Cryogenic Fuel Aviation – Challenges and Opportunities

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NASA Technology Development Focus in Aeronautics

- Primary focus will be the aircraft
- Single-aisle and larger is the ultimate long-term interest
- Experience with smaller applications should be leveraged
- Any propulsion systems using cryogenic fuels were within scope (gas-turbine, fuel cells, hybrid)

Less focus will be devoted to non-aircraft considerations

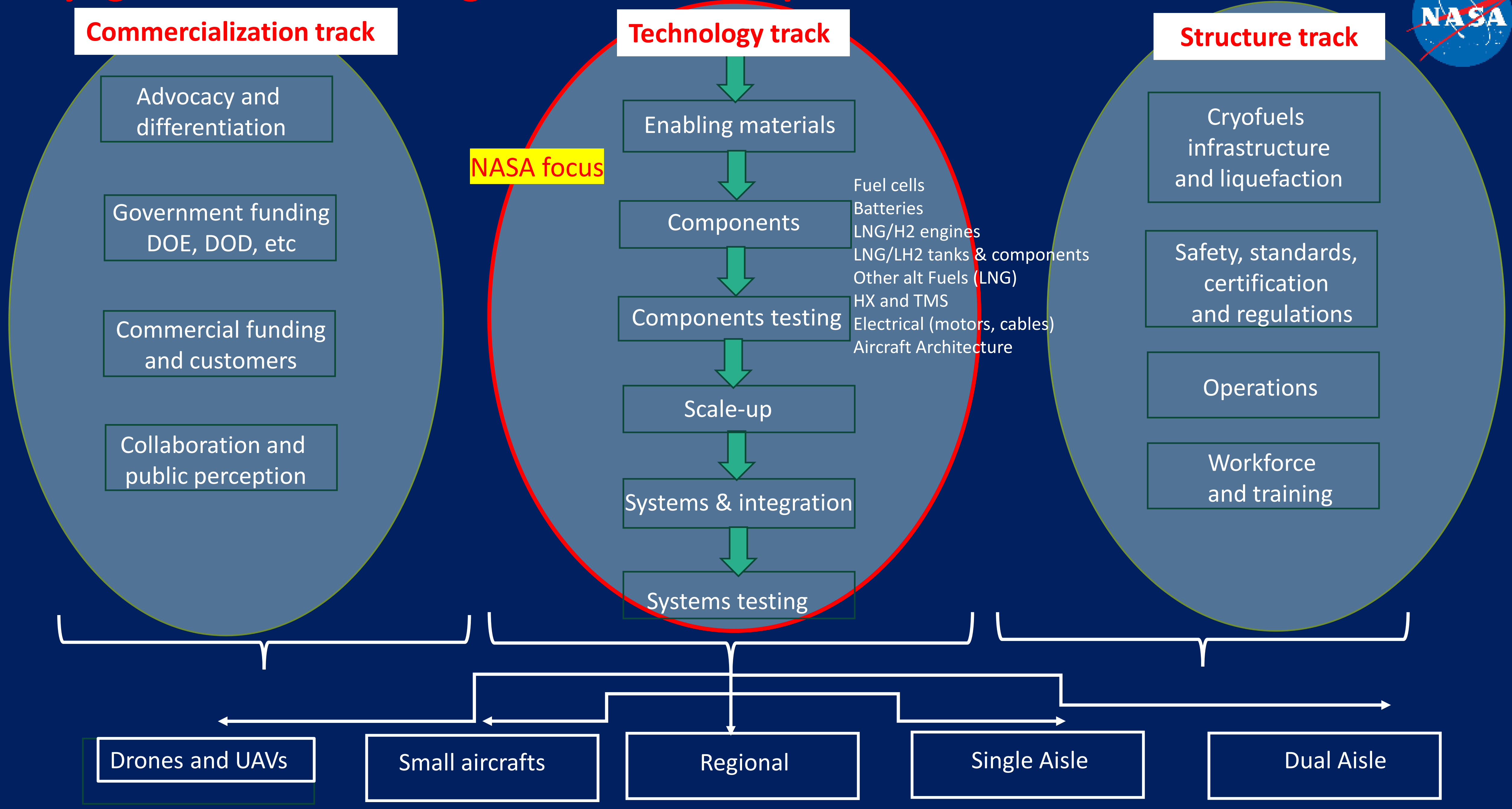
Not a direct part of NASA Scope

External Perspective on NASA Research Investment Opportunities
Results from September 2022 "Cryogenic Fuel Systems for Aircraft" Workshop at GRC

- Materials
  - Additive manufacturing and composites for cryo temperatures, cycle fatigue, and hydrogen permeation
  - Seals, insulation, embrittlement, thermal expansion
- Structures
  - Fuel tank, pressurized structure, conformal pressure vessels, impact absorbing structures
- Testing Capabilities and Techniques
  - Hydrogen enabled facilities, crashworthiness, impact testing, icing
- Operations
  - ConOps development, fuel system purging, fueling/defueling operations, tarmac hold, failure analysis, contingency scenarios unique to cryogenics
- Systems Studies
  - Concept studies, fuel cell vs hydrogen combustion vs combination, fuel cell as secondary power (APU replacement), impact of current vs future grid, exploration of acceptable boil-off, tank design trades
- Propulsion and Powertrain
  - Combustor design research (fundamental computational and experimental capability development), superconducting electrical components, fuel cell technology development, engine controls with phase changes, thermal management (especially heat exchangers), exploration of innovative turbine cycles
- Fuel Pumps and Valves
- Standards Development Support
- Cryo Technology Roadmap Development
- Sensor Technology
  - Tank level gauging, hydrogen fire detection, hydrogen leak detection
- Climate Research
  - Contrails modeling, simulation, and mitigation, cryo fuel leakage impacts at ground/altitude, low particulate impacts on contrail characteristics

Strong desire for NASA technical leadership role in pulling community together on cryo fuels for aircraft

