NASA vision for Technology Development Roadmap in Hydrogen Aircraft

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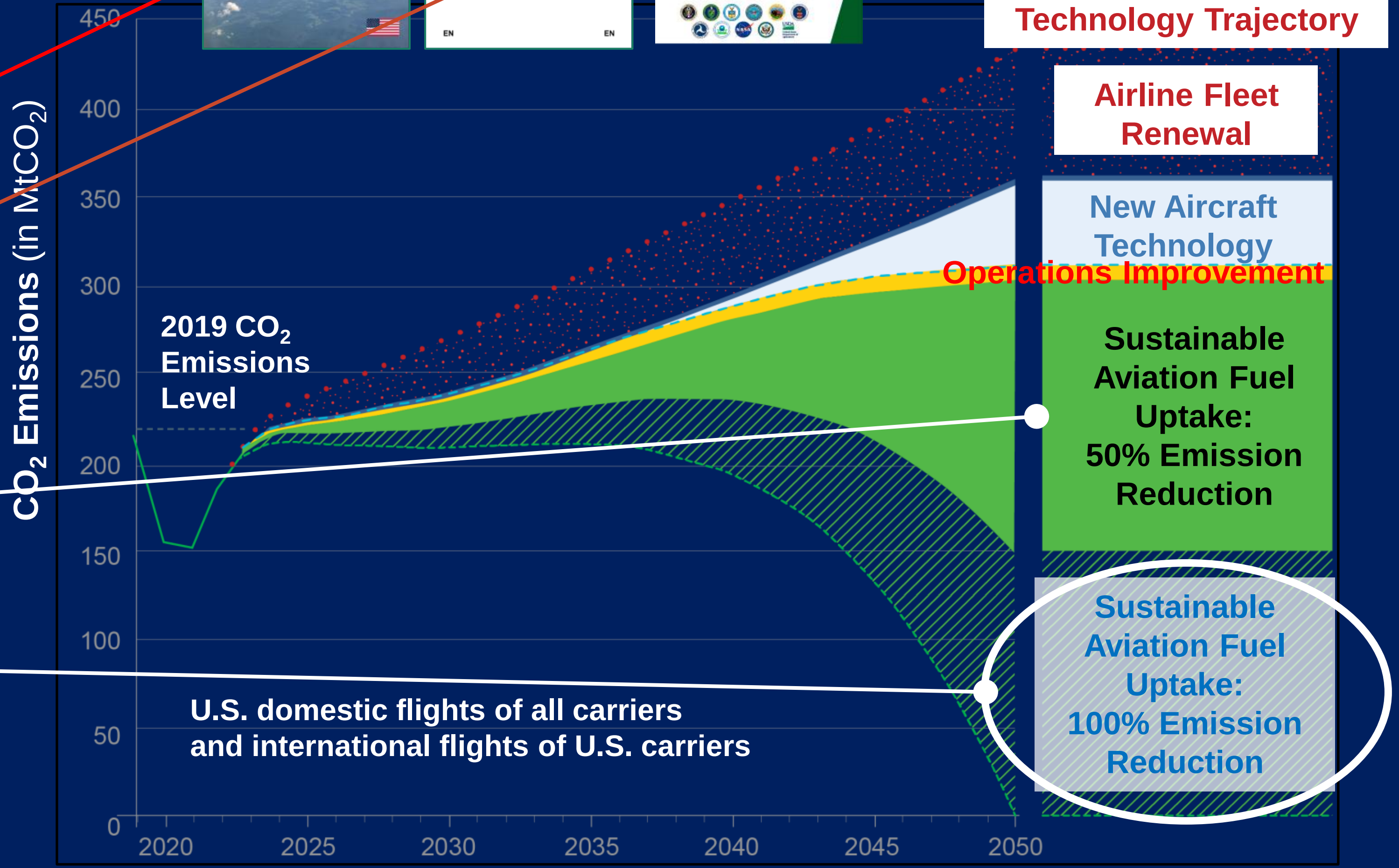
Path to Emissions-Free Aviation

