Electrified Aircraft Propulsion Integration Concepts: Primary Fuel Cells and Cryogenic Hydrogen Storage

9/12/2023

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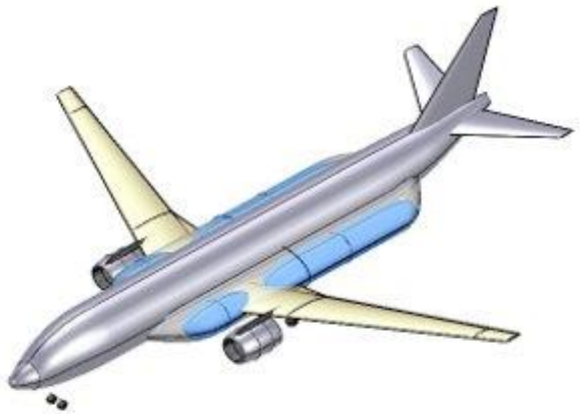
Presentation Overview

- Electrified Aircraft Propulsion (EAP) Integration Concepts
- Cryogenic Hydrogen Storage
- Primary Fuel Cells



EAP Integration Concepts

- Identify feasible enabling technology advancements meriting NASA investments:
  - Hydrogen-fueled Electric Aircraft Propulsion (EAP) systems
  - Long-life electric power systems
  - Cost-effective operation of hydrogen electric aircraft for commercial deployment

- Implement ***Deployable*** technologies over multiple classes of aircraft

- On-ramp ***Deployable*** technologies when matured

- Leverage evolving digital tools to accelerate development

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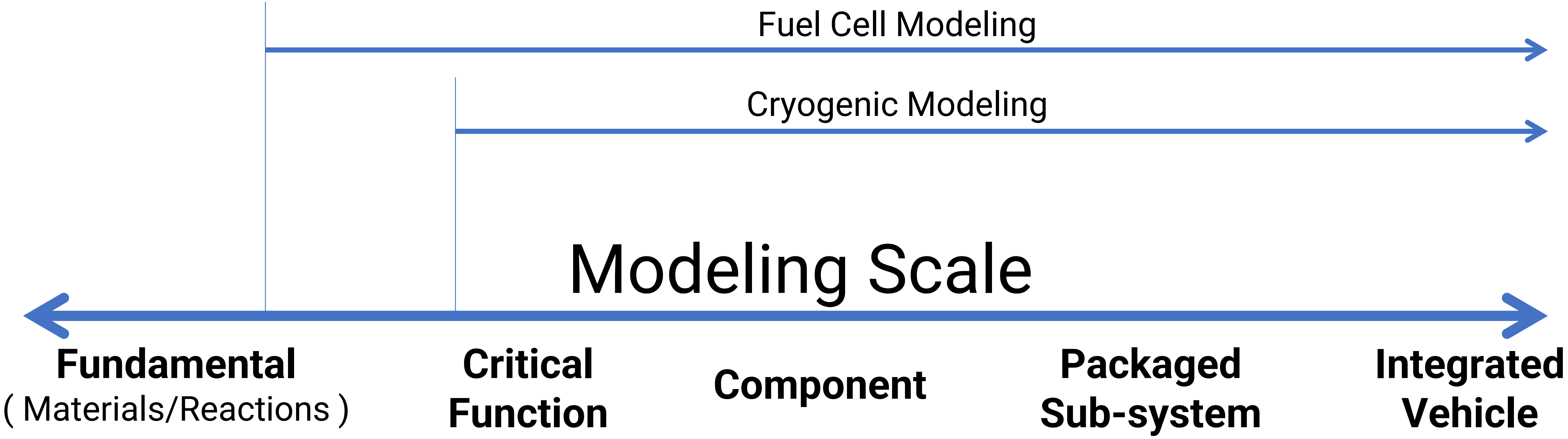
EAP Integration Process

- Assess current status of relevant technologies
- Identify primary and secondary limiting factors
  - Hydrogen management and storage
  - Fuel cell power density
  - Thermal Management
  - System Integration

This presentation is limited to these topics

- Establish implementation parameters
  - Aircraft architectures
  - Deployment timeframes
- Collaborate
  - Augment existing collaborations
  - Establish new collaborations

EAP Integration Process: Fuel Cells & Cryo



Normalization of Results

- Proposed metric to compare multiple EAP power systems across multiple aircraft architectures and mission profiles:

  Flight-specific fuel consumption (FSFC)

$$FSFC = \frac{Actergy}{Freight\ mass\ distance} = \frac{E_{Fuel} * t_{Flight}}{d_{Flight} * m_{Payload}}$$

