National Aeronautics and Space Administration

NASA Fuel Cell and Hydrogen Research Activities

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Presentation Overview

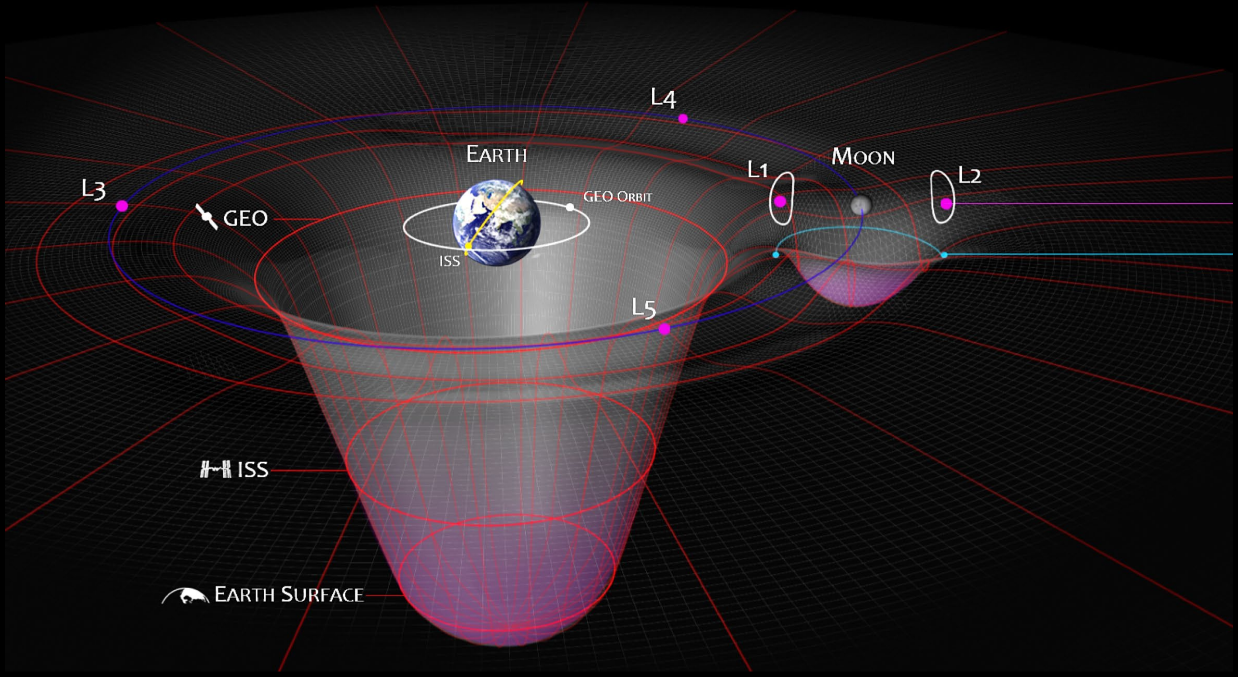
- **Overview of NASA Hydrogen Requirements**
- **Aeronautic Applications**
- **Space Applications**

IZEA *Integrated Zero Emission Aviation*

Grant Number: 80NSSC22M0068

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)

