NASA Liquid Hydrogen Aircraft Opportunities and Technologies

J. Moder
M. L. Meyer
W. L. Johnson
NASA Glenn Research Center
Cleveland, OH 44135

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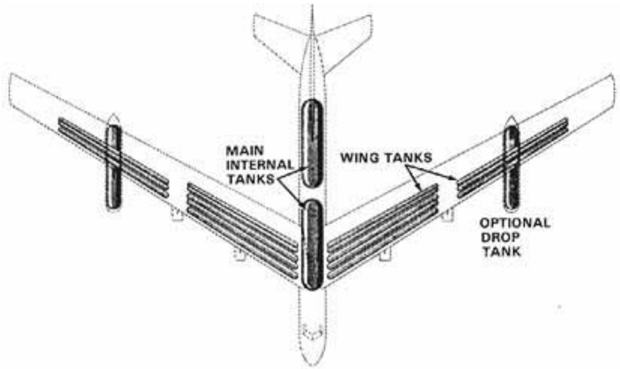
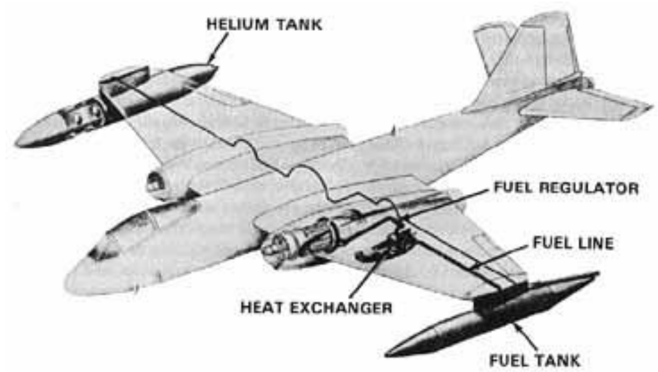
NASA History with Hydrogen Aircraft



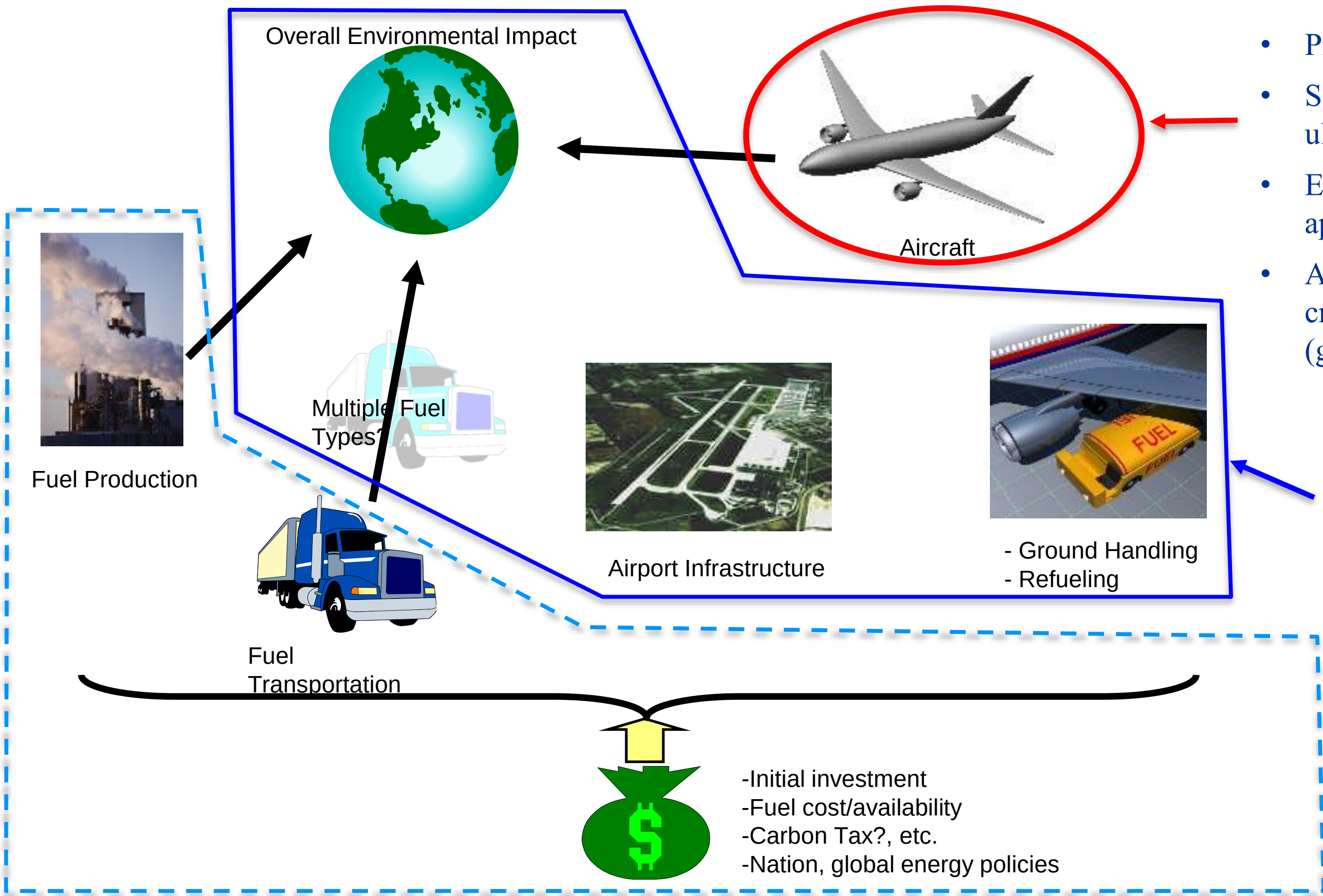
From Silverstein and Hall, "Liquid Hydrogen as a Jet Fuel for High-Altitude Aircraft," 1955.