Cryogenic Aircraft Configuration Roadmap

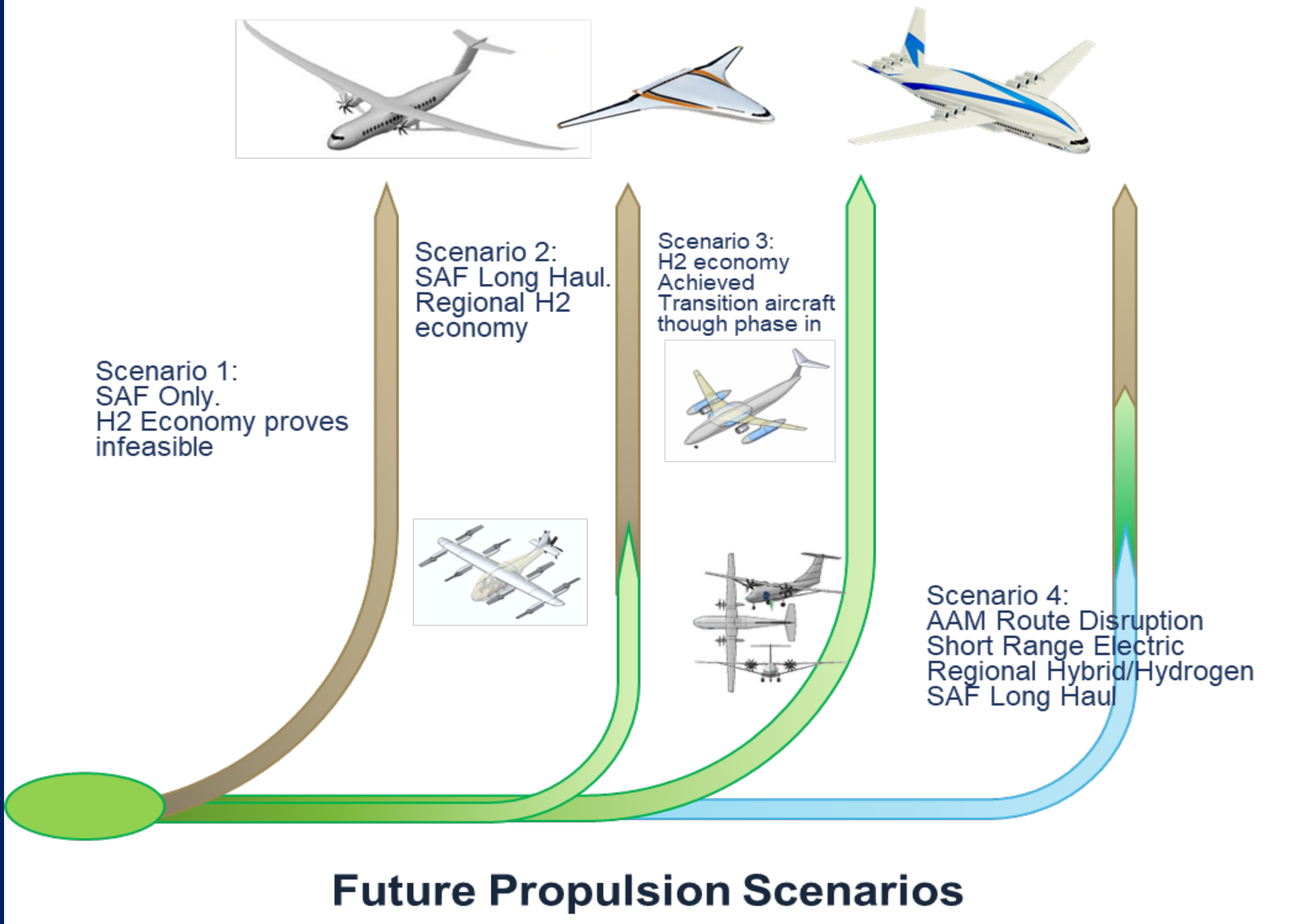


Aircraft Configuration Roadmap

Aircraft configurations may reflect different scenarios regarding cryofuels (H_2 example) utilization in the airspace

1. Cryofuels Economy infeasibility leads to aircraft configurations that maximize fuel efficiency per payload mile.
2. Cryofuels Economy limited to few regions. UAM/GA and some regional aircraft adapt to local Hydrogen utilization.
3. Cryofuels Economy proves feasible. Aircraft configurations reflect hydrogen adoption.
4. AAM Route Disruption. Vast changes to transportation system. Short and Medium range routes using Electric or Cryofuels Power. SAF for long range routes.

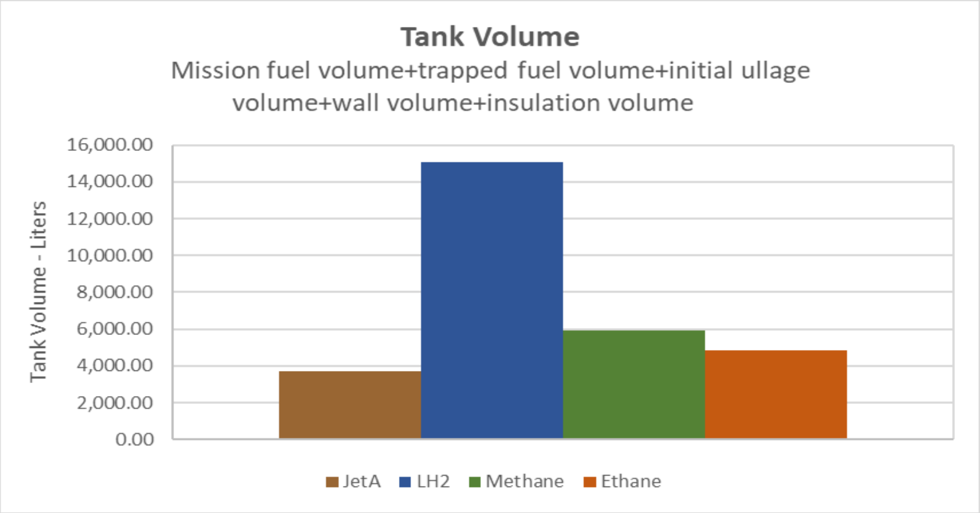
Scenarios 2 and 3 may allow for single aisle class Cryofuels aircraft.