- U.S. Aviation Climate Action Plan has set Sustainable Aviation Net-Zero Carbon Emissions Goals by 2050
- Europe established a strategy in 2020 and is engaging with industry for hydrogen-fueled aviation
  - A Hydrogen (H_2) Strategy for a Climate-Neutral Europe
  - Sustainable & Smart Mobility Strategy
- The *U.S. National Clean Hydrogen Strategy and Roadmap* presents a strategic framework for achieving large-scale production and use of clean hydrogen
- SAF reduces emissions and fossil fuel dependency, but transition to new approach required to achieve 2050 goals beyond SFNP (AACES 2050 study)
- Switch to renewable cryogenic fuels to eliminate carbon emissions from fuel production and aircraft propulsion (assuming sustainable fuel sources are available)

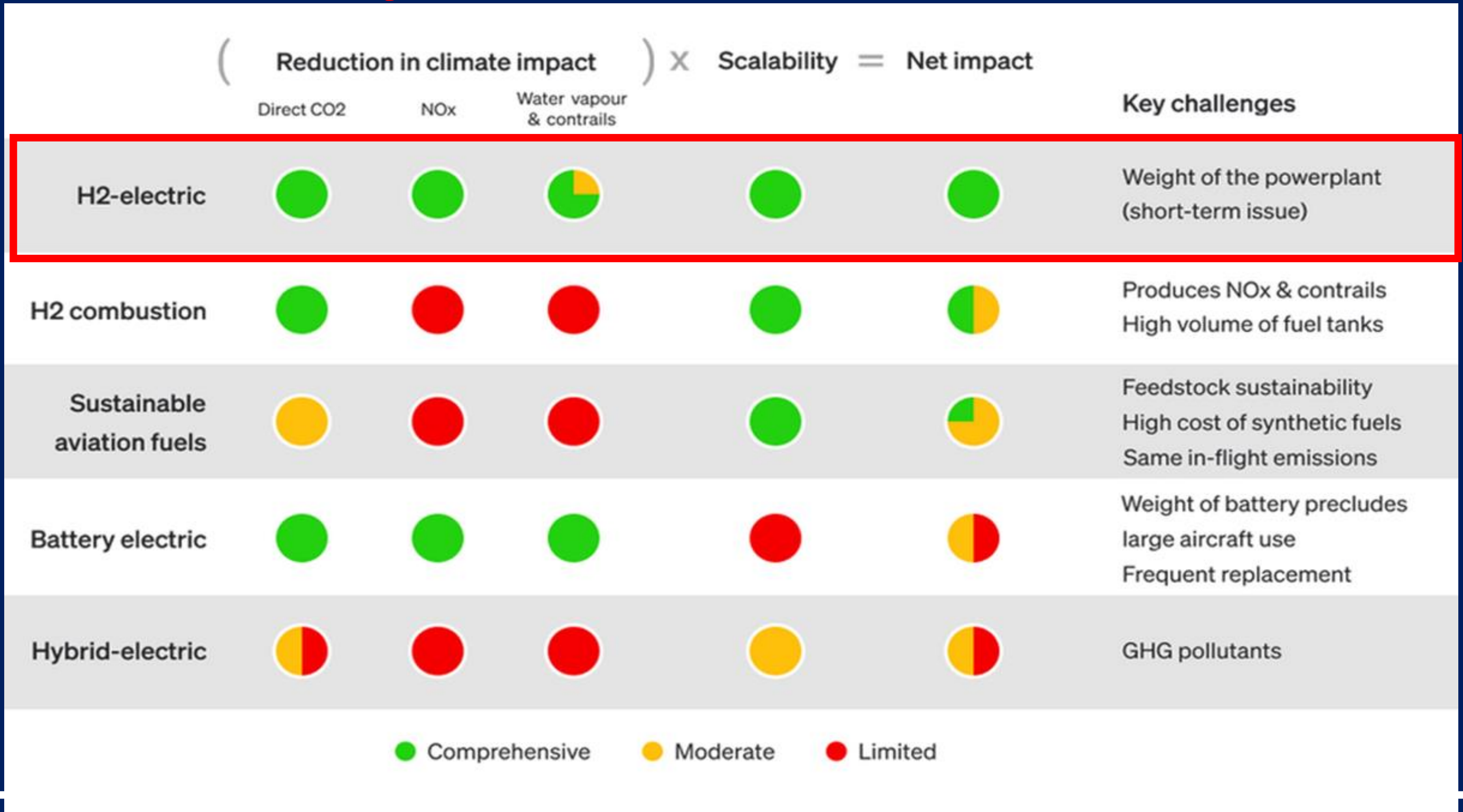


SAF = Sustainable Aviation Fuel; SFNP = Sustainable Flight National Partnership; AACES = Advanced Aircraft Concepts for Environmental Sustainability

