Vision for H2 Aircraft Technology Development

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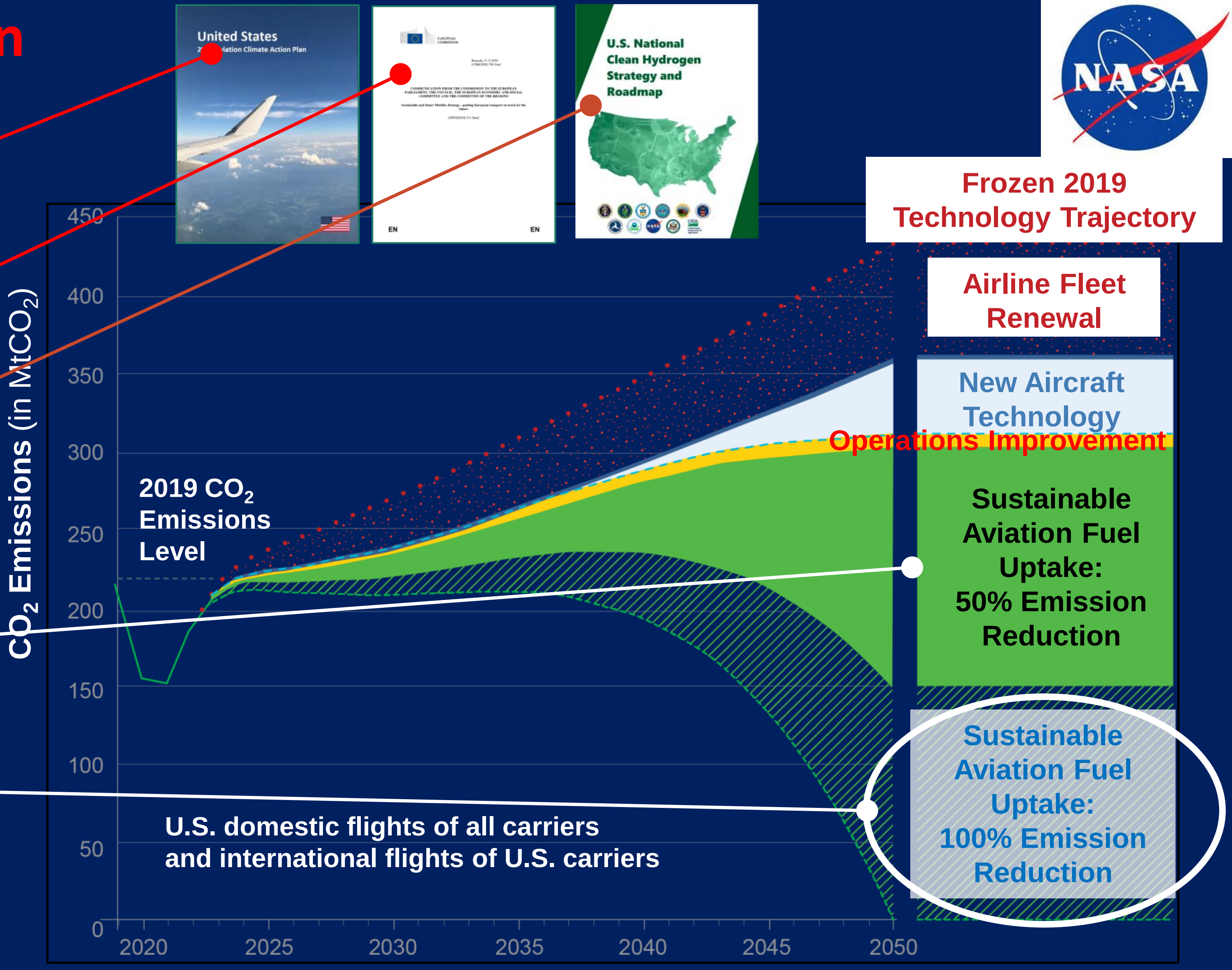
HYSKY MONTHLY Free Hydrogen Aviation Webinars

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)

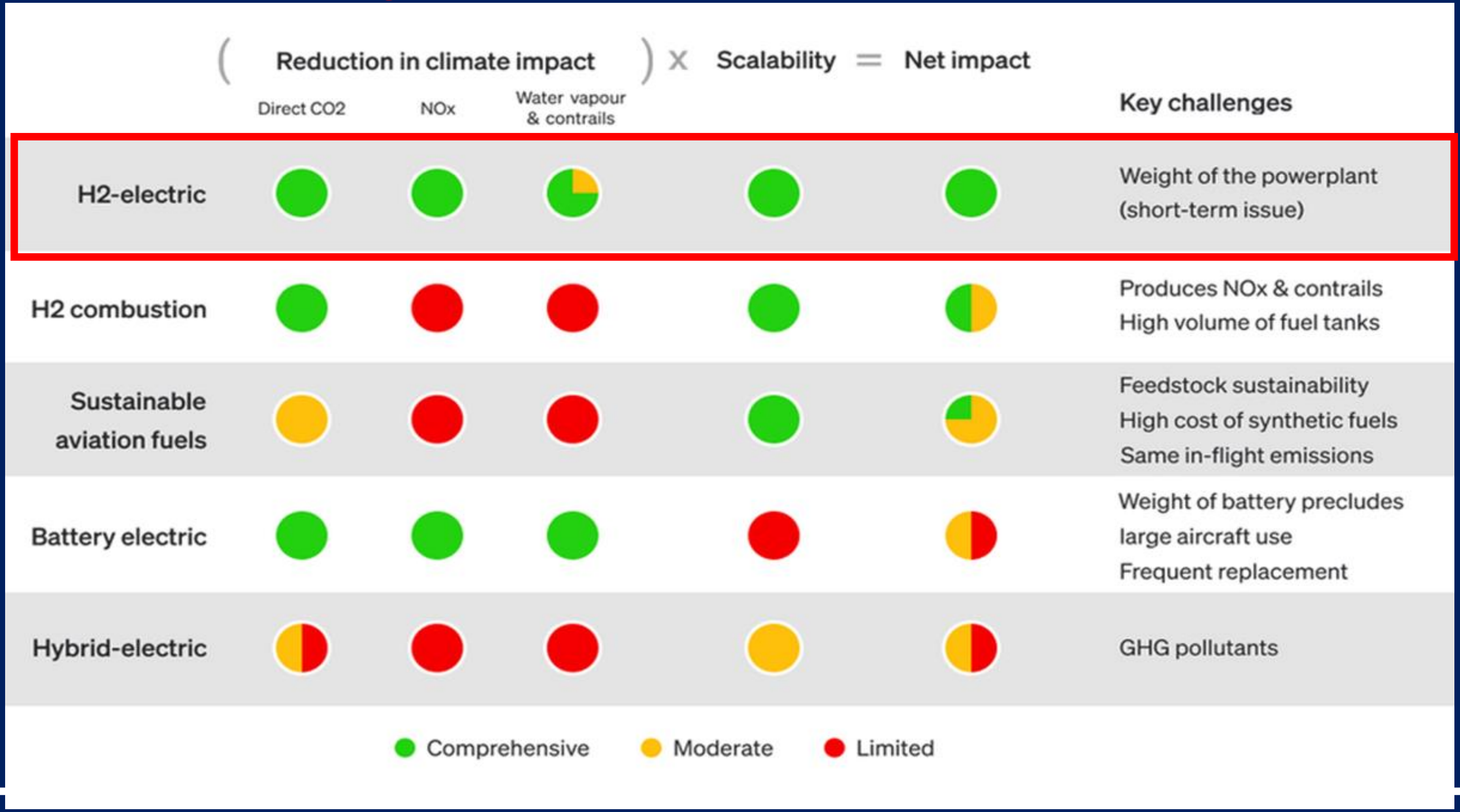


SAF = Sustainable Aviation Fuel; SFNP = Sustainable Flight National Partnership; AACES = Advanced Aircraft Concepts for Environmental Sustainability

