National Aeronautics and Space Administration

NASA Hydrogen and Fuel Cell Activities

Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) Hydrogen Portfolio Meeting

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11 April 2024

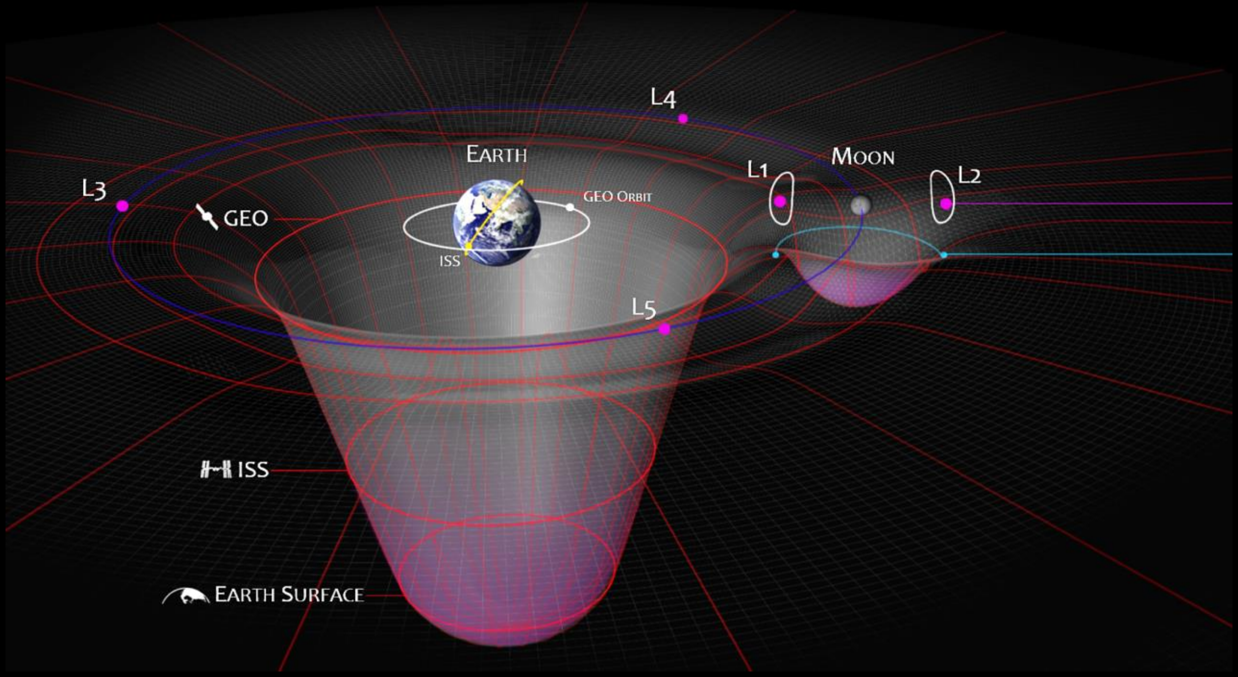
Overview

- Overview of NASA Hydrogen Applications
- Ground Operations
- Aeronautic Applications
- Space Applications
- Interagency Collaboration Opportunities

IZEA Integrated Zero Emission Aviation

Grant Number: 80NSSC22M0068

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)
Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage



Gravity profiles for Cis-lunar space

Concept fuel cell powered lunar lander

Fuel Cell and Hydrogen Applications Within NASA

Power Generation *(Fuel Cell Reaction)*

Electrochemically combine H_2 and O_2 into water, heat, and electricity

- *Launch Vehicles*
- *Mars/Lunar Landers*
- *Lunar/Mars surface systems*
- *Urban Air Mobility / Electrification of Aircraft*

H_2O →

Water Electrolysis

Generate H_2 and O_2 from water

- *Breathing O_2 for Life Support Systems*
- *In-situ H_2 and O_2 Propellant Generation*
- *H_2 and O_2 for Energy Storage*
- *Terrestrial Hydrogen Economy*

H_2 O_2

H_2 O_2

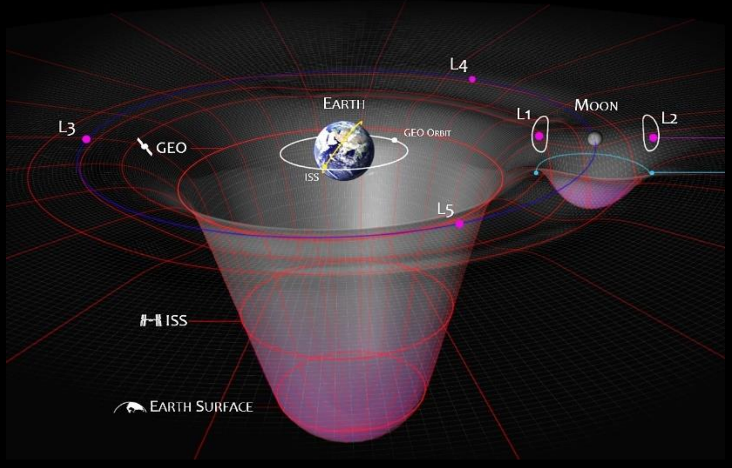
Energy Storage

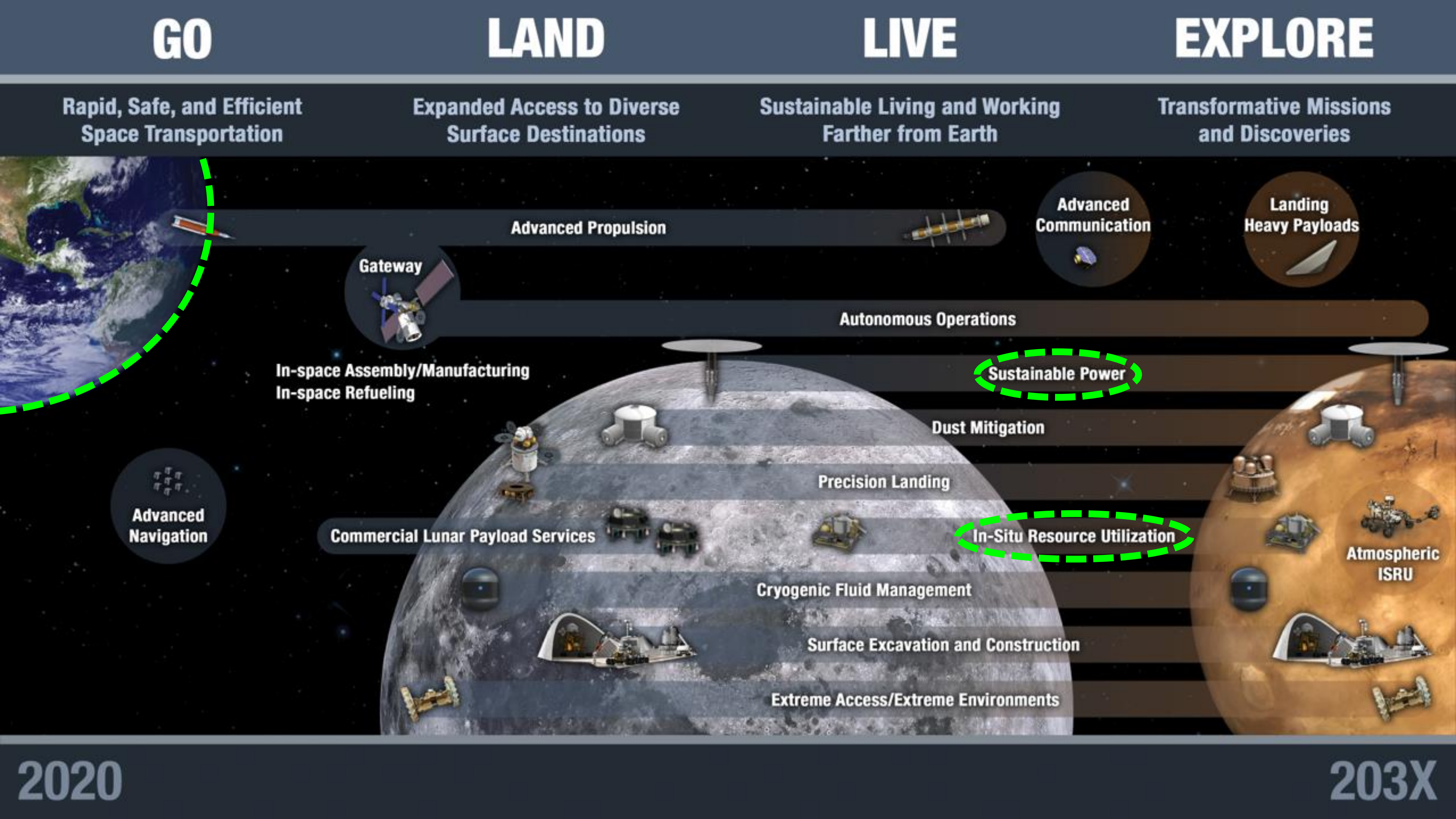
Long-term storage and management of H_2, O_2 and water

- *Launch Vehicles*
- *Mars/Lunar Landers*
- *Lunar/Mars surface systems*
- *Urban Air Mobility / Electrification of Aircraft*
- *Ground Support / Terrestrial Infrastructure*

Concept fuel cell powered lunar lander

Cis-lunar space




GO
LAND
LIVE
EXPLORE
Rapid, Safe, and Efficient Space Transportation
Expanded Access to Diverse Surface Destinations
Sustainable Living and Working Farther from Earth
Transformative Missions and Discoveries
Advanced Propulsion
Advanced Communication
Landing Heavy Payloads
Gateway
Autonomous Operations
In-space Assembly/Manufacturing
In-space Refueling
Sustainable Power
Dust Mitigation
Precision Landing
Advanced Navigation
Commercial Lunar Payload Services
In-Situ Resource Utilization
Atmospheric ISRU
Cryogenic Fluid Management
Surface Excavation and Construction
Extreme Access/Extreme Environments
2020
203X

Hydrogen History

Hydrogen History

Sir Robert Boyle

Defined GH2 flammability limits

Jacques Charles

First Hydrogen Balloon Flight

1st Water Electrolysis Demonstration

William R. Grove

Develops 1st practical fuel cell

Sir James Dewar

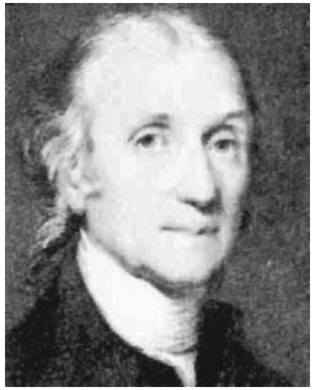
Liquefies GH_2
Invents vacuum container

Dr. Herrick Johnston

Develops practical H_2 liquefaction process

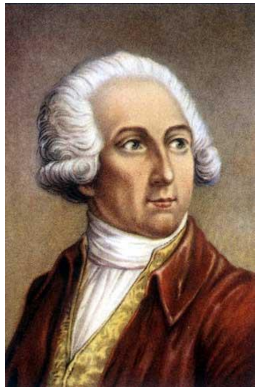
1520 1673 1766 1783 1784 1789 1801 1839 1898 1903 1937 1943

1st recorded observation of Hydrogen



Henry Cavendish

Determined density and GH_2 flammability limits in air

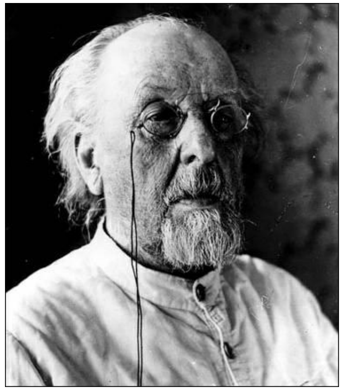


Antoine Lavoisier

Measures GH_2 heat of combustion

Sir Humphry Davy

Demonstrated fuel cell principles



Konstantin Tsiolkovskiy

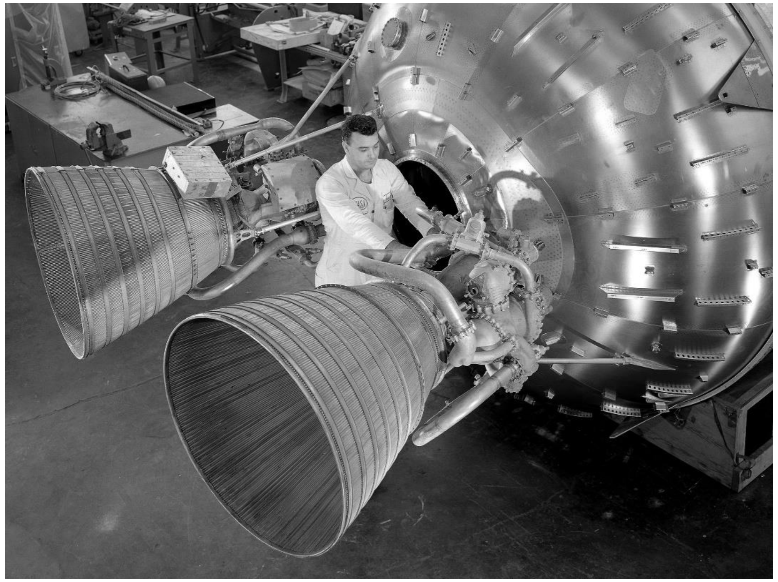
Proposes H-O as rocket propellant
Derives "Rocket Equation"

1st H_2-cooled Electrical Power Generator

Historical Hydrogen-Oxygen Rockets

Damage at Lewis' Rocket Engine Test Facility following a test of high-energy fuels (4/27/1955)

A researcher prepares a Centaur 6A second-stage rocket for a series of tests in the Space Power Chambers' vacuum tank