Global climate goals by 2050 require new approach to fuels beyond Sustainable Flight National Partnership (SFNP): Renewable cryogenic fuels can enable net-zero carbon emissions

Hydrogen-Electric is the Only Scalable Zero Emission Solution

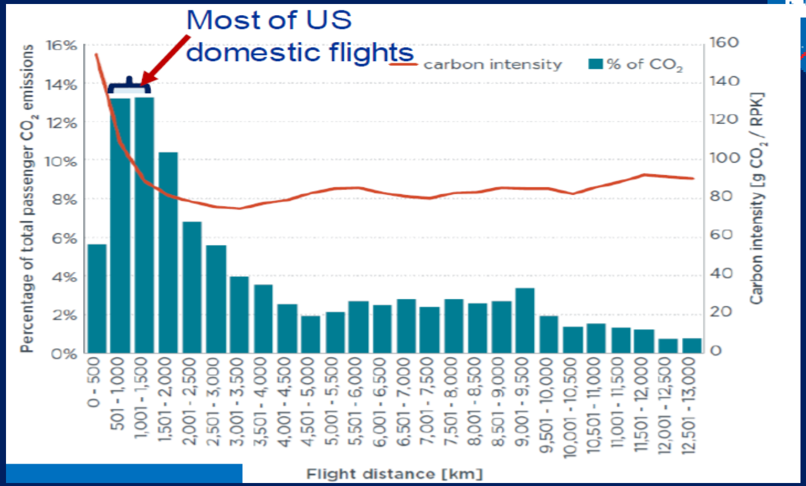
Ranking potential impacts of H2 implementation



- Establishing Airports as Hydrogen Hubs https://youtu.be/nn9rp1IHEjA

June 2023 – Paris Air Show
https://www.zeroavia.com

Commercially-viable Hydrogen Aircraft for Reduction of Greenhouse Emissions (CH$_2$ARGE)



The Opportunity:

The main focus on decarbonizing aviation is on short- and medium-range aircraft 100-300 passengers flying 1000 - 3000 km. Hydrogen is the only fuel that can provide zero carbon emissions by 2050.

How can we make Hydrogen Aircraft work in commercially viable manner?

How to use the hydrogen most effectively on the aircraft and turn it into energy?

The Strategy:

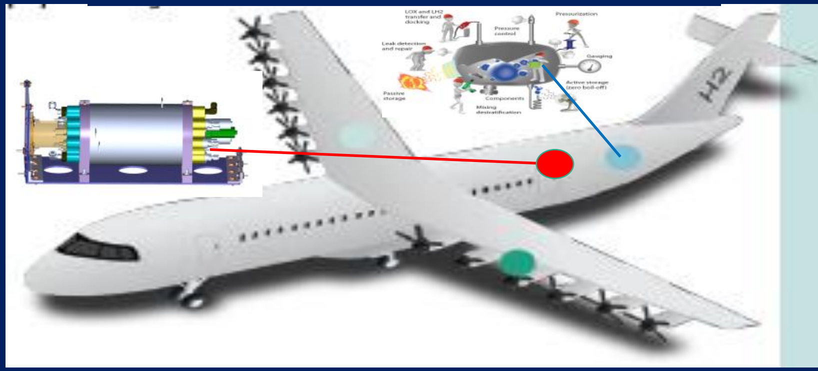
Develop integrated conceptual and experimental methodology that enable industry-wide adoption of medium-range Hydrogen Aircraft based on hydrogen-air fuel cells & cryogenic hydrogen system synthesis. Allow for the methodology maturation and identify system level closure plans and technology development targets. Develop an integrated aircraft concept of operations, exploring opportunities such as non-active time frames to simplify aircraft lifecycle requirements.

Considerations:

The <u>MAIN PRACTICAL GOAL is to increase specific energy of the whole aircraft by 2-3X</u> and will be achieved <u>at the system level by integrating</u> optimized lightweight, durable and safe composite cryotanks, on board cryofuel management system, and Fuel Cells. This requires a comprehensive system-specific studies and practical solutions in identifying advanced materials, modeling tools, & evaluation criteria.

NASA based team – capitalize on technology synergies and test facilities.