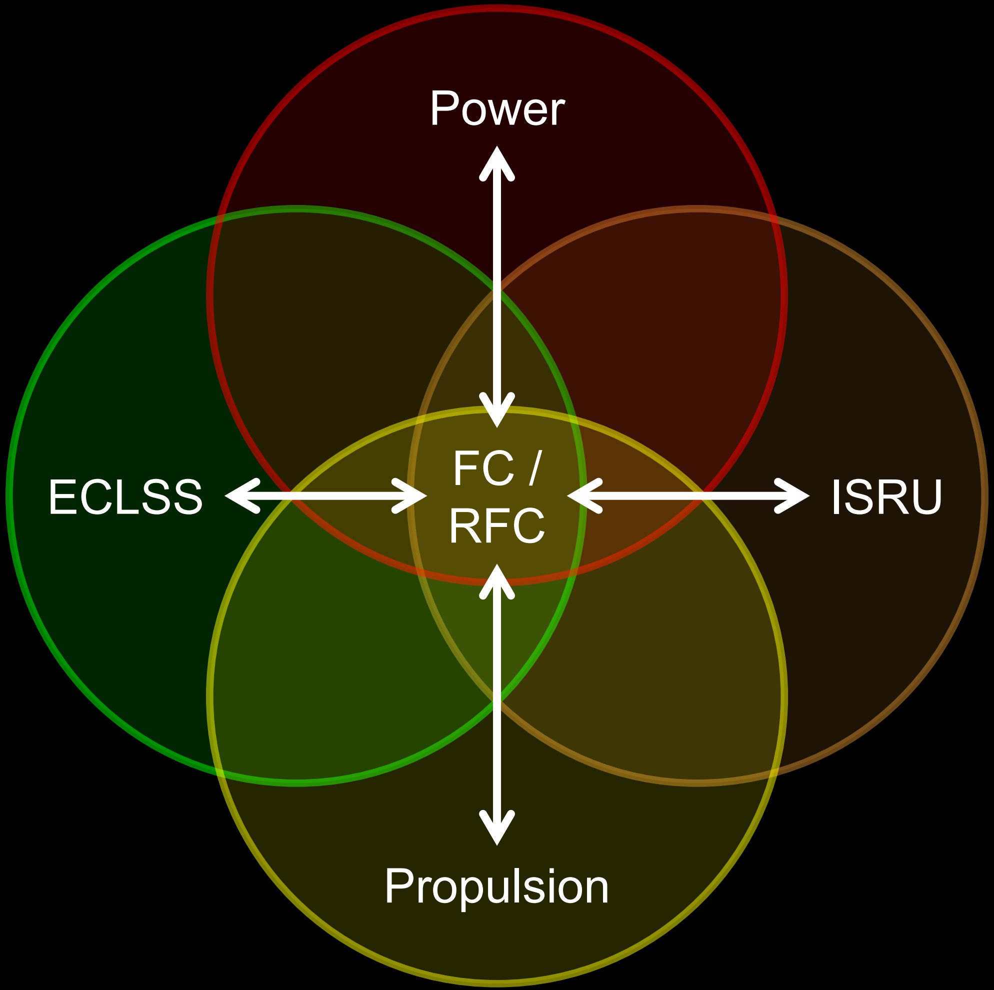
Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage



NASA's all-electric X-57 Maxwell prepares for ground vibration testing at NASA's Armstrong Flight Research Center in California.
Credits: NASA Photo / Lauren Hughes