Where:

d_{Flight} = Distance traveled aloft between take-off and landing, meters

E_{Fuel} = Stored energy of fuel in Aircraft at take-off, joules

$m_{Payload}$ = Aircraft payload, kilograms

t_{Flight} = Time between take-off and landing, seconds

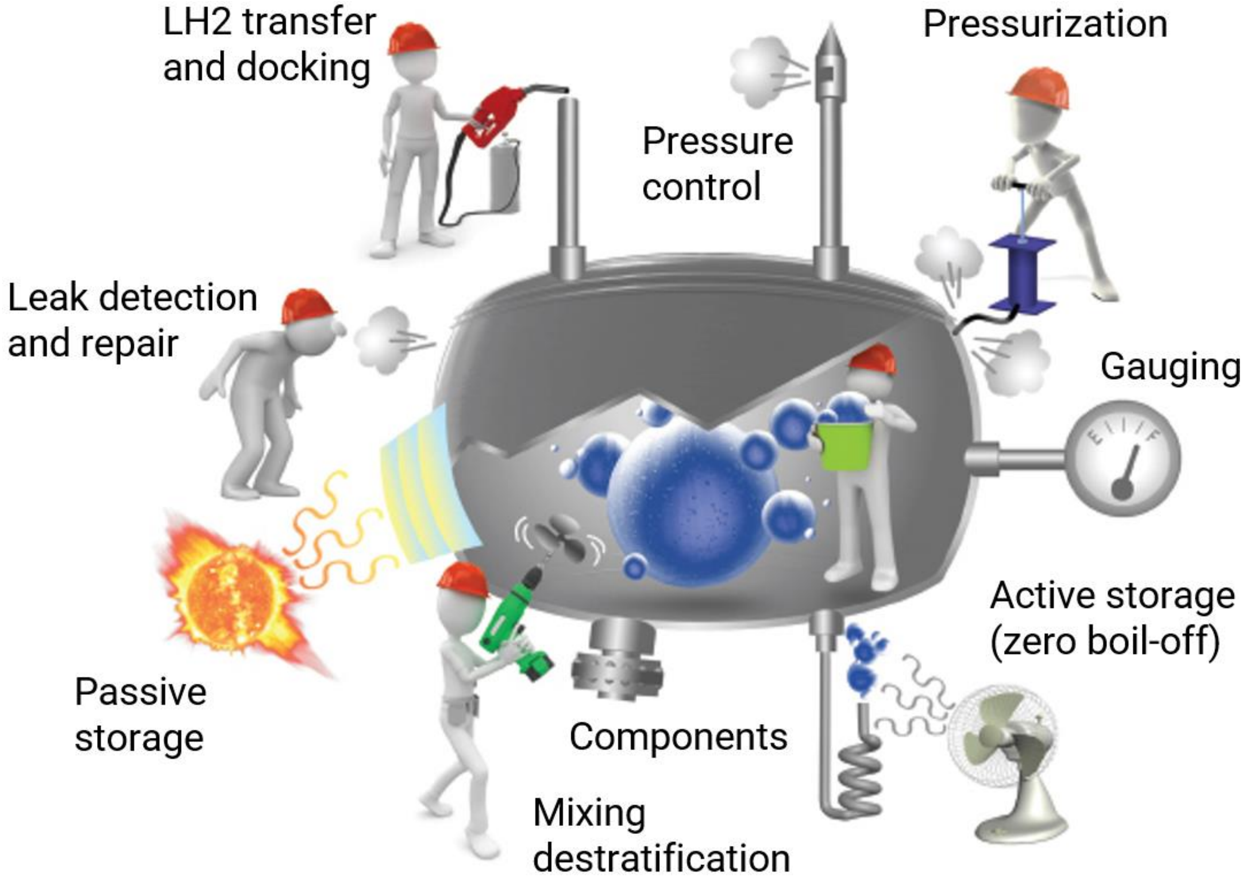
Cryogenics

Subtopics

- Basic Cryogenic Management
- Conceptual Block Diagram
- Challenges and Opportunities

Cryogenic Hydrogen Management

- Must address the full cryogenic fluids system functions and requirements
- Hydrogen venting must be controlled both in location and quantity
- Maintain safe operations through multiple flight system failures
- Provide fuel to user systems at desired pressure, temperature, and flow rates



