On-Board Pathways

- Hydrogen has 2.8 times the amount of energy per weight than jet fuel (light weight)
- Gaseous hydrogen requires 7-8 times more volume stored at 700 bar or ~4 times more volume at 20 K
- Power conversion can occur using two methods:
  - Thermal combustion
  - Fuel cells (electrical)
- Two options:
  - Compressed gas tank (typically composite)
  - Cryogenic storage tank
    - Variety of insulation and material options
    - Fill rate limits
- Necessary associated sub-systems:
  - Health monitoring / leak detection / safety
  - Pressure management
  - Fuel delivery lines / pumps

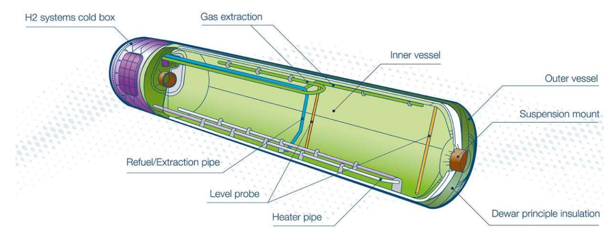
LH2 Turbofan Engine
Image Source: Airbus



H2 Fuel Cell
Image Source: Wikipedia Commons

H2 Fuel Cell Test Aircraft
Image Source: Universal Hydrogen

Toyota Mirai GH2 Tank
Image Source: Wikipedia Commons



LH2 Turbofan Engine
Image Source: Airbus

Hydrogen Storage Configuration Considerations

Tank Location:
- Rear of fuselage? -> CG issues -> need to move wing, large CG float
- Fore and aft tanks? -> passenger access and safety issues

Integral vs Non-integral:
- Is tank integrated or separate from fuselage structure?
- Integral has a weight/length benefit but requires new fuselage structure

Swappable vs Non-swappable:
- Swappable allows filling before airplane arrives and tailoring fuel storage to mission range
- Weight penalty due to smaller tank sizes

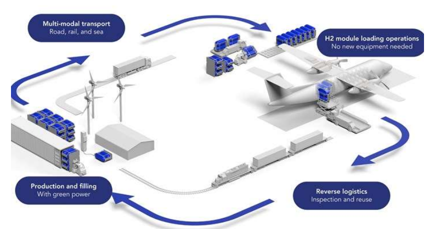
Image Source: Airbus

Fore+Aft tanks [2]

Image Source: Cryoplane study

Integral

Non-Integral [3]



Swappable [4]

Image Source: Universal Hydrogen

1. "How to store liquid hydrogen for zero-emission flight," *Airbus* Available: Online
2. Airbus Deutschland GmbH. (2003). Liquid Hydrogen Fuelled Aircraft - System Analysis. *Cryoplane, May 2003*, 1–80.
3. Brewer, G. D., Morris, R. E., Lange, R. H., & Moore, J. W. (1975). *Study of the application of hydrogen fuel to long-range subsonic transport aircraft Volume 2. 2*, 1–386.
4. "Product," *Universal Hydrogen* Available: Online

Storage Technology

- **Measures of merit:**
  - Volume / Form factor of tank
  - Gravimetric efficiency/index (GI) – Weight of H2 / (Weight of H2 + Weight of Tank)
- **Compressed gas tech:**
  - No cryogen storage needed, but high pressure → Less volume, but more weight / cost
  - Typical GI = 1–10% (now), 10-20% possible
  - Toyota Mirai 700 bar tank (~5% GI)
  - Universal Hydrogen has a dual tank (850 bar) design (17% GI claimed) by removing resin from the design
  - Generally applicable for short range and regional designs
- **Cryogenic Liquid Tanks:**
  - Lower pressure design, much less volume (factor of 2-3)
  - Higher gravimetric indices (> 50%, scales better with size)
  - Proposed for essentially any large commercial turbofan replacement

  Issues:
  - Significant insulation to limit boil-off at 20K
  - Foam (thermal cycle limited) or vacuum insulation + MLI (heavier)
  - Past studies and designs (Boeing Phantom Eye) have used SOFI (foam)
  - Airbus appears to have chosen vacuum insulation
  - Material strength and compatibility at low temperatures, many cycles
  - Layered materials and insulation (thermal expansion compatibility)

  Areas of innovation:
  - Low cost, effective materials
  - Conformal tank geometries


Toyota Mirai GH2 Tank
Image Source: Wikipedia Commons


Image Source: Universal Hydrogen

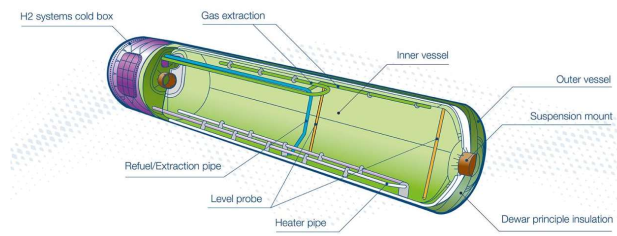


Image Source: Airbus ZeroE

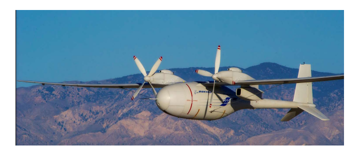


Image Source: Boeing

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Propulsion Technology: Combustion