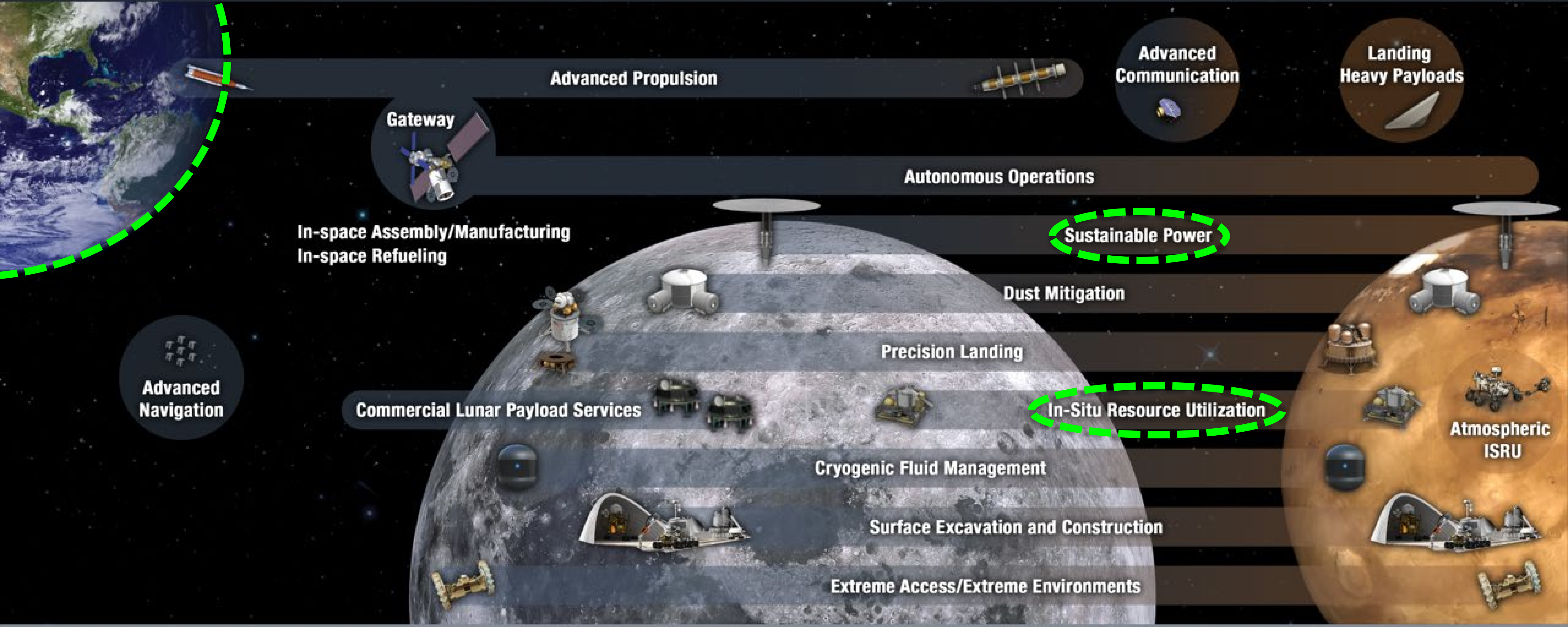
Electrochemical Interoperability

The core fuel cell and water electrolysis chemical reactions share common reactants and power/energy requirements across support multiple aerospace electrochemical applications.



Legend
ECLSS = Environmental Control and Life Support Systems
FC = Fuel Cell (Primary Power)
ISRU = In Situ Resource Utilization (On-site Production)
PMAD = Power Management and Distribution
RFC = Regenerative Fuel Cell (Energy Storage)

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



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)*

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*

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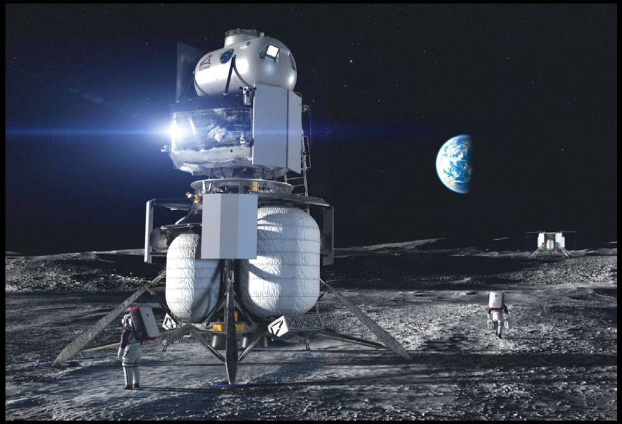


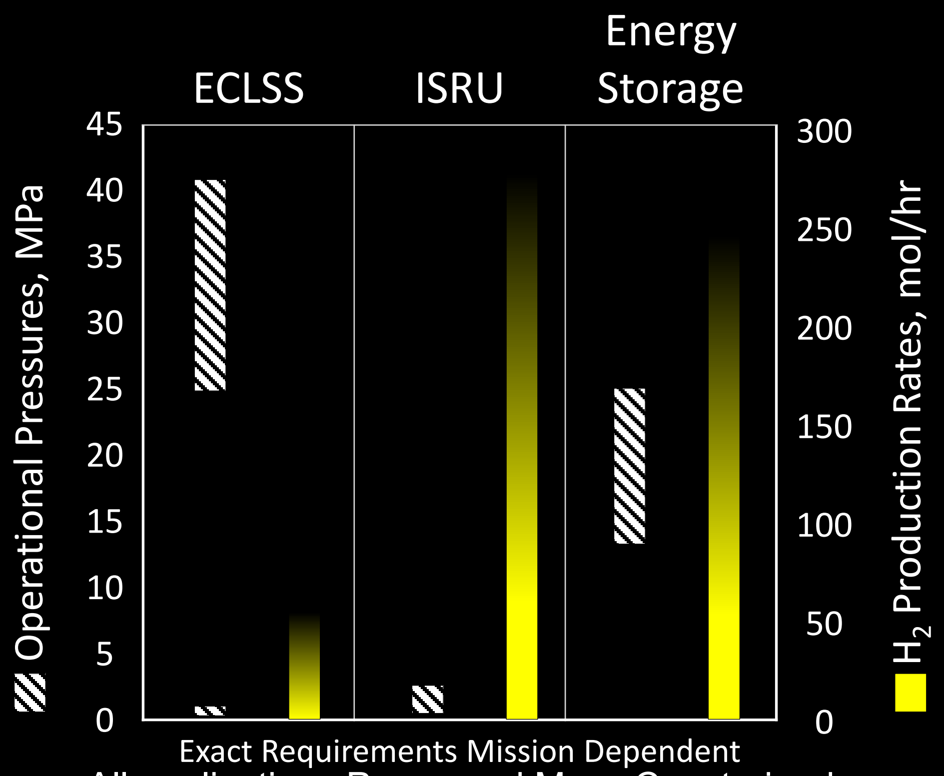
Blue Origin Lunar Lander Baselined Fuel Cell Power as primary power source