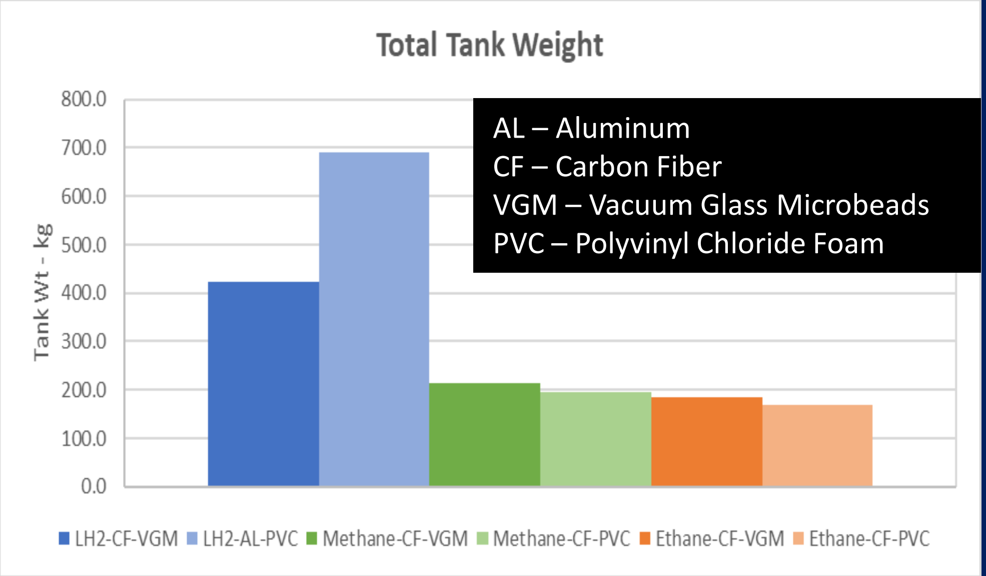


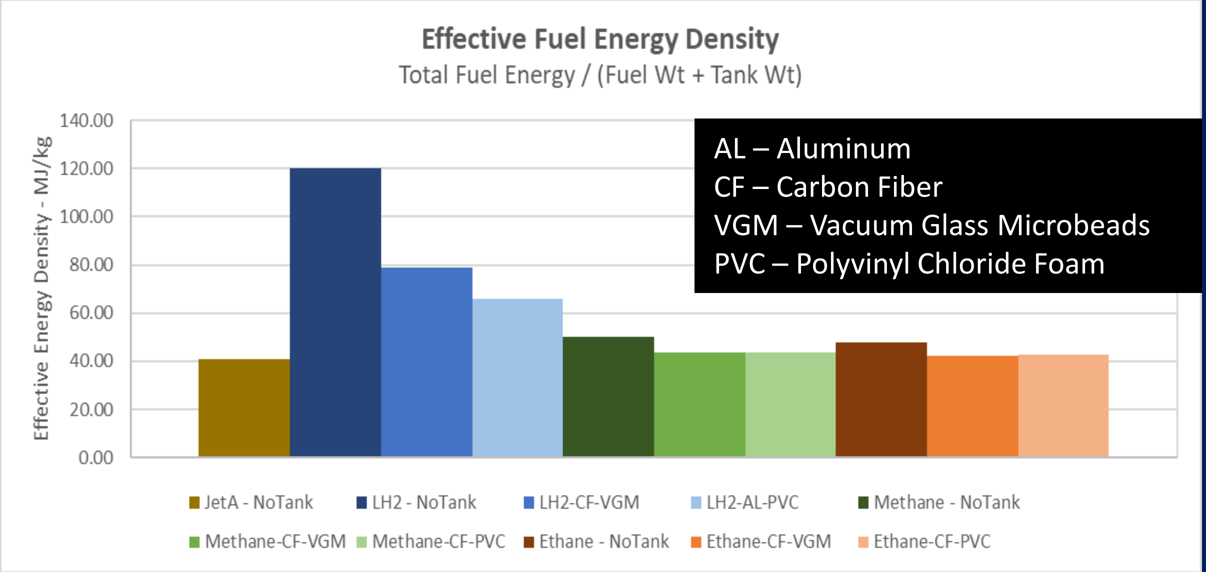
Predicted Cryofuels economy will have impact on aircraft mission requirements and resulting configuration

Which Cryogenic Fuel?

- The energy density of the fuel itself is not a suitable metric for deciding which cryogenic fuel to use.
  - Cryogenic fuels require a separate tank to contain it.
  - The weight of tanks is largely a function of the volumetric energy density of the fuel. And so, while hydrogen contains 2.5 times more energy per kg than methane or ethane, it has just 40% and 30% of the energy per liter of these fuel respectively.
- The result is a much larger and heavier H_2 tank adding much more drag to the aircraft than that require by methane or ethane.
- When the weight of the tank is included, the effective energy density of hydrogen drops from 120 MJ/kg to 66-80 MJ/kg while methane drops from 50 MJ/kg to 44 MJ/kg and ethane from 47.8 MJ/kg to 42.5 MJ/kg.
- So, while hydrogen still has a greater energy density, it is not nearly as much as a comparison of just the fuels themselves would imply.