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



	(Reduction in climate impact		)	x Scalability	= Net impact	
	Direct CO2	NOx	Water vapour & contrails			Key challenges
H2-electric	🟢	🟢	🟢🟡	🟢	🟢	Weight of the powerplant (short-term issue)
H2 combustion	🟢	🔴	🔴	🟢	🟢🟡	Produces NOx & contrails High volume of fuel tanks
Sustainable aviation fuels	🟡	🔴	🔴	🟢	🟢🟡	Feedstock sustainability High cost of synthetic fuels Same in-flight emissions
Battery electric	🟢	🟢	🟢	🔴	🟡🔴	Weight of battery precludes large aircraft use Frequent replacement
Hybrid-electric	🟡🔴	🔴	🔴	🟡	🟡🔴	GHG pollutants

🟢 Comprehensive 🟡 Moderate 🔴 Limited

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

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

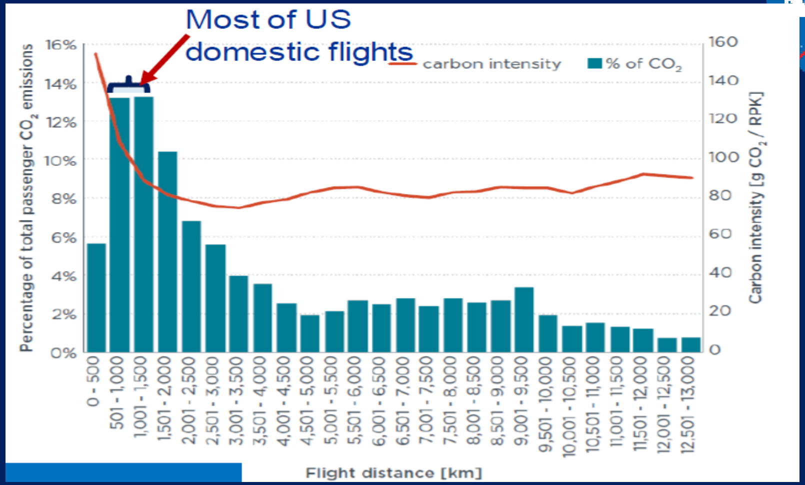
Commercially-viable Hydrogen Aircraft for Reduction of Greenhouse Emissions (CH_2ARGE)

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:

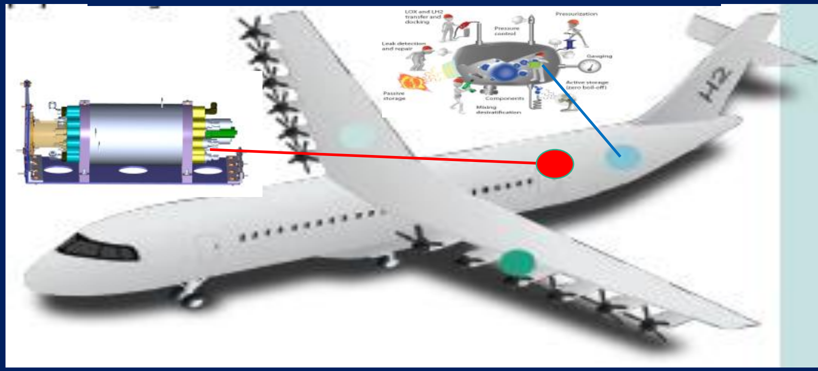
Develop integrated conceptual and experimental methodology that enable industry-wide adoption of medium-range Hydrogen Aircraft based on hydrogen-air fuel cells & cryogenic hydrogen system synthesis. Allow for the methodology maturation and identify system level closure plans and technology development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

Considerations:

The MAIN PRACTICAL GOAL is to increase specific energy of the whole aircraft by 2-3X and will be achieved at the system level by integrating 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

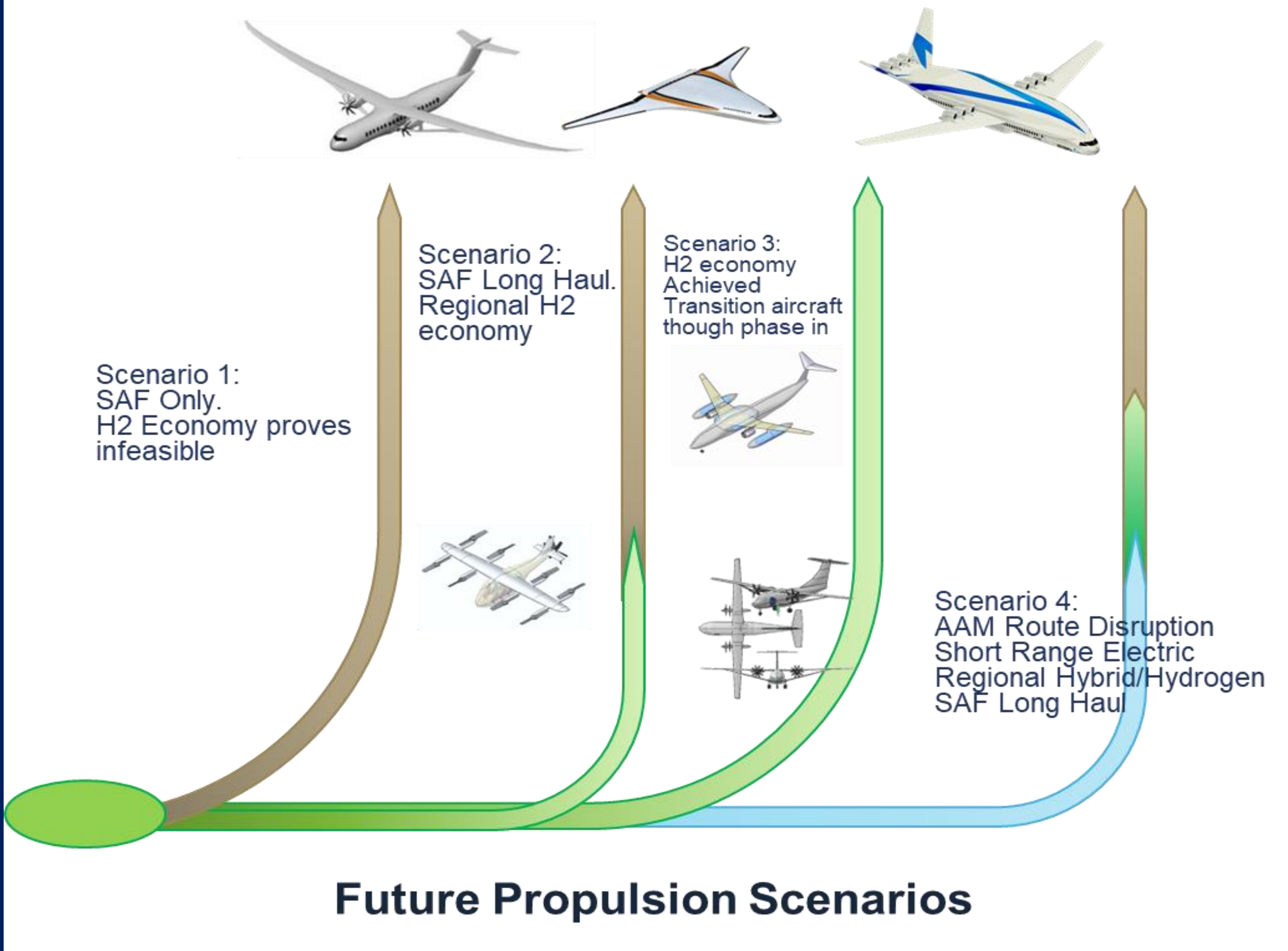
- ● Distributed Electric Propulsion using electric motors for thrust
- ● LH2 tanks on wings or behind PAX cabin – added weight 4 tons
- ● Fuel cell system and / or hydrogen burning turbines (10-25 MWt) powering electric motors

Aircraft Configuration Roadmap

Aircraft configurations may reflect different scenarios regarding Hydrogen utilization in the airspace

