Cryogenic Hydrogen Studies and Testing for Advanced Aircraft at NASA

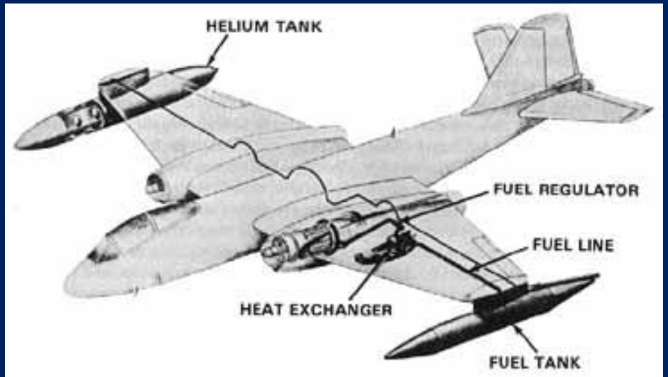
Vadim F Lvovich, Wesley L. Johnson, Stephanie L. Vivod
NASA Glenn Research Center

April 3, 2025

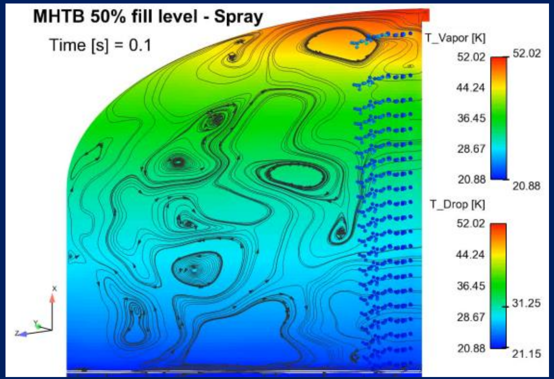
4th Annual VFS H2-Aero Symposium, Long Beach, CA

NASA's Experience with Cryogenic Hydrogen Systems

- NASA has been a major user of Liquid Hydrogen for the past 80 years.
- While many outside of the space sector only see the large storage / distribution system at KSC, there is a wide variety of activities suited for engaging with the liquid hydrogen push in addition to those at KSC.
- How can this be leveraged to help US Industry move forward in it's interest in hydrogen aviation?



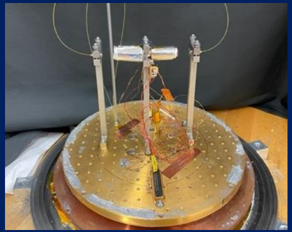
Liquid-hydrogen fuel system for one engine of a B-57 flew successfully in 1957. Image from NASA SP-4404, "Liquid Hydrogen as a Propulsion Fuel, 1945-1959"



Liquid Hydrogen System Modeling

Liquid Hydrogen Technology Development and Testing

Liquid Hydrogen Operations on Launch Pads



Low Temperature Materials Development and Characterization

Transportation Systems Vehicles

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

Cryogenic Systems – Terrestrial, Space, 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

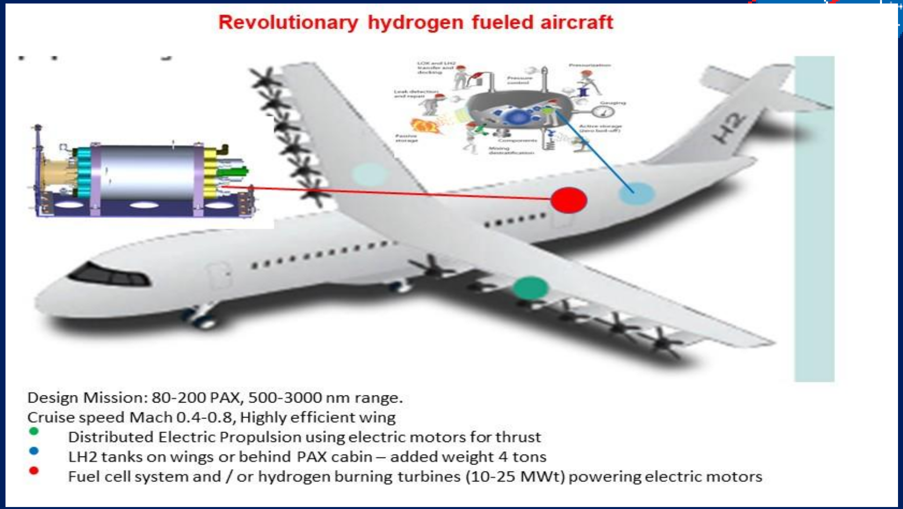
NASA experience with cryogenic fuel systems for space and ground support require development to help close gaps in the integration of cryogenic fuel systems and propulsion into aircraft