H_2 and O_2 Reactant Generation

Electrolysis

- *Electrochemically dissociate water into gaseous hydrogen and oxygen*
- *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



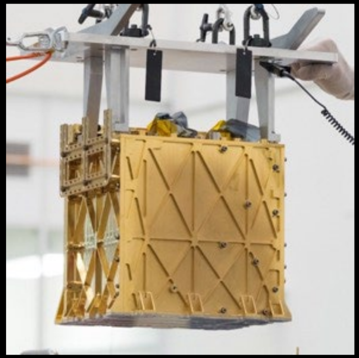
All applications Power and Mass Constrained

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.)*

Fuel Cell and Hydrogen Activities Within NASA

Electrolyte Chemistry	Power	Electrolysis	Regenerative	# Projects
Alkaline	0	3	3	6
Proton Exchange Membrane (PEM)	6	7	4	17
Solid Oxide	3	3	0	6
Other	3	1	0	1
Total	12	14	7	33



Mars Oxygen ISRU Experiment (MOXIE)
Aboard Perseverance, demonstrated the first production of oxygen from the atmosphere of Mars Apr. 2021.

Power Generation and Storage

- *Propellants*
  - *Launch Vehicles*
  - *Mars/Lunar Landers*
- *Fuel hydrogen-based fuel cells*
  - *Lunar/Mars surface systems*
  - *Urban Air Mobility / Zero Emission*

Reactant Generation

- *Electrochemically dissociating water into gaseous hydrogen and oxygen*
  - *Environmental Control and Life Support Systems (ECLSS)*
  - *Energy Storage*
  - *In-Situ Resource Utilization (ISRU)*
  - *Contaminated Water Sources for ISRU*
- *Recover raw materials from local sources*
  - *Water (ice) Mining*
  - *Contaminated Water Processing*
  - *Regolith Processing*
- *Metal Processing*

Aeronautics

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) program to develop, mature, and design disruptive technologies for electric commercial aviation.

- **Provide a direct line-of-sight path to**
  - Meet/exceed aviation goals for alternative propulsion and energy options
  - An aircraft system with a quiet, efficient propulsion system that produces zero CO_2, NO_X, and particulate emissions
- **Research associated technologies**
  - Distributed aero-propulsion system integration
  - High-efficiency electrochemical power conversion
  - Flight-weight electric machines and power electronics,
  - Materials and systems for superconducting high-efficiency power transmission
  - Methods for complex system integration and optimization.
  - Unconventional energy storage and power generation architectures (e.g. liquid hydrogen fuel and fuel cell systems)
- **Identify Technology Gaps for future research**

Principal Investigator: Phillip Ansell
Lead Organization: University of Illinois
Supporting Organizations:

- Boeing
- Chicago State University
- General Electric (GE)
- Massachusetts Institute of Technology (MIT)
- Ohio State University
- Rensselaer Polytechnic Institute
- University of Arkansas
- University of Dayton

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

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

IZEA Integrated Zero Emission Aviation

Grant Number: 80NSSC22M0068

The project goals and broader impacts can be summarized as:

- **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 the potential for global warming reduction across the passenger aviation fleet
  - Use a multi-disciplinary design, analysis and optimization approach to identify and model hydrogen-fueled aircraft for the fleer
  - Develop a feasible power generation and energy conversion subsystem
  - Develop a feasible power electronics, distribution and motor-driven propulsion subsystem
  - Develop a 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