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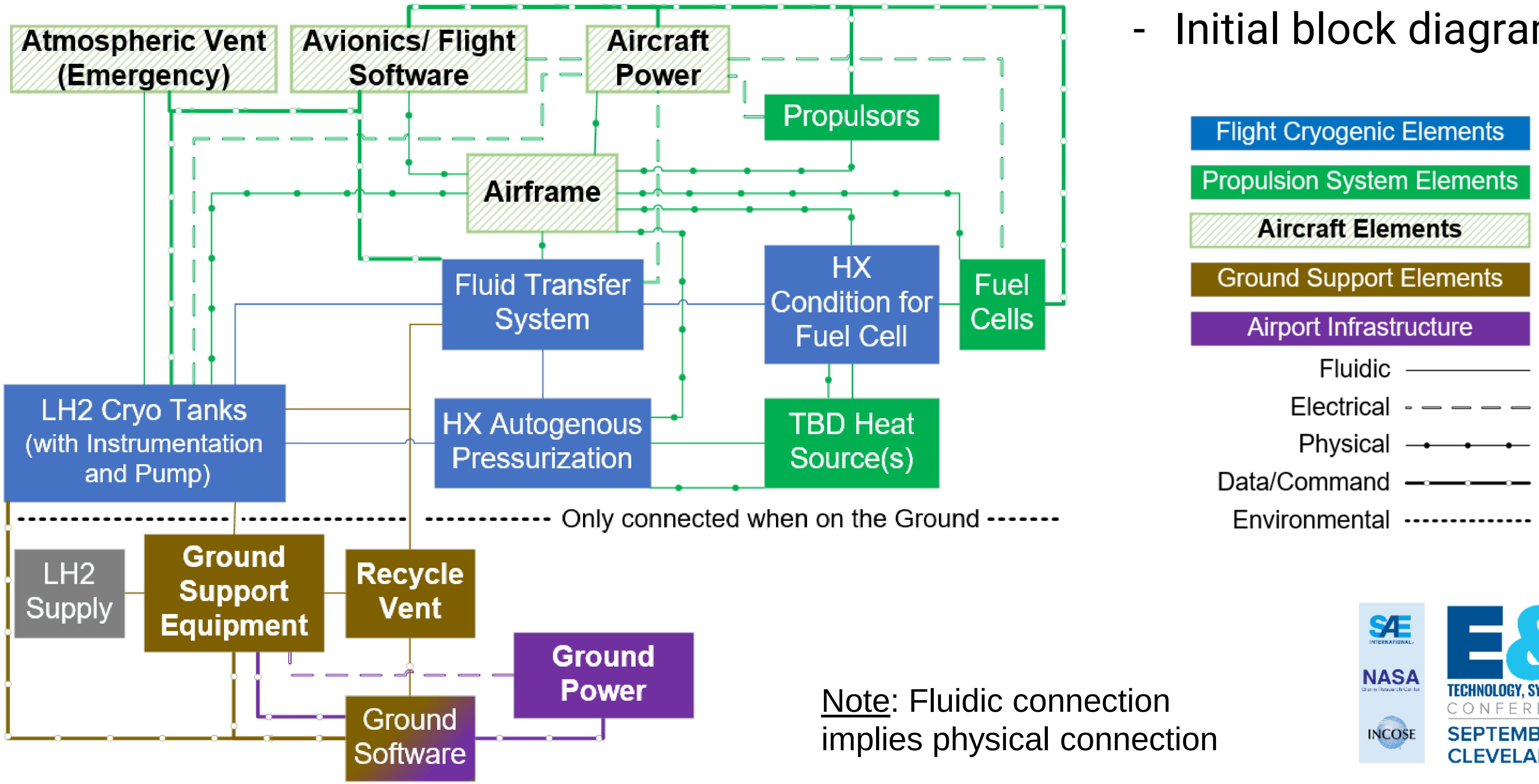
Fuel Cell Aircraft Cryogenic System

- Initial block diagram



Note: Fluidic connection implies physical connection

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Cryogenic Tank Efficiency Metric

$$\varepsilon_{tank} = \frac{m_{nom\ usable\ fuel}}{m_{total\ fuel} + m_{tank} + m_{ins} + m_{tank\ internal} + m_{tank\ support}}$$

$m_{nom\ usable\ fuel}$: Fuel used on maximum nominal mission, includes flight operations reserves
$m_{total\ fuel}$: the total amount of fuel that can be loaded into the tank, includes tank operation reserves and ullage
$M_{tank\ support}$: vacuum pumps, pressurization system, safety purge gas (eventually need to purge out compartment)
$M_{tank\ internal}$: pump(s), baffles, maintenance items

Note: FAA requires each tank to have independent fuel distribution system + redundancy.
May require up to 3 pumps per tank for redundancy requirements.
This index is multiplying normal gravimetric index by usable fuel fraction

Can also convert $m_{nom\ usable\ fuel}$ to a useful energy metrics:

$$\varepsilon_{energy} = \varepsilon_{tank} 131_{MJ/kg} \qquad \varepsilon_{volumetric} = \frac{V_{nom\ usable\ fuel} * 8\ {}^{MJ}/_{liter}}{V_{tank,OML} + V_{tank\ support}}$$