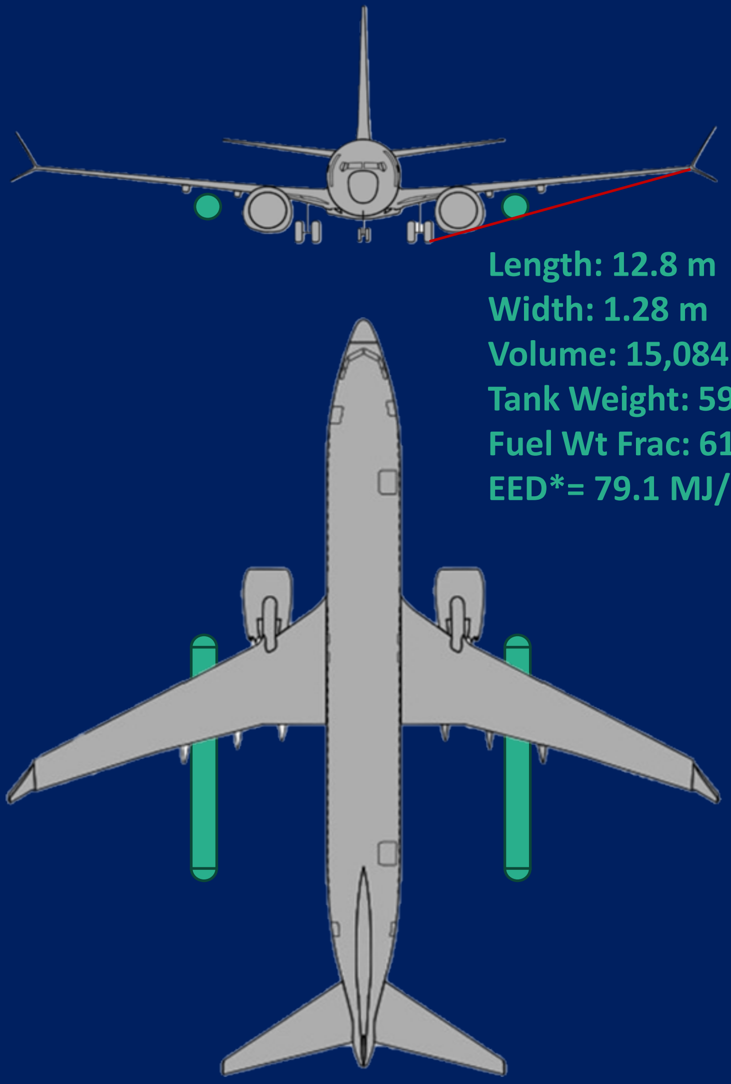




Comparison of Tanks Sizes Relative to Boeing 737 Max 8

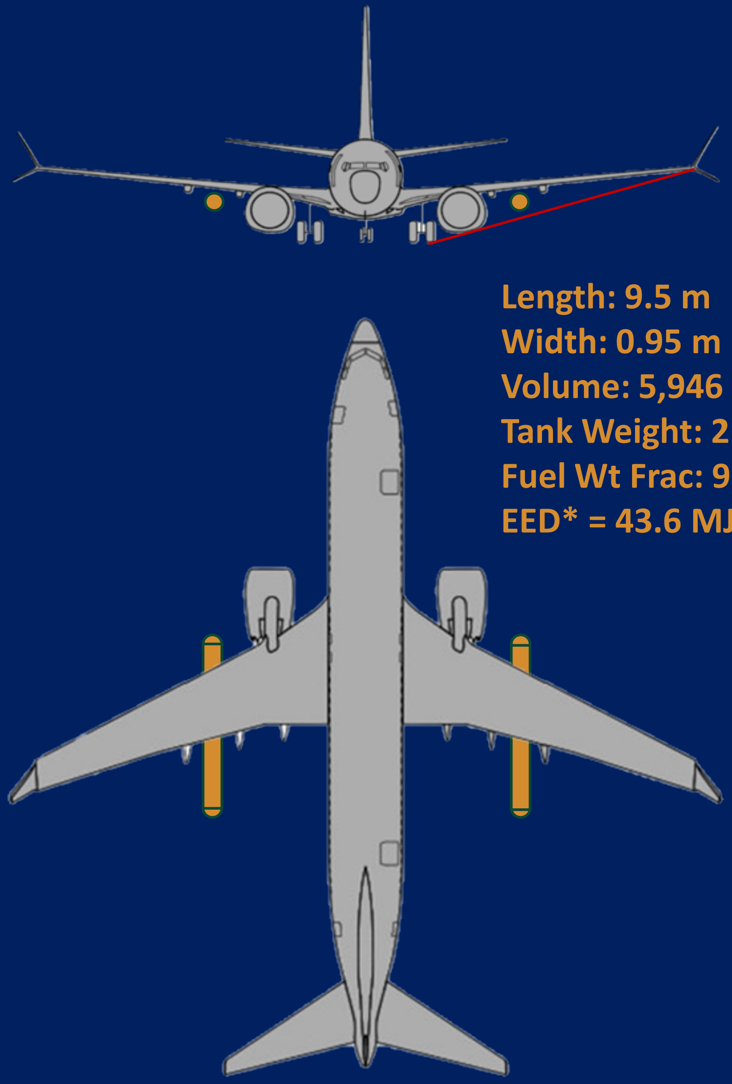
Tanks sized to provide 1000 nm of range (jet fuel as reserve) with a Fineness Ratio of 10

Hydrogen



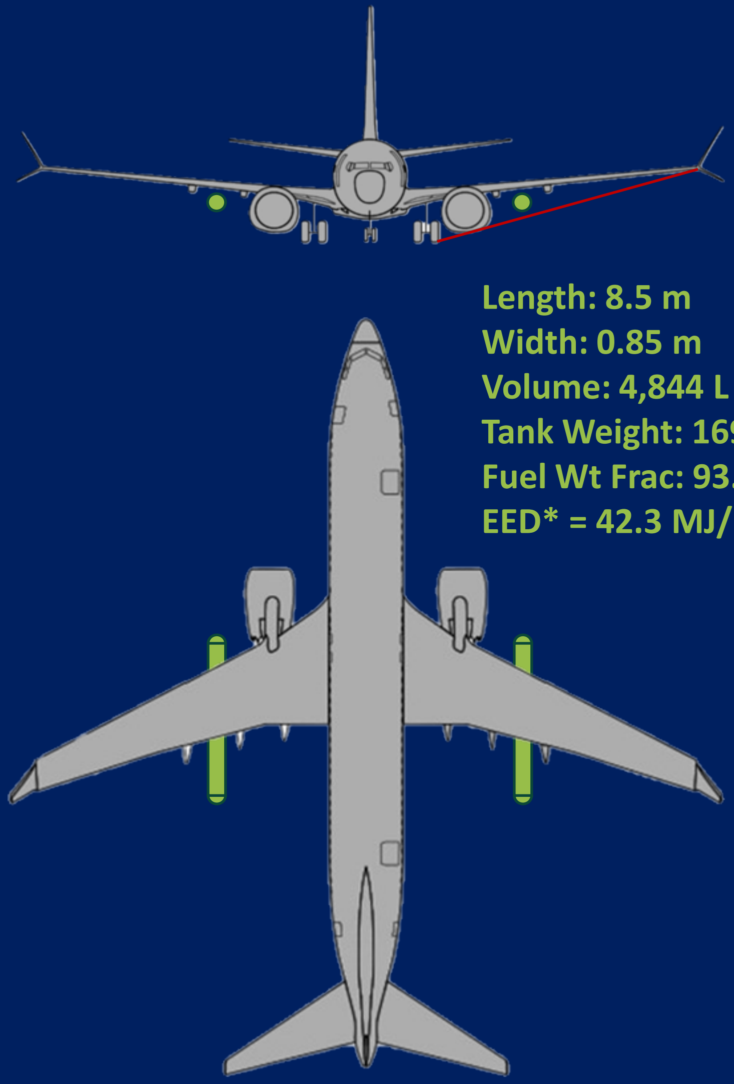
Length: 12.8 m
Width: 1.28 m
Volume: 15,084 L
Tank Weight: 594 kg
Fuel Wt Frac: 61.5%
EED*= 79.1 MJ/kg

Methane



Length: 9.5 m
Width: 0.95 m
Volume: 5,946 L
Tank Weight: 213 kg
Fuel Wt Frac: 91.4%
EED* = 43.6 MJ/kg