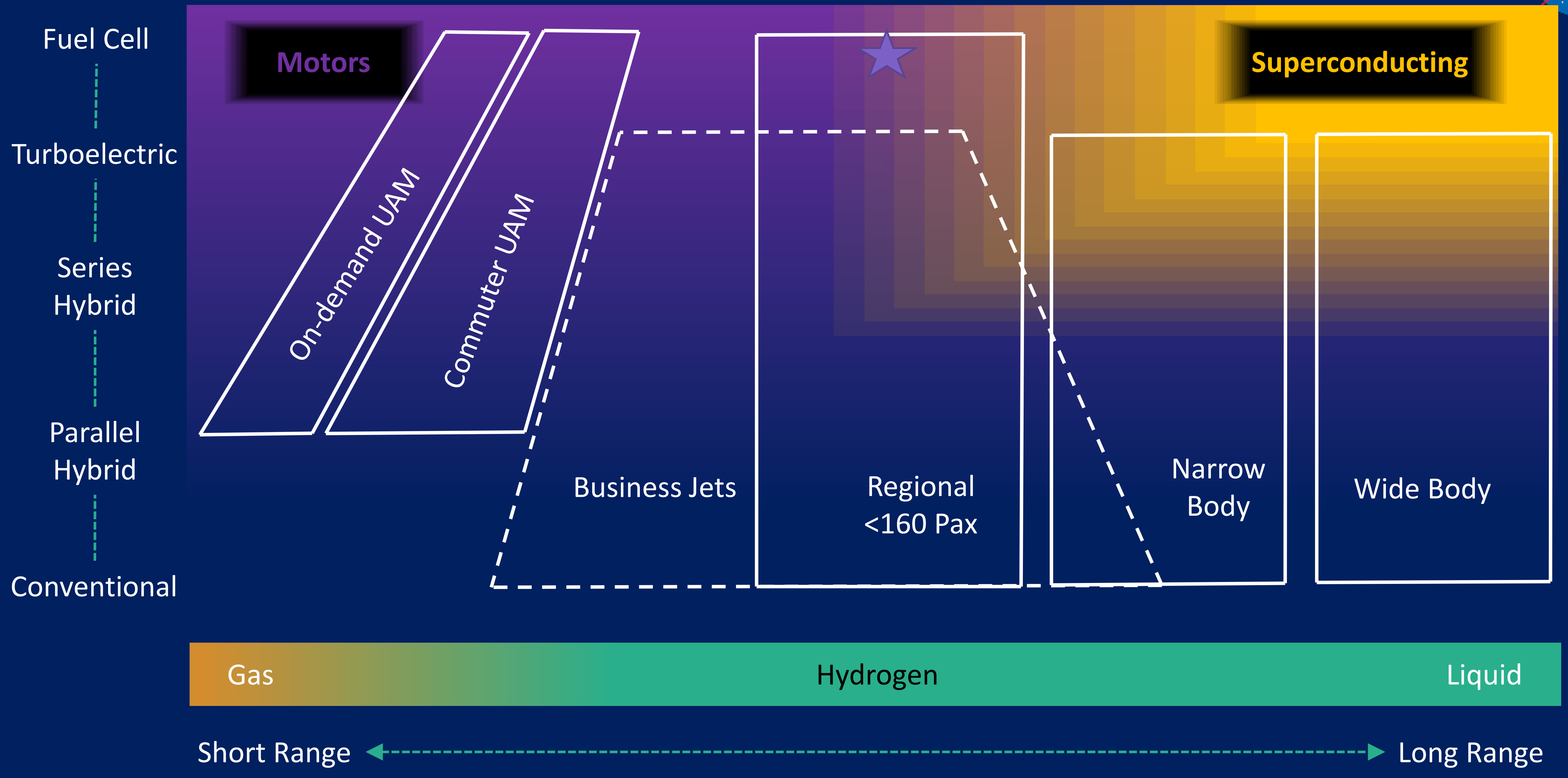
1. H2 Economy infeasibility leads to aircraft configurations that maximize fuel efficiency per payload mile.
2. H2 Economy limited to few regions. UAM/GA and some regional aircraft adapt to local Hydrogen utilization.
3. H2 Economy proves feasible. Aircraft configurations reflect hydrogen adoption.
4. AAM Route Disruption. Vast changes to transportation system. Short and Medium range routes using Electric or Hydrogen Power. SAF for long range routes.

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

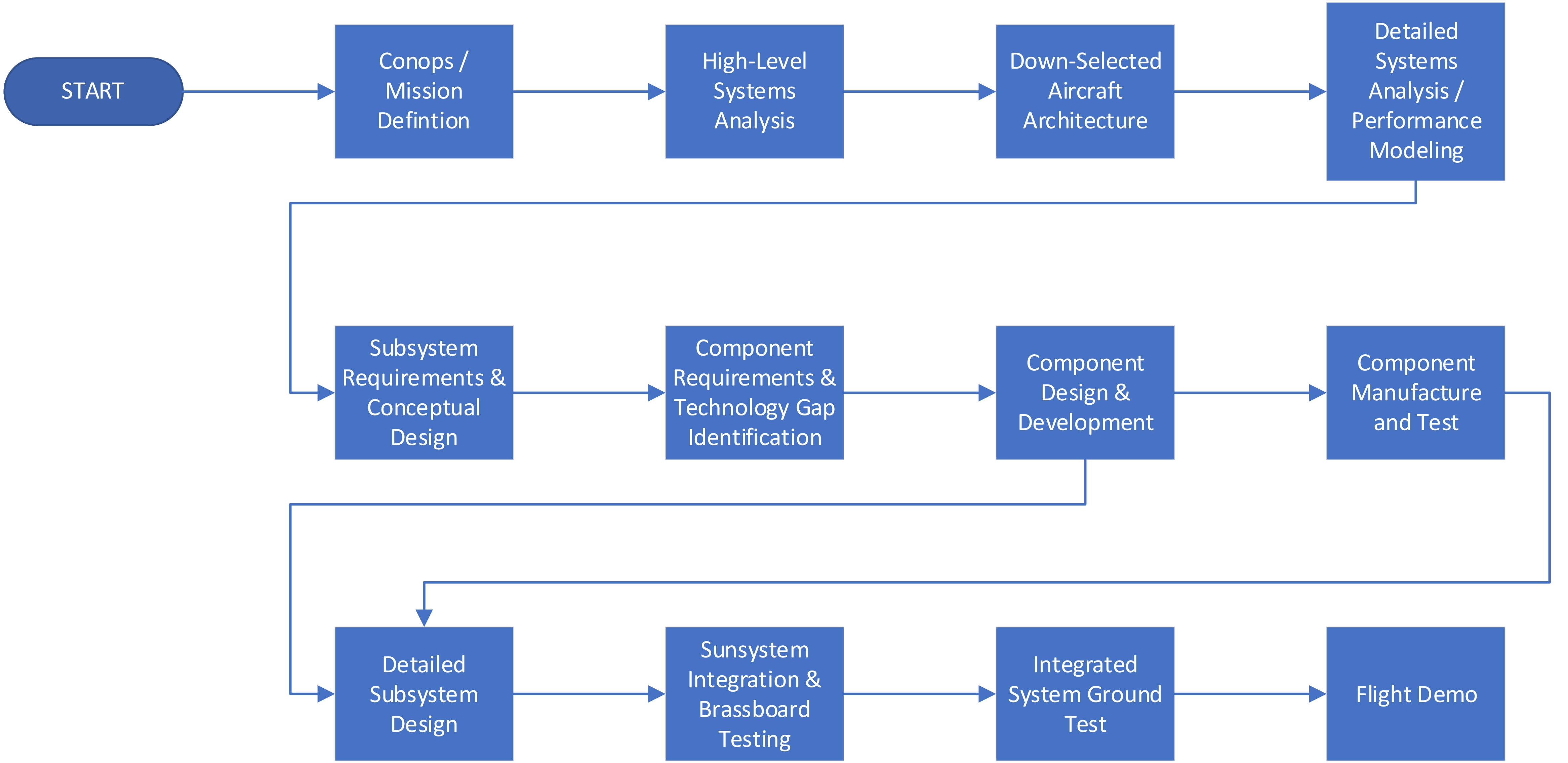


Predicted Hydrogen economy will have impact on aircraft mission requirements and resulting configuration

Technology Maturation



Hardware Development



START

Conops / Mission Defintion

High-Level Systems Analysis

Down-Selected Aircraft Architecture

Detailed Systems Analysis / Performance Modeling

Subsystem Requirements & Conceptual Design

Component Requirements & Technology Gap Identification

Component Design & Development

Component Manufacture and Test

Detailed Subsystem Design

Sunsystem Integration & Brassboard Testing

Integrated System Ground Test

Flight Demo

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 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