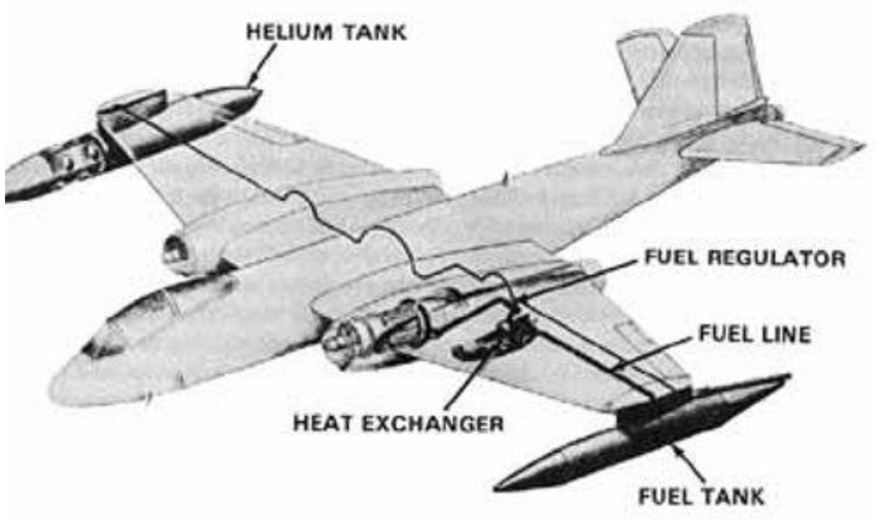


NASA Engineers developing instrumentation to measure LH_2 aboard spacecraft

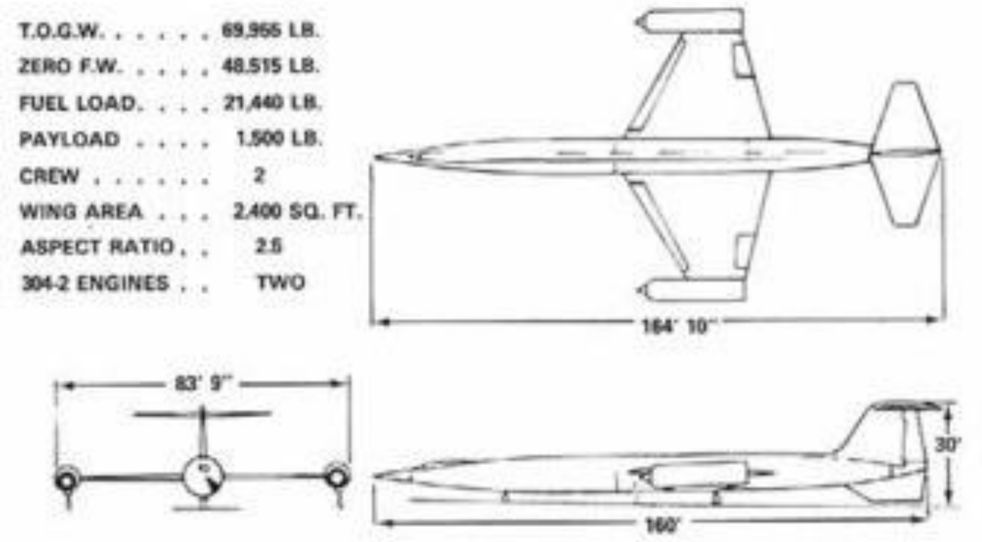
Historical Hydrogen-Fueled Aircraft

Project Bee: Hydrogen-fueled B-57B

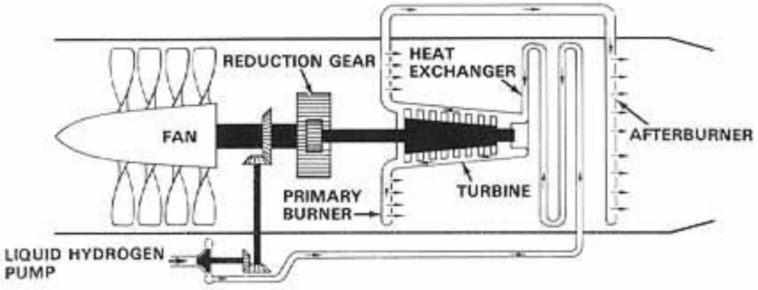
Martin B–57B Canberra using LH2 J-65 engines with wing tip fuel tanks used for an experimental liquid hydrogen fuel system, referred to as Project Bee



Project Suntan: H_2-fueled P&W Model 304



Suntan Airplane CL400

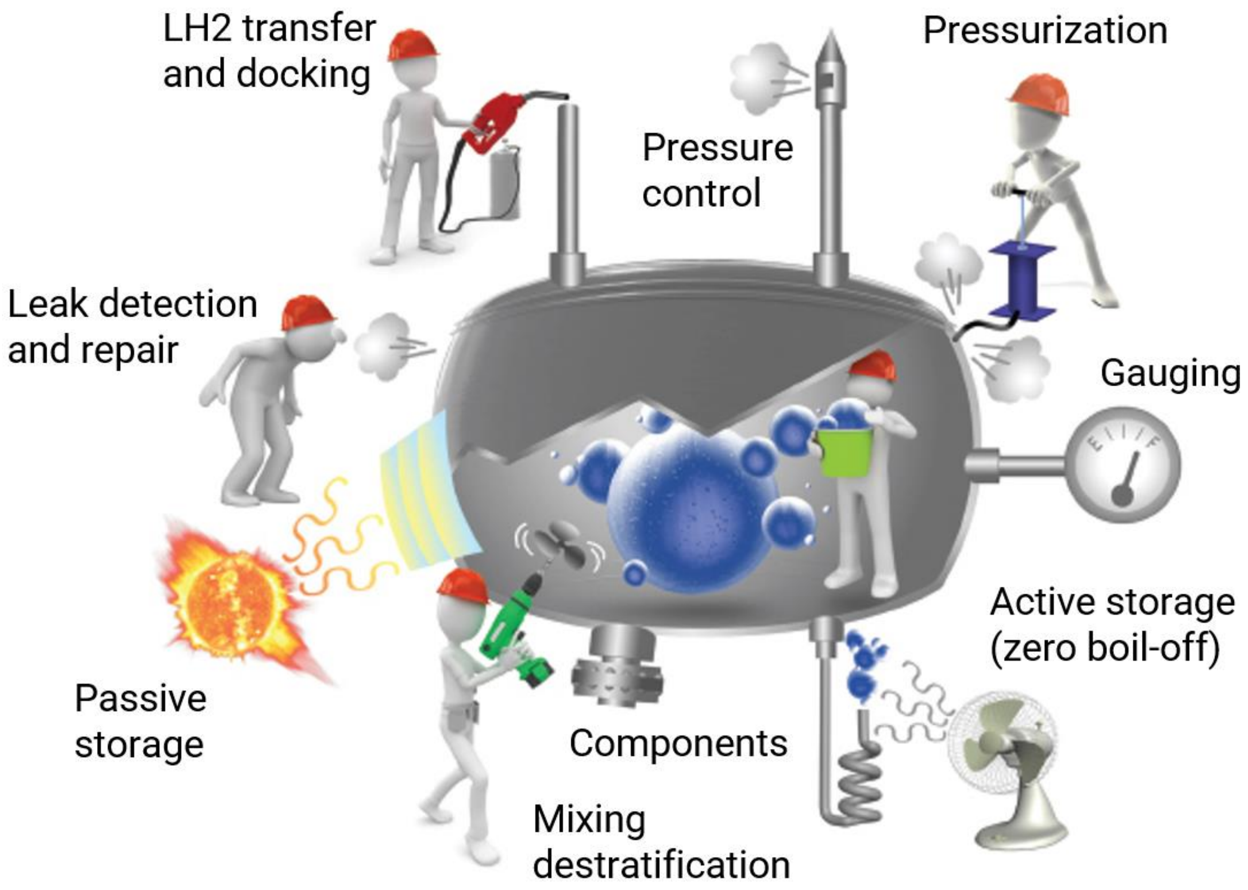


P&W Model 304 Engine

Hydrogen in Ground Support Operations

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



Cryogenic Hydrogen Management

Implementing Codes, Standards, and Infrastructure to use H_2 safely

Tanker trucks deliver liquid hydrogen (LH2) to replenish the large sphere at NASA's Kennedy Space Center in Florida, Launch Pad 39B.
(NASA Image NHQ202208310013)

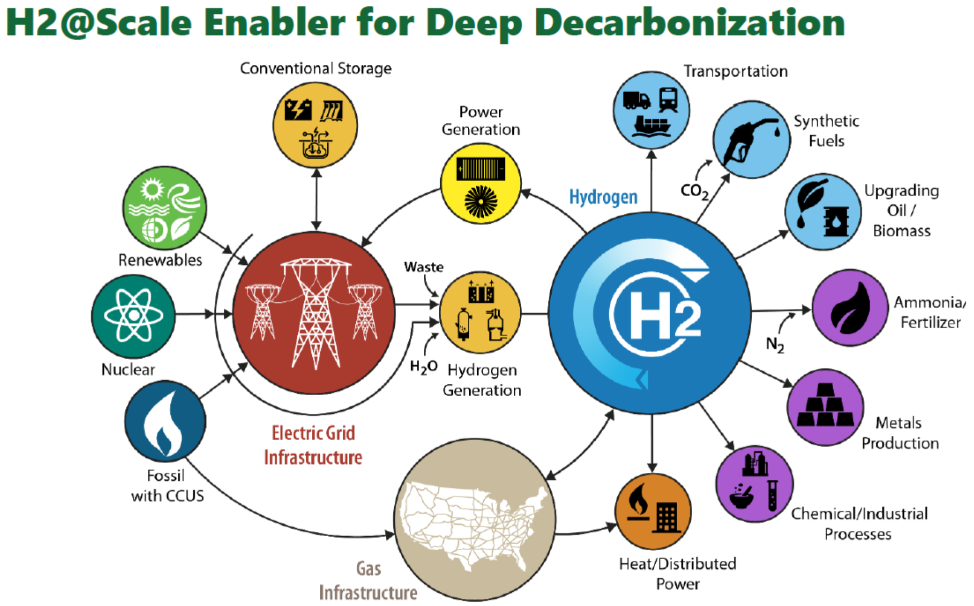
800,000 gal (3,3028 m^3) LH2 Tank at Pad 39B
(NASA Image KSC-20191108-PH-JBS01_0001)

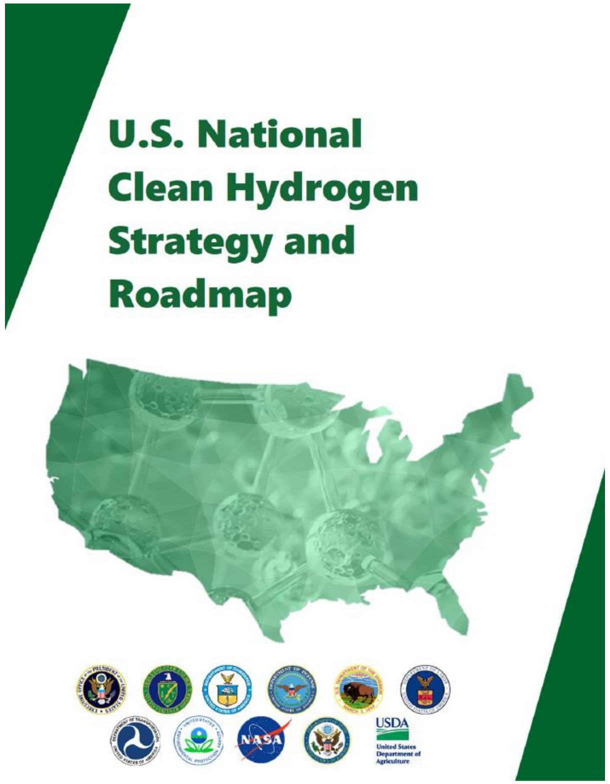
Incomplete List of Lessons Learned

- Hydrogen
  - NASA/TM-2003-212059 Guide for Hydrogen Hazards Analysis on Components and Systems
  - ANSI/AIAA G-095A (2017) Guide to Safety of Hydrogen and Hydrogen Systems
  - ISO/DIS 14687-2 Hydrogen fuel – Product specification – Part 2: Proton exchange membrane (PEM) fuel cell applications for road Vehicles
  - ISO/DIS 14687-3 Hydrogen fuel – Product specification – Part 3: Proton exchange membrane (PEM) fuel cell applications for stationary applications
  - SAE J2719 Hydrogen Fuel Quality for Fuel Cell Vehicles
  - ISO 22734 – Hydrogen Generators Using Water Electrolysis – Industrial, Commercial, and Residential Applications
  - ISO 14687 – Hydrogen fuel quality – Product specification
  - MIL-PRF-27201E – Performance Specification – Propellant, Hydrogen
  - NFPA 70 – National Electric Code (particularly Article 500)
- Water: ASTM D6504 Standard Practice for On-line determination of Cation Conductivity in High Purity Water
- Fuel Cells
  - SAE J2617 – Fuel Cell Vehicle Terminology
  - IEC 60050-485 International Electrotechnical Vocabulary – Fuel Cell Technologies
  - IEC 62282 Fuel Cell Technologies – Multiple fuel cell special topics
  - ASTM D7606 (2017) Sampling of High-Pressure Hydrogen and Related Fuel Cell Feed Gases
  - ISO 21087 Gas Analysis – Analytical methods for hydrogen fuel – Proton exchange membrane (PEM) fuel cell applications for road vehicles
  - ISO 23828 – Fuel Cell Road Vehicles – Energy Consumption Measurement – Vehicles fuelled with compressed hydrogen
  - SAE J1766 – Recommended practice for Electric, Fuel Cell and Hybrid Electric Vehicle Crash Integrity Testing
  - SAE J2572 – Recommended Practice for Measuring Fuel Consumption and Range of Fuel Cell and Hybrid Fuel Cell Vehicles Fueled by Compressed Gaseous Hydrogen
  - SAE J2617 – Recommended Practice for Testing Performance of PEM Fuel Cell Stack Sub-system for Automotive Applications
  - SAE J2908 – Vehicle Power and Rated System Power Test for Electric Powertrains
- Piping and Components
  - ASME B31.12 (2014) Hydrogen Piping and Pipelines
  - ASME B31.3 (2012) Process Piping
  - ISO 12619 – Road Vehicles – Compressed Gaseous Hydrogen (CGH2) and hydrogen/natural gas blends fuel systems components
  - ASME Boiler and Pressure Vessel Code (BPVC)
  - SAE J2600 Compressed Hydrogen Surface Vehicle Fueling Connection Devices
  - NASA-STD-8719 – NASA Requirements for Ground-based Pressure Vessel and Pressurized Systems (PVS)
  - SAE J2616 – Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System
- Safety
  - AIR6464 – EUROCAE/SAE WG80/AE-7AFC Hydrogen Fuel Cells Aircraft Fuel Cell Safety Guidelines
  - AIR7765 – Considerations for Hydrogen Fuel Cells in Airborne Applications
  - AS6858 – Installations of Fuel Cell Systems in Large Civil Aircraft
  - ASME PTC 25 (2018) Pressure Relief Devices
  - IEC 62282-2-100 Fuel Cell Technologies – Fuel Cell Modules – Safety
  - IEC 62282-3-100 Fuel Cell Technologies – Stationary Fuel Cell Power Systems – Safety
  - IEC 62282-5-100 Fuel Cell Technologies – Portable fuel cell power systems – Safety
  - IEC 62282-6-100 Fuel Cell Technologies – Micro fuel cell power systems – Safety
  - ISO 23273 – Fuel cell road vehicles – Safety Specifications – Protection against hydrogen hazards for vehicles fueled with compressed hydrogen
  - MIL-STD-1330 Standard Practice for Precision Cleaning and Testing of Shipboard Oxygen, Helium, Helium-Oxygen, Nitrogen, and Hydrogen Systems
  - NASA-STD-6016 – Standard Materials and Processing Requirements for Spacecraft
  - NFPA 853 – Standard for the Installation of Stationary Fuel Cell Power Systems
  - SAE J2344 – Guidelines for Electric Vehicle Safety
  - SAE J2578 – Recommended Practice for General Fuel Cell Vehicle Safety
  - SAE J3089 – Characterization of On-Board Vehicular Hydrogen Sensors
  - SAE J3121 – Hydrogen Vehicle Crash Test Lab Safety Guidelines

