An Overview of The Photovoltaic and Electrochemical Systems Branch at the NASA Glenn Research Center

Eric Clark/NASA GRC

25th Space Photovoltaic Research and Technology (SPRAT XXV) Conference

Ohio Aerospace Institute

Cleveland, Ohio

September 19, 2018

Outline

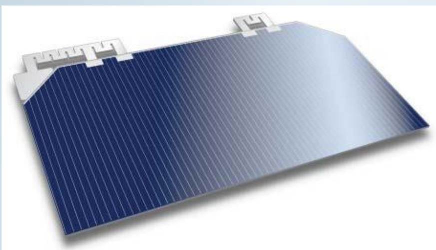
- Introduction/History
- Current Projects
  - Photovoltaics
  - Batteries
  - Fuel Cells
- Future Technology Needs
- Conclusions

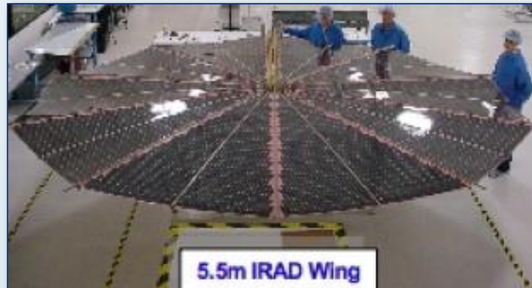
Introduction

- The Photovoltaic and Electrochemical Systems Branch (LEX) at the NASA Glenn Research Center (GRC) supports a wide variety of space and aeronautics missions, through research, development, evaluation, and oversight.
  - Solar cells, thermal energy conversion, advanced array components, and novel array concepts
  - Low TRL R&D to component evaluation & flight experiments
  - Supports NASA missions through PV expertise and facilities
  - Management of SBIR/STTR Topics, Subtopics, and individual efforts.
- LEX works closely with other NASA organizations, academic institutions, commercial partners, and other Government entities.