Liquid-hydrogen fuel system for one engine of a B-57 flew successfully in 1957. Image from NASA SP-4404, "Liquid Hydrogen as a Propulsion Fuel, 1945-1959"

- Consideration of liquid hydrogen as a propulsion fuel dates to at least 1945
- Originally rejected as a fuel for rocket propulsion, it has been utilized for many rockets since
- The NACA (NASA's predecessor) original interest in hydrogen as an aircraft fuel was motivated by its combustion performance at high altitude
- Later interest in LH_2 and/or LNG was motivated by the desire for greater domestic fuel security, concerns about future "peak oil," or higher aircraft performance (e.g., long endurance)
- **The sustainability motivation is new, but challenges and opportunities are similar to the past**

NASA Technology Development Focus

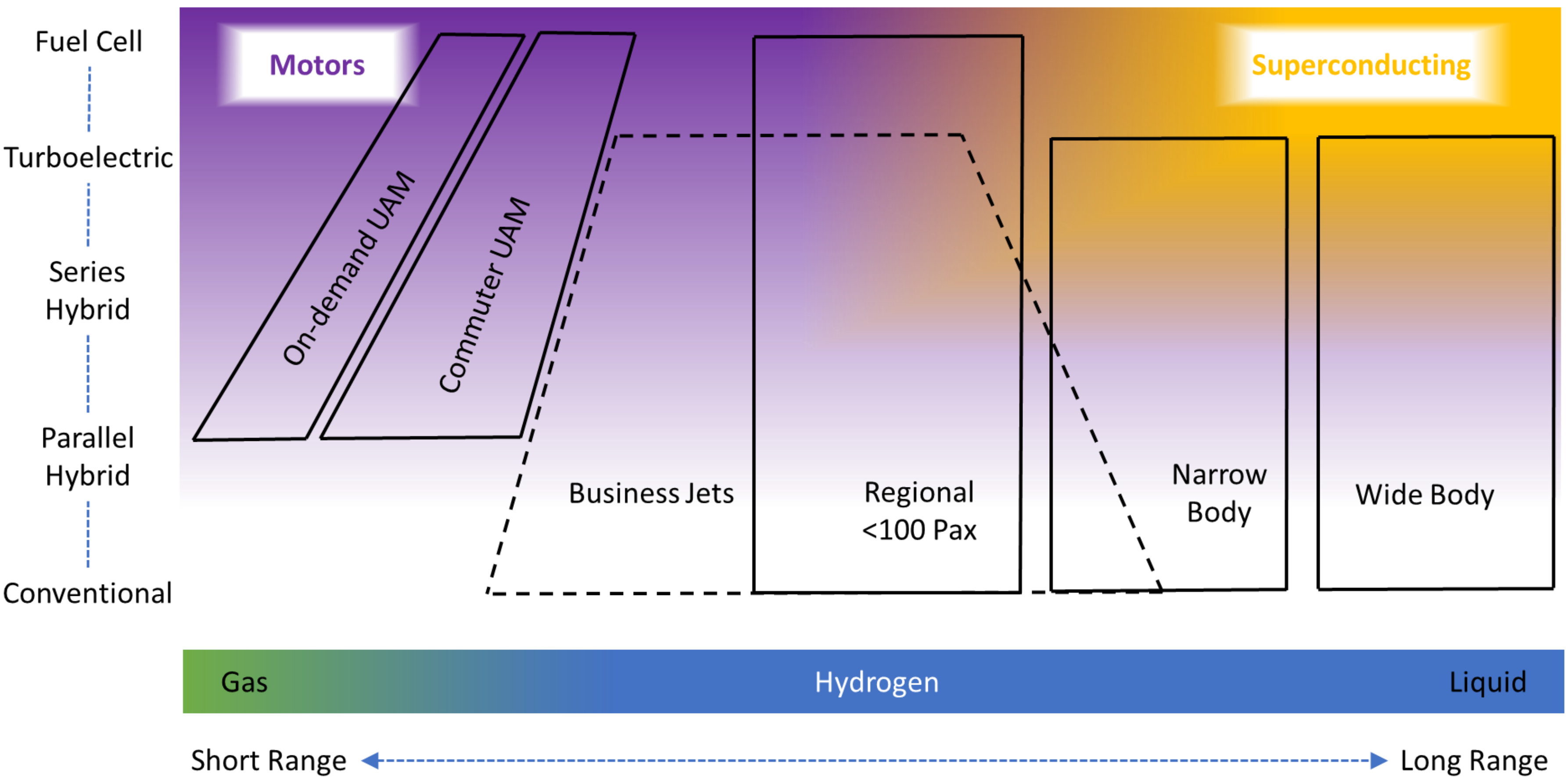


- Primary focus will be the aircraft
- Single-aisle and larger is the ultimate long-term interest
- Experience with smaller applications should be leveraged
- Any propulsion systems using cryogenic fuels were within scope (gas-turbine, fuel cells, hybrid)

- Less focus will be devoted to non-aircraft considerations

- Not a direct part of NASA Scope

A Spectrum of Hydrogen Aircraft Solutions



Credit Lee Kohlman and Dave Koci

NASA Hydrogen Aircraft Research Opportunities

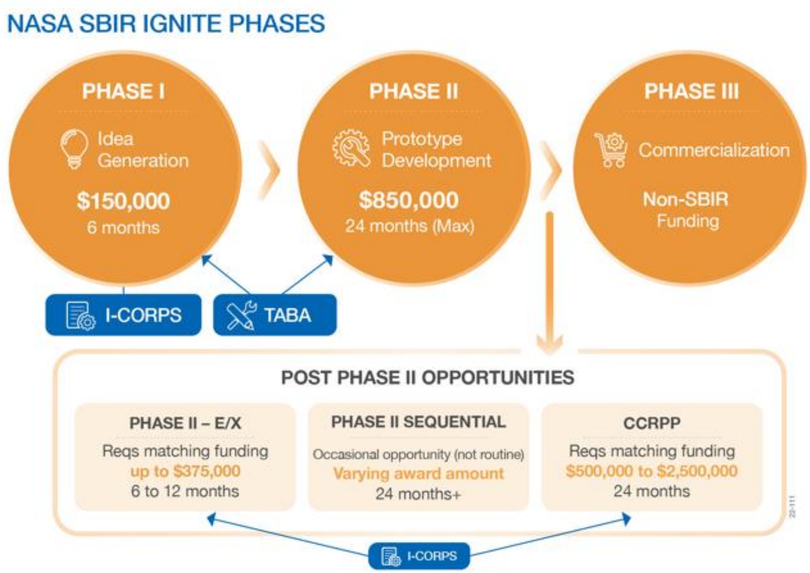
Currently the Aeronautic Research Mission Directorate has a suite of hydrogen related research activities.