U.S. National Clean Hydrogen Strategy and Roadmap

- U.S. National Clean Hydrogen Strategy and Roadmap outlines the Administration's plan to implement the Carbon-reduction activities outlined in the Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA) https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf
- Department of Energy (DOE) leads an "all-of-government" Hydrogen Interagency Taskforce (HIT) to guide the implementation of the Hydrogen Strategy and Roadmap https://www.hydrogen.energy.gov/interagency.html





Hydrogen Interagency Taskforce (HIT)

- NASA supporting all Working Groups and some Cross-cutting teams
- Proposed mechanism for improved inter-agency collaboration

WH and Deputies Group Co-Chairs → **Enable National Goals**

- 10 MMT/yr supply and end use by 2030
- 20 MMT/yr supply and end use by 2040
- 50 MMT/yr supply and end use by 2050

HIT Director (Deputy Director(s))

Secretariat | **Program Leadership Group**

Working Groups

Supply and Demand at Scale

- Enabling large scale production and demand creation
- Financing, incentives, and compliance tools for commercial scale up
- Metrics for deployment and USG as off-taker
- Supply chains and resiliency (critical materials, strategic reserve)
- R&D to accelerate cost reductions and end use commercialization (JST interface)

Infrastructure, Siting, Permitting

- Siting, permitting, pipelines, storage, and infrastructure
- Harmonized codes and standards
- Interoperability and global standardization
- Safety, emissions (including secondary), sensors, risk mitigation, environmental impact
- Environmental review and best practices (NEPA, etc.)
- Pipeline and blending test facilities

Analysis and Global Competitiveness

- National strategy and commercial liftoff analysis
- Impacts and gap assessments (technoeconomic analysis, incentives, resource/water availability, emissions, jobs, manufacturing, etc.)
- Intellectual property and global landscape assessment
- Export market analysis
- Systems integration and optimization

DOE JSC Tech Teams: Production, Delivery, Storage, Conversion, Applications H2 Hubs, Workforce, Equity, and Justice

Cross-cutting Teams

Hydrogen in Aviation Applications

Known Electrified Aircraft Technical Gaps

1. Thermal management:
    - High Power applications = large thermal loads
    - Electric aircraft have multiple distributed thermal loads
    - Advanced Hydrogen combustion technologies have localized thermal loads
2. Power Management and Distribution
    - High Electrical Current
    - High Power / High Voltage Conversion
    - Wiring mass
3. On-board Hydrogen management
    - Cryogenic Storage
    - Hydrogen Monitoring
    - Hydrogen Materials
4. System Integration
    - Putting it all together in a cost-effective package for commercial applications

Hydrogen-Electric Aircraft Cryogenic System

- Initial block diagram

Flight Cryogenic Elements

Propulsion System Elements

Aircraft Elements

Ground Support Elements

Airport Infrastructure

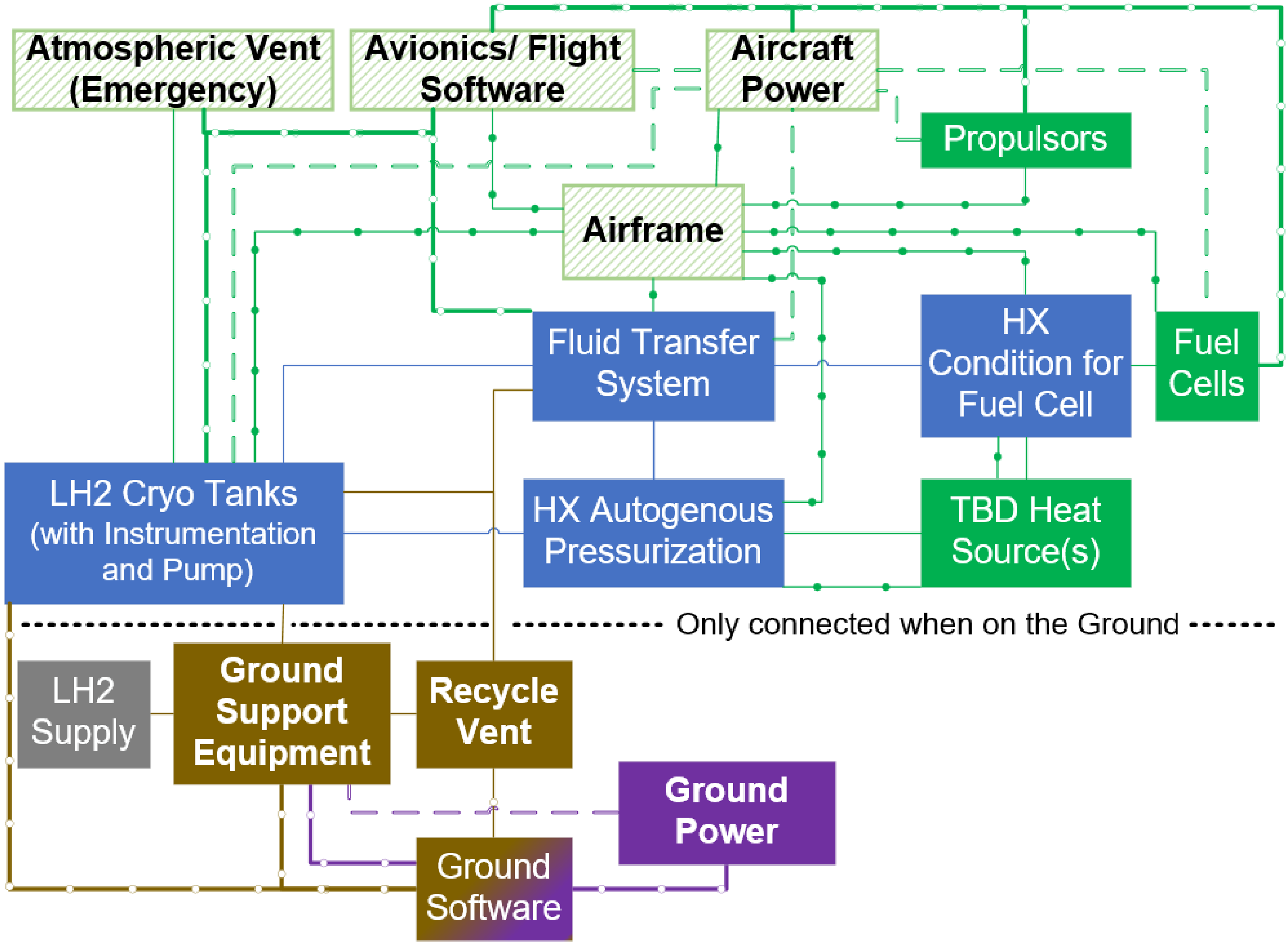
Fluidic

Electrical

Physical

Data/Command

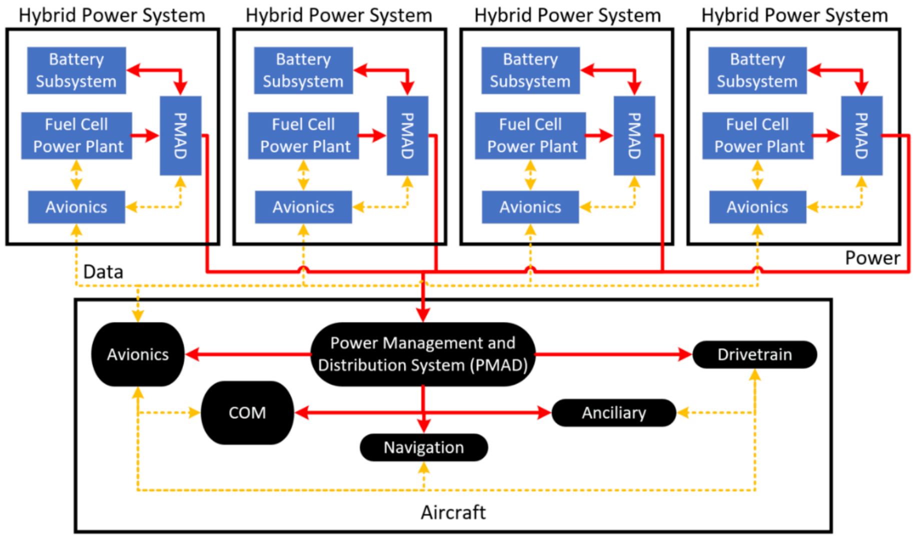
Environmental

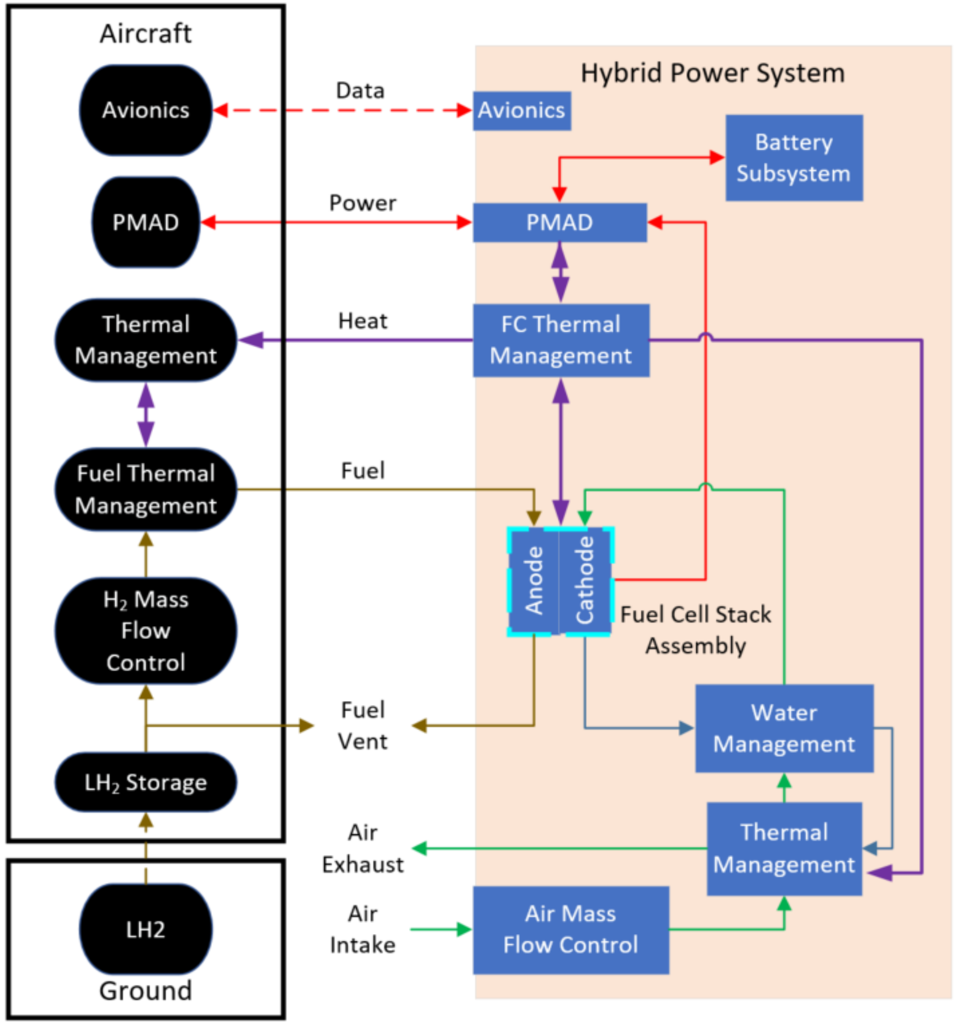


Note: Fluidic connection implies physical connection

Aviation Fuel Cell Technology Status

- No current technology meets all requirements
  - 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





Aviation 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:

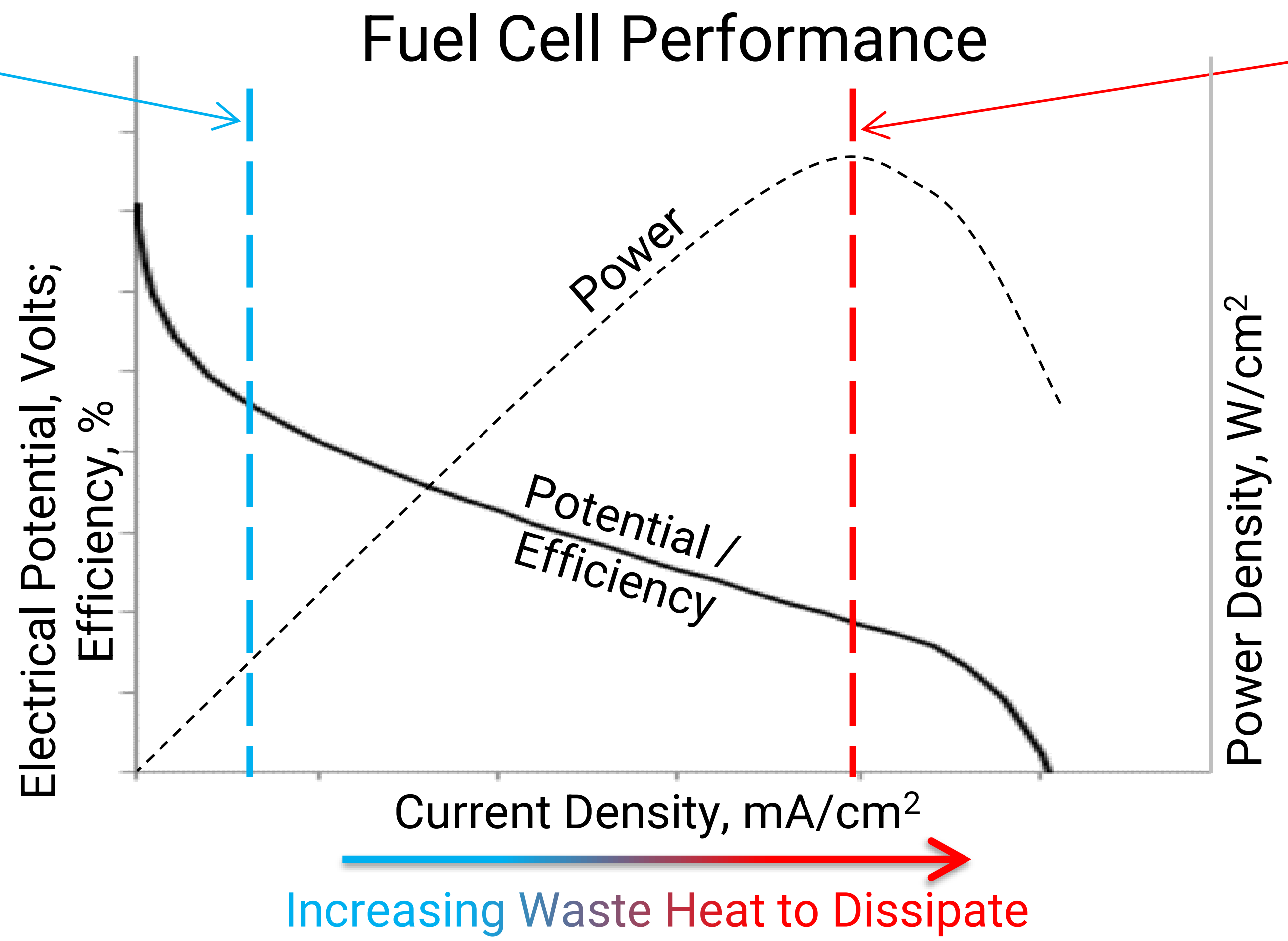
- Low dT
- Air Thermal Capacitance
- Surface Area