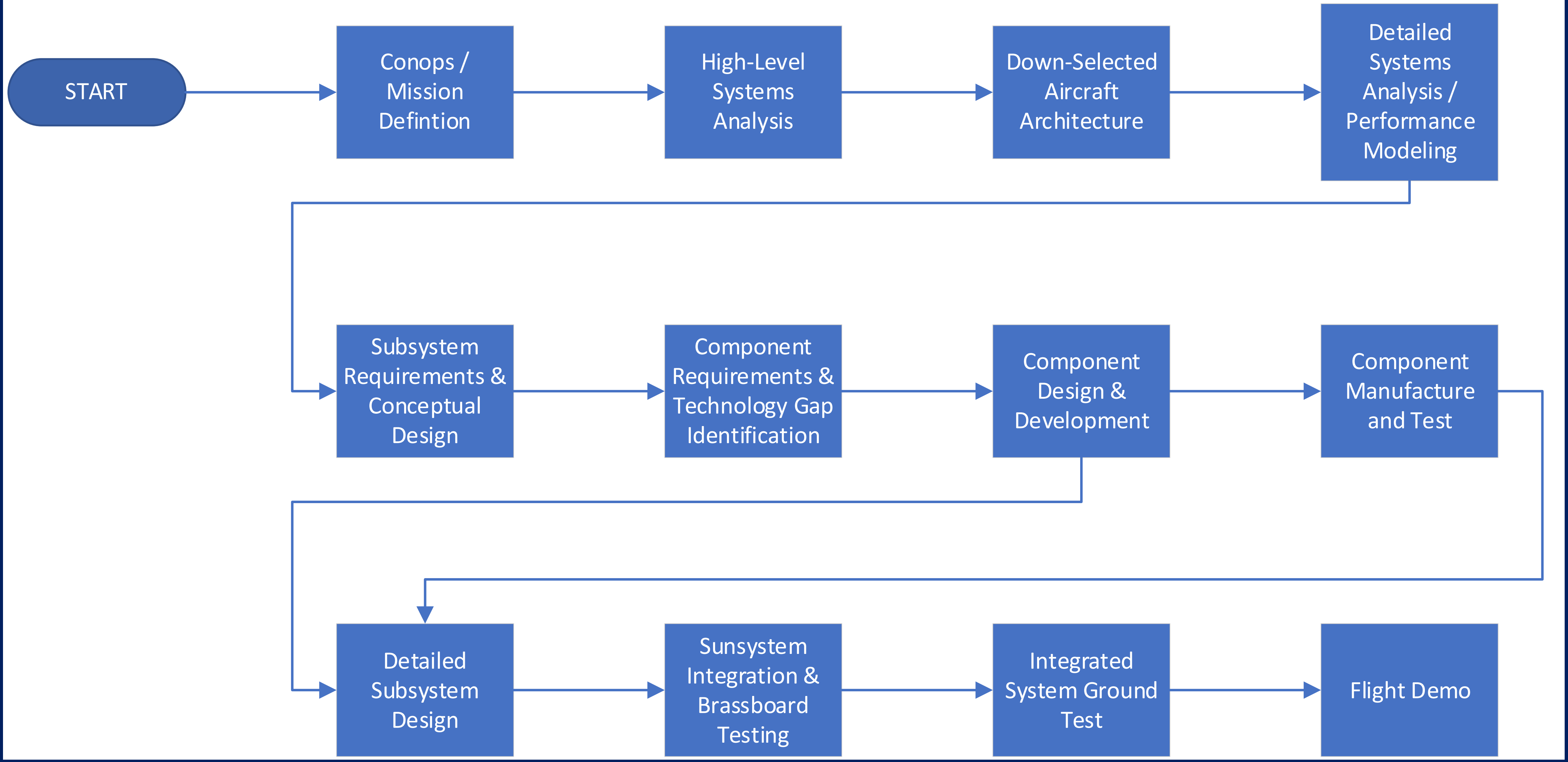
Revolutionary hydrogen fueled aircraft



Design Mission: 80-200 PAX, 500-3000 nm range.
Cruise speed Mach 0.4-0.8, Highly efficient wing

- Distributed Electric Propulsion using electric motors for thrust
- LH2 tanks on wings or behind PAX cabin – added weight 4 tons
- Fuel cell system and / or hydrogen burning turbines (10-25 MWt) powering electric motors