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 leadership role in pulling community together on cryogenic fuels for aircraft

“Commercially-viable Hydrogen Aircraft for Reduction of Greenhouse Emissions - and Remarkably Great Efficiency” (CH_2ARGE) Scope and Direction



The Opportunity:

Hydrogen is the leading candidate fuel that can provide efficient and low-emissions aviation by 2050.

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

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

Determine the role of NASA in emerging hydrogen economy.

The Strategy:

Develop integrated conceptual and experimental methodology that enables industry-wide adoption of medium-range Hydrogen Aircraft. Mature the methodology and identify system level closure plans and technology development targets. Develop an integrated aircraft concept of operations. Develop critical roadmaps in aircraft architecture, thermal management, cryogenics and fuel cells. Study the concepts' efficiency at scale and relative environmental impact.

Considerations:

The MAIN PRACTICAL GOAL is to increase specific energy of the whole aircraft by 2-3X by synthesis of on-board lightweight, durable and safe cryogenic hydrogen system, thermal management, hydrogen-air fuel cells / turbines, and distributed electric propulsion.

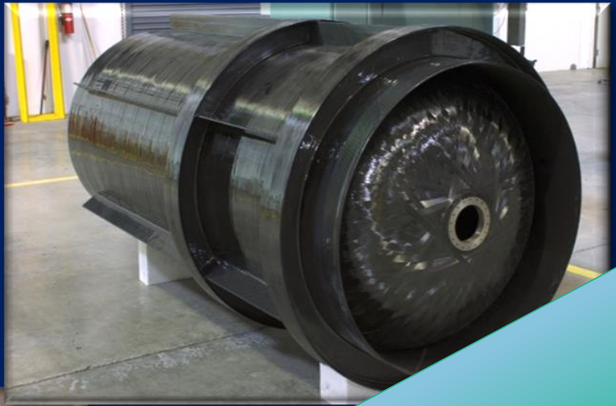
This requires a comprehensive system-specific studies and practical solutions in identifying advanced materials, modeling tools, & evaluation criteria.

Capitalize on technology synergies and test facilities across multiple NASA centers.

Possible Test Considerations

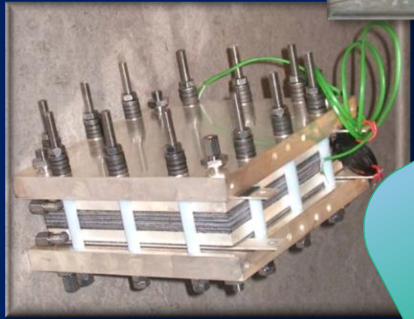
All of these components have room for improvement for material advances