Aviation 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

Integrated Zero-Emission Aviation using a Robust Hybrid Architecture (IZEA)

The project goals and broader impacts:

- Figure out how to use liquid hydrogen as fuel
  - Burning hydrogen to produce electricity has water vapor as exhaust.
  - Solving challenges related to safety, engineering, electrical, thermal, infrastructure, and societal acceptance helps aviation.
- Increase power and efficiency without increasing weight
  - Liquid hydrogen is very cold (cryogenic), which enables using superconductors to greatly increase power density.
  - Fuel cells and electric motors provide cruise thrust instead of heavy batteries and turbofans.
- Research tasks
  - Evaluate potential for global warming reduction across passenger aviation fleet
  - Use multi-disciplinary design, analysis and optimization approach to identify and model hydrogen-fueled aircraft for the fleet
  - Develop feasible power generation and energy conversion subsystem
  - Develop feasible power electronics, distribution and motor-driven propulsion subsystem
  - Develop thermal management system to optimize efficiency
- Unify all tasks with real demonstrations on a system testbed

Principal Investigator: Lance Cooley
Lead Organization: Florida State University (FSU)
Supporting Organizations:

- Advanced Magnet Lab, Inc. (AML)
- Florida Agricultural and Mechanical University (FAMU)
- Georgia Institute of Technology-Main Campus (GA Tech)
- Illinois Institute of Technology
- Raytheon Technologies Research Center
- SUNY Buffalo State
- The Boeing Company (Boeing)
- University of Kentucky

Funded by:
Aeronautics Research Mission Directorate (ARMD) Transformative Aeronautics Concepts Program (TACP) University Leadership Initiative (ULI, https://uli.arc.nasa.gov/)

Hydrogen in Space Applications

Terrestrial vs Aerospace Fuel Cell Systems

Aerospace

Differentiating Characteristics

- Pure Oxygen (stored, stoichiometric)
- Water Separation in reduced gravity

≠

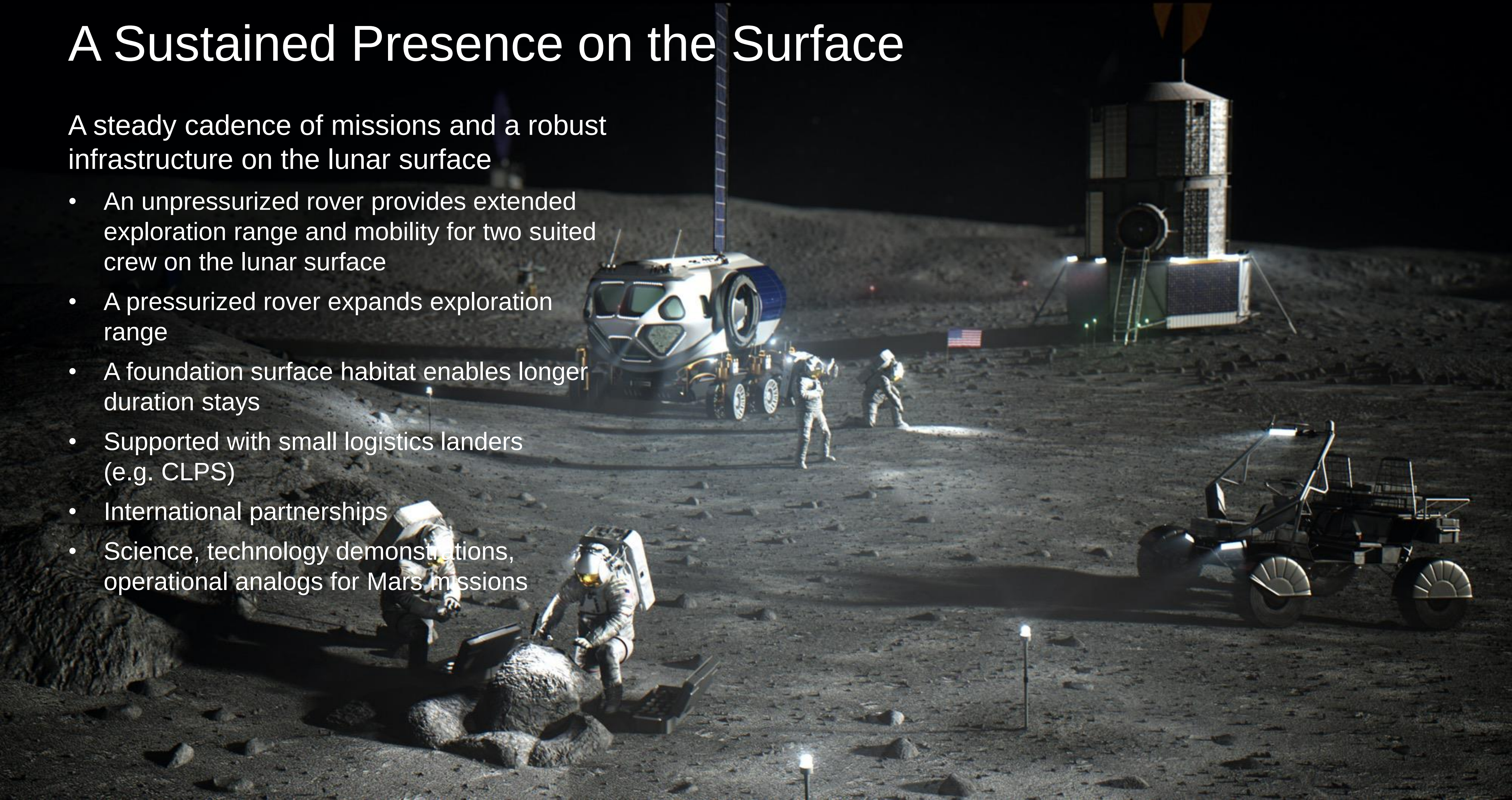
Terrestrial

Differentiating Characteristics

- Atmospheric Air (conditioned, excess flow)
- High air flow drives water removal

Fluid management issues make aerospace and terrestrial fuel cells functionally dissimilar

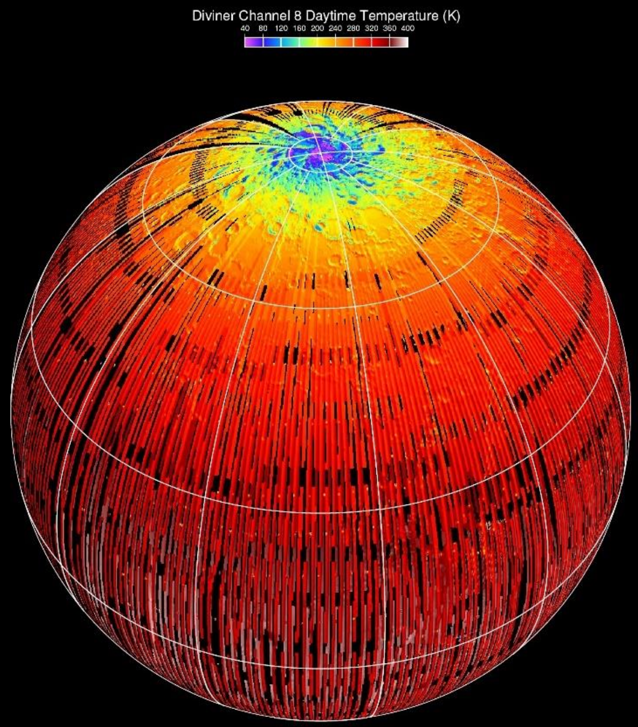
A Sustained Presence on the Surface

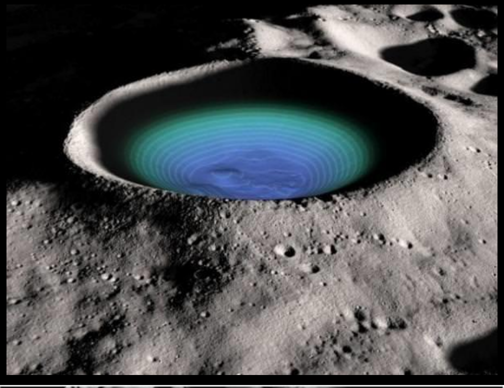


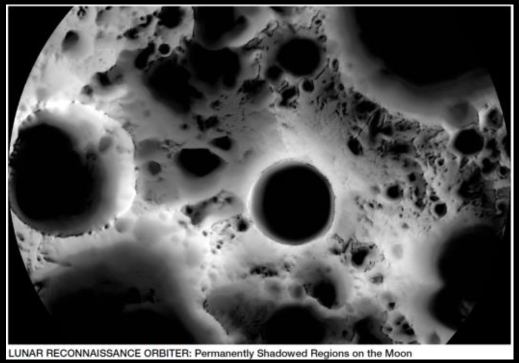
A steady cadence of missions and a robust infrastructure on the lunar surface

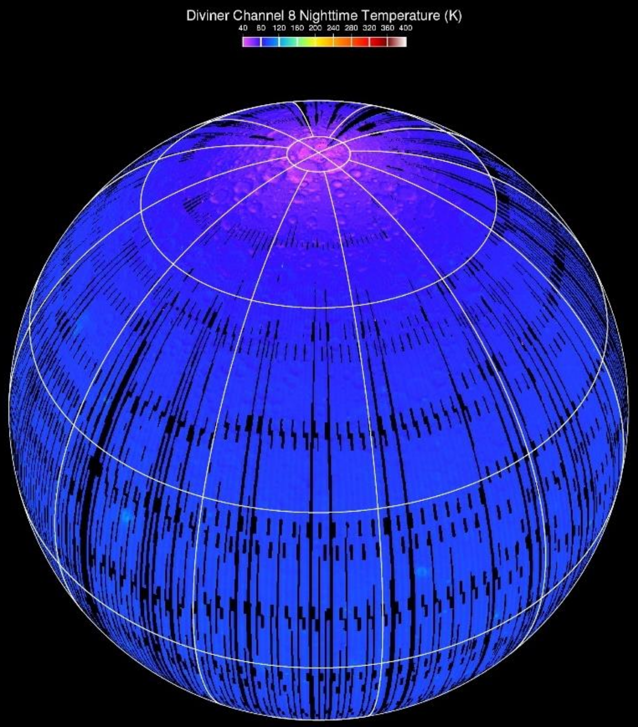
- An unpressurized rover provides extended exploration range and mobility for two suited crew on the lunar surface
- A pressurized rover expands exploration range
- A foundation surface habitat enables longer duration stays
- Supported with small logistics landers (e.g. CLPS)
- International partnerships
- Science, technology demonstrations, operational analogs for Mars missions

The Lunar Environment







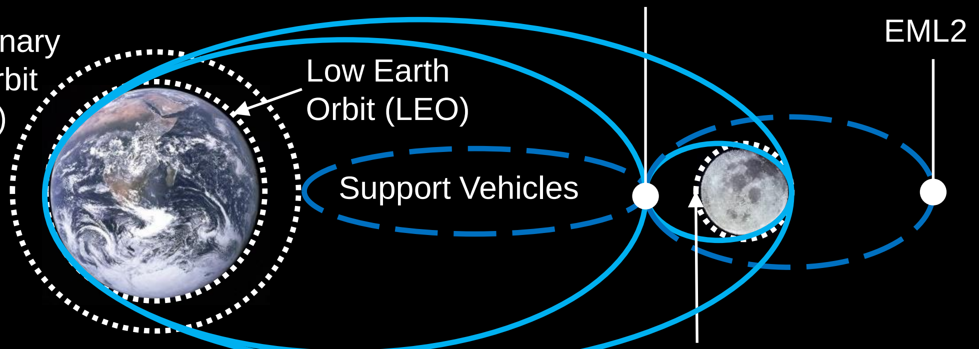


- The average temperature on the Moon (at the equator and mid latitudes) varies from 90 Kelvin (-298 ºF or -183 ºC), at night, to 379 Kelvin (224 ºF or 106 ºC) during the day.
- Extremely cold temperatures within the permanently shadowed regions of large polar impact craters in the south polar region during the daytime is at 35 Kelvin (-397 ºF or -238 ºC)
- Lunar day/night cycle lasts between 27.32 and 29.53 Earth days (655.7 to 708.7 hours)
- Regulating hardware in this environment requires both **power** and **energy**

Making Propellants on Planetary Surfaces Saves on Launches and Cost (Gear Ratio Effect)

Every 1 kg of propellant made on the Moon or Mars saves 7.5 to 11.2 kg in LEO

- Enable exploration by staging required resources in forward locations
  - Earth Orbit (LEO, GEO)
  - LaGrange Points (EML1 and EML2)
  - Lunar Orbit
  - Lunar Surface
- Resources include propellant depots, propellant production facilities (initially H_2 and O_2), and consumable storage

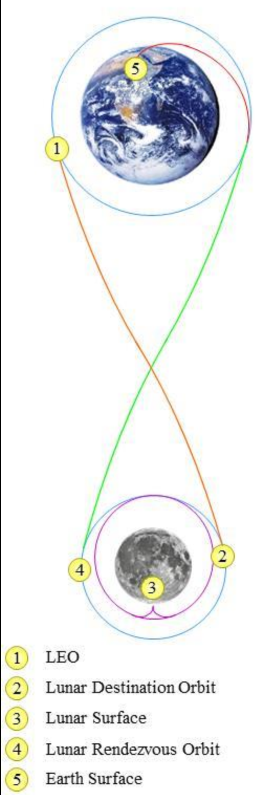


Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

- Savings depend on in-space transportation approach and assumptions; previous Mars gear ratio calculations showed only a 7.5 kg saving
- 25,000 kg mass savings from propellant production on Mars for ascent = 187,500 to 282,500 kg launched into LEO

Moon Lander: Surface to NRHO

- Crew Ascent Stage (1 way): 3 to 6 mT O_2
- Single Stage (both ways): 40 to 50 mT O_2/H_2