Ethane

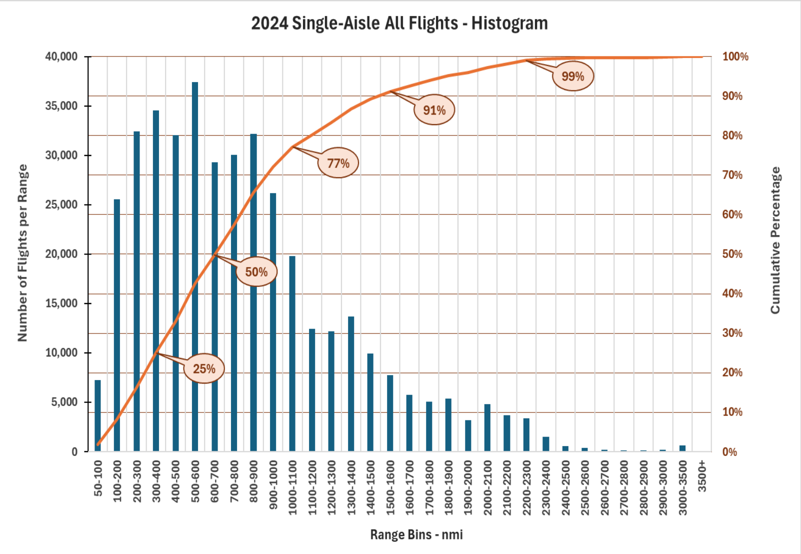


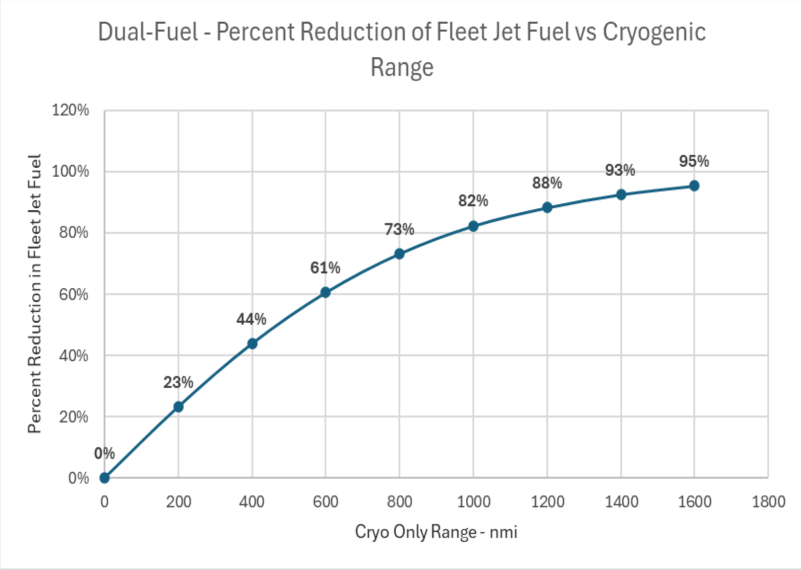
Length: 8.5 m
Width: 0.85 m
Volume: 4,844 L
Tank Weight: 169 kg
Fuel Wt Frac: 93.4%
EED* = 42.3 MJ/kg

*EED = Effective Energy Density

The Case for Cryogenic Fuels and Dual-Fuel Aircraft

- Transition from jet fuel to another fuel like hydrogen or other cryogenic fuels could represent a “Chicken or the Egg” issue
  - A hydrogen-only aircraft can’t fly into an airport until it has hydrogen refueling capabilities.
  - But airports would be reluctant to invest in creating hydrogen infrastructure until there was a significant number of hydrogen powered aircrafts.
  - An aircraft capable of burning both cryogenic and jet fuel can smooth out this transition by operating out of airports that do not offer cryogenic fuels.
  - But when an airport has cryogenic fuel service, the aircraft can use that fuel to take advantage of the benefits of the cryogenic fuel.
  - As more dual-fuel aircraft enter service, more airports will install cryogenic fueling services.
- Dual-fuel also addresses the low volumetric energy density, especially of H_2, which has a volumetric energy density that is ¼ of jet fuel.
  - Hydrogen tanks large enough to power a single-aisle aircraft to its maximum range of 3500 nm would need to be 4 times the volume of the wing tanks resulting in larger aircraft volume and weight
  - However, roughly 70% of all flights are shorter than a 1000 nm for a single-aisle aircraft, and cryogenic tanks ~¼ the size of those required for the full range could provide all the fuel required.
- Amount of SAF greatly reduced
  - Use of cryogenic fuels for flights less than 1000 nm means that the amount of SAF to replace jet fuel would be 80% less than it would be if jet fuel provided all the fuel.
  - This mean that a given supply of SAF could meet the fuel needs for a liquid storable fuel in 5 times as many aircraft than possible if SAF would have to be the only fuel used.
  - BUT: safe handling of TWO fuels with very different safety standards becomes a great challenge.

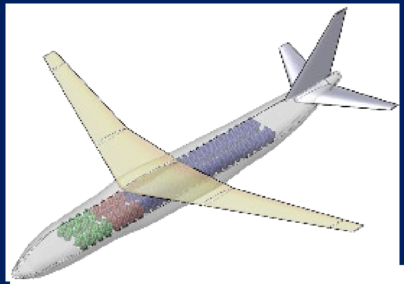




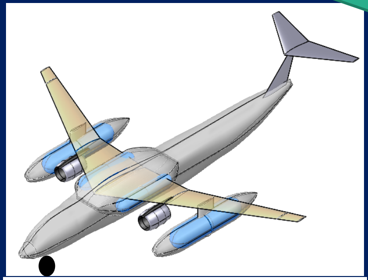
These considerations underpin a need for continuous investigation of cryogenic fuels and relevant aircraft architecture, components, subsystems and technologies to develop a comprehensive approach to optimization of future aviation concepts.

Trade of Aircraft Architecture Concepts

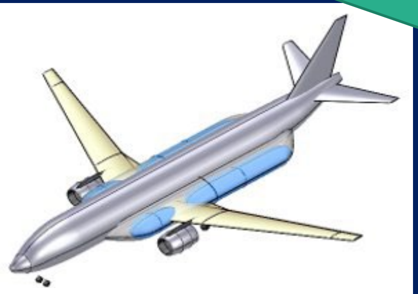
ISABE 2024, Lvovich et al., “Commercially-viable Hydrogen Aircraft for Reduction of Greenhouse Emissions”; 3rd H2-Aero Symposium, Lvovich et al., “Technology Development Roadmaps in Hydrogen Aircraft”, and Aviation Week articles



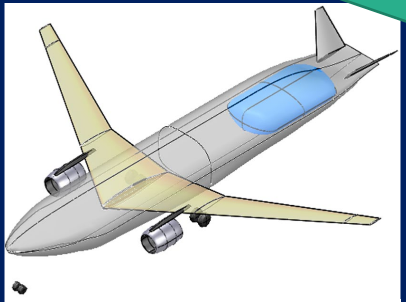
Baseline 150 PAX Aircraft



“External Tank” LH2 Carriage 150 PAX Aircraft



“Wide Baseline” 150 PAX Aircraft LH2 Carriage)



Internal LH2 Carriage 150 PAX Aircraft – “HWB”

“Blended Wing” Advanced 150 PAX Aircraft for Future Study

Increasing Aerodynamic Efficiency

Moving Away from Traditional Designs

Design Mission

- 3,500 n. mi. traveling at a [illegible]ise Mach and 43,000 ft. altitude
- 154 passengers generating 30,800 lb. payload weight.