Composite Tanks

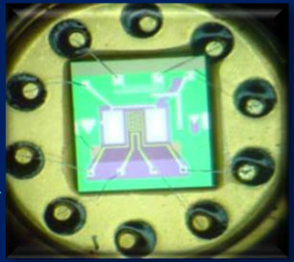


Pumps, Valves, and High Efficiency Transfer Lines

High Temperature PEM Fuel Cells

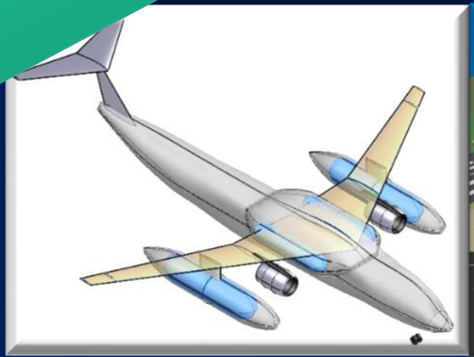


Leak Detection



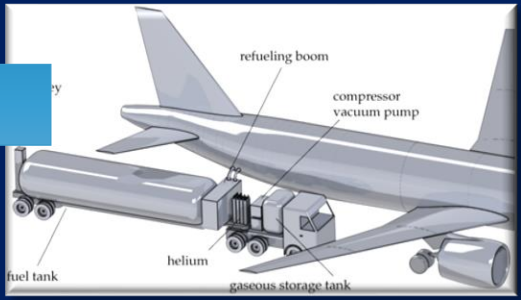
Polymer Aerogel Infused Tanks

ted Aircraft



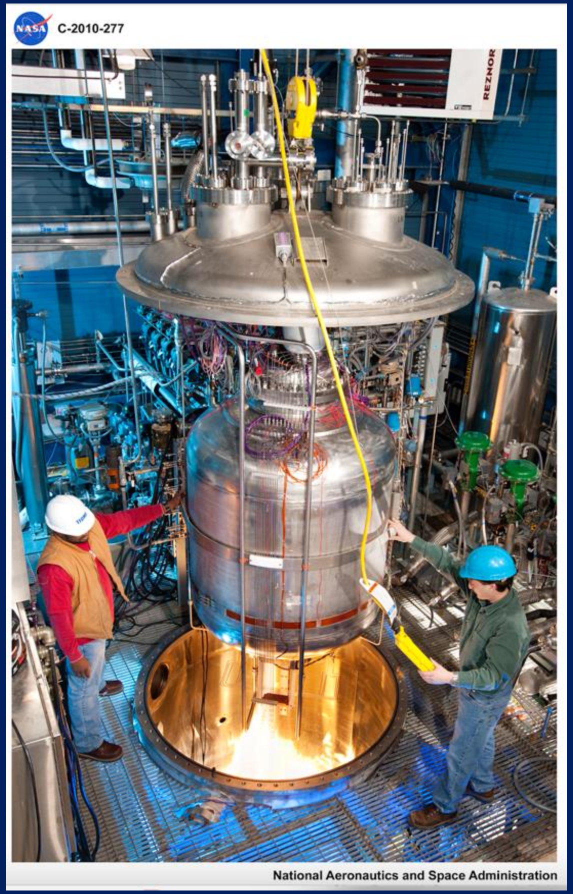
Airport Energy Hub

Aircraft Refueling Ops



Material Characterization Needs

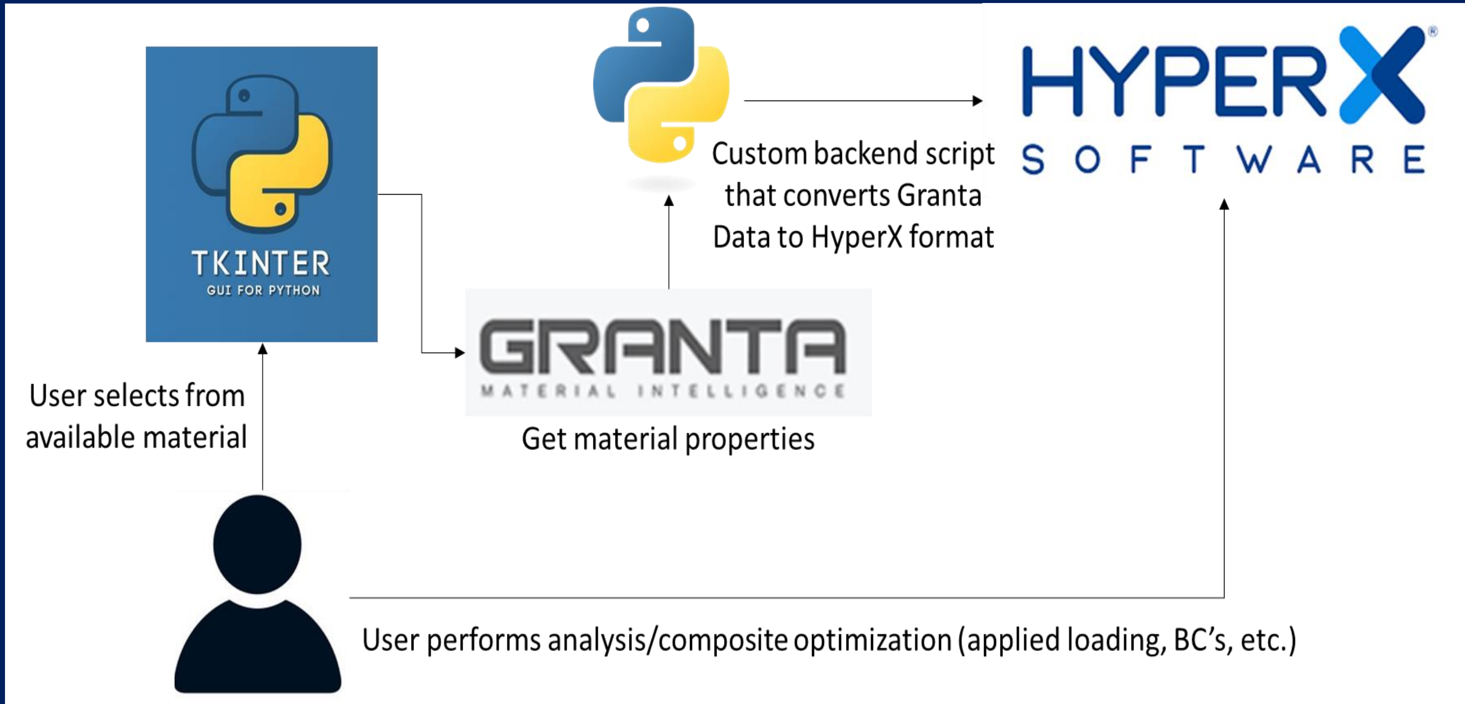
- All hydrogen test facilities will require advanced concepts and materials to enable new solutions for hydrogen storage, transport and transfer
- Appropriate and efficient materials characterization in a relevant environment
  - Properties need to be measured as a function of temperature down to at least 20 K
- Development of testing capabilities providing key performance parameters (property targets) include :
  - Thermal Properties (CTE, Tc)
  - Mechanical Properties (Static and dynamic loading)
  - Physical Properties (density, pore structure)