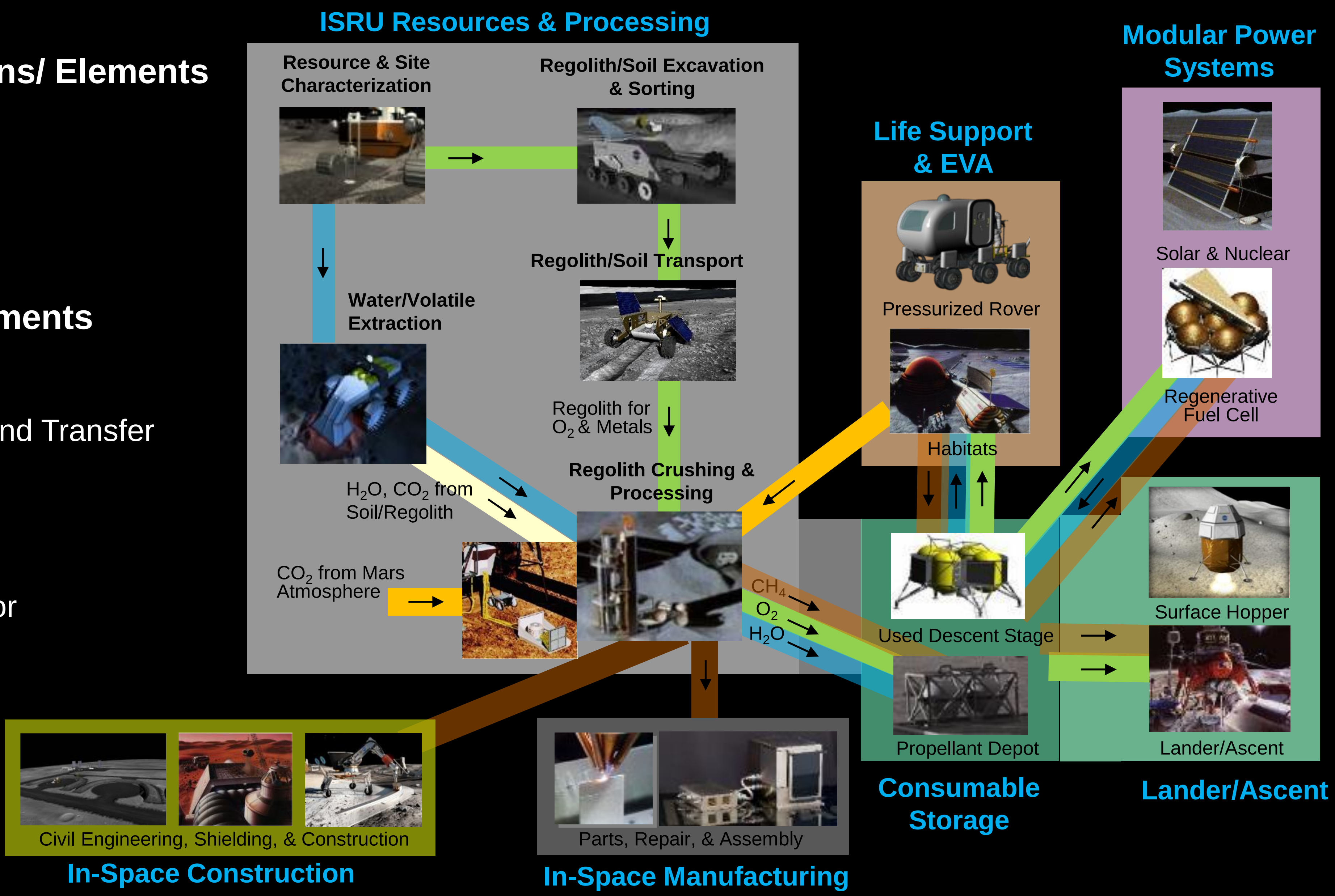
A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

In-situ Resource Utilization (ISRU)

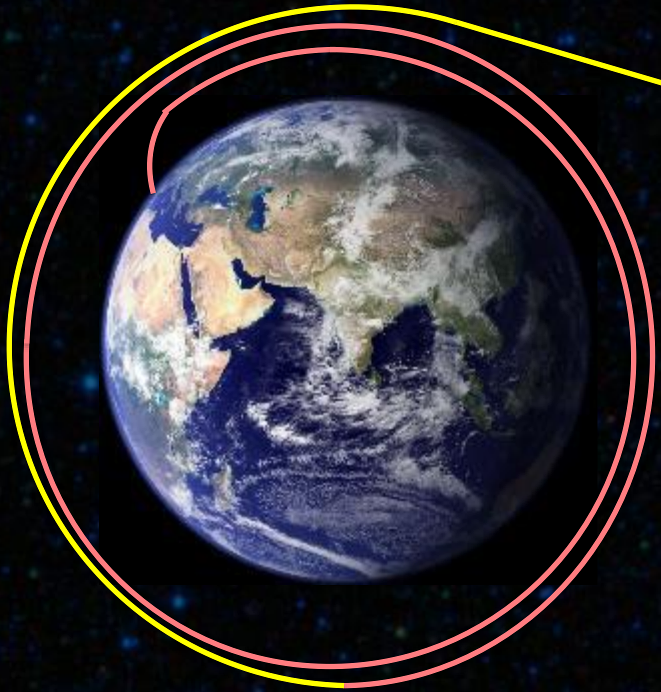
Modular Power Functions/ Elements
- Power Generation
- Power Distribution
- Energy Storage (O_2 & H_2)

Support Functions /Elements
- ISRU
- Life Support & EVA
- O_2, H_2, and CH_4 Storage and Transfer

Shared Hardware to Reduce Mass & Cost
- Solar arrays/nuclear reactor
- Water Electrolysis
- Reactant Storage
- Cryogenic Storage
- Mobility



Electrochemistry Applicability by Lunar Mission Phase



Cis-Lunar Transit:
Use fuel cells only when vehicle dynamics complicate deployment of solar/PV systems

Launch to Trans-Lunar Injection (TLI):
Upper-Stage Launch Vehicle using propellant boil-off to extend loiter time

Lunar Orbit & EDL:
Power Landers in Lunar Orbit and during Entry, Descent, & Landing (EDL) to avoid bus voltage droop due to battery State of Charge

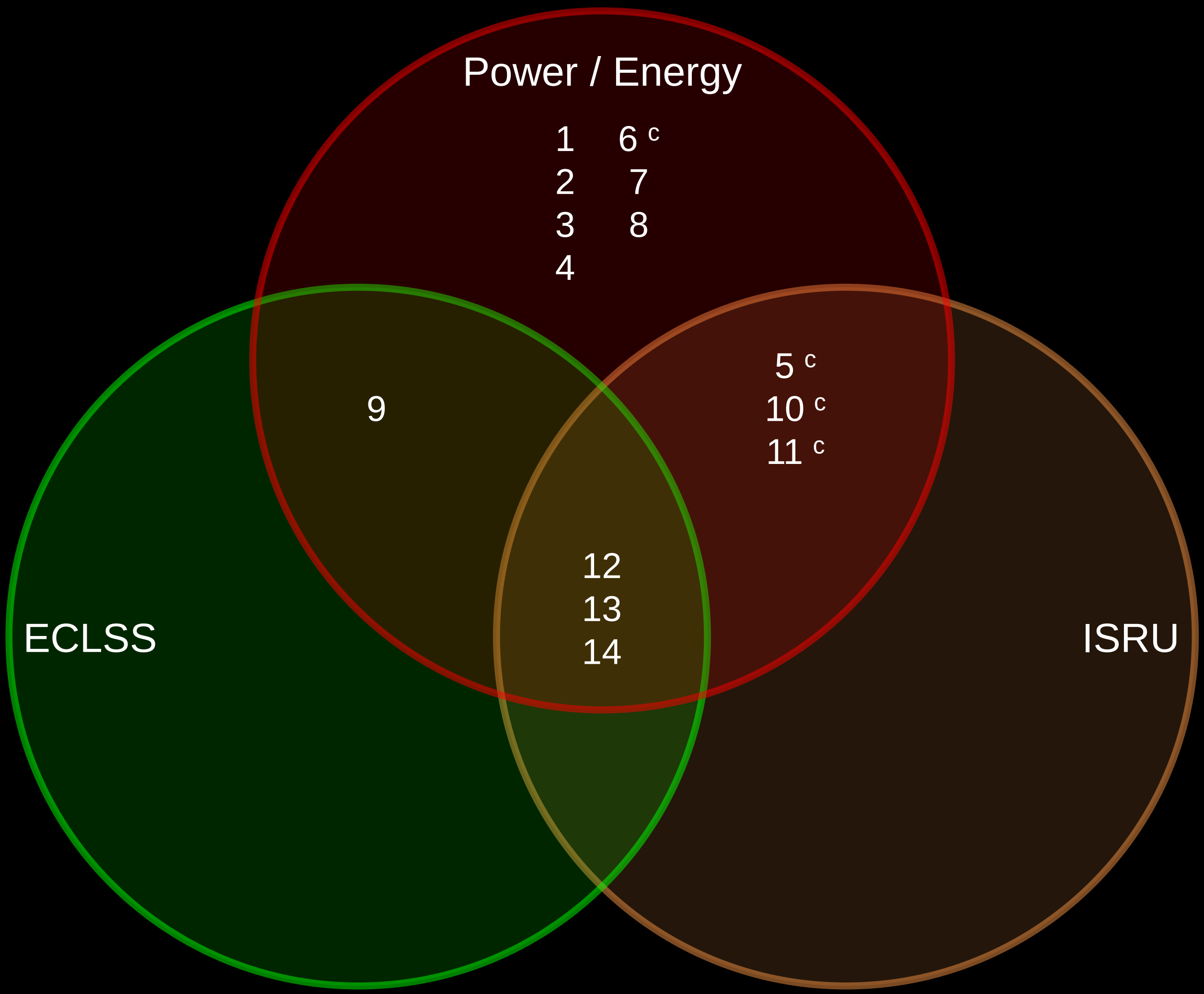
Lunar Surface:
- RFC to survive the lunar night
- Primary fuel cell to extend rover range

Mission Phase	Launch to TLI	Cis-Lunar Transit	Lunar Orbit and EDL	Lunar Surface
Overall Applicability	High	Low / Mission Specific	Mission Specific	High / Mission Specific
Primary Technical Challenge	System dynamics	µg operation	µg operation, System dynamics	Environment, Longevity
Applicable Technology	Fuel Cell	Fuel Cell or Electrolysis	Fuel Cell	Fuel Cell, Electrolysis, RFC
Applicable Chemistry	PEM	Mission Specific	Mission Specific	Mission Specific

Known Space Technical Gaps

1. **Availability:**
   - New technologies not yet flight qualified for microgravity applications
   - No flight-qualified fuel cell since the end of the Space Shuttle Program
2. **Operational Life:**
   - Pure oxygen reactants provide challenging operational environment
   - Space Missions have limited maintenance options
   - Long dormancy periods with large thermal variations
3. **System Integration**
   - Advantageously leveraging different systems to reduce overall vehicle mass
   - Putting it all together in a low-mass cost-effective package
4. **Specific Energy**
   - Increase system-level specific energy to increase vehicle payload capacity

Active Projects



	Tag	Activities [a]	Funding Source	Description
Power	1	CH_2RGE	ARMD	Electrification of single-aisle aircraft
Power	2	HEPS	TDM	Sub-orbital μg flight demonstration
Power	3	HLS Appendix P GTA	HLS	Primary fuel cells for lunar landers
Power	4	IZEA	ULI	Electrification of single-aisle aircraft
Power	5 [c]	MOWS / NITE	GCD	Combined Thermal/Power for lunar night
Power	6 [c]	PaCeSS	JSC (IRAD)	Passive fuel cell thermal management
Power	7	PropFC	GCD	SOFC power from LOX/CH_4 propellant
Power	8	WVU-NASA IV&V Fuel Cell	DOE	Facility SOFC CH&P demonstration
Electrolysis	9	AOGA	ESDMD	Next Gen. Crew O_2 supply system
Electrolysis	10 [c]	Co-electrolysis Methanation	GCD	Generate CH_4 & O_2 from ECLSS
Electrolysis	11 [c]	MRE	GCD	Generate O_2 from lunar regolith
Storage	12	BRACES	STMD	Lunar surface URFC energy storage
Storage	13	PR	EHP	Lunar surface mobility
Storage	14	RFC	GCD	Lunar surface RFC energy storage

Legend
ECLSS = Environmental Control and Life Support Systems
ISRU = In Situ Resource Utilization (On-site Production)
PMAD = Power Management and Distribution

Notes

a	Excludes SBIR activities
b	Excludes SME support for reviews / consulting
c	Scheduled to end in FY24

Fuel Cell Power Generation

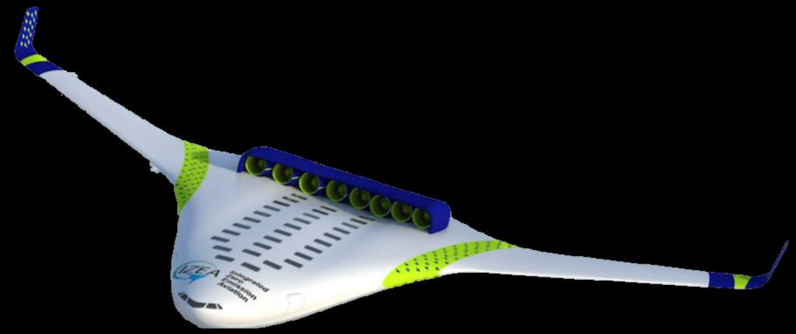
Fuel cells provide primary direct current (DC) electrical power

- *Use pure to propellant-grade O_2 / H_2 or O_2 / CH_4 reactants*
- *Uncrewed experiment platforms*
- *Crewed/uncrewed rovers*
- *Electric aircraft / Urban Air Mobility (UAM)*

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)
Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage

Applications

- *Electric Aircraft / Urban Air Mobility: 120 kW to > 20 MW*
- *Lunar / Mars Landers: ~ 2 kW to ≤ 10 kW*
- *Lunar / Mars surface systems: ~ 2 kW to ≤ 10 kW modules*
- *Venus atmosphere sensor platforms: ≤ 1 kW*