Economic Mission

- 900 n. mi. traveling at 0.78 Cruise Mach and 43,000 ft. altitude.
- Maximum Payload of 52,000 lb.

NASA Team utilized a combination of analytical tools including Vehicle Synthesis Program (VSP), National Propulsion System Simulator (NPSS), FLight OPtimization System (FLOPS), Weight Analysis of Turbine Engines (WATE), and Electrical Power System Sizing and Analysis Tool (EPS-SAT) to analyze hydrogen aircraft architecture, determine architectural sensitivity to key metrics

Cryogenic Systems for Future Aviation

KSC LH_2 Sphere

Ground Storage Tanks:

- Stationary metallic tanks
- Pressure/thermal life cycle typically very long
- Conservative design (thick walled)
- Requires metallic vacuum jacket to contain insulation
- E.g.: KSC LH_2 Spheres

Ground Transportation Tank

Ground Transportation Tanks:

- Cargo tanks for rail, highway, water
- Requires metal jacket over insulation
- Static, dynamic & impact loading
- Pressure cycling
- Protection of valves, relief devices
- Subject to ASME/DOT regulations

SLS LH_2 Tank

Space Launch Vehicle Tanks:

- Much lower design safety factors than ASME/DOT (≥1.5)
- Service life ≥13 cycles
- Spray-on foam insulation lacks durability and performance

CRYOGENIC TANKS FOR FUTURE AVIATION:

Requirements:

- *Durability* – 1000s of pressure/ thermal cycles
- *Safety* – crashworthiness, reliability, maintainability, inspectability, passenger safety
- *Operations* – rapid turn-around refueling
- *Weight/Volume* – tank efficiency improves with increased diameter and reduced surface area (minimize boil-off)
- *Manufacturing Rate* – number of aircraft/ month >> other cryogenic tank applications

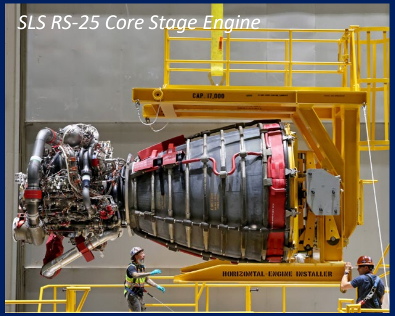
Technology Gaps:

- Materials and Structures solutions that enable viable, reliable, affordable cryogenic tanks and fluid components on-board aircraft
  - Lightweight tanks and fluid systems with high pressure/thermal cycle capability
  - Lightweight, high thermal performance insulations
- Systems Analysis to assess new vehicle configurations

KSC = Kennedy Space Center; LH_2 = liquid hydrogen; ASME/DOT = American Society of Mechanical Engineers/Department of Transportation; SLS = Space Launch System; H_2 = hydrogen

NASA experience with cryogenic fuel systems for space and ground support require development to help close gaps in the integration of cryogenic fuel systems and propulsion into aircraft

Cryogenic Fueled Turbines for Future Aviation


SLS RS-25 Core Stage Engine


LNG Fueled TU-155 with NK-88 Engines


LM9000 65MW Aeroderivative Turbine


LNG Powered Francisco ferry

NASA Experience and Aerospace Applications:

- NASA and industry have extensive experience with cryo fuels and turbines for launch vehicle engines
  - RS-25 engines for Space Shuttle and SLS utilize LH_2/LO_2 staged combustion cycle
  - SpaceX Raptor and Blue Origin BE-4 engines utilize Liquid Methane/LO_2
- LNG and LH_2 have been investigated as an aircraft fuel since the 1970s
  - In 1989 USSR developed and flew a TU-155 with NK-88 Turbines modified to use LNG or LH_2
  - NASA and Industry have studied LNG and LH_2 for commercial aviation applications
  - Rolls Royce is constructing LH_2 turbine test stands at NASA's Stennis Space Center

Ground and Marine Power Turbines

- Extensive industrial/power generation applications dating back to the 1950s
  - Aeroderivative engines such as the Allison 501-K5 and GE LM900 produce electrical power running on LNG
  - LNG and multifuel turbines produce 10s to 100s of MWs
- LNG turbines have been applied to marine power applications

CRYOGENIC TURBINES FOR FUTURE AVIATION:

Requirements:

- *Reliability and Robustness*– cryo fueled turbines and aircraft must match existing standards for reliability
- *Fuel tanks and systems*– lightweight, robust cryogenic tanks on aircraft
- *Cost, Infrastructure, and Availability* – must be comparable to existing Jet A infrastructure
- *Safety* – must meet or exceed existing state-of-the-art

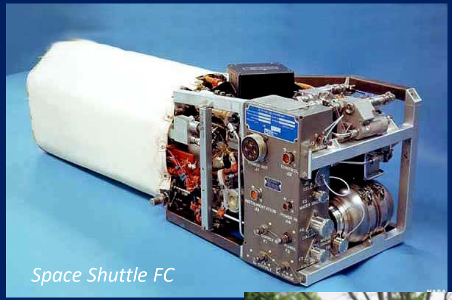
Technology Gaps:

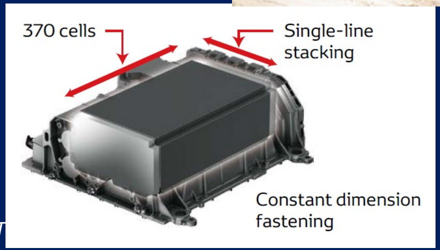
- Materials and structures for cryogenic fuels storage and handling
- Advanced cycles and propulsion architectures to maximize advantage of cryo fuels
- Advanced thermal management systems and optimal energy management strategies
- Systems Analysis to assess new air vehicle configurations and architectures
- Safety including leak detection, fuel handling

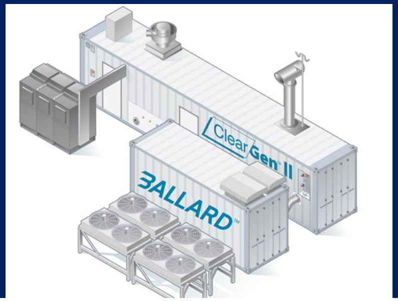
LH_2 = liquid hydrogen; LO_2 = liquid oxygen; cryo = cryogenic; LNG = Liquified Natural Gas, MW = megawatt

NASA has extensive experience with cryogenic fueled turbines through launch vehicle and spacecraft operations. Industry has extensive experience with LNG turbines for stationary and marine applications, including aeroderivative designs. LNG and LH2 powered aviation turbines have been demonstrated but never entered regular production. Technology gaps exist around supporting infrastructure, fuel storage and handling, thermal management systems, and aircraft configurations.