Hardware Development



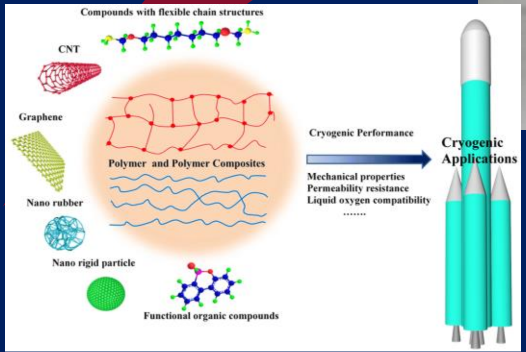
Lightweight, Long-life, Cryogenic Tanks Roadmap

Challenges

- Developing materials capable of high-cycle-life between 20K and ambient temperature
- Developing materials that start and remain low-permeability (to hydrogen) over lifetime
- Differing CTE between composite and appurtenances (liner, fluid connections, etc.)
- Aircraft architectures that permit requisite tank inspection
- Light-weight, durable, volume-efficient insulation

2024-2026
Composite materials capable of surviving low number of cycles from ambient to ~20K

Starting TRL 2-3

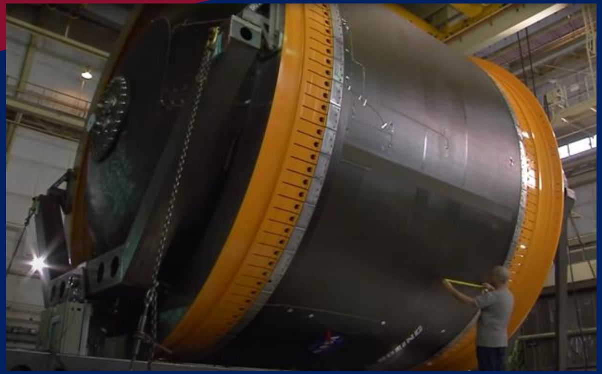


2026-2030
Sub-scale composite tanks demonstrating large number of thermal cycles with low H2 permeability

TRL 4-5

2030-2036
Full scale vacuum jacketed composite tank demonstrating manufacturing capability and tested in relevant temperature and pressure environment

TRL 5-6



2037-2045

Flight demo with integrated LH2 fuel system

TRL 7

Strategy

- Work with materials developers to perform characterization and life testing of new composite materials at cryogenic temperatures
- Work with tank manufacturers to develop and conduct cryogenic cycle-life testing of composite tanks at relevant scales and conditions
- Investigate emerging insulation approaches
- Use identified aircraft architecture to design appropriate LH2 storage/transfer system

Flight-weight, Long-life, LH2 Fluid System Components Roadmap

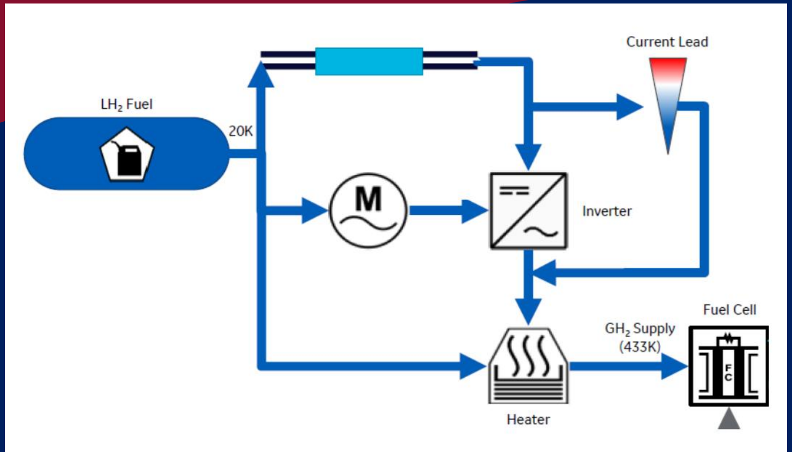
Challenges

- Developing long-life, light-weight LH2 pumps given LH2's low temperature, low viscosity, and lack of lubricity
- Developing fluid systems that remain "primed" with LH2 for extended periods with low/no flow
- Long-life, flight weight LH2 valves not subject to internal or external leakage
- Light-weight, volumetrically-efficient heat exchangers with high effectiveness
- Light-weight, durable, volume-efficient insulation
- Fluid system transient operability

2024-2026
SBIT/STTR Phase 1&2 development efforts.
In-house low-TRL research.
Starting TRL 2-4