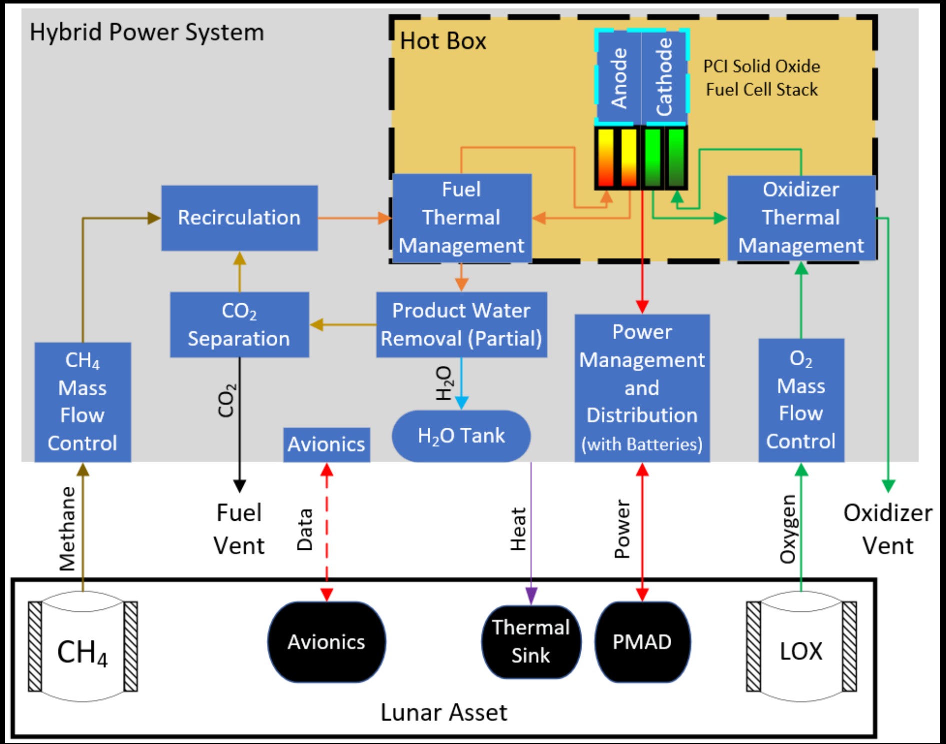
Concept H_2-fueled Aircraft for the Integrated Zero Emission Aviation (IZEA) ULI activity led by the University of Kentucky

Blue Origin Lunar Lander Baselined Fuel Cell Power as primary power source

Propellant Fueled Solid Oxide Fuel Cell (PropFC) Tipping Point

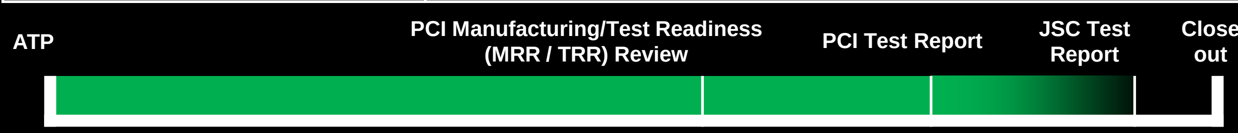
- Advance primary solid oxide fuel cell technology to generate electrical power directly from residual CH_4/LOX propellants
- Advance H_2/air & CH_4/air stack seal design for pure oxygen
- Conduct system-level trade study to evaluate technology for potential inclusion into lunar surface missions

Simplified PropFC Functional Block Diagram



PropFC Tipping Point Overview

Design & Build Fuel Cell Stack (PCI)	• 250-Watt Solid Oxide Fuel Cell stack • H_2/O_2 and CH_4/O_2 reactants
System-level Trade Study (GRC)	• Develop system-level design study • Identify system-level technology gaps
Verification Testing (PCI)	• Envelope and performance testing
Environmental Testing (JSC)	• Shock and Vibration testing



PCI
- Component Development
- Component Verification Testing

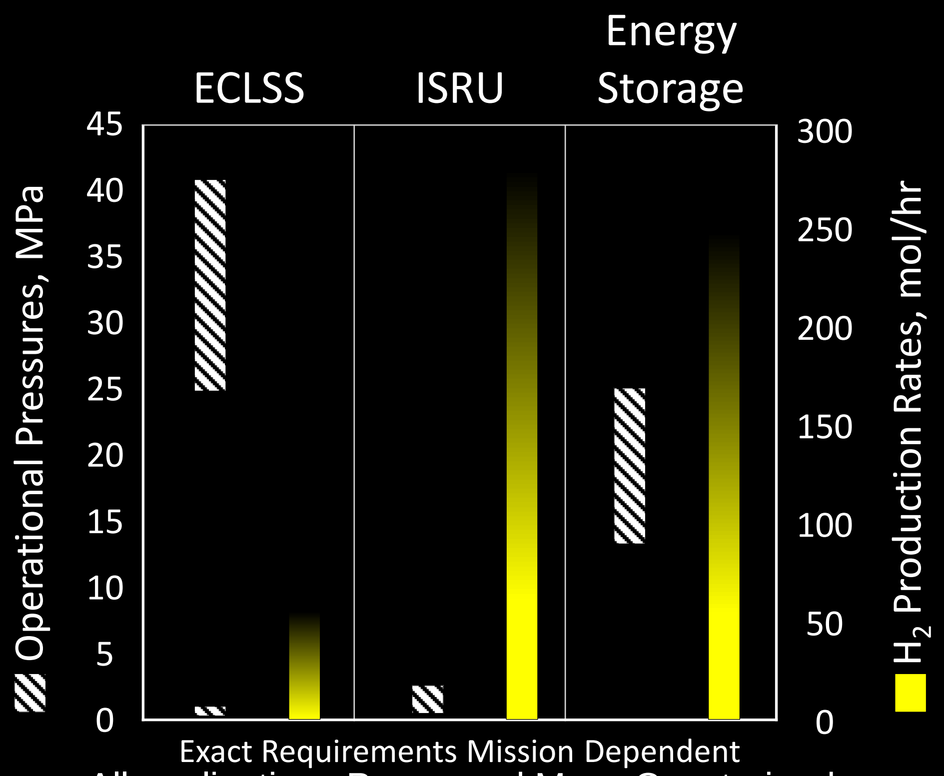
JSC
- Stack Performance Testing
- Stack Environmental Testing

H_2 and O_2 Reactant Generation

Electrolysis

- *Electrochemically dissociate water into gaseous hydrogen and oxygen*
    - *Balanced and Unbalanced designs*
    - *Low Pressure (< 0.3 MPa, < 45 psia)*
    - *Medium Pressure (<1.7 MPa, < 250 psia)*
    - *High Pressure (> 10 MPa, > 1,500 psia)*
    - *Contaminated Water Sources for ISRU*
- *ECLSS*
    - *Unbalanced Design ($H_2 << O_2$)*
    - *Unmet long-term requirements for reliability, life, or H_2 sensors stability*
- *Energy Storage*
    - *Balance Design ($H_2 \approx O_2$)*
    - *Unmet long-term requirements for performance, reliability, life, sensors availability, sensor stability*
- *In-situ Resource Utilization (ISRU)*
    - *Balance Design ($H_2 \approx O_2$)*
    - *Unmet long-term requirements for performance, reliability, or life*
    - *Tolerate contaminated water sources to minimize pre-conditioning requirements*

Notional Electrolysis Requirements



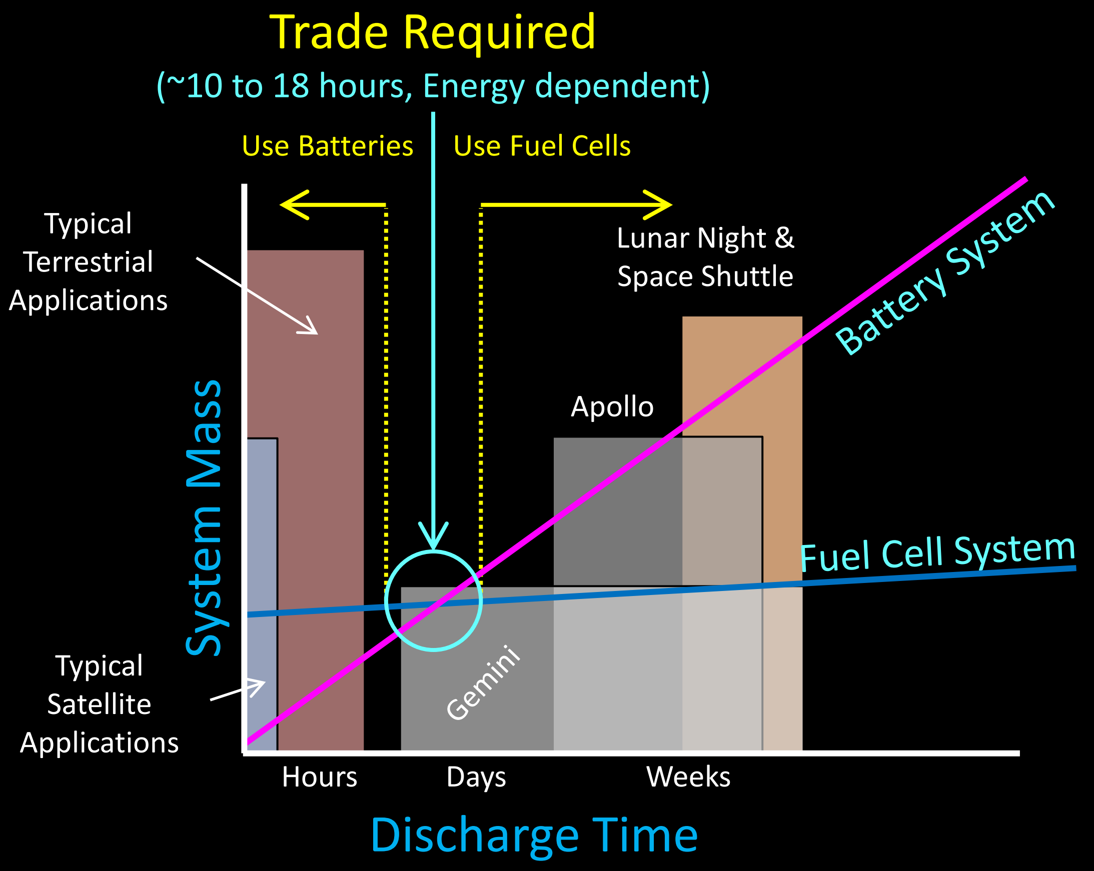
All applications Power and Mass Constrained

Processing Mined Lunar Water-Ice

- *Contaminated Water Processing*
    - *Minimize water cleaning system complexity and mass*
    - *Remove inert contaminants (e.g. Ca^+ and Mg^+ salts)*
    - *Remove chemically active contaminants (e.g. H_2S, NH_3, H_2CO_3, H_2SO_4, Hg, Methanol, etc.)*

Power and Energy Options

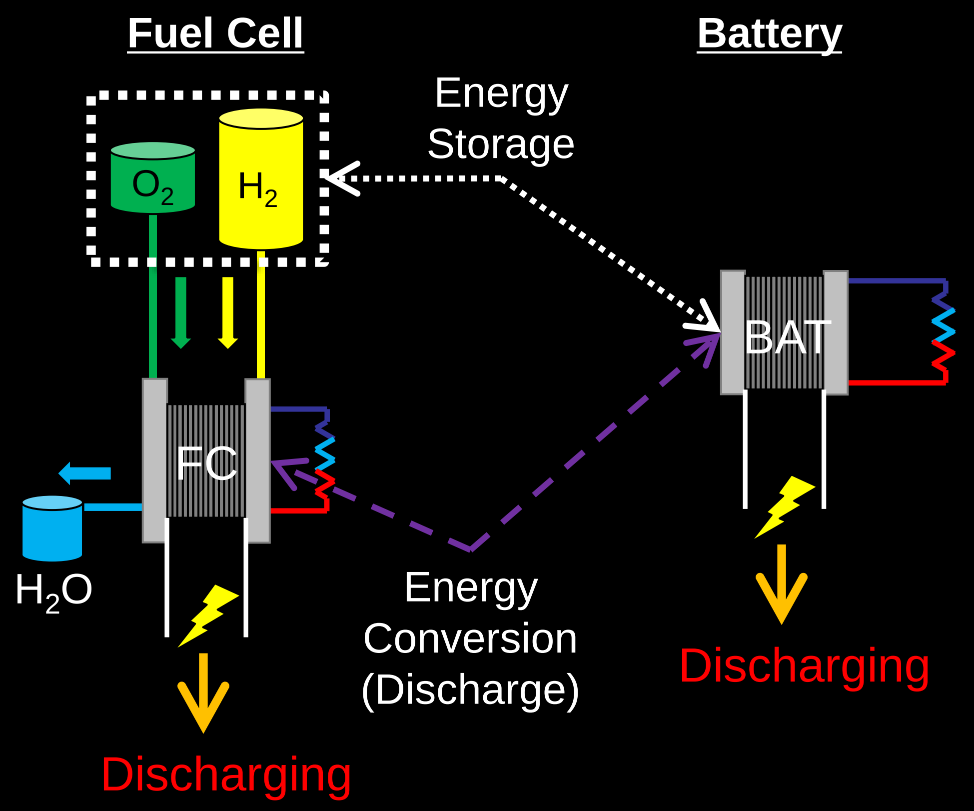
- Battery and Fuel Cell Technologies are *Complementary* not *Competitive*
  - No power or energy storage technology meets all requirements for all applications
  - Each technology has a place within the overall exploration space
  - Energy Storage Metric = Specific Energy (W·hr/kg)
    - Packaged Li-ion Battery Systems *~ 160 W·hr/kg*
    - Regenerative Fuel Cell Systems *< 100 to > 600 W·hr/kg* based on location and energy requirements
- Lunar night survival requires high specific energy (W·hr/kg) storage for both electrical and thermal energy
  - Lunar night: ~100 hrs (south pole) to 367 hrs (equator)
  - Waste heat helps systems survive the lunar thermal environment (-173ºC to +105ºC)
  - Targeting ≥ 50,000 hours maintenance interval
- NASA Applications
  - Crewed Lunar surface systems (36 kW·hr to ≥ 1 MW·hr)
  - Lunar sensor network (≤ 5 kW·hr)