Fuel Cells for Future Aviation







NASA Historic Applications:

- Gemini, Apollo, Space Shuttle
- Two types of fuel cell using LH_2 & stoichiometric LO_2
- UTC alkaline fuel cell for Space Shuttle (1981 ~ 2011)
- 3 X 12kW units; each 14" x 15" x 45", 118 kgs
- Produces all onboard electrical power, drinking water
- Short service life
- 1kW NFT LT PEM module tested with ground vehicle

Automotive applications (LT-PEM):

- Several years long service life in cars, trucks, busses
- Powertrain: 100 kW (Toyota Mirai) ~ 400 kW (bus)
- Mirai FC power density: 0.83 $\rightarrow$ 2.5 kW/kg since 2008
- Standardized gas storage pressure 70 MPa: ~0.9 kWh/L (vs 1.2 for cryo)

Stationary power generation (LT-PEM & SOFC):

- 1 MW containerized PEM FC system in Martinique, France for Hydrogène de France by Ballard is the latest
- Typical SOFC <300 kW with heat & power cogeneration
- Low power density, easy fuel storage, HC fuel for SOFC

FUEL CELLS FOR FUTURE AVIATION:

Requirements:

- *Durability* – 300,000 hrs of electrical power generation
- *Large scale* – several MW size FC for a ~20 MW power system of Boeing 737
- *Safety* – crashworthiness, reliability, maintainability, inspectability, passenger safety
- *Operations* – rapid turn of power generation
- *Weight/Volume* – KW/kg high volumetric power density / gravimetrical power density
- *Manufacturing Rate* – number of aircraft/ month >> other FC applications

Technology Gaps:

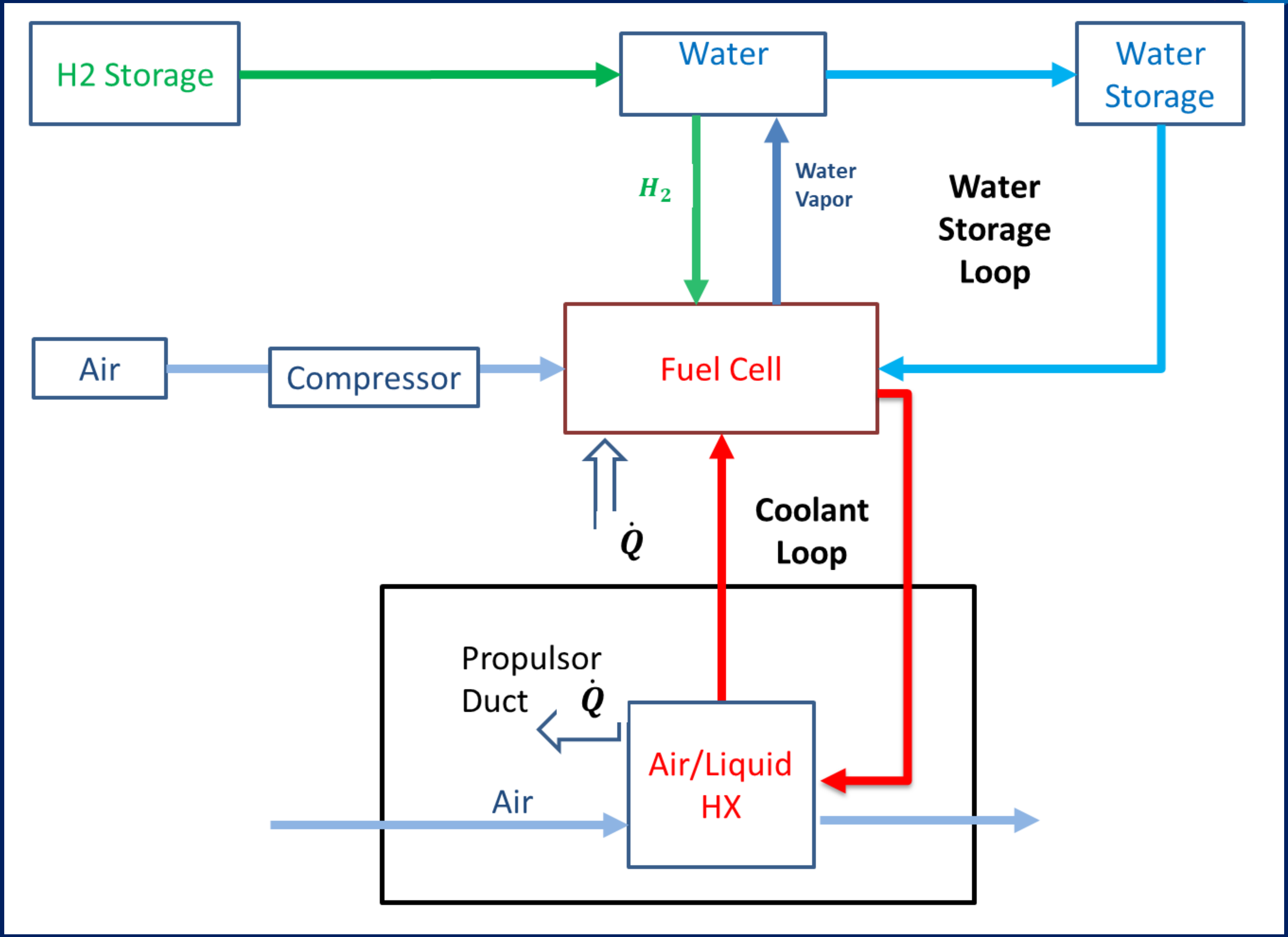
- Materials and Structures enabling solutions for scalable, durable, efficient, lightweight fuel cells
  - High power and KW/kg energy density with 300,000 hours durability and cycle rate capability
  - Introduction of High Temperature PEM FC
  - Scale up approaches for MW fuel cell stacks
  - Lightweight BOP, water and thermal management
- Systems Analysis to assess new vehicle configurations

LH_2 = liquid hydrogen; LO_2 = liquid oxygen; UTC = United Technologies Corporation; NFT = non-flow-through; cryo = cryogenic; HC = hydrocarbon

High thermal efficiency of fuel cells implies a fuel volume reduction of ~30%.
NASA experience with kW fuel cell systems for space missions can be leveraged for aviation.
Terrestrial fuel cell industry capabilities are limited to 100-500 kW range for heavy fuel cell systems and BOP.
It requires significant development to close gaps for introduction of fuel cell systems into aircraft.