2026-2032
Cryogenic component testing progressing to lab-scale subsystem demonstrations
TRL 4-5

2033-2039
Subsystem testing of integrated LH2 fluid system components; iron bird testing including full TMS and fuel cell
TRL 5-6



2040-2045
Flight demo with integrated LH2 fuel system
TRL 7

Strategy

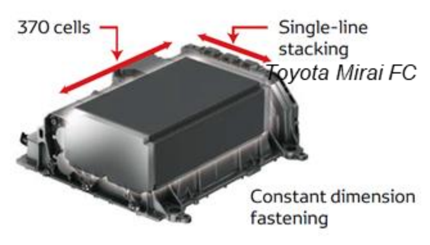
- Work with AM materials SMEs to perform characterization, life testing, and permeability of AM materials and components at cryogenic temperatures
- Work with composite components manufacturers to develop and conduct cryogenic characterization/life tests of composite VJ lines at relevant (LH2) conditions
- Functional and life testing of LH2 pumps, valves, heat exchangers, etc. → subsystems
- Use identified aircraft architecture to design appropriate LH2 storage/transfer system

General Fuel Cell Roadmap

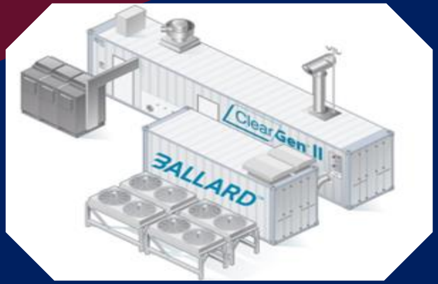
Challenges

- Terrestrial: DOE Million Mile Fuel Cell Truck Consortium improving Heavy Duty Vehicles (HDV) efficiency & lifetime
- LT PEM fuel cell developed for passenger car, bus, and marine applications (0.1 ~ 0.4 MW)
- Single MW class LT PEM fuel cell only is for stationary power generation
- Low temperature operation limits power density and system efficiency for aviation