Liquid Hydrogen Technology Development and Testing

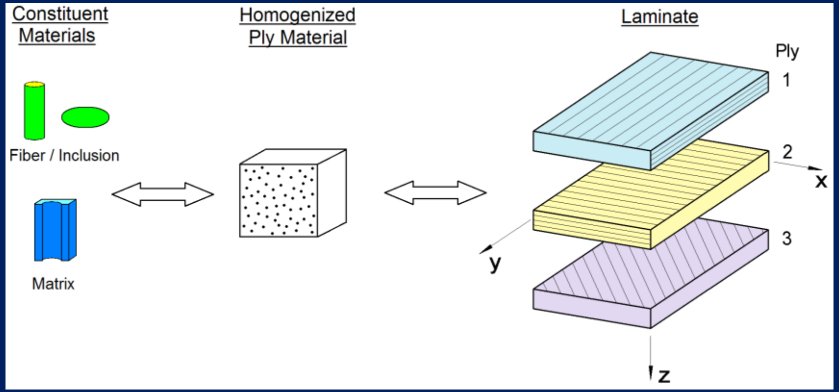
Material database and testing progress

- Conducted testing for aerogels, metallic composites, and carbon-polymer composites
- Synthesized samples, measured thermal conductivity, fatigue life testing
- Collaborating with NASA MSFC, NASA GSFC and LeTourneau University
- Working to determine the input file requirements for temperature dependent material properties
- Developing materials database that allows modelers to select a material, connect to Granta MI, and automatically write the material card
  - Need to configure current schema to HyperX attribute names and automate the writing process

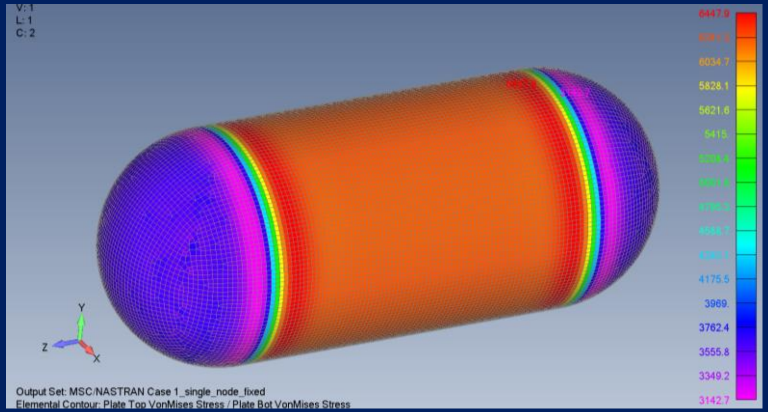


Modeling for cryogenic materials and components evaluation

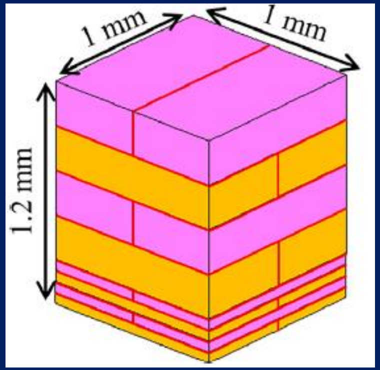
1. In Progress: Multiscale model of laminate and ply microstructure
   – Cool to cryo and evaluate residual stresses per material system