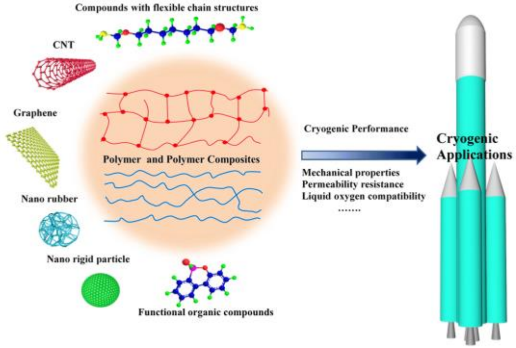
Lightweight, Long-life, Cryogenic Tanks Roadmap

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
- Aeronautical facilities for cryogenic testing

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

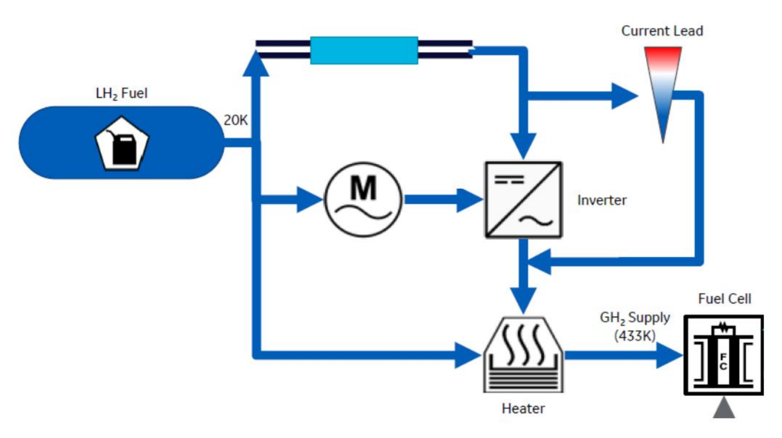
Challenges

- 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

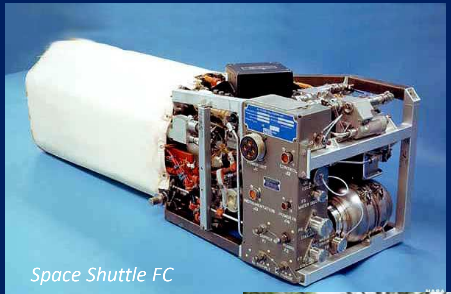


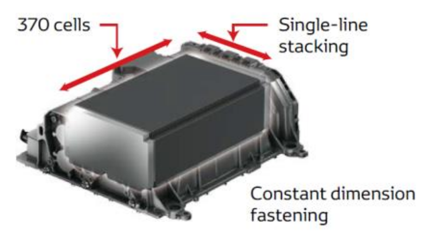
2040-2045
Flight demo with integrated LH2 fuel system
TRL 7

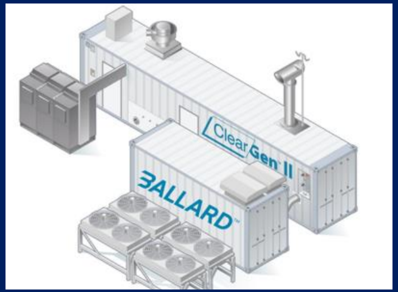
Strategy

- 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

Fuel Cells for Future Aviation


Space Shuttle FC





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

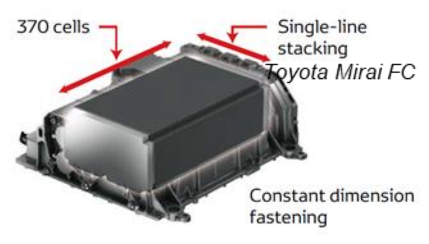
High thermal efficiency of fuel cells implies a fuel volume reduction of ~30%.
NASA experience with kW fuel cell systems for space missions can be leveraged for aviation.
Terrestrial fuel cell industry capabilities are limited to 100-500 kW range for heavy fuel cell systems and BOP.
It requires significant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

General Fuel Cell Roadmap

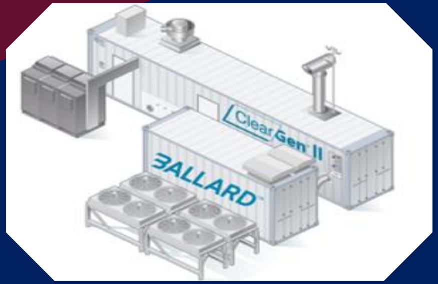
Challenges

- 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
- Diverging performance requirements and environments for aeronautical vs terrestrial and space