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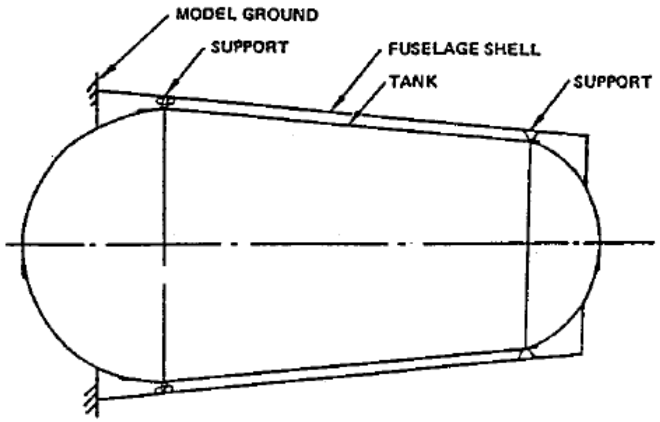
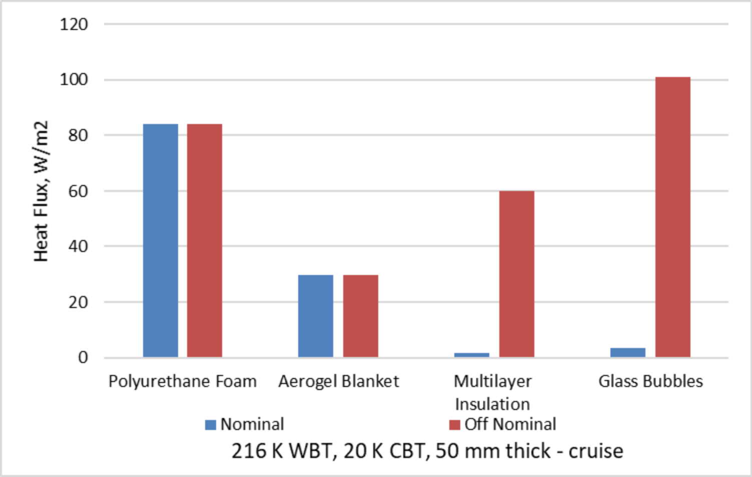
Sustainable Aviation Demo (Liquid Hydrogen Aircraft)

- **Description**
  - Develop smart buyer approach for gaps required for hydrogen aircraft development through the next few years
  - Focused on single aisle replacement aircraft for mid 2030s.
- **Activities**
  - Support Georgia Tech Conceptual design studies
  - Develop methodologies to size metallic and composite tanks
  - Develop concepts for improved insulation systems required to maintain hydrogen storage on aircraft.
  - Investigate concepts of operation for loading/distribution of hydrogen to aircraft
  - Support joint US/European hydrogen aircraft standards development with WSTF
- **Significance**
  - Find ways to help guide US aircraft industry as it explores development of liquid hydrogen aircraft.
  - Leverage space technologies and knowledge base as applicable





POC: Dave Koci (f.d.koci@nasa.gov)

Known Aeronautic 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

Space

Do Terrestrial Systems apply to Aerospace Applications?

Answer: Sometimes

Aerospace		Terrestrial
Differentiating Characteristics ➢ Pure Oxygen (stored, stoichiometric) ➢ Water Separation in μg	≠	Differentiating Characteristics ➢ Atmospheric Air (conditioned, excess flow) ➢ High air flow drives water removal

Fluid management issues and environmental conditions make aerospace and terrestrial fuel cells functionally dissimilar

A SUSTAINED PRESENCE ON THE SURFACE

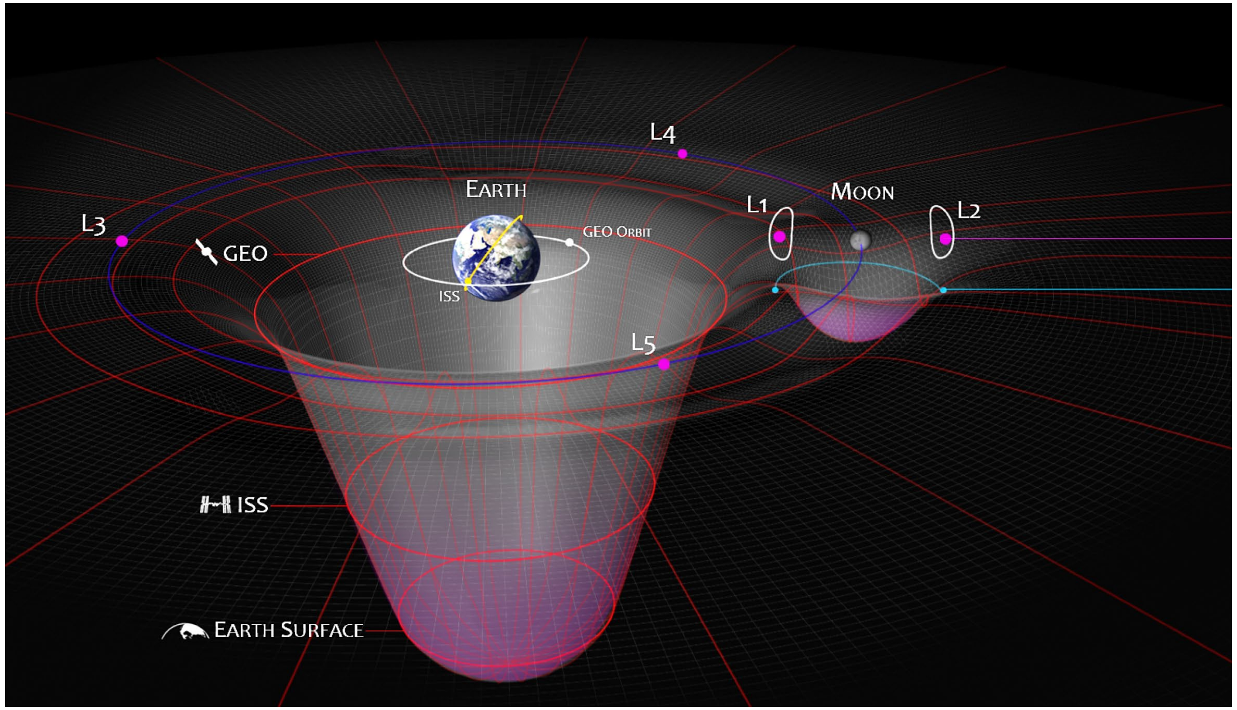
A steady cadence of missions and a robust infrastructure on the lunar surface