2024– 2026
LT PEM FC
60% efficiency
5,000 hours

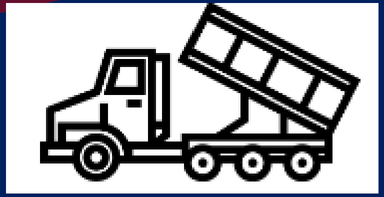


2027-2035
65-68% efficiency
25,000 hours



2036-2040
70-72% efficiency
30,000+ hours

DOE HDV

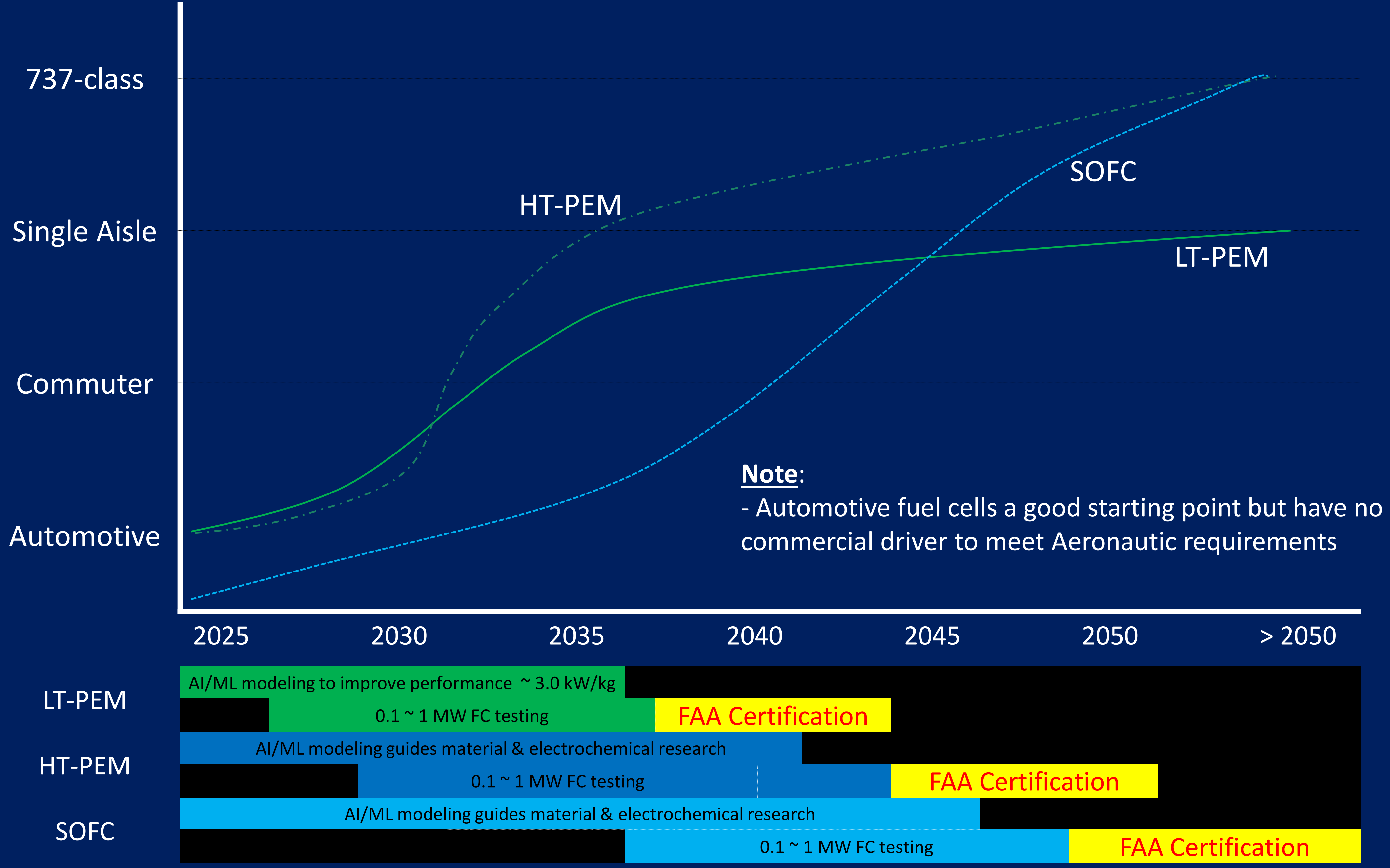


~ 2041-2045
MW fuel cells with high efficiency ready for aviation

Strategy

- Power density, mass, lifetime, and energy efficiency are the key requirements for commercially viable aeronautical fuel cells
  - Materials determine fuel cell performance and mass
  - Higher temperatures improve efficiency and reduce mass
  - Scale up to MW size reduce mass
- Material, electrochemical, and manufacturing breakthroughs required to meet stringent performance requirements of Boeing 737 sized fuel cell aircraft
- Work with fuel cell materials developers to perform characterization and life testing of new performance enabling materials

Anticipated Aeronautic Fuel Cell Module Development



NASA Fuel Cell Development Roadmap

Challenges

- Low temperature operation limits power density and system efficiency, 0.1-0.4 MW LT PEM is the only mature technology now
- Performance improvement for LT PEM is limited, a gap for aviation
- Need to transition to and mature high temperature fuel cells – enabling technology and major challenge

2024 – 2028
eVTOL
LT PEM FC
60% efficiency
5,000 hours
Starting TRL 2~3

FC eVTOL ~ 2027

2029-2035
Commuter aircraft
LT PEM optimization with ML,
HT PEM electrochemical
Scale up to 1~5 MW
65-68% efficiency 25,000 hours
Larger, more efficient, longer life
TRL 4~5

2036- 2040
Regional jet
Scale up HT FC system size to ~10MW
70-72% efficiency 30,000+ hours
10 MW FC testing
TRL ~6

~ 2041-45
Boeing 737 flight demo with
20 MW HT FC
TRL 7~8

Strategy

- Power density, low mass, lifetime, scale up and energy efficiency are the key requirements for commercially viable fuel cell aircraft
  - Reduction heavy BOP / TMS for FC (LT PEM)
  - Pivot to HT to improve efficiency and reduce mass
- Material, electrochemical, and manufacturing breakthroughs augmented by ML algorithms are required to meet stringent performance requirements of Boeing 737 sized fuel cell aircraft
- Facility for MW FC testing