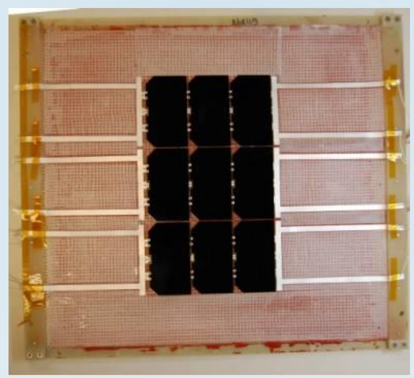
Examples of LEX activities

Solar Cells

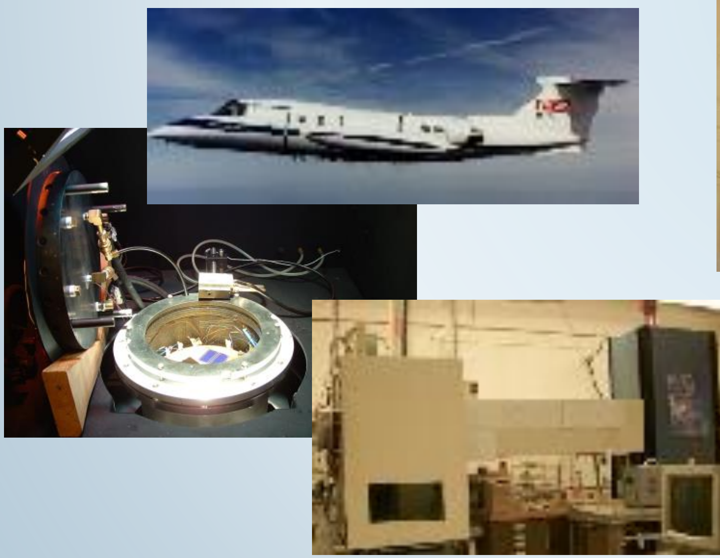




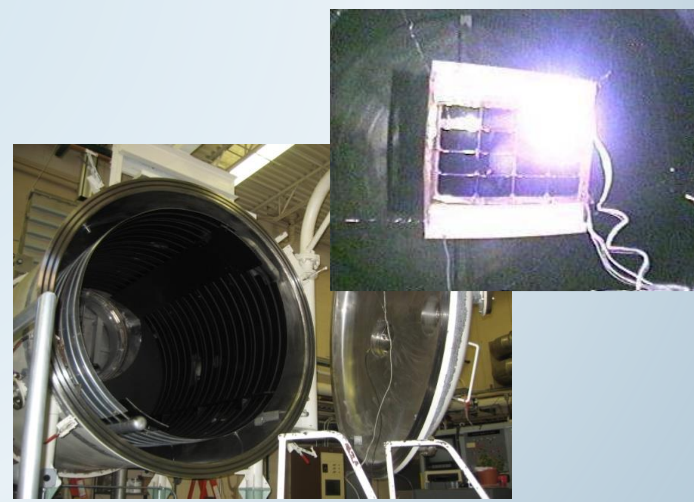
Array Blanket and Component Technology



Advanced Solar Arrays



Solar Cell Measurements & Calibration



Solar Array Space Environmental Effects

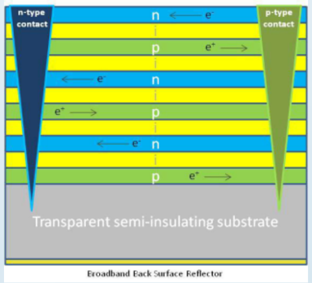
History

- 1991The Photovoltaic Branch
  - Multijunction Cell development, Advanced Metalization, Radiation hardness, Measurement and Calibration
- 1997 The Photovoltaic Branch combines with the Space Environmental Effects Branch and becomes the Photovoltaic and Space Environments Branch
  - Capabilities in spacecraft charging, and plasma interactions
- 2014 The Photovoltaic and Space Environments Branch combines with the Electrochemistry Branch and becomes the Photovoltaic and Electrochemical Systems Branch
  - Research and development in Batteries and Fuel Cells

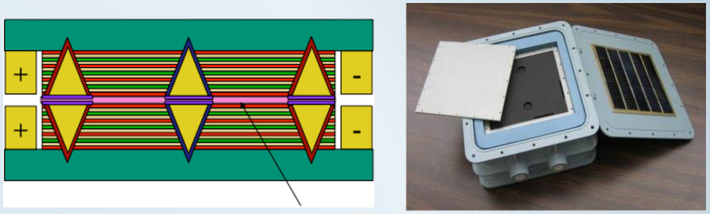
Photovoltaic Branch Historical Areas of Expertise

High Efficiency III-V Photovoltaic Development

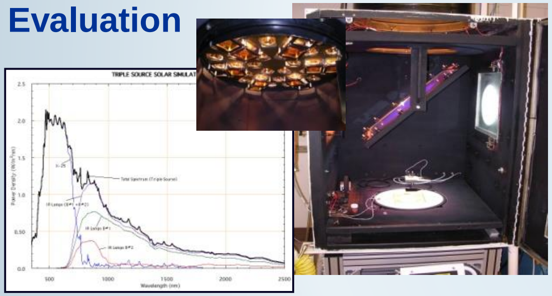
Nanomaterials and Nanostructures for Space Photovoltaics



Radioisotope-based Direct Energy Conversion (Thermophotovoltaic and Alpha/Beta-voltaic Technology)



Solar Cell Measurement and Performance Evaluation



Research and development on a wide variety of solar cell, blanket component, and array concepts to support NASA missions and aerospace technology needs.

Extended Temperature Operation of Solar Arrays

Solar Cell Air Mass Zero Calibration

Advanced Blanket and Array Technologies

Space Power Arcing, Radiation, and Charging

Current Photovoltaics Focus

- Development of solar cells for operation in extreme environments.
  - Low Intensity Low Temperature (LILT) operation
  - Extended Environment Solar Power (EESP)
  - Venus Power
- Measurement and Calibration
  - X25 Solar Simulator
  - ER2 Flights
- Perovskite research, advanced array design support, environmental effects of high voltage arrays, Lunar/Mars power systems

NASA GRC Energy Storage Technology Activities

- Batteries
  - X-57 SCEPTOR
  - Convergent Aeronautics Solutions – M-SHELLS
  - Convergent Aeronautics Solutions – LION
  - High Temperature Tolerant Batteries - LLISSE
  - International Space Station (ISS)
- Fuel Cells
  - Convergent Aeronautics Solutions – FUELEAP
  - Advanced Exploration Systems Modular Power Systems

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    - SBIRs

Scalable Convergent Electric Propulsion Technology Operations Research (SCEPTOR) (X-57 Maxwell)