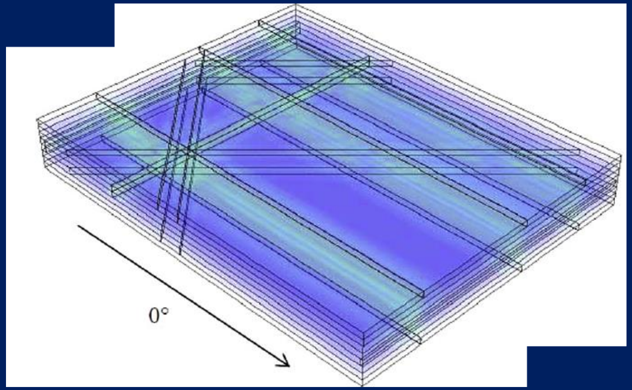


2. In Progress: NASTRAN/HyperX model of tank
   – Use HyperX with realistic thermo-mechanical load cases to evaluate optimized designs per material system



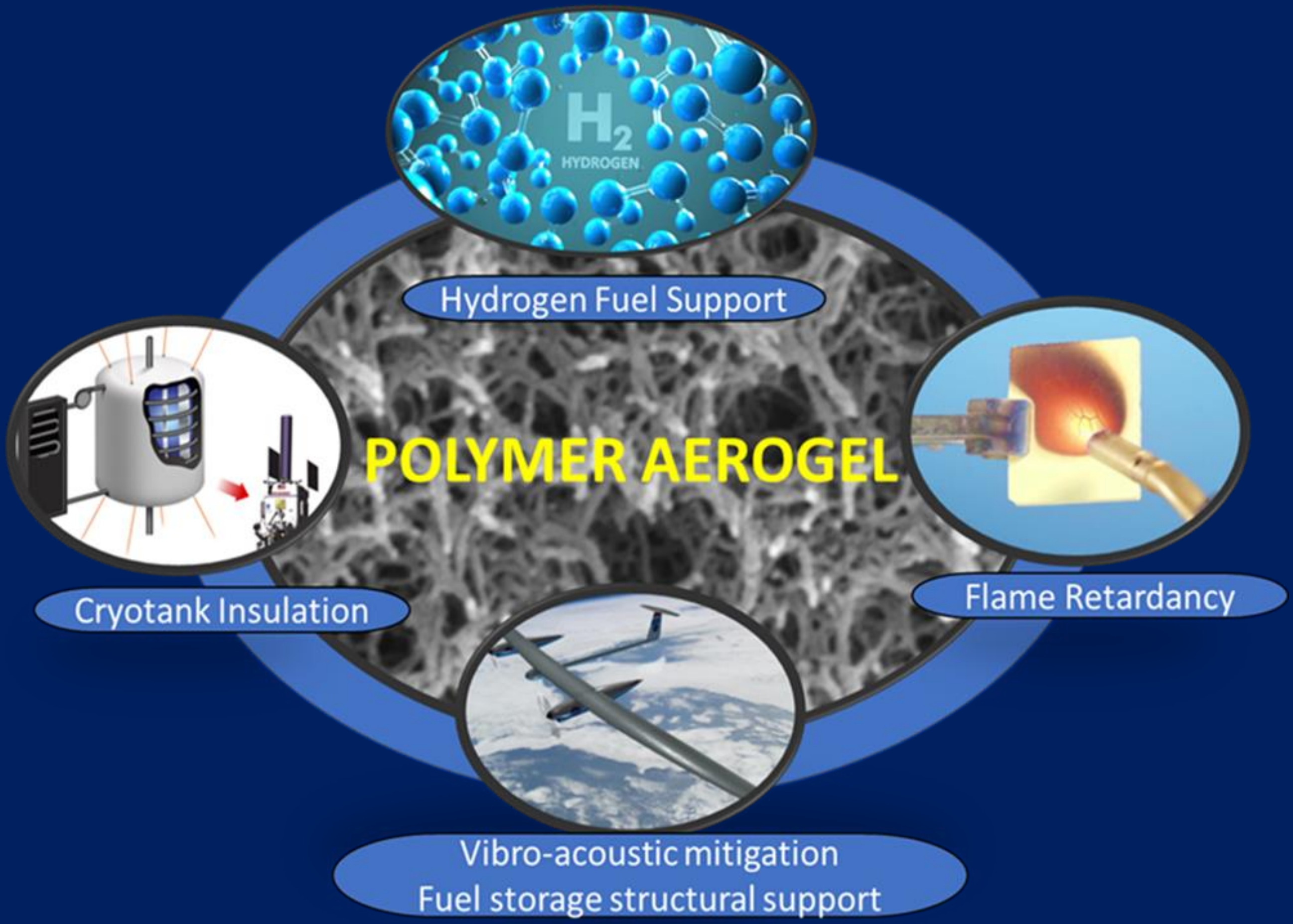
3. Progressive damage modeling to model microcracking and permeability
   – Laminate level or full multiscale FEM
   – Possibly beyond current resources