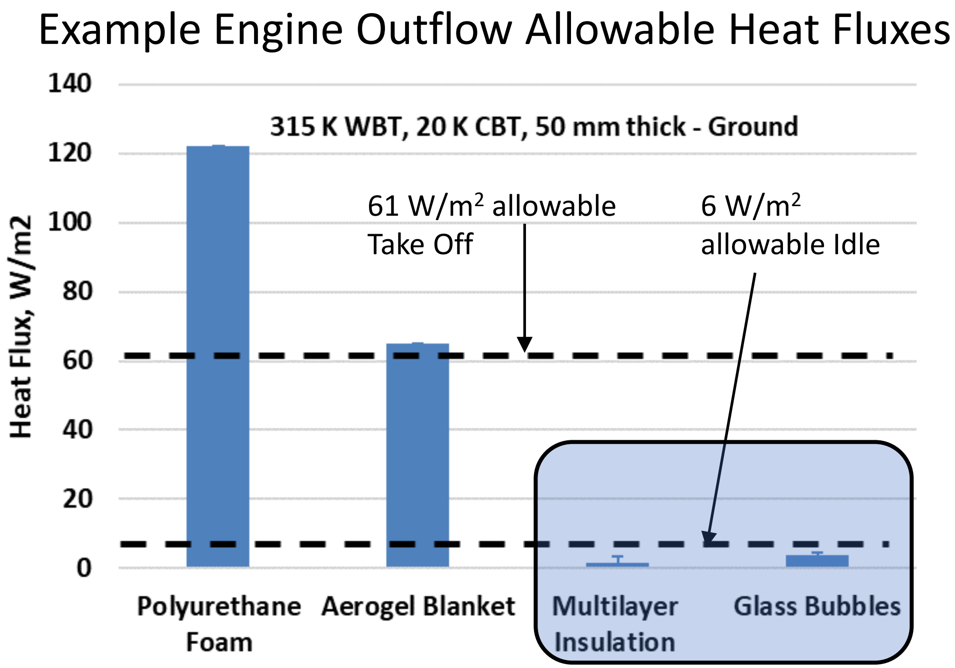
$V_{tank\ OML}$: includes insulation and structure to connect tank to airframe
$V_{tank\ support}$: includes all components outside tank required to support tank operation (i.e. press system)

Liquid Hydrogen Challenges

- Not possible to prevent air contamination or leakage (it will never be zero)
  - Control the order of magnitude and the location
- Define reasonable maintenance requirements and implementations
- Aircraft cryogenic hydrogen Storage & Distribution:
  - Keep hydrogen from boiling-off in a wide variety of environments.
  - Get the hydrogen balance of plant to work in a wide variety of environments.
- Cryogenic Hydrogen Production & Distribution enable the aircraft
- Safety:
  - How can people interact with the hydrogen systems (airport workers, passengers, maintenance, etc)?
  - How does the system respond in failure scenarios?

Cryogenic Technology Opportunities

- Lightweight vacuum jacketed insulation systems
  - While spray foam is light and easy to install [incorrectly], it's poor thermal performance drives increase in hydrogen venting requirements and subsequent system mass.
  - Can use volume created by engine outflow to allow for boil-off within tank to maintain pressure.
    - Largest challenges on the ground (idle & take-off)
- Lightweight Tanks
  - Requires 10s of thousands of thermal and pressure cycles.
  - Outside current design codes
  - Both metallic and composite tank types
- Lightweight Components
  - Pumps and Heat Exchangers developed for different environments (aviation vs. industrial)
- Material Properties
  - Lack of data characterizing additive manufacturing material properties down to 20 K.



Primary Fuel Cells

Subtopic

- Fuel Cell Technology Status
- Preliminary Architecture
- Preliminary Model Structure

Fuel Cell Technology Status

- No current fuel cell technology meets all requirements
  - No viable test data at scale
  - Low power density
  - Challenging thermal management

- Multiple fuel cell technologies under development
  - Low-Temperature PEM near-term potential option
  - High-Temperature PEM under development
  - Solid Oxide under development for co-generation with combustion systems

- System integration development required

Fuel Cell Thermal Management Dilemma

Primary Cooling Path

Limited by:

Chemistry and construction --

In-plane thermal gradients $\left(\frac{\partial T}{\partial x \partial y}\right)$ --

Thermal interfaces --

Low dT --

T_1 = Electrodes

T_2 = Cell cold sink

T_3 = Stack Manifold

T_4 = Fuel cell system thermal loop

T_5 = Atmosphere

Secondary Cooling Path

Limited by:

- Low dT
- Air Thermal Capacitance
- Surface Area

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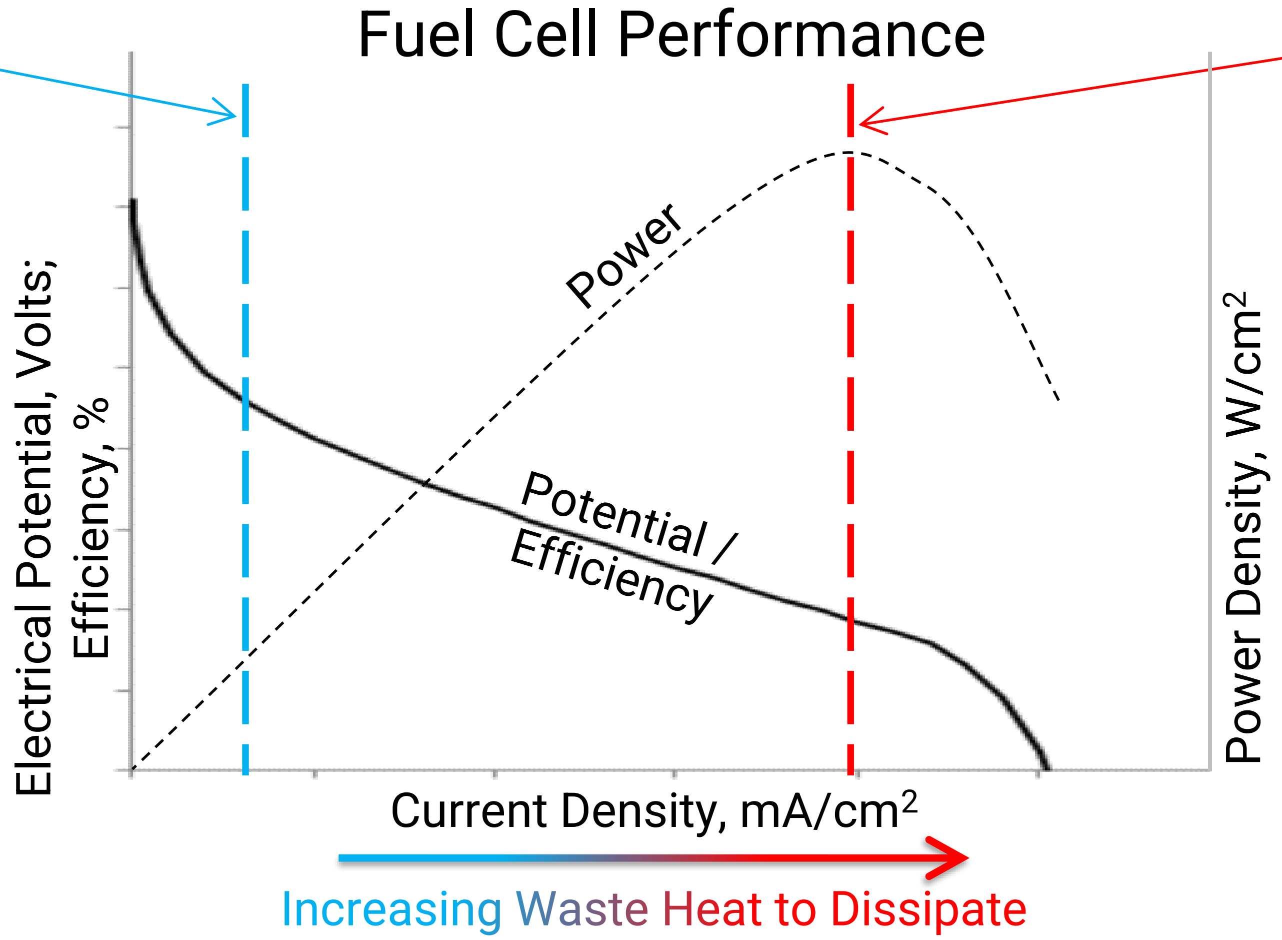
Fuel Cell Thermal Management Dilemma

Peak Efficiency

High Efficiency / low power
- **Small** thermal radiator
- High H_2 Utilization Efficiency (Smaller H_2 Tanks)



Peak Specific Power

High Power / low efficiency
- **Large** thermal radiator
- Low H_2 Utilization Efficiency (Larger H_2 Tanks)

Given the same system-level power requirements, operating at lower current density reduces H_2 storage requirements and thermal management system mass in exchange for larger fuel cell system