These include activities in liquid hydrogen aircraft:

- University Leadership Initiatives:
  - CHEETA (University of Illinois led, multiple partners)
  - IZEA (Florida State University, University of Buffalo)
- Internal NASA “smart buyer” activities/studies designed to quantify system level performance and sensitivity on various components
- Small Business Innovative Research Awards:
  - 2023 call requested proposals regarding tanks, pumps, valves, fueling technologies, and energy management (aka heat exchangers and thermal balancing)
  - NASA SBIR Ignite (https://sbir.nasa.gov/ignite) proposals due Sept 1, 2023
    - Focused more on near term commercialization

NASA SBIR Ignite Aircraft

Problem Statement: The purpose of this topic is to stimulate U.S. entrepreneurship in the emerging markets of hybrid electric aircraft. Components are sought for integration, ground, and potential flight testing for a 1500 lbs. class hybrid electric drone. Proposals should support market introduction to the existing large UAV or the emerging electric and hybrid electric aircraft markets. The topic seeks solutions applicable for Unmanned Aerial Vehicle (UAV) and Aircraft in the 1500 to 5000 lbs size class with near term market entry onramp.



NASA / Industry/ Academia /Other Agencies Workshop

- In September 2022, NASA hosted a workshop with industry and academia
- All participation was in person, restricted to US persons, and by invitation only
- Total number of attendees: 88
  - 57% non-NASA, 43% NASA
- Government
  - AFRL, DOE, FAA, NASA
- Industry: 18 different companies from component level to large propulsion and airframe suppliers.
- Academia

Motivation

- As Commercial Aviation pushes towards greater sustainability and a “net-zero” future air transportation system, cryogenic alternative fuels have been postulated as possible solutions
- LH2 aircraft concepts are currently being developed by industry, with significant programs funded in Europe and the U.K.
- “Green LNG” could also be a possible approach, and ideas to utilize liquid methane or natural gas for aircraft have also been postulated in the past
- NASA Aeronautics does not currently have significant investment in developing cryogenic aircraft technologies, but NASA does have significant expertise and capabilities with cryogenic fuels from its space exploration activities

Meeting Objectives

1. Provide a forum to facilitate interaction between cryogenic experts supporting NASA space endeavors and entities interested in cryogenic fuels for aviation

2. Hear from industry, academia, other government agencies about their experiences with cryogenic aircraft

3. Have a community dialogue about the challenges and opportunities associate with cryogenic fuels for aviation

4. Provide information to be used by NASA Aeronautics in developing a future research strategy for sustainable aviation

Prospects for a Cryogenic Fuel Aviation Future

1. Meeting attendees had a broad range of opinions on future aviation fuels and the challenges of cryogenic fuels – from “no problem, we can do it now” to “we are many decades away”
   - Part of the discrepancy may be attributable to the application domain (small vehicles vs. large commercial transports)
   - Many see a future “H_2 economy” as inevitable and therefore aviation’s participation in the economy is certain
2. The capital investments required just to make the fuel available at airports are staggering (not including the introduction of new vehicles)
   - Other sustainability approaches, such as SAF, also require large investments
3. Given the large amount of renewable electricity required to produce “green” hydrogen for aviation, aviation may have to build a dedicated electricity/fuel infrastructure instead of tapping into the grid
   - Decarbonizing aviation by using renewable energy to produce green cryogenic fuels before first making the overall electricity grid 100% green may result in a net negative climate impact
4. No consensus was reached on the prospects for green LNG/LCH_4
   - LNG challenges are not as severe as LH_2
   - Some pointed to the ability of LNG to leverage the existing natural gas infrastructure throughout the world (as with LH_2, “greening” of the LNG supply is still necessary)
   - Others felt zero “tailpipe” CO_2 emissions was absolutely necessary
   - Strongest advocacy for LNG was for DoD applications

External Perspective on NASA Research Investment Opportunities

- 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 leadership role in pulling community together on cryogenic fuels for aircraft.