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

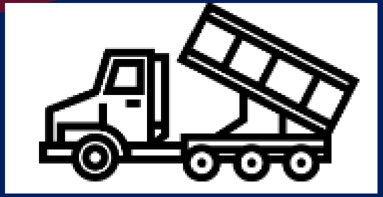


2027-2035
65-68% efficiency
25,000 hours



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

DOE HDV

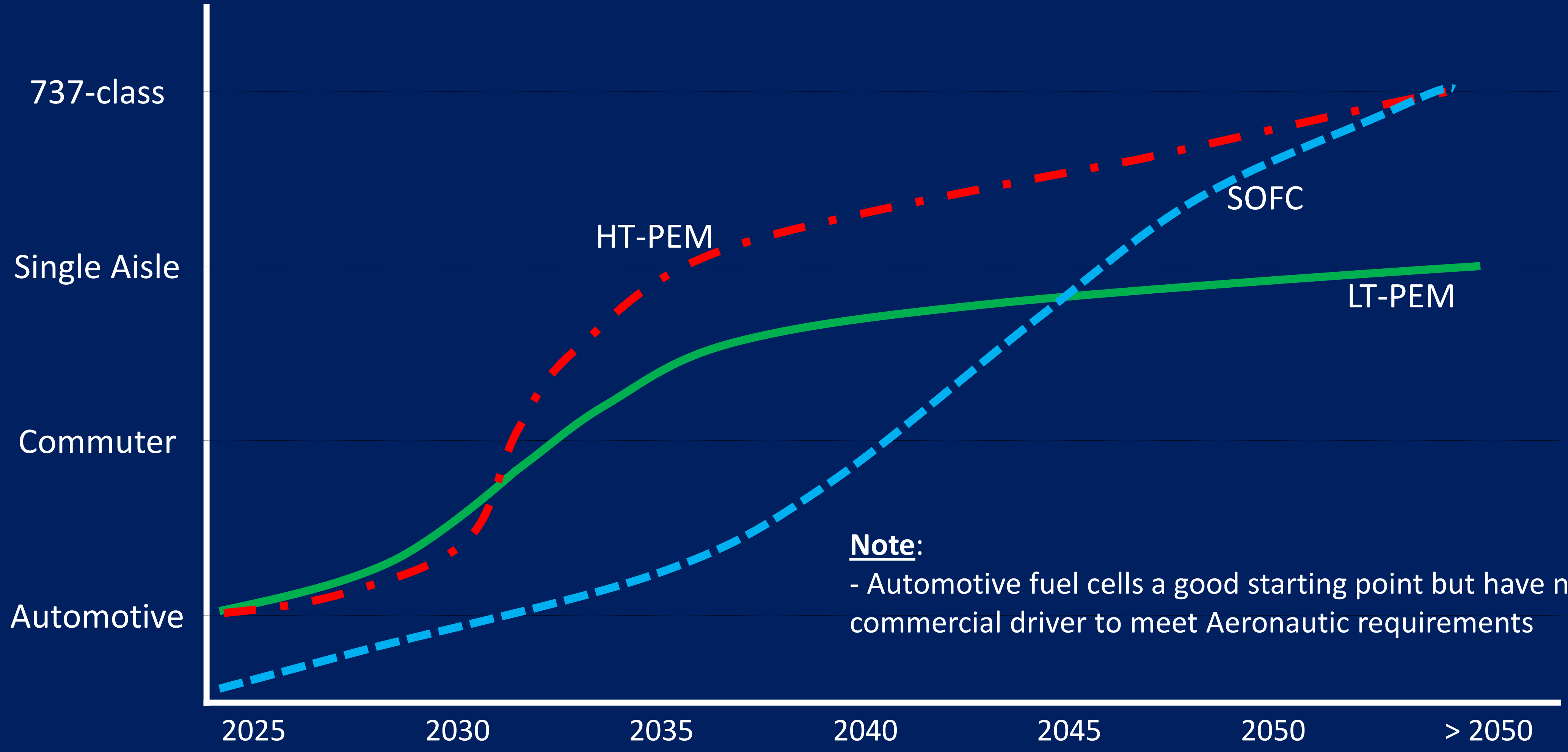


~ 2041-2045
MW fuel cells with high efficiency ready for aviation

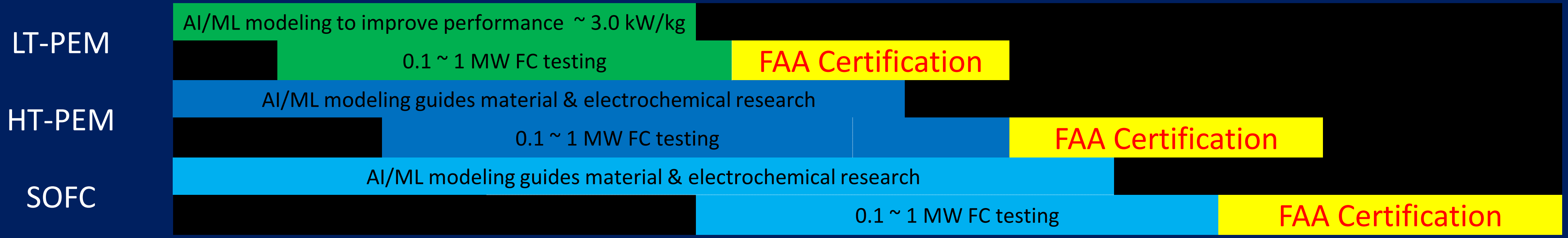
Strategy

- 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

Anticipated Aeronautic Fuel Cell Module Development



Note:
- Automotive fuel cells a good starting point but have no commercial driver to meet Aeronautic requirements


LT-PEM
AI/ML modeling to improve performance ~ 3.0 kW/kg
0.1 ~ 1 MW FC testing
FAA Certification

HT-PEM
AI/ML modeling guides material & electrochemical research
0.1 ~ 1 MW FC testing
FAA Certification

SOFC
AI/ML modeling guides material & electrochemical research
0.1 ~ 1 MW FC testing
FAA Certification

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
- Work with fuel cell materials developers to perform development, characterization and life testing of enabling materials, components and systems
- Facility for MW FC testing

Thermal Management Solutions Roadmap

Challenges

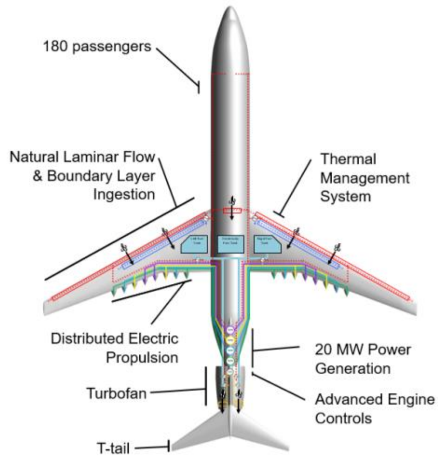
- High Power densities → Higher heat loads that require more invasive cooling methods
- Complex Cooling Strategies → High Performing, dielectric & non-corrosive coolants; need high heat flux, passive components
- Heat Transport → Require lighter heat exchangers, pumps and lines
- Low Quality Heat → Limited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

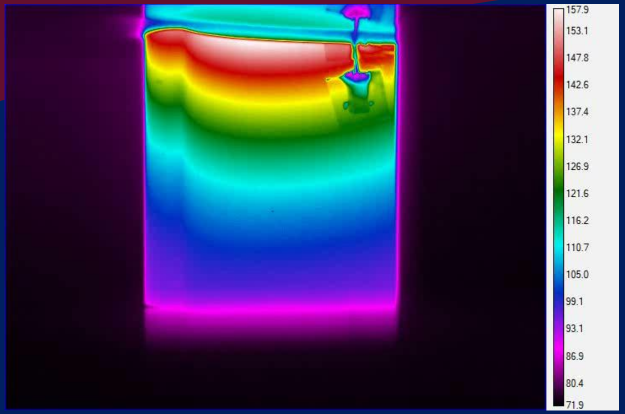
2024-2026
Novel cooling concepts and TMS architectures
Starting TRL 2-3

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

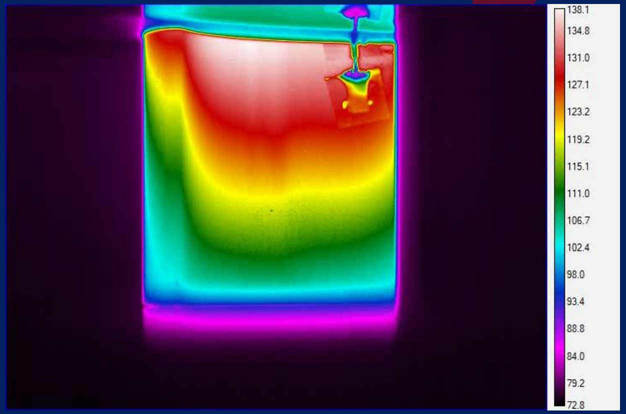
2032 - 2036
Integration of novel concepts into components and subsystems
TRL 4-5

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





80W Power – Baseline (Empty Turbine Vane)

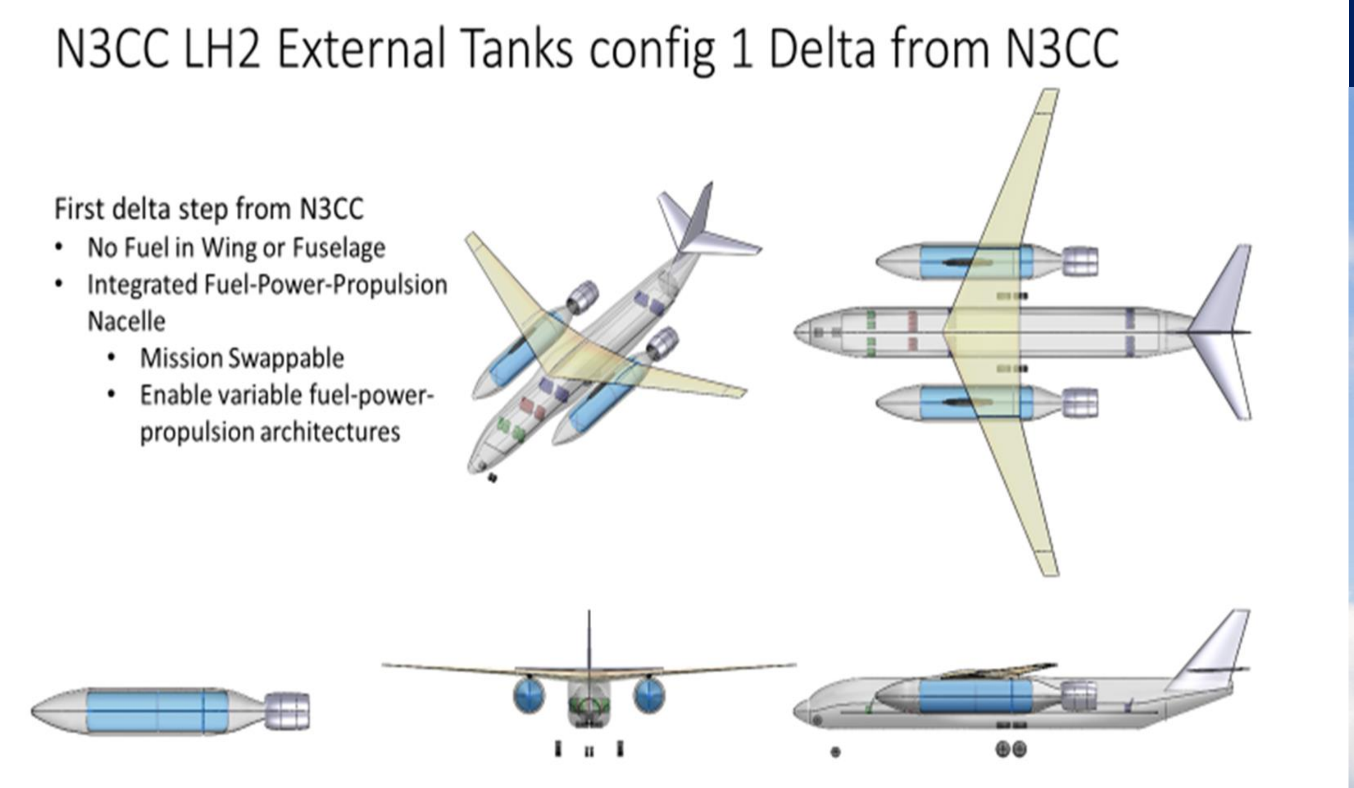


80W Power – Working OHP

Strategy

- Explore, test, 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.)