POCs: Tom Miller, NASA GRC, (216) 433-6300
Dr. Dionne Hernandez-Lugo, NASA GRC, (216) 433-5911

Modified Tecnam Aircraft

Project Objective: Distributed Electric Propulsion enabling ultra-high efficiency, low carbon emissions, low community noise, and low operating costs with a primary goal of 5X lower energy use (Aeronautics Flight Demonstration and Capabilities)

Team: Led by NASA AFRC; GRC providing oversight for battery development and build, with support from NASA JSC on safety design issues

Architecture: Two 20P/128S batteries in parallel, each comprised of eight 20P/16S modules to produce a total of 120Ah at ~460V nominal based on Samsung 30Q 18650 Li-ion cells

Flight Battery Modules

Accomplishments: GRC assisted battery vendor with re-design of human-rated battery .

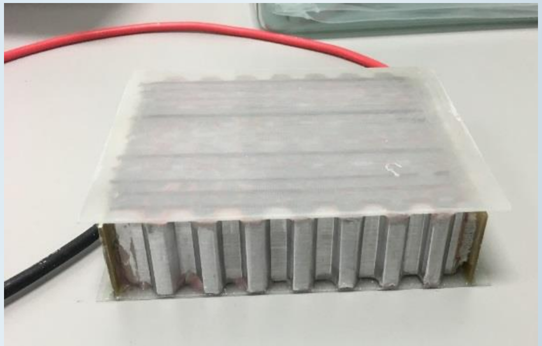
- Revised cell packaging with assistance from NASA JSC's Eric Darcy resulted in no thermal runaway with 4 separate trigger cell attempts in a battery module
- Average Battery Module weight is 51.1 lbs (+1.1 lb per module); +17.6 lbs to baseline total battery weight
- 18 Battery Modules successfully fabricated and tested under DO-311 for shock and vibration.
- Integrated 8 series-connected modules and BMS system underway at Logan, Utah to validate Ahr, Whr, and cell balancing performance. After passing acceptance, batteries will be installed in the aircraft for end-to-end integration testing.
- 5. First flight now scheduled for 4Q 2018

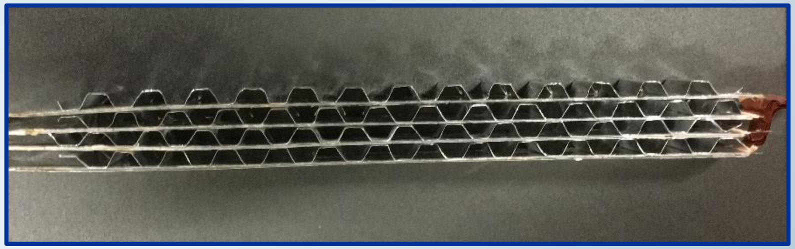
Multifunctional Structures for High Energy Lightweight Load-bearing Storage (M-SHELLS)

POC: Patricia Loyselle, NASA GRC, (216) 433-2180

- **Convergent Aeronautics Solutions (CAS) Effort**
- **Objective:** Meld load-carrying aircraft structure with energy storage for aeronautics applications
- **Approach:**
  - Combine supercapacitor and battery chemistries in a synergistic arrangement with good mechanical properties.
  - Develop novel structural concepts that leverage mechanical properties of energy storage components while maintaining sufficiently high energy and power density
  - Develop weight, performance, and structural models for representative aircraft to estimate the impact at vehicle level.
- **Partners:** NASA Glenn, Langley and Ames; Collaborations with University of Cincinnati and Case Western Reserve University

- **Accomplishments:**
  - Designed new cell format with ribbon cell
  - Integrated functional battery cells into structural honeycomb concept
  - Demonstrated multifunctional configuration that can store/deliver power under mechanical load
  - Demonstrated potential for 11% system weight savings





Integrated Computational-Experimental Development of Li-Air Batteries for Electric Aircraft (LION)

PIs: John Lawson (ARC), Vadim Lvovich (GRC); Lead Centers: ARC, GRC; Partner Centers: AFRC
External Collaborators: Stanford, UC Berkeley, Carnegie-Mellon, IBM Almaden

Project Objective: Can we design and build a viable battery which satisfies the significant requirements (400 Wh/kg -750+ Wh/kg) for electric aircraft applications?