Some Relevant NASA Experience from Space Applications

- Ground operations logistics
- LH2 test facilities: from laboratories to ~ million pound thrust propulsion stands; research, technology maturation, and system development
- Flight qualified hydrogen components and systems
  - Typically with industry partners
  - Hardware and operations
- Cryogenic System Safety and standards for test facilities, ground operations, and flight
- Characterization of materials, material design implementation, structural characterization for cryogens and cryogenic temperatures
  - metallic and non-metallic
- Low loss/weight optimized on-board storage and handling of cryogens
- Sensors/instrumentations: new concept development and implementation for operational systems
- Systems studies and climate research
- Simplified and physics based cryogenic fluid/thermal simulation

New Pad B LH_2 Storage Vessel

- 1,250,000 gal ($4{,}732\ m^3$) usable volume – 47% larger than Apollo-era tank
- 83 ft. (25 m) outer diameter; MAWP = 90 psig (6.2 bar)
- Spec NER = 0.048% (600 gal/day, 2,271 L/day)
- Being built adjacent to existing tank; construction to end July 2021

Design includes <u>2 new technologies</u>: **Glass Bubble bulk fill insulation** in lieu of perlite, and an **Integrated Refrigeration and Storage (IRAS)** heat exchanger

Laboratory Test Capability Examples

Thermal Conductivity Measurement

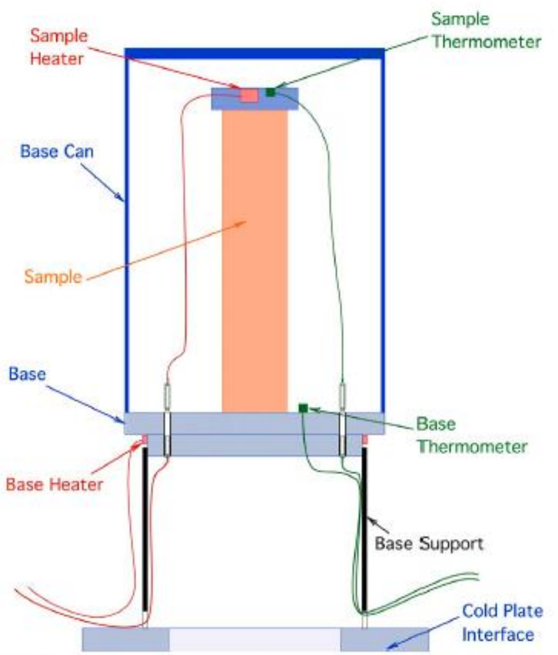


Fig. 1. A schematic representation of a basic thermal conductivity measurement apparatus. There are problems with this approach which make it inappropriate for high-precision measurements.