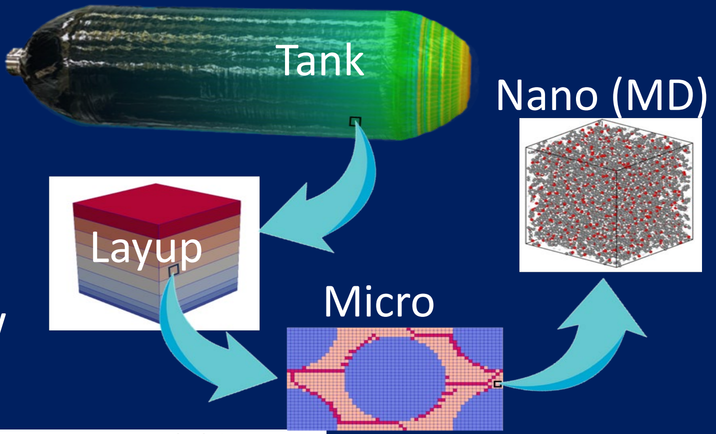
Thermal Management System Considerations

- Need to reject 40% to 60% of the fuel cell heat energy (~10 MWt)
- Need to transition from LT PEM (80C) to HT PEM (200C) to achieve large temperature differential between coolant and airstream during takeoff and climb
- Heat rejection must close at zero flight speed, necessitating the placement of the heat exchanger in the propulsor duct
- At takeoff, the air is relatively hot, making heat transfer difficult
- Potential solution is to include battery power for takeoff and initial climb to reduce heat rejection requirement
- Currently working on heat exchanger conceptual design to get initial size and weight



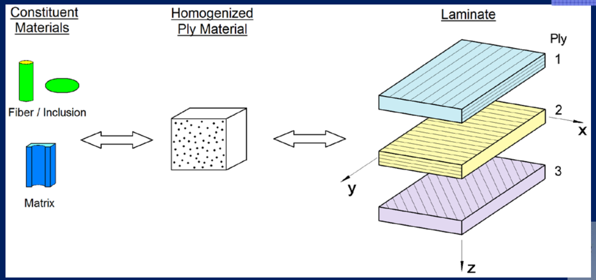
Development of cryogenic materials and components evaluation

Use multiscale progressive damage modeling to evaluate novel tank matrix material candidates (i.e. thermoplastics) under realistic thermo-mechanical loading with molecular dynamics data for the neat resin.

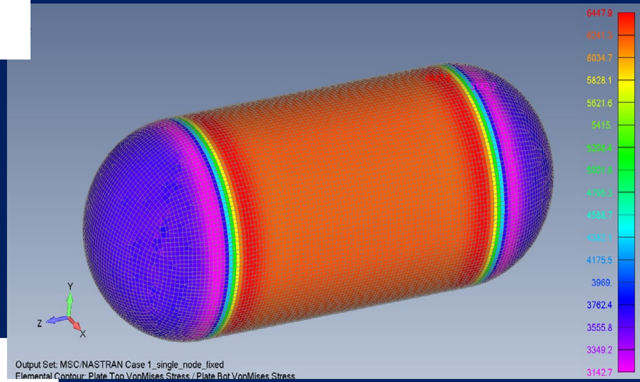


Manufacturing demonstration of thermoplastic composite tank with new insulation materials.

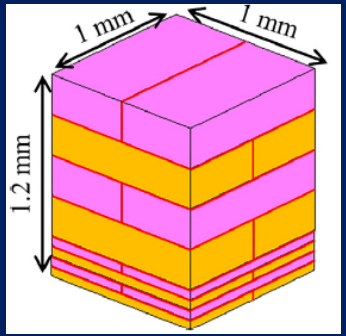
1. Multiscale model of laminate and ply microstructure
   - Cool to cryo and evaluate residual stresses per material system

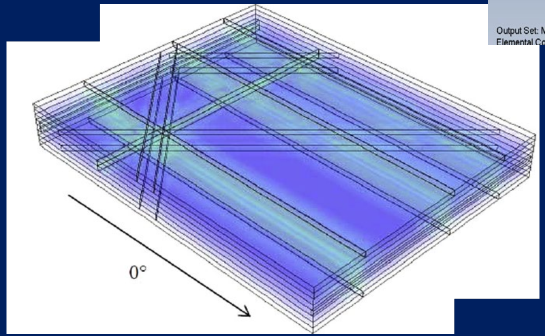


2. NASTRAN/HyperX model of tank
   - Use HyperX with realistic thermo-mechanical load cases to evaluate optimized designs per material system



3. Progressive damage modeling to model microcracking and permeability
   - Laminate level or full multiscale FEM
   - Possibly beyond current resources





Cryogenic Fuels for Future Aviation Risks

Commercial Aviation Propulsion Cycles and Utilization: The primary issues unique to aviation propulsion not directly addressed by current commercial transport technologies or NASA space propulsion revolve around the challenging transition of cryo-fuel handling and power/propulsion systems, from space propulsion applications having short lives, very low occupancy to commercial transport applications requiring much longer service lives, much higher occupancy and using high occupancy commercial airports.

Cryo-fueled propulsion systems would be required to safely operate in occupied vehicles that are used several times daily.

Disruptive technology innovations in materials, engineering and scale-up manufacturing are needed.

Other challenges:

- Make concept cost competitive.
- Safety requirements, certifications and regulation.
- Cryogenic fuels production at scale, availability, cost.
- Managing airport production, delivery and distribution of cryogenic fuels, airport infrastructure and safety.
- Operations and flight profile of cryogenic aircraft.

Cryogenic Fuels for Future Aviation Opportunities

- Charting a cause for future of flight – a game changing transformation to high fuel efficiency & zero emissions operation
- Cryogenic Aircraft technologies are on a critical path for development of next generation aviation as well as many terrestrial applications and space planetary exploration
- Aligned efforts and resource-sharing across government agencies, academia, and industry leveraging a significant legacy expertise, enabling technology adoption at scale
- More electric propulsion systems leverage cross-mission, industry and international collaborations
- Public Interest
- Motivated commercial entities
- Continued to advance cryogenic aircraft concept and architectures, developing performance metrics and requirements, system analysis, implement and test key components and full systems
- Advances in computing capabilities and computational theories (e.g. Digital Twins, Machine Learning, Artificial Intelligence, etc.)