Nanostructured Insulation

Benefits: Lightweight, structurally sound aerogels (over 200 MPa compressive modulus) as internal and external insulation for hydrogen storage tanks can improve efficiency and safety while expanding volume capability and range limits of the craft



- Polymer based network that is chemically and thermally compatible with high energy liquid propellants
- High porosity, large surface areas = advantages of housing a liquid with handling characteristics of a solid (reduce sloshing induced vibration)
- Tortuosity of underlying matrix has insulative effect to reduce boil off. Reduction of heat ingress.
- Flexibility retention and lower Tc in cryogenic environment

Collaborative Hydrogen Aero Testing Area

Opportunity:
There is a large and increasing need for hydrogen test capabilities for the development of components, subsystems, and systems for aircraft and other transportation systems. Industry is showing a desire to develop systems for clean energy solutions, but testing with hydrogen, and especially liquid hydrogen is challenging and costly. Furthermore, there is a need to explore the trade-space around operational aircraft refueling. There may be synergistic ways to combine the two problems.

"Wicked-Wild" Idea:
Development of an airport-like liquid hydrogen test and development center of excellence that can support US Industry and US Government development needs utilizing NASA's facilities and experience that provides capabilities within practical timelines.

RFI “Development for Test Facility in Advancing Hydrogen Technology Development for Aeronautic Applications” Scope

What this is:

An exploratory activity to understand:

- What a test facility might look like / need.
- What the needs are for testing with various forms of hydrogen.
- What industry groups and government agencies are interested in participating in this conversation.
- Widely advertised in trade journals, technical societies, working groups, perspective responders

What this is not:

- A commitment on behalf of NASA to fund anything.
- Looking for proposals for technology development or testing.
- A detailed conversation with all of industry.
    - Can follow up with key respondents

RFI Areas of Interest

- Testing –
  - What are the testing needs/objectives that might drive the requirements for this capability?
  - What gaps are there in testing standards or protocols are there in testing?
- Facilities –
  - What are the essential characteristics/functions of the facility?
  - How can that be developed over time?
- Materials –
  - What are the general materials gaps in hydrogen systems?
- Collaboration –
  - How can NASA participate in external collaborations?
  - How do others want to participate with us?

How will the Information be Used

- The goal of this activity is to get a better understanding of the needs, challenges, and requirements for a testing facility from as many different perspectives as possible.
- Data will be used for advocacy in a manner that is not traceable to the submitter.
- Plan to use data in a manner that is sharable without identification of individual respondents.

Conclusions

- Cryogenic Hydrogen Systems are on a critical path for development of next generation aviation as well as many terrestrial applications and space planetary exploration
- Developing materials capable of high-cycle-life between 20K and ambient temperature with low-permeability (to hydrogen) over lifetime
  - Light-weight, durable, volume-efficient insulation
  - Composite materials for tanks and fluid components (pumps, valves, etc)
  - Develop databases, physics and ML-based model to predict performance and durability of materials at cryogenic temperatures
  - Test promising materials in laboratory to demonstrate performance of advanced materials and generate data that can be used to refine models
- Design, implement and test tanks and cryo components
- Facilities development - Collaborative Hydrogen Storage and Testing
- Next steps in collaborations with industry, academic, government partners