Credit: Cryogenics 88 (2017) 36–43

Precision CTE measurement down to 6 K

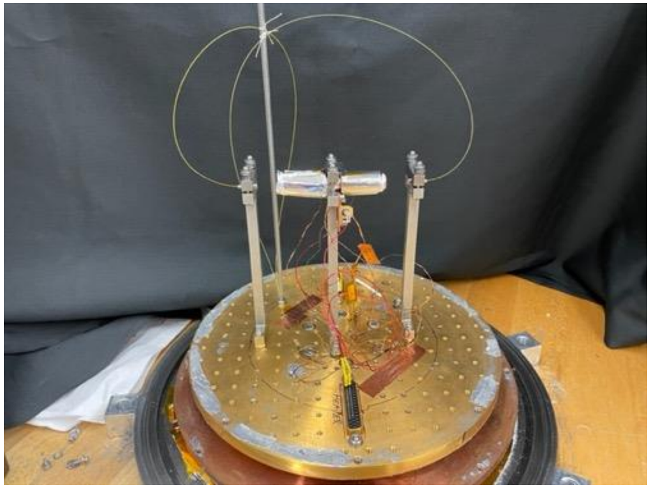
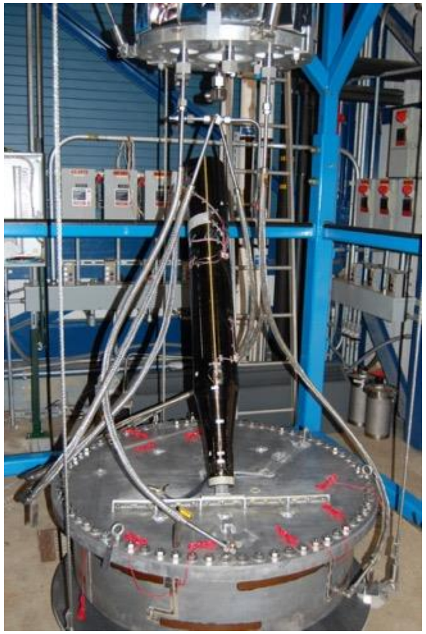
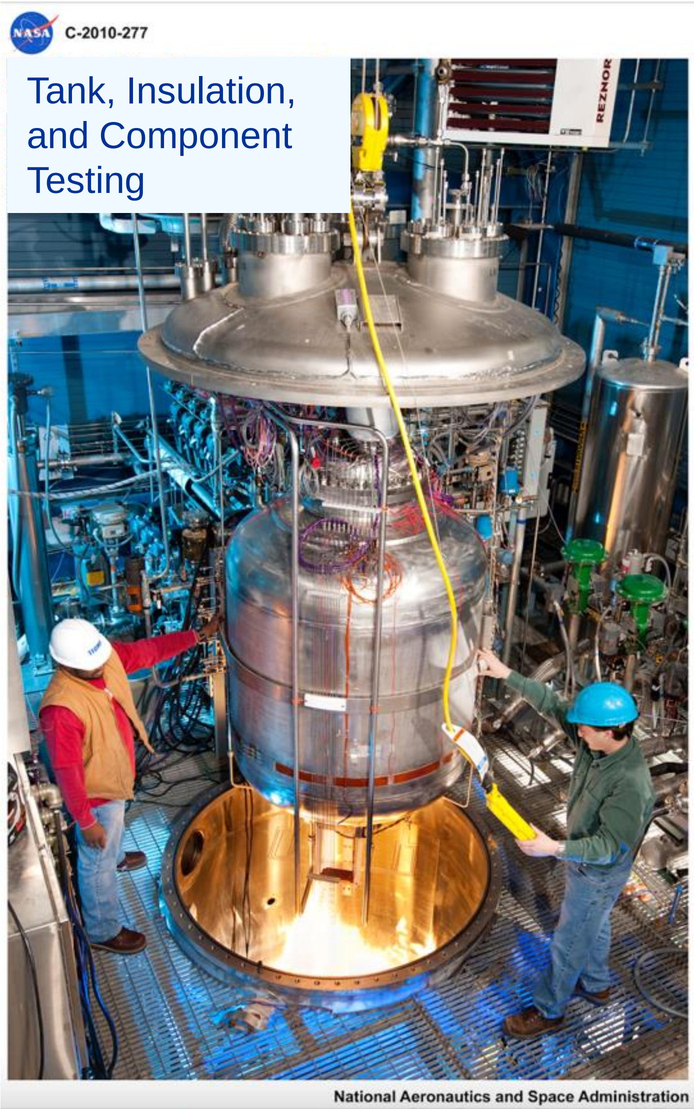


Image Credit: NASA/GSFC



Structural Component Testing

Example Component and System Level Test Capability



Tank, Insulation, and Component Testing

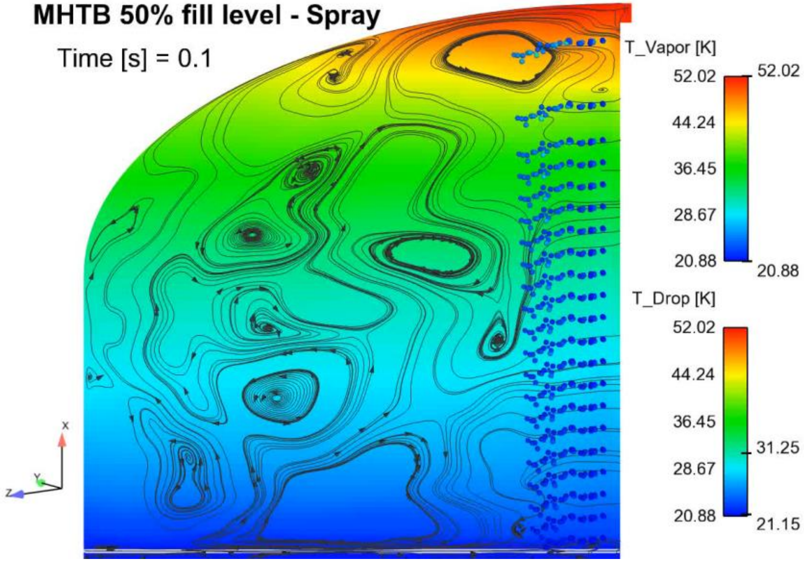
RS-25 Engine Test (~500 Klbf thrust)