Fuel Cells vs Batteries

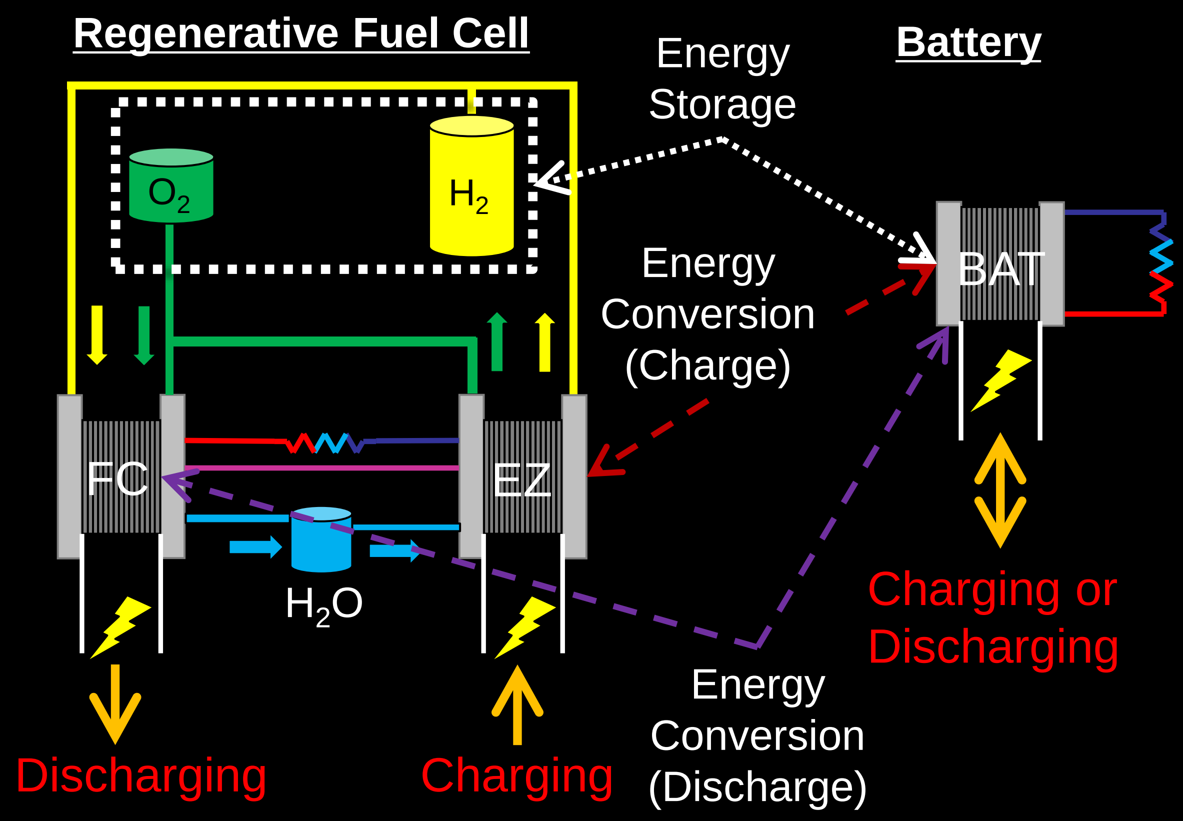
Primary Fuel Cell vs. Primary Battery

Discharge Power Only



RFC vs. Rechargeable Battery

Charge + Store + Discharge



Legend
BAT = Battery
EZ = Electrolyzer
FC = Fuel Cell Stack

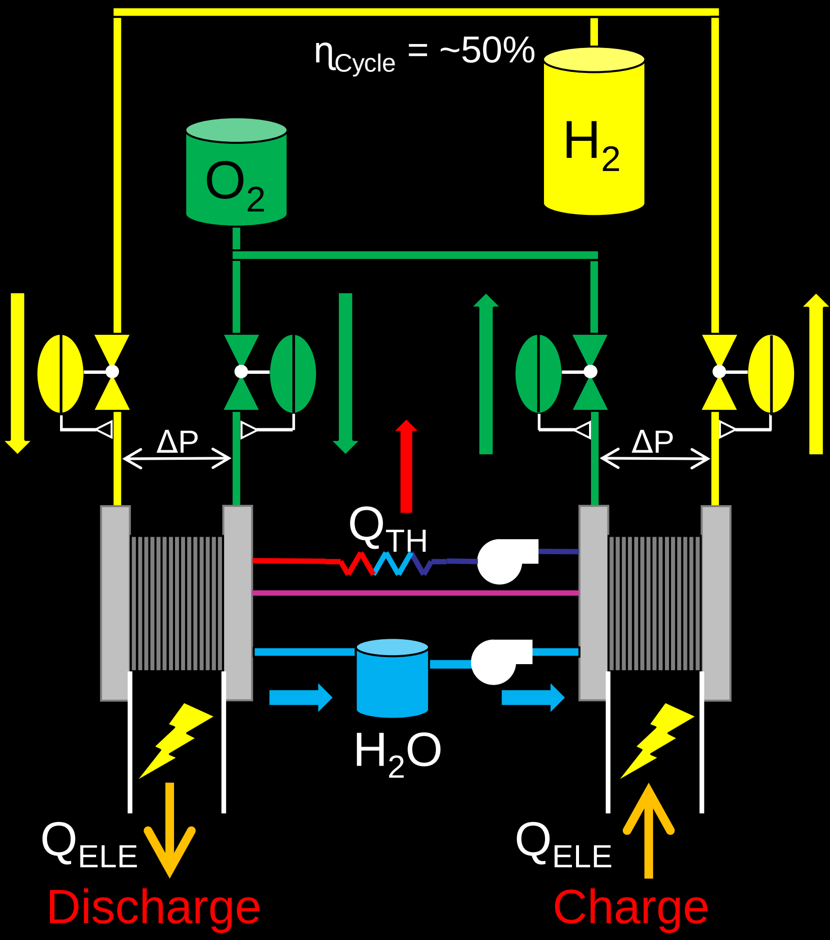
Fuel cells and Batteries ***Convert*** and ***Store*** Energy differently, resulting in:

- ***Different*** Safety Hazards
- ***Different*** Voltage response to State-of-Charge (SoC)
- ***Different*** Specific Power and Specific Energy

Regenerative Fuel Cell System Architectures

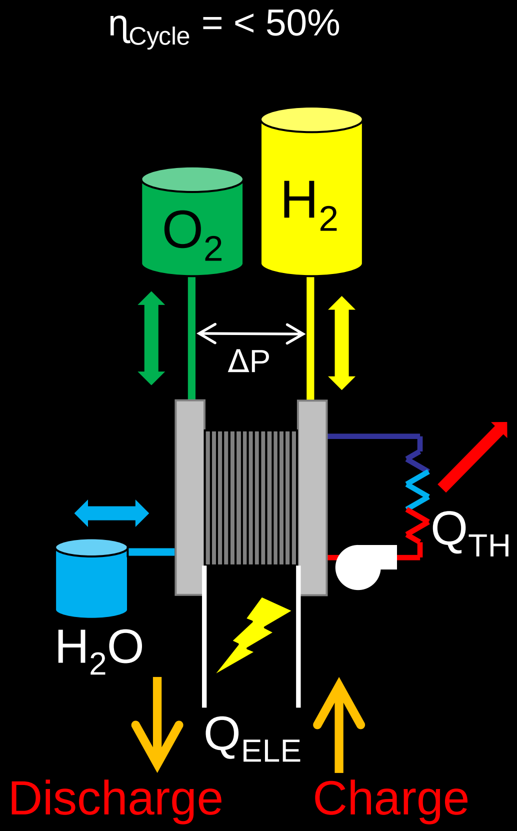
Discrete RFC

Optimized Processes



Unitized RFC

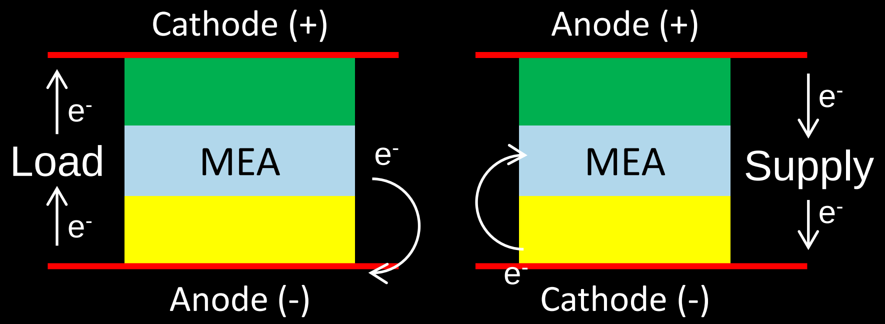
Hybrid Processes



Constant Gas

Change Ion Flow Direction

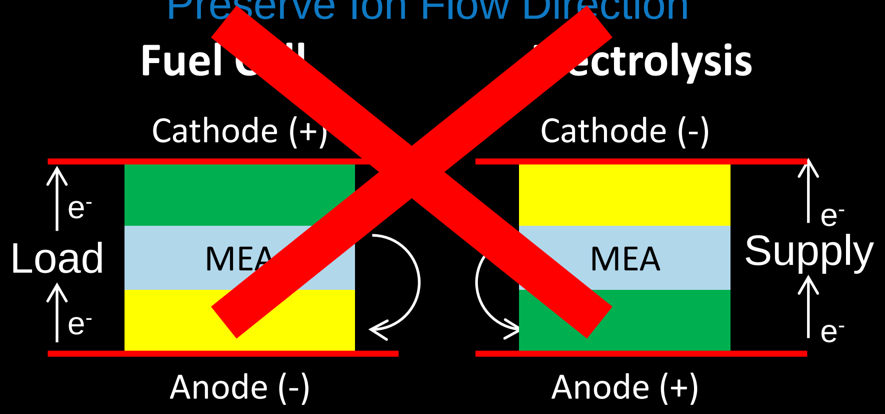
Fuel Cell **Electrolysis**



Currently not viable for crewed missions

Constant Electrode

Preserve Ion Flow Direction



RFC System Sizing Design Parameters

Parameter[1]	Units	Function	Influences
Thermal Environment[2,3]	°C	Specifies thermal and water management requirements	Roundtrip efficiency, specific energy, recharge system requirements, thermal management requirements
Energy Storage Quantity	kW•hr	Specifies reactant mass	Specific energy, thermal management requirements
Discharge Power	kW	Specifies fuel cell stack and fluid system size	Roundtrip efficiency, recharge system requirements, thermal management requirements
Recharge Power Availability[4]	kW profile	Specifies electrolyzer and fluid system size	Roundtrip efficiency, specific energy, recharge system requirements, thermal management requirements
Design Number of Lunar Equator Day/Night Cycles	#	Influences component and system reliability requirements	Mass, volume

Notes:

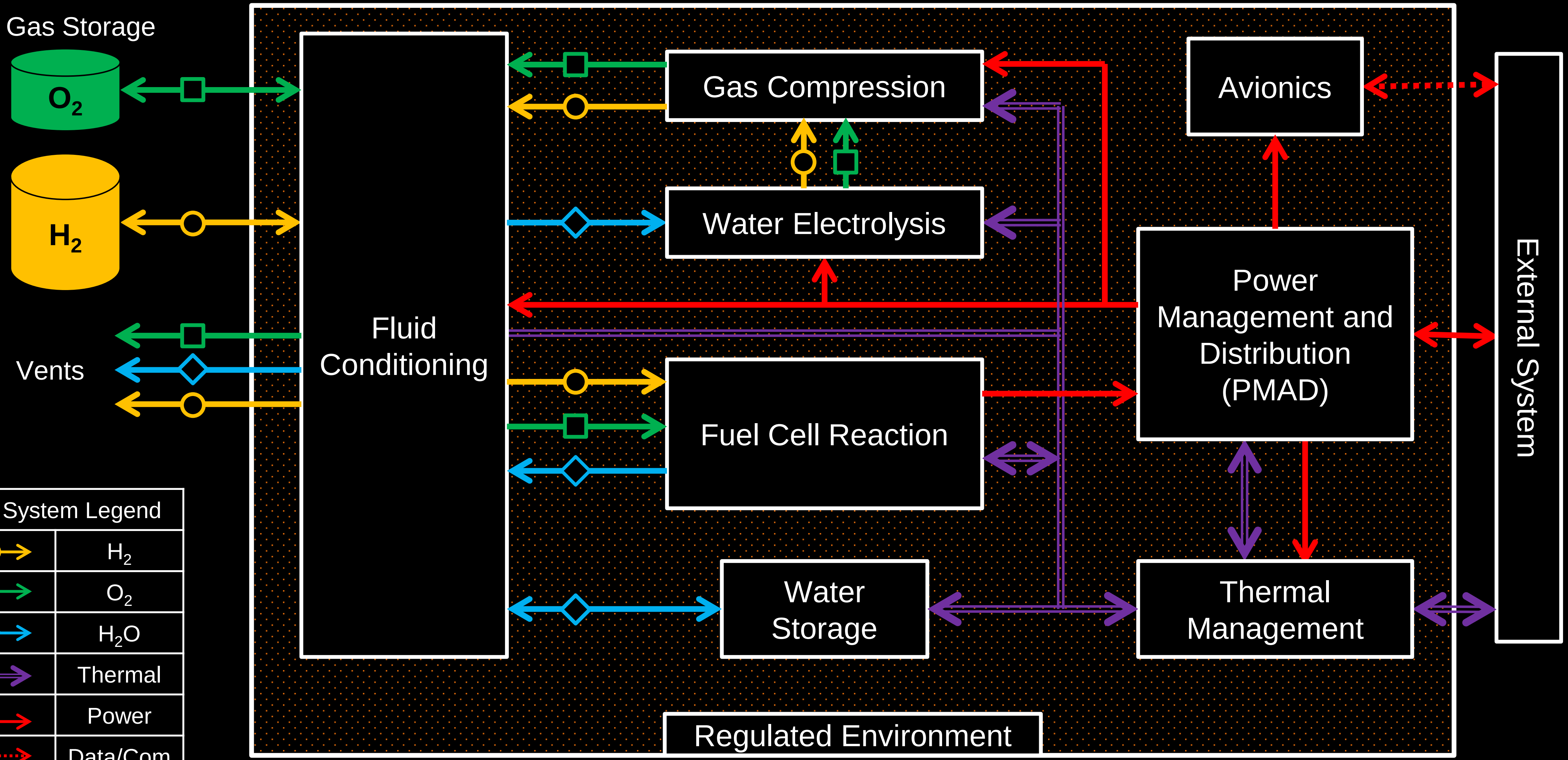
(1) Ranked in order of decreasing impact magnitude

(2) Highly dependent on location and architecture; Selections can increase or decrease RFC specific energy

(3) Least researched/developed element of RFC system designs

(4) Assumes a solar power (PV) system for the entire lander that both recharges the RFC and powers science payloads during lunar day

Regenerative Fuel Cell Functional Elements



RFC System Legend	
←○→	H_2
←□→	O_2
←◇→	H_2O
⟺	Thermal
⟷	Power
←·····→	Data/Com

RFC Technology Challenges by Element

O_2 Gas Storage
- ○ Water-accelerated *corrosion*
- • Cleanliness
- • Pressure Cycles
- • Thermal Cycles

H_2 Gas Storage
- ○ Water-accelerated *embrittlement*
- • Cleanliness
- • Pressure Cycles
- • Thermal Cycles

Fluid Processing and Control Module
- ➢ DI Water Lift Pumps
- ➢ Electrolysis-compatible Biocides***
- ➢ Sensor Calibration Stability
- ➢ Water Polishers / De-ionizers
- ➢ Water Quality
- ○ Catalytic Recombiner
- ○ Phase Separators
- ○ Regenerative Gas Dryers
- • Cleanliness
- • Corrosion
- • Material Compatibility
- • Operations / Procedures
- • Pressure Cycles
- • Thermal Cycles