- 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

Gear Ratio Effect Reduces Launches and Cost

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
- Resources include propellant depots, propellant production facilities (initially H_2 and O_2), and consumable storage

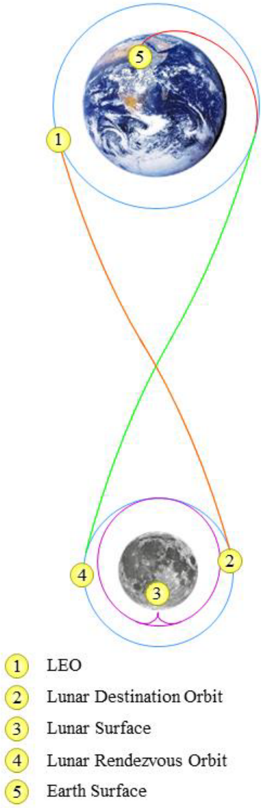


Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

- 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

Exploration

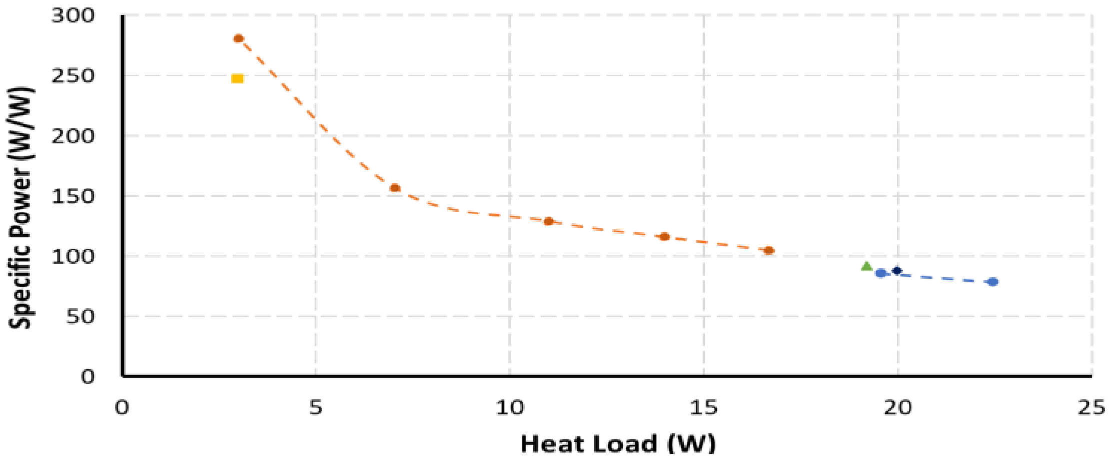
- **NASA continues to pursue Lunar Exploration goals through the Human Landing System**
  - Multiple risk reduction and development activities with regards to the long duration storage and transfer of liquid hydrogen in orbit
- **The Space Technology Mission Directorate is pursing multiple Tipping Point flight demonstrations:**
  - Lockheed Martin, Cryogenic Demonstration Mission – storage and transfer of liquid hydrogen
  - United Launch Alliance – transfer of liquid hydrogen and liquid oxygen
- **Continue the development of Radio Frequency Mass Gauge for mass gauging in unsettled conditions**
- **Hydrogen liquefaction for the Lunar and Martian surface – completed conceptual design trades**
  - Demonstrated oxygen liquefaction techniques that partially apply to hydrogen
- **Completed Testing of 20 W at 20 K cryocooler prototype for spaceflight applications**

Key Performance Parameters for the 20 W/20 K RTB Cryocooler Project

Parameter	State of the Art	Threshold Value	Project Goal	Tested Values[1]	Projected Values[2]
1) Lift Capacity (W)	1	17	20	19.2	20.4
2) Specific Mass (kg/W)[3]	18.7	5.5	4.4	5.5	5.2
3) Specific Power (W/W)	370	80	60	91.6	86.3

Notes:
KPPs assume a fully integrated cryocooler operating and are based on a 20K design point, and do not include the mass and inefficiency of the drive electronics.