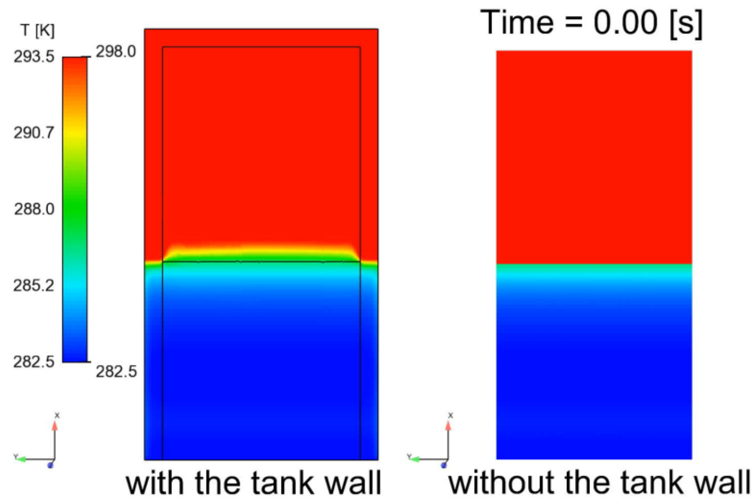
Image Credit: NASA/SSC

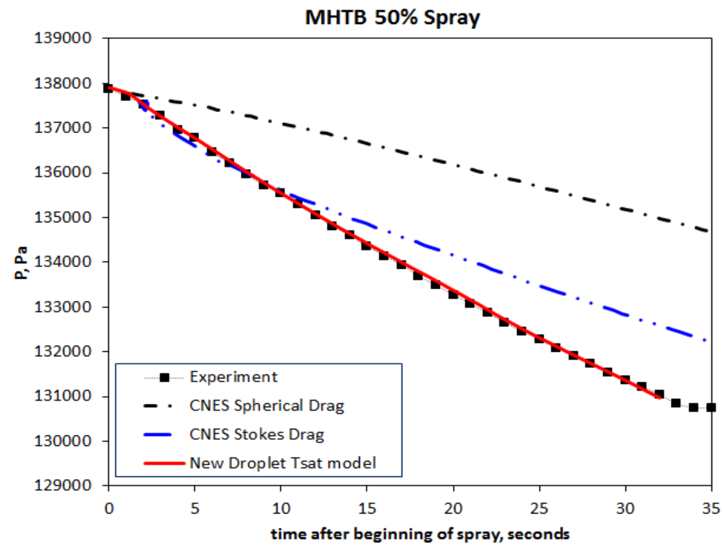
LH2 and LO2 storage barges

High and Low Fidelity Fluid/Thermal Simulations

- Sloshing
- Mixing
- Self-Pressurization







NASA Overall Perspective

- NASA is interested in the development of liquid hydrogen aircraft.
  - But NASA must develop plan forward that includes existing activities planned.
  - Address the full life-cycle of the aircraft
  - Address safety and operational activities around the aircraft
- In aeronautics, NASA doesn’t develop the full solution on its own.
  - NASA partners with industry to both leverage industry’s resources/expertise and ensure better infusion of results into operational systems.
  - Focus of US government resources to support US capability.
  - Lower funding than the space areas and pragmatic about changing investment focus.
- NASA doesn’t believe there is one solution that will meet all of he energy needs by itself.
  - A suite of solutions is needed with each solution needing it’s own R&D
  - Enables earlier and phased impact toward a goal of “green” aviation.