Benefits:

- Utilize existing, mature, and wide-spread gas turbine technology
- High specific power (low weight) (5x that of fuel cell depending on size)
- *Significant* synergy with hydrogen (especially cold hydrogen) – Better cycle, lean burn, cooling opportunities
- Studies show minimum of 1-5% benefit just from switching to hydrogen
- Generally preferred technology in studies for large commercial vehicles >100 pax

Downsides:

- Still generates NOx and water vapor (GHGs) – Relative amount depends on design choices
- New combustor and injector designs required, no pre-mixing due to wide flammability range
- Safety related to fuel delivery, leakages, etc.
- Scales poorly at small size

Research and Development Status:

- The 4 major OEMs have published plans to build and test
- CFM – Modifying a GE passport turbofan – A380 demo plans [1]
- Pratty & Whitney HySIITE program – Steam injection for reduced Nox with very high claimed benefits [2]
- Rolls Royce performed ground test of an AE2100 in 2022 and more future plans [3]

LH2 Turbofan Engine
Image Source: Airbus

Image Source: Ref [4]

Image Source: Airbus

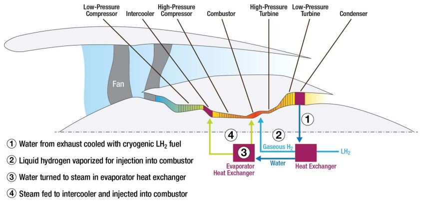

Image Source: Aviation Week

Image Source: Rolls Royce

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Propulsion Technology: Fuel Cells

Fuel Cell Types:

- Solid oxide fuel cell (SOFC) – High Temperature, Challenges and benefits
- Proton electron membrane (PEMFC) – Low Temperature, Challenges and benefits

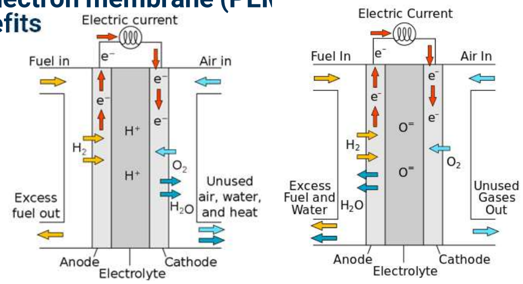

Image Source: Wikipedia Commons

Benefits:

- Only water vapor emissions
- Relatively high efficiency (50-60%, depending on design choices, polarization curve, etc.)
- Scales well to small size
- Doesn't fall off as much with altitude like gas turbines
- High efficiency at low part power
- Preferred power conversion device for many studies < 50 pax, but potentially up to 100pax
- Can be used in gas turbine hybrids or secondary power (APU)

Downsides:

- "Balance of plant" components (air supply and compression, H2 and water management, thermal management)
- Needs pressurized air at altitude
- Weight (heavy) -- Specific powers currently 1.5-2 kW/kg including BOP
- High cost (driven by a variety of factors, economy of scale, materials, etc.)
- Low durability

Recent Developments:

- Toyota self-humidifying fuel cell design (2 kW/kg stack achieved) [1]
- Transitioning to HT-PEMFCs [2], Hypoint Inc Tech 140-180C design [3] – Better delta T, less susceptible to CO poisoning
- Roadmap to reach 3-3.5 kW/kg by 2050 – all fuel cell single aisle theoretically possible, but very heavy
- Universal hydrogen regional aircraft flight
- Multiple regional flight demos planned (H2FLY+Deutsche Aircraft)

Image Source: Universal Hydrogen

Image Source: Zero Avia

Image Source: H2FLY

[1] Yoshida et al. (2015), Toyota MIRAI Fuel Cell Vehicle and Progress Toward a Future Hydrogen Society
[2] Webber et al. (2022), Thermal Management Roadmap Report
[3] HyPoint Inc. (2021), HyPoint Technical WhitePaper

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Emissions and Climate Impact

- CO_2:
  - Entirely depends on infrastructure assumptions and how the hydrogen is produced
- Contrails:
  - Engine exhaust cooling in the presence of vapor causes saturation and ice formation in supersaturated region
  - Formation of ice crystals especially around soot particle nucleus
  - Recently determined that this has a quite large, but uncertain impact on overall warming
  - Hydrogen produces more water vapor, but no soot
  - More frequent formation, but less optical depth and overall reduced warming
  - Ponater et al. [1] estimate that the changes from eliminating soot outweigh increase in water vapor
  - Fuel cells likely to also produce even more frequent contrails but with lower lifetimes and optical depth [2]
- NOx:
  - Combustion: Probably about the same as kerosene (possibly less or more)
  - Fuel Cell: Almost none (high temperature does produce some)
- Water vapor:
  - 2.6 times more water vapor per unit of energy released
  - Minor contribution to climate change
- Net effect is likely a reduced Non-CO_2 related climate impact

[1] Ponater et al. (2006), Potential of the cryoplane technology to reduce aircraft climate impact: A state-of-the-art assessment
[2] Gierens (2021), Theory of Contrail Formationfor Fuel Cells

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Thank you!