Aircraft Configuration and Architecture

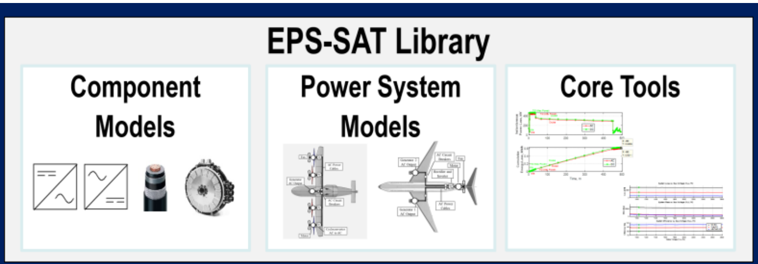


N3CC LH2 External Tanks config 1 Delta from N3CC

First delta step from N3CC
- No Fuel in Wing or Fuselage
- Integrated Fuel-Power-Propulsion Nacelle
  - Mission Swappable
  - Enable variable fuel-power-propulsion architectures

Alternate platform is LM-100J

LM-100J has a cruising speed of ~410 mph and a maximum range of ~2650 miles



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 and quantify key metrics, demonstrate architectural sensitivity to key metrics

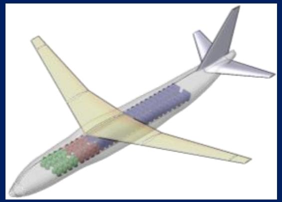
Long Term Fuel Cell Aircraft Configuration Development – 150 PAX

2026-2027
Explore advanced aircraft configurations for improved packaging of LH2/fuel cells
Explore battery hybrids

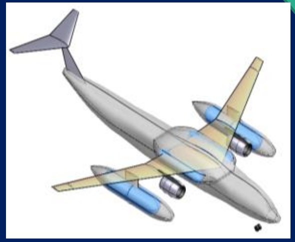
2028-2030
Incorporate improved fuel performance, weight, and increased operating temperature to reduce fuel load for full design range

2031-2034
Incorporate clarified safety requirements into design for internal and external carriage of LH2. Wind tunnel testing of sub-scale vehicle models.

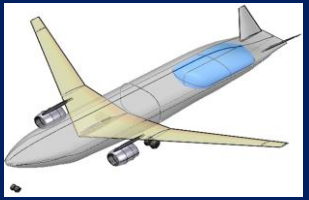
2035-2040
Continued refinement of vehicle concepts with improved component technology. Development of certification requirements. Subscale flight demo.



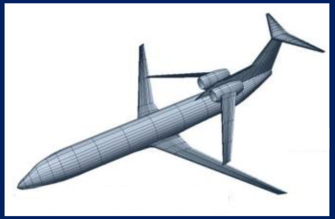
Baseline cryo systems designs



Thermal management systems designs



Next generation Fuel Cell Technology



Update cryo and thermal management technology

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 ~1-2 $/kg, supply and liquefaction developed

Metrics Achievable within next 10 years:

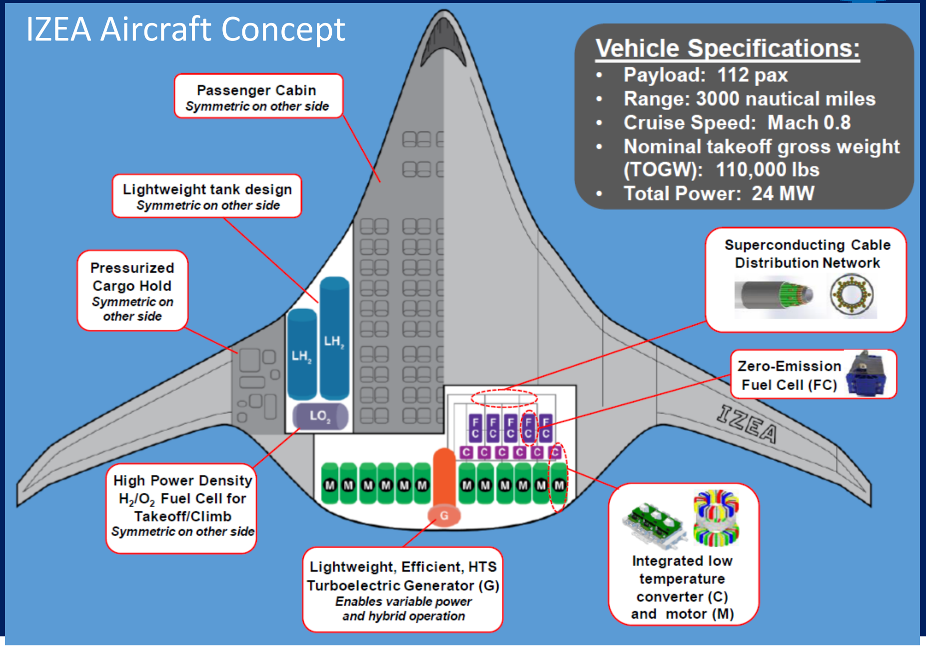
- LH2 →tank mass reduced by 50 % compared to SOA (as a result of boil off requirements change, better tank designs, new lightweight composites for walls and insulation materials) and fuel distribution components
- Fuel cells → 2 KW/kg (at system level) and >60% efficiency, scale up to 25 MWt, reliability to 25000 hrs, water treatment, maturation of high temperature technology
- Thermal management → optimized heat exchangers
- PMAD → 97-99% efficient
- New Aircraft architecture → evolutionary or revolutionary, scalable, distributed hybrid propulsion
- Manufacturability at scale

NASA University Leadership Initiative Zero Emissions Aviation Portfolio

Project IZEA – Integrated Zero Emissions Aviation

Lead by: Florida State University

- Blended Wing Body concept
- LH_2, LO_2 Fuel Cell and H_2 Turbogenerator electric propulsion
- Superconducting power transfer from electrical sources to distributed motor-driven propulsors


IZEA Aircraft Concept

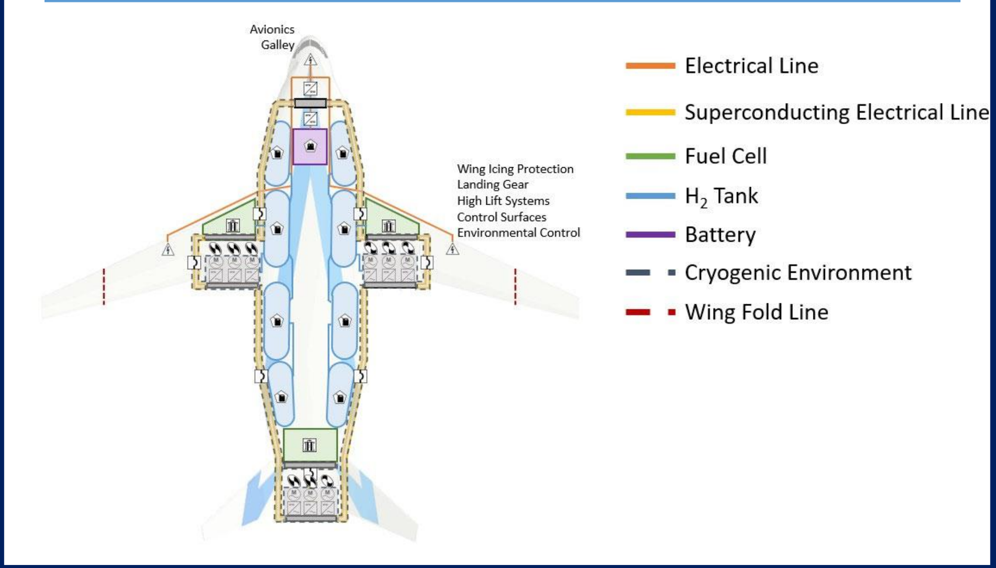
Vehicle Specifications:

- Payload: 112 pax
- Range: 3000 nautical miles
- Cruise Speed: Mach 0.8
- Nominal takeoff gross weight (TOGW): 110,000 lbs
- Total Power: 24 MW

Project CHEETA – Center for Highly Efficient Electrical Technologies for Aircraft

Lead by: University of Illinois Urbana-Champaign

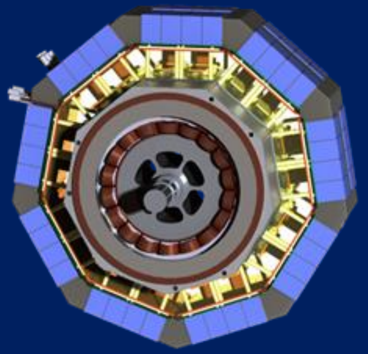
- Superconducting electric machines and high-power transfer
- Novel vehicle planform utilizing distributed electric propulsion and boundary layer ingestion – three sets of three distributed motors
- Hydrogen thermal management and storage system development



Project: Electric Propulsion - Challenges and Opportunities

Lead by Ohio State University

- Designed, Built, Tested a 1 MW Integrated Electric Machine and Inverter Drive
- Tested at NASA's NEAT Facility
- Team conducted regional electric aircraft and battery system studies

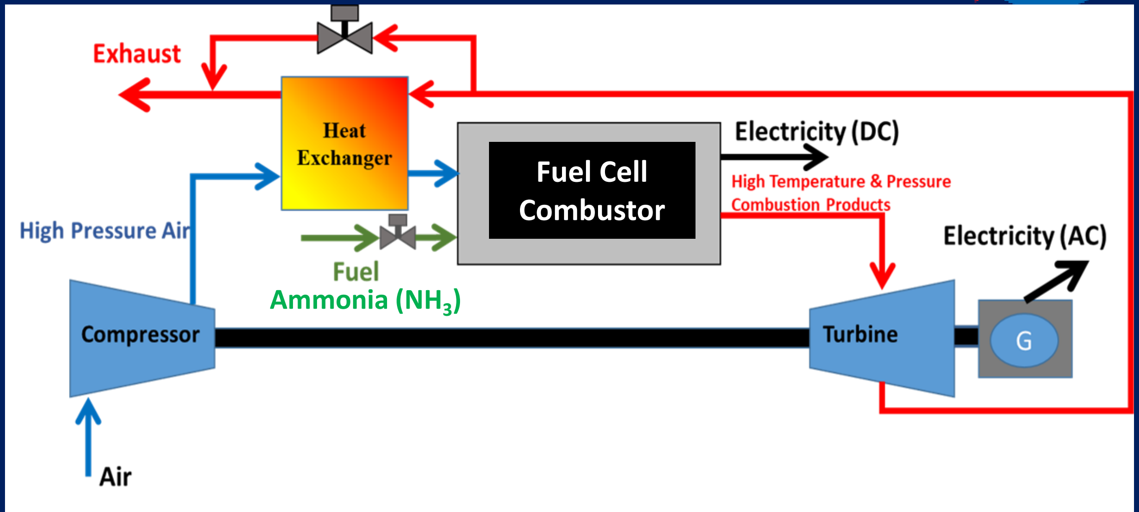

MW Machine (U. Wisconsin)
Power Electronics (Ohio State)

NASA University Leadership Initiative Zero Emissions Aviation Portfolio

Project CLEAN - Carbonless Electric Aviation

Lead by: Tennessee Technological University

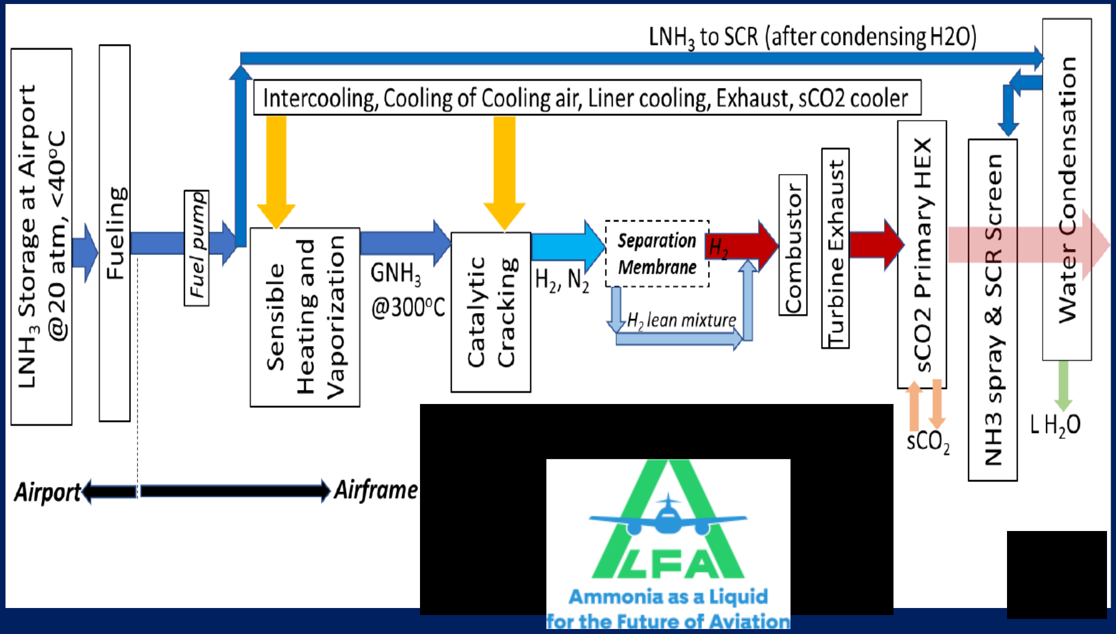
- Solid Oxide Fuel Cell Combustor which utilizes Ammonia (NH_3) as a fuel
- Combustion gas used to generate electrical power in two different ways: fuel cell and turbine-powered generator
- Electrical energy used to power motor-driven fan propulsors
- Team will study environmental impact of concept's emissions



Project ALFA – Ammonia as a Liquid for the Future of Aviation

Lead by: University of Central Florida

- Liquid Ammonia (LNH_3) is stored onboard
- NH_3 gas is partially cracked into H_2 and N_2 and burned in novel gas turbine combustor
- NH_3 used to reduce NO_x emissions through Selective Catalytic Reduction (SCR)
- Supercritical CO_2 cycle used to convert exhaust heat into electrical energy