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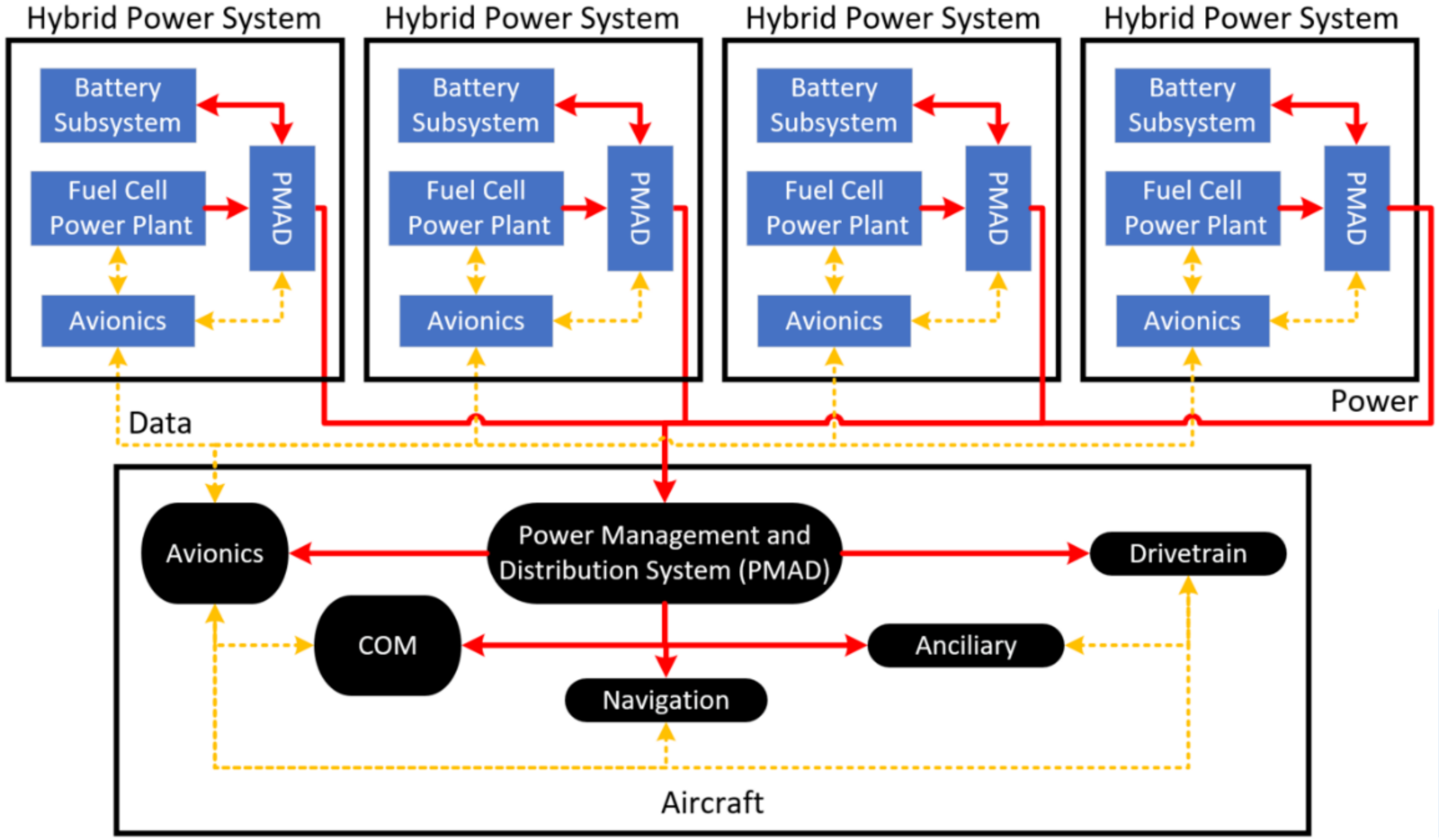
EAP Aircraft Architecture

- Hybrid power system utilizes fuel cells and batteries for power
- Distributed power systems address redundancy and mitigates some limitations