1. **Tested values were only able to be achieved at a heat rejection temperature of 285K.**
2. **Projected values are based on data projections from a heat rejection temperature of 285K to 270K.**
3. **Specific mass values are based on flight-like projections.**

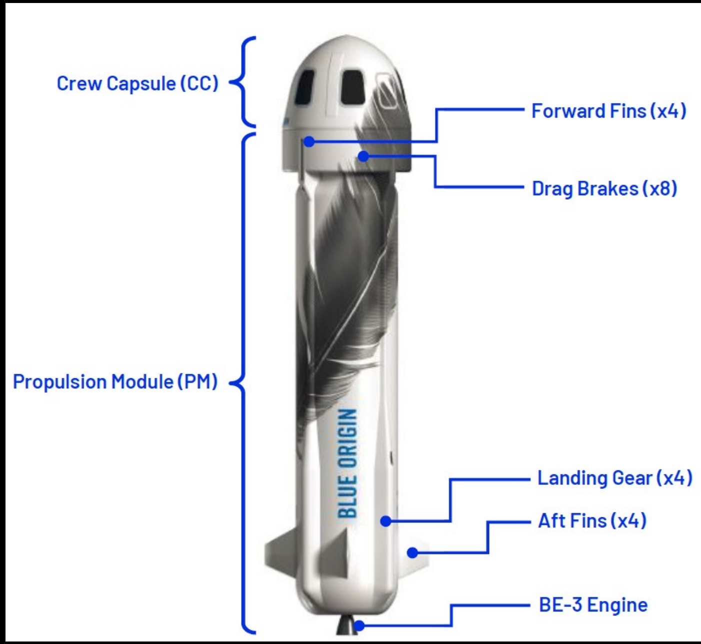


POC: Wes Johnson (wesley.l.johnson@nasa.gov)

Space Fuel Cell Power Development Activities

PEM (Nafion-based)

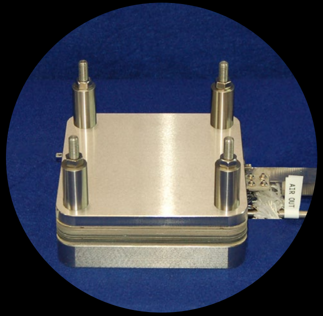
1. Sub-orbital Flight Technology Demonstration
   - Advanced Modular Power and Energy System (AMPES) – Infinity Fuel Cell & Hydrogen
   - Hydrogen Electrical Power System (HEPS) – Teledyne



Integrated
New Shepard Vehicle
Crew Capsule and
Propulsion Module

Solid Oxide

1. Solid Oxide Fuel Cells (SOFC)
   - Surface Power Generation from Lunar Resources and Mission Consumables (PropFC) - Precision Combustion
   - Efficient, High Power Density Hydrocarbon-Fueled Solid Oxide Stack System- Precision Combustion



SOFC Sub-Stack for space applications

Funding Sources

NASA Funds	Tipping Point / ACO	SBIR / STTR

Space Fuel Cell Electrolysis and Energy Storage Development Activities

PEM (Nafion-based)

1. Electrolysis Advancement:
   Component
   - Static Vapor Feed Electrolysis
2. Electrolysis Advancement:
   System
   - Advanced Oxygen Generator Assembly
3. Energy Storage Advancement:
   System
   - Regenerative Fuel Cell Project

Alkaline

1. Electrolysis Storage Advancement:
   Component
   - Advanced Alkaline Electrolyzer (AAE) – Teledyne
2. Energy Storage Advancement:
   Component
   - Advanced Alkaline Reversible Cell (AARC) – pH Matter
   - Bifurcated Reversible Alkaline Cell for Energy Storage (BRACES) – pH Matter

Solid Oxide

1. TRL Advancement:
   Component
   - Highly Efficient, Durable Regenerative Solid Oxide Stack - Precision Combustion
   - Efficient, High Power Density Hydrocarbon-Fueled Solid Oxide Stack System- Precision Combustion