Idea/Concept:

- Li-Air batteries have high theoretical energy densities and potential to leverage on-board oxygen systems, but electrolytes are limiting
- Investigating novel "electrolyte engineering" concepts to enable Li-Air batteries with high practical energy densities, rechargeability and safety.
- Utilizing predictive computation, material science, fundamental chemistry and electric flight testing.

Architecture: 100 W 10-cell battery, 24 V nominal

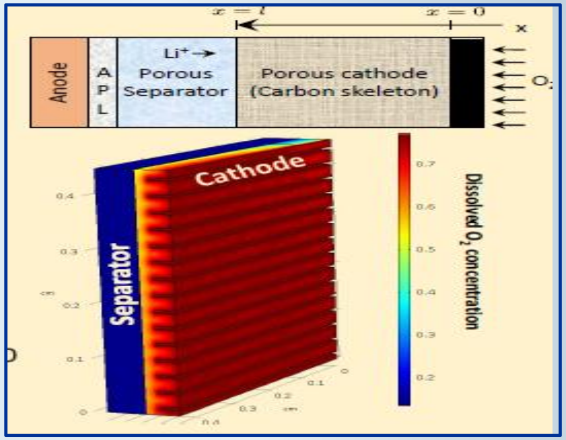
Team:

- ARC providing computational modeling
- GRC providing experimental validation of battery components, development and build
- AFRC providing support on safety design issues

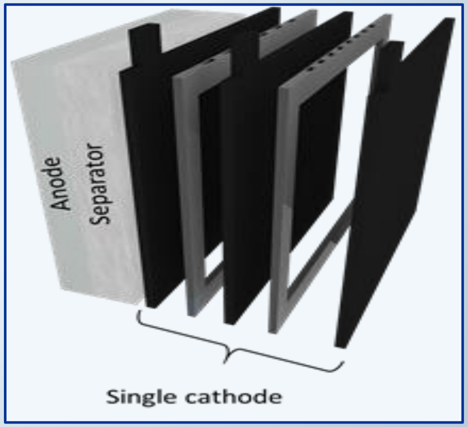
Accomplishments:

- Electrolyte data mining; materials simulations; computational chemistry
- Electrolyte evaluation: inorganic electrolytes may be promising
- Cathode coatings: transparent conducting oxide coatings may be promising

Multiphysics Li-Air Cell Simulation



Efficient O_2 diffusion in Li-Air cells critical for performance.

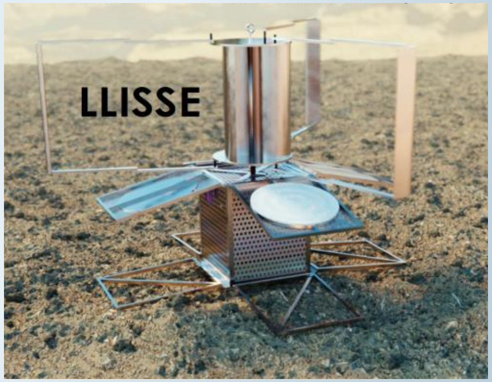


High-Temperature Tolerant Batteries
Long-Life In-situ Solar System Explorer (LLISSE) for Venus

POC: Tom Miller, NASA GRC, (216) 433-6300

- Battery development effort to foster competition for rechargeable high temperature batteries for future Venus surface missions
- Missions
  - LLISSE-B - battery only for duration of 60 Earth days to provide scientific data on temperature, pressure, and wind speed
  - LLISSE-W - 120 Earth day duration with wind turbine to provide recharge capability to battery
- Operating Environment
  - Surface Temperature +460^{0}C
  - Surface Pressure 95 atmospheres
  - Impact shock 12g (with 5 cm crush pads)
- Battery Performance Targets
  - Minimum Battery Level Specific Energy = 28.60 Wh/kg
  - Minimum Battery Level Energy Density = 40.45 Wh/l
  - Deliver ~ 80 Whr over 60 Earth days operating for 2 minutes every 8 hours
- Status
  - Initial 4-cell battery testing (2X) failed to determine self-discharge rate values due to cell-to-cell shorting
  - Procurement in process to bring alternate thermal battery vendor on-board that has demonstrated successful LLISSE cycling without shorts
  - Battery performance to be tested under a simulated Venus surface conditions in the Glenn Extreme Environments Rig (GEER) (T, P, gas mixture) and integrated with sensors, PMAD, and Comm systems by 4Q 2019

LLISSE-B probe powered only by charged battery.