Water Storage
- ➢ Water Quality
- ○ Contaminant Mitigation
- ○ Dormancy / Shelf Life
- • Cleanliness
- • Corrosion
- • Fluid Volume Management
- • Material Compatibility
- • Pressure Cycles

Water Electrolysis & Gas Compression
- ➢ Efficient / Reliable Reactant Compression
- ➢ Electrolyte Mechanical Properties***
- ➢ Safety Sensor (H_2–in–O_2, High Pressure)
- ➢ Stack Integration (Life, Performance, Reliability)***
- ○ Bipolar Plate / Interconnect Performance***
- ○ Catalyst Performance***
- ○ Electrode Performance***
- ○ Electrolyte Ionic Conductivity***
- ○ Safety Sensor (O_2–in–H_2, High Pressure)
- ○ Water Quality***
- • Cleanliness
- • Corrosion
- • Material Compatibility
- • Pressure Cycles

Fuel Cell Reaction
- ➢ Electrolyte Mechanical Properties***
- ➢ Electrolyte Performance Stability***
- ➢ Stack Integration (Life, Performance, Reliability)***
- ○ Bipolar Plate / Interconnect Performance***
- ○ Catalyst Performance***
- ○ Degassing Product Water***
- ○ Electrode Performance***
- ○ Electrolyte Ionic Conductivity***
- ○ Gas Diffusion Layer Performance***
- ○ Internal Water Management
- • Cleanliness
- • Corrosion
- • Material Compatibility

Avionics
- ➢ Radiation-tolerant Avionics
- • Software

Power Management and Distribution
- ➢ Radiation-tolerant Power Electronics
- ○ Power Standards (Quality, Interfaces)

Thermal Management
- ➢ High Flux Thermal Switch (kW-scale)
- ○ Radiator / Heat Sink
- • Multi-range thermal systems
- • Long-life coolant pumps

External System

Legend
- ➢ Tech Dev Required
- ○ Tech Dev Recommended
- • Engineering Required

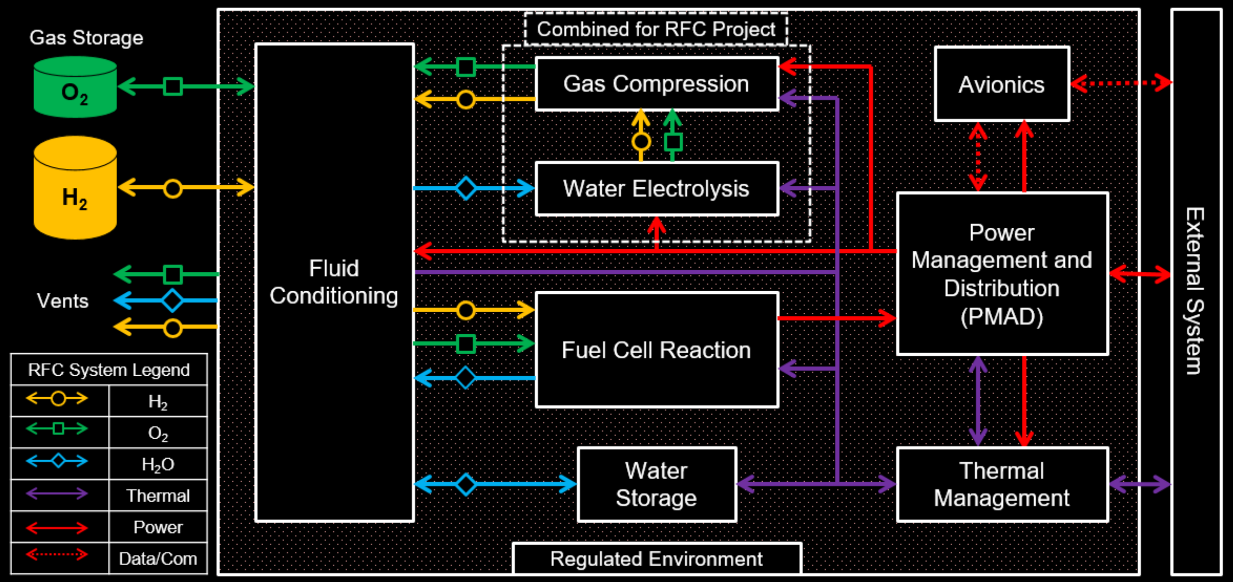
*** = Required development depends on electrolyte: PEM vs Alkaline vs Solid Oxide

For more details, see P. Smith, et al.; *Aerospace Regenerative Fuel Cell Fluidic Component Design Challenges*, NASA/TM-20210024659.

Regenerative Fuel Cell Project

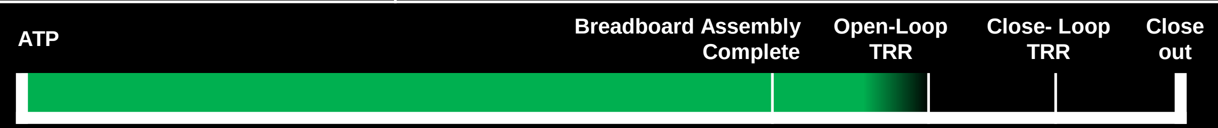
- Available energy storage technologies have low specific energies (W·hr/kg) imposing unacceptable mass onto lunar surface missions
- NASA funds research of multiple technologies to maximize specific energy, including hydrogen (H_2) / oxygen (O_2) regenerative fuel cell (RFC) energy storage technology
- RFC project to assess viability of optimized discrete *system* technology for potential inclusion into lunar surface missions

Simplified RFC Functional Block Diagram



Regenerative Fuel Cell Project Overview

Design & Build H_2 / O_2 RFC System	• 50 psia Fuel Cell stack (Infinity Fuel Cell and Hydrogen) • 1800 to 2500 psia Electrolyzer (Giner) • Self-supporting sub-systems • Automated control system
≥ 2 month autonomous closed-loop test under laboratory conditions	• Full system pressures and multiple cycles • Open-loop operation for system functional verification • Closed-loop operation for reactant purity verification



<u>Open Loop Testing</u>
- Component Verification Testing
- Breadboard System Assembly
- Breadboard System Verification
- Breadboard Open-loop Testing

<u>Closed Loop Testing</u>
- RFC Breadboard System Closed-loop Testing

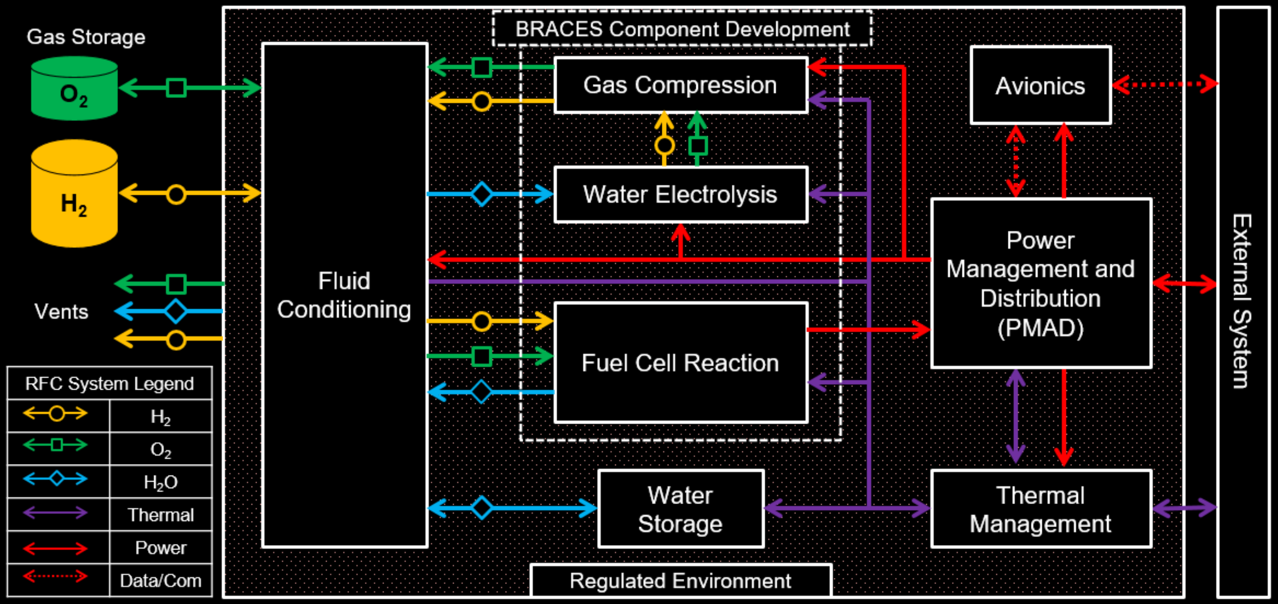
Bi-furcated Reversible Alkaline Cell for Energy Storage (BRACES) Tipping Point

- Available energy storage technologies have low specific energies (W·hr/kg) imposing unacceptable mass onto lunar surface missions
- NASA funds research of multiple technologies to maximize specific energy, including hydrogen (H_2) / oxygen (O_2) regenerative fuel cell (RFC) energy storage technology
- BRACES project to assess viability of *unitized stack* design for potential inclusion into lunar surface missions

BRACES Tipping Point Overview

Design & Build Unitized Stack (pH Matter)	• 250 bar (~3600 psia) Unitized stack • Unitized stack to demonstrate electrolysis and fuel cell reactions
Design & Build Test Systems (pH Matter)	• Automated independent control system • Breadboard system for Laboratory testing • Brassboard system for Thermal-Vacuum test
Brassboard Verification Testing (GRC)	• Verify open-loop operation for system cyclic operation and performance metrics

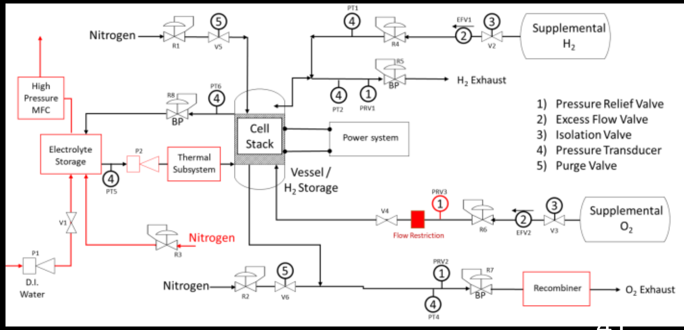
Simplified BRACES Functional Block Diagram



ATP | Breadboard CDR | TAPR | Brassboard DDR | Brassboard TRR | Close out

pH Matter
- Component Development (Stack)
- Breadboard System Design, Assembly, and Verification

GRC
- Breadboard System Open-loop Laboratory Testing (No Reactant Storage)



Interagency Collaboration Opportunities

NASA TechPort

NASA STMD and ESDMD coordinating Technology Gap Identification for Closure:

- TechPort Website
- https://techport.nasa.gov/dashboards
- Contains Operational Life:
- Pure oxygen reactants provide challenging operational environment
- Space Missions have limited maintenance options
- Long dormancy periods with large thermal variations

LSIC / LOGIC

LSIC

- Lunar Surface Innovation Consortium (LSIC) (http://lsic.jhuapl.edu/)
- LSIC run by Johns Hopkins Applied Physics Laboratory (JH-APL)
- Mechanism for open collaboration between Academia, Industry, Government, and the public in the following lunar sectors:

1. Power
2. < ? TBR ? >
3. < ? ISRU ? >
4. Cross-< ? TBR ? >

LOGIC

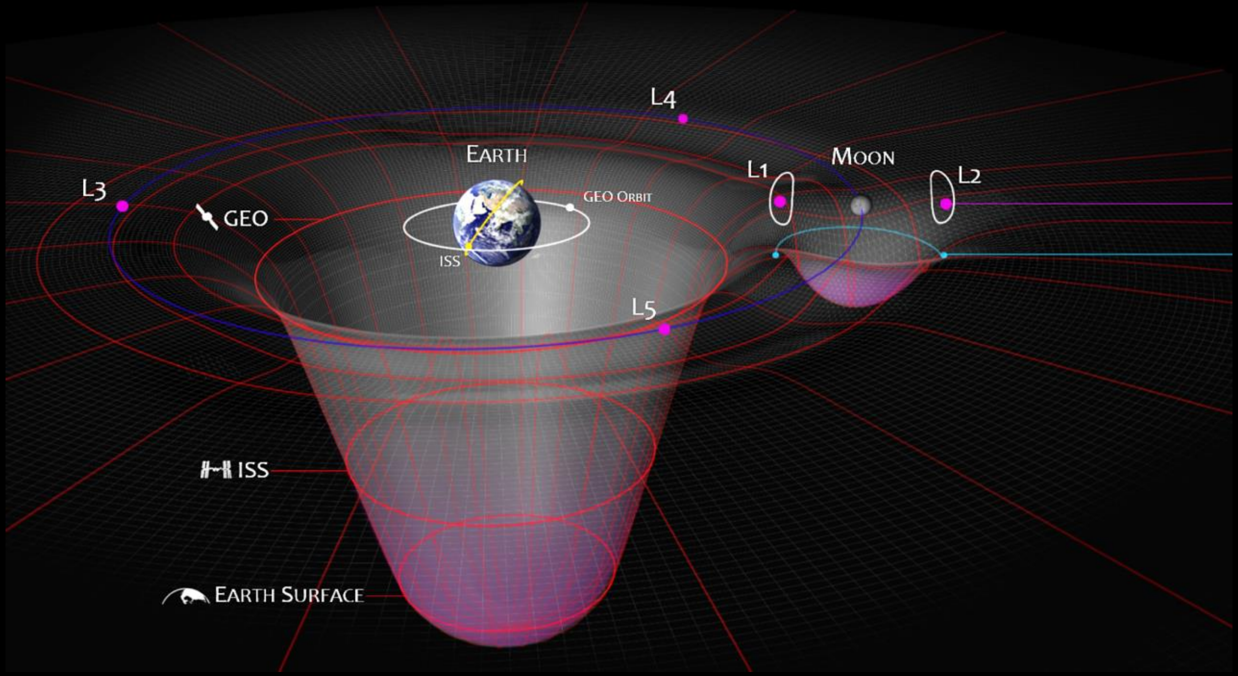
- Lunar Operating Guidelines for Infrastructure Consortium (LOGIC) (https://logic.jhuapl.edu/)
- LSIC run by Johns Hopkins Applied Physics Laboratory (JH-APL)
- LOGIC to identify, recommend, and accelerate development of interoperability standards of lunar infrastructure and technologies in lunar:

1. Power
2. Communications / Position, Navigation, Timing (PNT)
3. Mobility
4. In-Situ Resource Utilization (ISRU) / Mining
5. Robotics / Construction
6. Market Analysis

Review

- Overview of NASA Hydrogen Applications
- Ground Operations
- Aeronautic Applications
- Space Applications
- Interagency Collaboration Opportunities

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)
Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage



Gravity profiles for Cis-lunar space

Concept fuel cell powered lunar lander

Questions?


Thank you for your attention.