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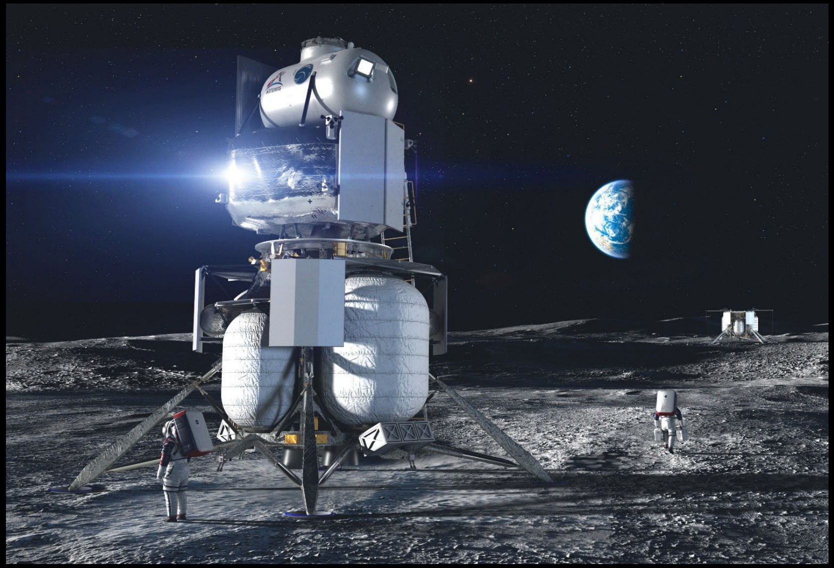
Known Space Technical Gaps

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



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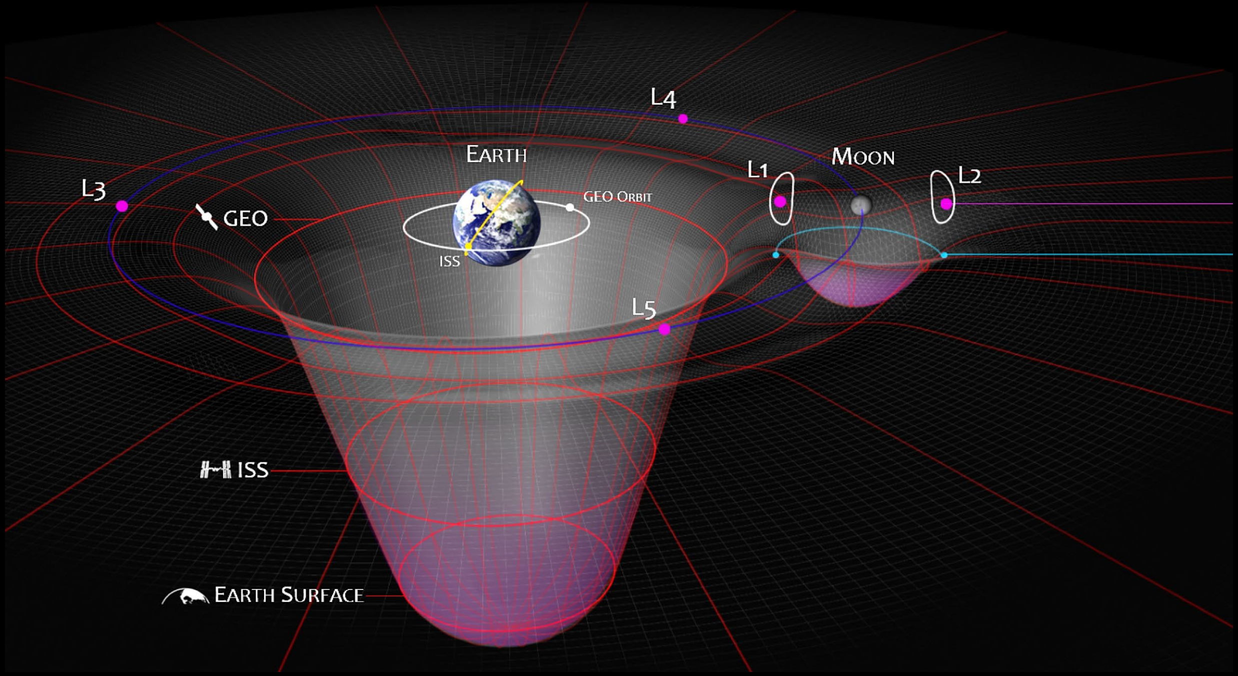

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Questions

Thank you for your attention.