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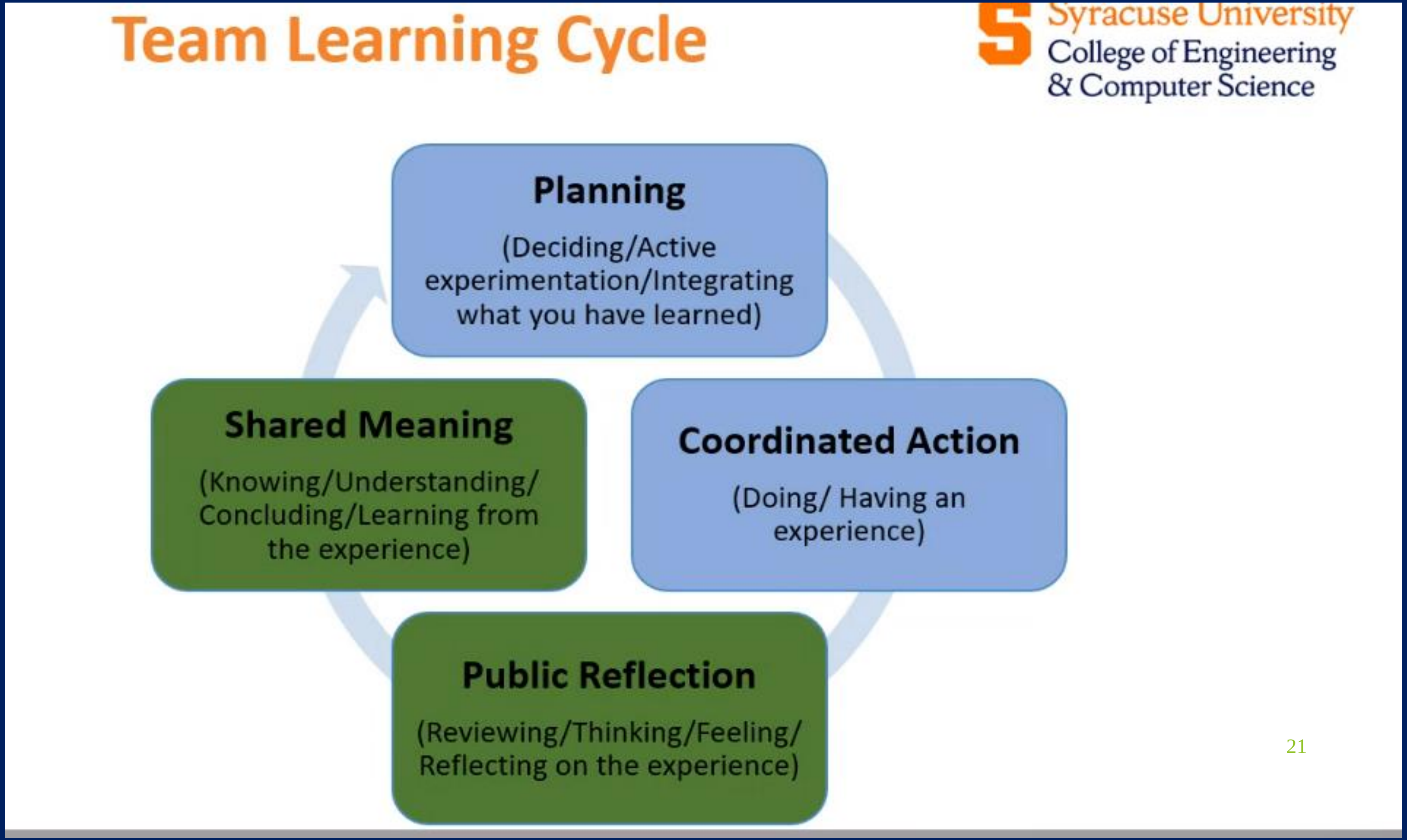
Hydrogen Aircraft Project Development Philosophy

- Wicked problem (John C Redding / The Radical Team Handbook):
- Breakthrough results required, project involves a new / unknown situation the organization has not encountered previously, no ready answer available, solution has been tried unsuccessfully in the past. Approach project as iterative learning process, not a detailed project plan, steps are not well defined / predetermined.



Team Learning Cycle

Syracuse University
College of Engineering
& Computer Science

Planning

(Deciding/Active experimentation/Integrating what you have learned)

Coordinated Action

(Doing/ Having an experience)

Public Reflection

(Reviewing/Thinking/Feeling/ Reflecting on the experience)

Shared Meaning

(Knowing/Understanding/ Concluding/Learning from the experience)

Many thanks to contributors!

Aircraft Architecture:

- Hugh Perkins
- Chris Hartman
- Tom Lavelle
- Tommy Hallock
- Patrick Hanlon
- Lee Kohlman

Thermal Management:

- Hashmattulah Hasseeb
- Jessica Cashman
- Ezra McNichols

Cryogenic Systems:

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- David Koci

Fuel Cell Systems:

- Zhimin Zhong
- Ian Jakupca
- Chris Teubert

Materials and Structures:

- Josh Stuckner
- Fred Holland
- Brandon Hearley
- Sandi Miller
- Stephanie Vivod
- Sadeq Malakooti
- Andrey Boddorff

Regulations and Standards:

- Douglas Feikema

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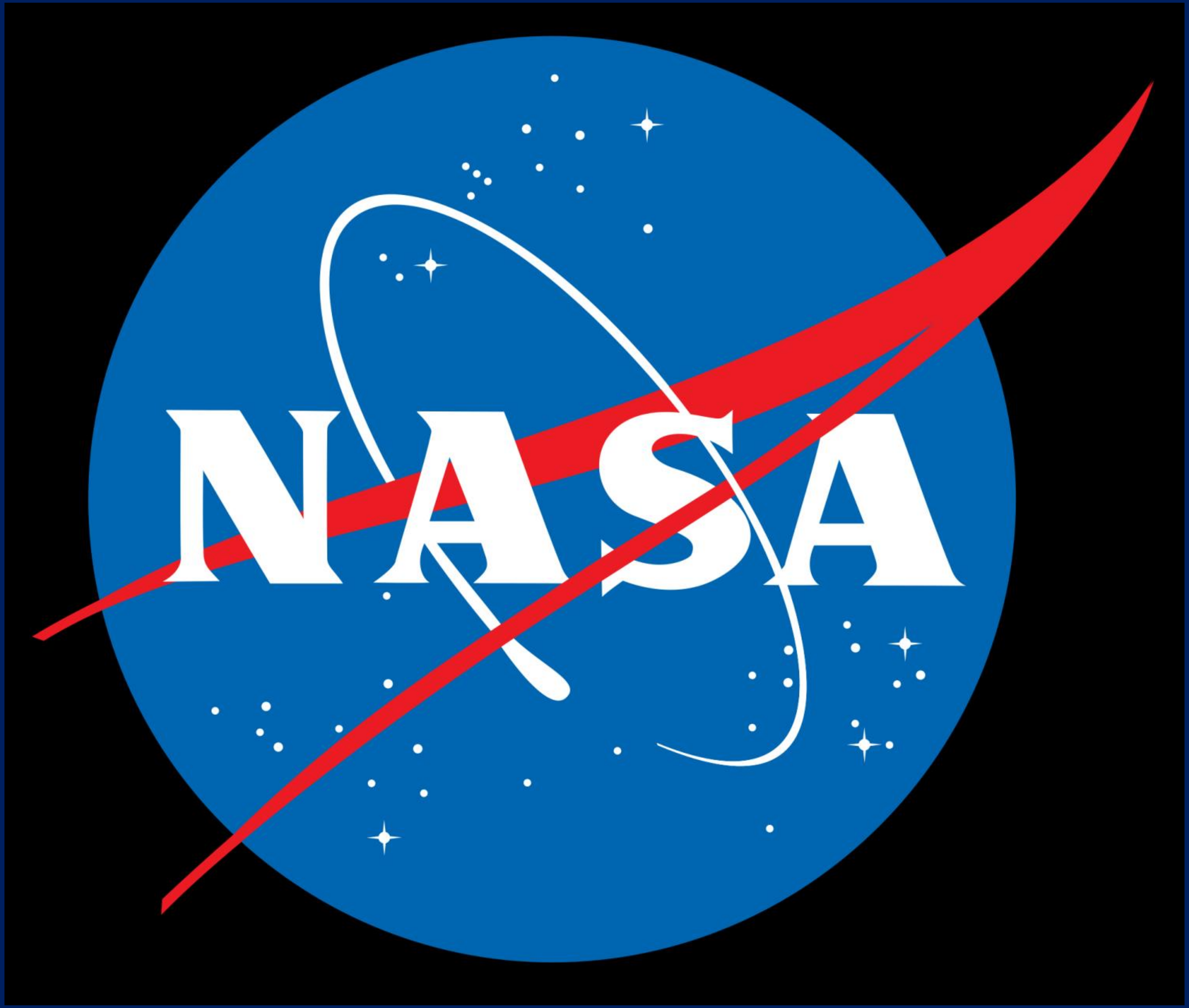
NASA