Thermal Management Solutions Roadmap

Challenges

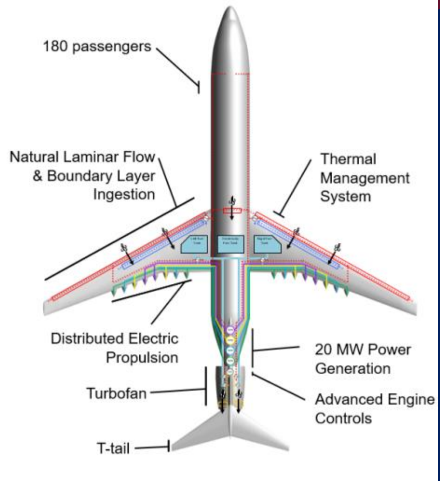
- High Power densities → Higher heat loads that require more invasive cooling methods
- Complex Cooling Strategies → High Performing, dielectric & non-corrosive coolants; need high heat flux, passive components
- Heat Transport → Require lighter heat exchangers, pumps and lines
- Low Quality Heat → Limited area for heat rejection, heavy heat exchangers

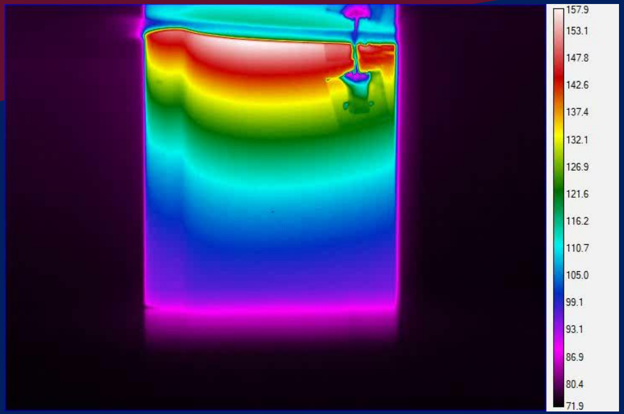
2024-2026
Novel cooling concepts and TMS architectures
Starting TRL 2-3

2027-2031
Individual component development utilizing novel concepts; laboratory testing of concepts
TRL 3-4

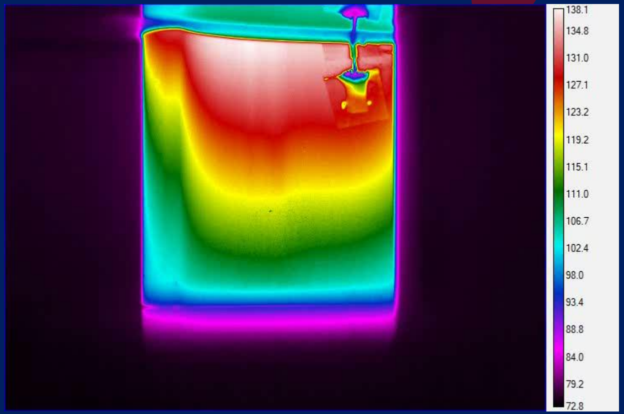
2032 - 2036
Integration of novel concepts into components and subsystems
TRL 4-5

2037-2040
Relevant demonstration / flight demo that will take entire TMS
TRL 5-6





80W Power – Baseline (Empty Turbine Vane)



80W Power – Working OHP

Strategy

- Explore, develop experiments for, and improve different TMS technologies and architectures to enable component power density targets
- Explore novel materials and manufacturing techniques for the development of optimized TMS technologies
- Optimize co-design and integration of components and TMS (e.g., Fuel Cell, converters, etc.)

Hydrogen Aircraft Development Perspectives

Some initial projections from various Hydrogen Aircraft and Zero Emission Aircraft trade studies and white papers:

- Commercial Hydrogen Aircraft with 2500+ miles and 150+ PAX can be expected around 2040, but with 50% shorter range
- Contrails will be dealt with
- Airport operations and service developed
- Safety and Regulations developed
- Hydrogen cost decrease from 5 $/kg to ~2 $/kg, supply and liquefaction developed

Metrics Achievable within next 10 years:

- LH_2 → tank mass reduced by 50 % compared to SOA (as a result of boil off requirements change, better tank designs, new lightweight composites for walls and insulation materials) and fuel distribution components
- Fuel cells → 2 KW/kg (system level) and 60% efficiency, scale up to 25 MWt, reliability to 25000 hrs, water treatment, maturation of high temperature technology
- Thermal management → volumetric optimized heat exchangers
- PMAD → 97-99% efficient
- New Aircraft architecture → evolutionary or revolutionary, scalable, distributed hybrid propulsion
- Manufacturability at scale