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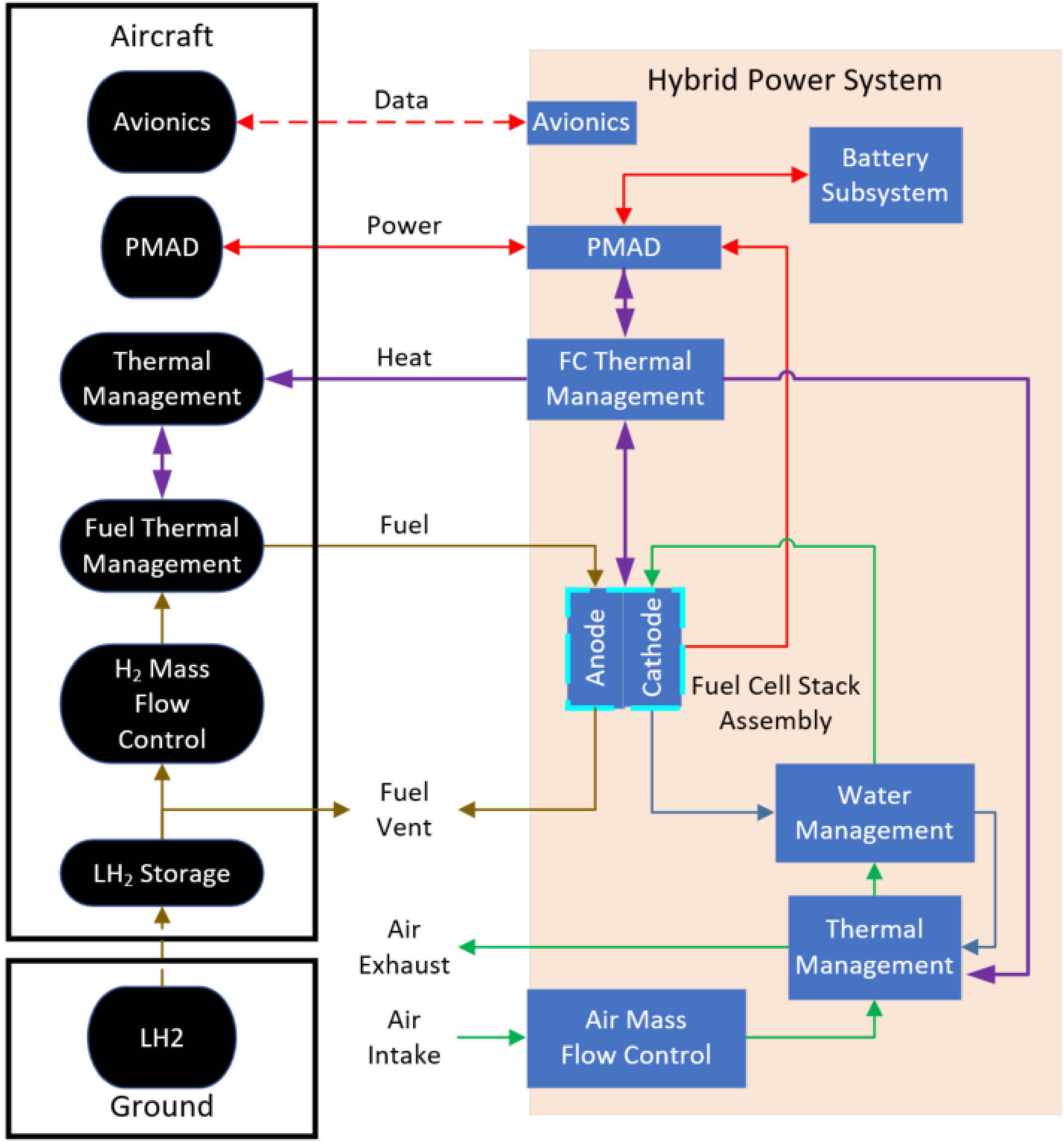
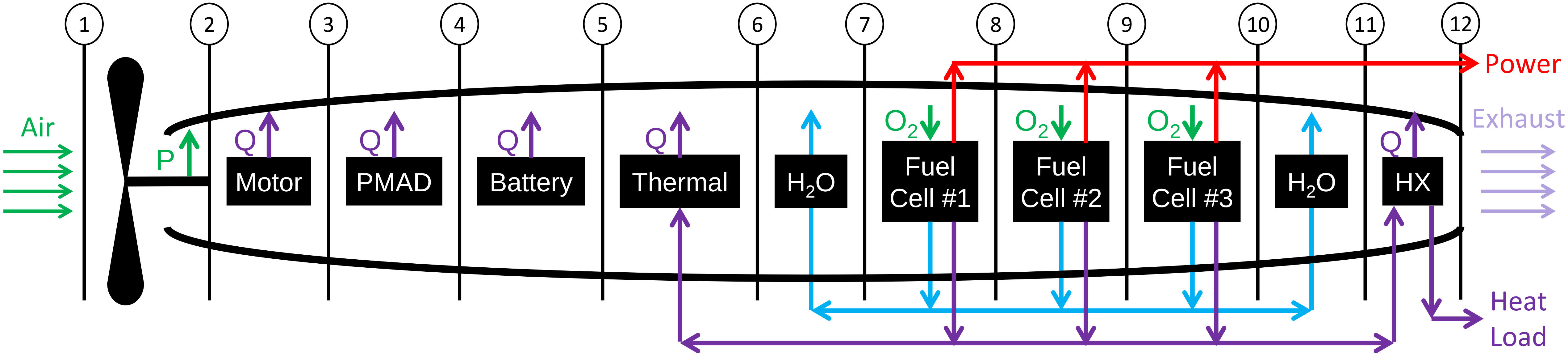
Hybrid Power System Analysis



- Stand-alone power module contains battery subsystem, fuel cell stack, and fuel cell balance-of-plant (BoP)
- Other systems manage aircraft power levels, hydrogen storage, management, and distribution, thermal management
- Fuel cell stack assembly likely to include multiple sub-stacks to minimize power electronics
- Detailed system modeling required

Hybrid Power System Analysis

- Develop initial performance model of a Hybrid Power system
- Evolve into a Digital Twin by integrating lower-level models



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Summaries

Subtopic

- **Preliminary Findings to date**
- **Impending work to be done**

Preliminary Findings

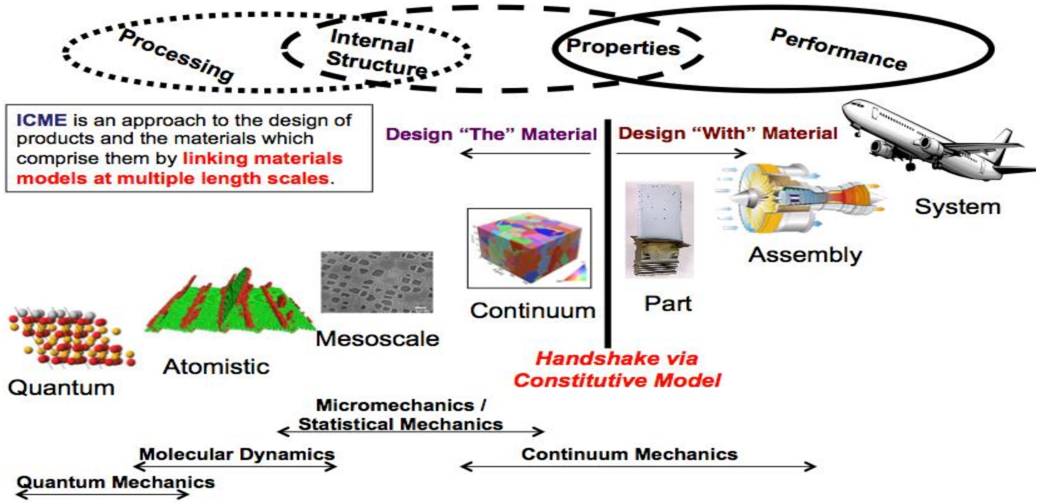
- Near-term
  - System Integration
  - Thermal Management
  - FAA Certification
  - Public Engagement

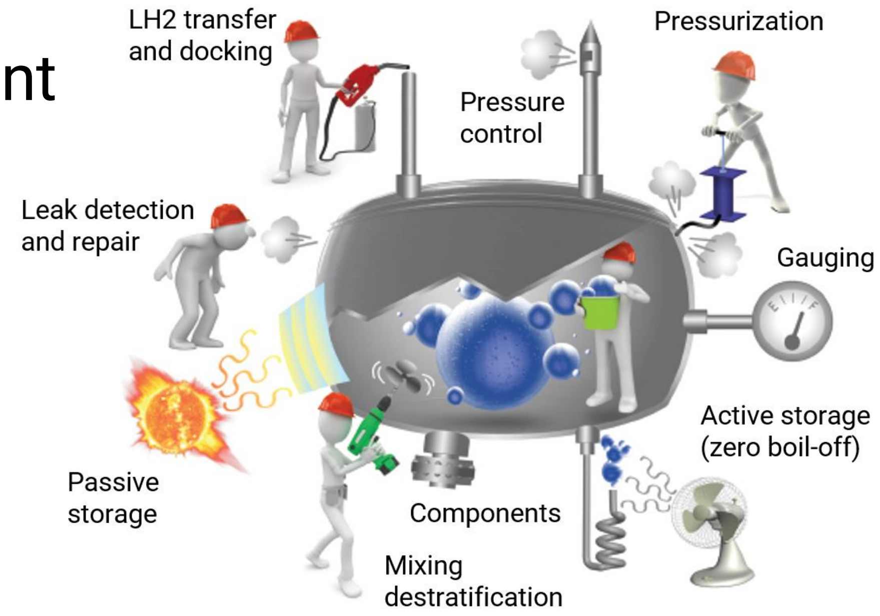
- Mid-term
  - Electrochemistry Advancements
  - Improve Manufacturing Processes
  - Stack Design Advancement

- Far-term
  - Electrochemistry Development
  - Materials Development

Impending Work

- Develop models towards a Digital Twin
  - Fuel Cells
  - Cryogenics
  - Materials
- Materials research
  - Electrochemistry Development
  - Materials Development
- Collaboration
  - Expand existing
  - Create new





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