LLISSE-W probe with wind turbine for recharging the battery.

ISS Lithium-ion Battery Replacements

POC: Penni Dalton, ISS Battery Subsystem Manager, (216) 433-5223

- Second set of 6 Flight Batteries and 6 Flight Adapter Plates launch September 10, 2018
- Original set of 6 Flight Batteries and 6 Adapter Plates have been providing power to the ISS since January 2017
  - No on-orbit issues to date
  - I year degradation rate is <2 Ah/1.5%, better than expected
- Cell Life testing continues, no anomalies or issues
  - LEO cycling, ~20% DOD
  - Constant current charge with 16 step-down to taper
  - Constant power discharge
  - 6 month 92 minute contingency discharge/1 year full discharge
  - Crane, GS Yuasa LSE134-101
    - 1P10S Lot1 cells: 33,890 cycles completed
    - 1P2S Lot 2 cells: 28,450 cycles completed
    - 1P2S Lot 3 cells: 22,600 cycles completed
    - 1P2S Lot 4 cells: 19,600 cycles completed
    - 1P2S Lot 5 cells: 17,300 cycles completed
    - 1P2S Lot 6 cells: 16,250 cycles completed
    - 1P2S Lot 7 cells: 14,950 cycles completed
    - 1P2S Lot 8 cells: 12,000 cycles completed
    - 1P2S Lot 9 cells: 550 cycles completed
    - Lot 10, 11, 12 completed characterization test, to start life cycling in August 2018
  - GRC, GS Yuasa LNF51
    - 1P10S : 37,166 cycles completed

- Aerojet Rocketdyne, QM01
  - Battery completed 43 weeks open circuit storage, one month of nominal LEO cycling, and 3 months of off-nominal (higher power) LEO cycling
  - Loss of 0.3 Ah/0.3%, better than model predicted loss of 1.5Ah/1.5%

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CAS FUELEAP - Fuel Cell Testing

Convergent Aeronautics Solutions (CAS) Project for NASA Aeronautics Transformative Aeronautics Concepts (TAC) Program Fostering Ultra-Efficient, Low-Emitting Aviation Power (FUELEAP)

Lead Center: LaRC

Principal Investigator: Nick Borer (757-864-4818)

- FUELEAP is an FY17-18 effort funded under CAS to "establish the feasibility of an integrated heavy fuel hybrid-electric solid oxide fuel cell (SOFC) power system as a transformational source of airborne power"
- This feasibility analysis includes a preliminary design of a primary propulsive power system for a notional flight demonstrator, key technology components development (Solid Oxide Fuel Cell (SOFC)), and concept development of a secondary power system for integration into other classes of aircraft

FUELEAP Fuel Cell Testing

Contributing Center: GRC

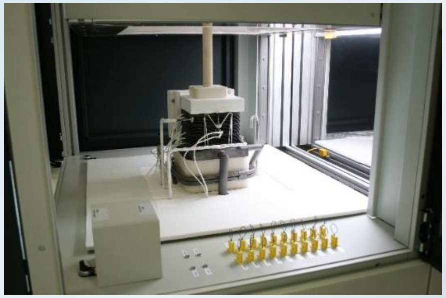
Team Lead: Jon Goldsby (216-433-8250)

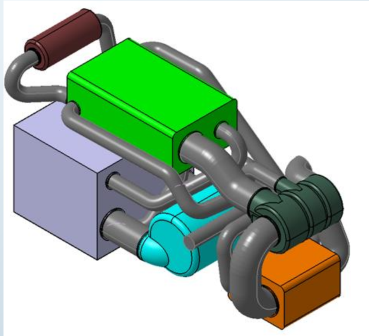
- Establish nominal and off-nominal SOFC subscale stack performance in the presence of reformed fuel products
- Establish life-cycle behavior of representative SOFC hardware in a flight-like environment.

NASA X-57 Mod II "Maxwell" Flight Demonstrator

Lancair Columbia 300 @ Cessna TTx Gross Weight (credit: NASA)

Cessna 172P Skyhawk with 180hp STC (credit: NASA)





National Aeronautics and Space Administration

Advanced Exploration Systems (AES)
Modular Power Systems (AMPS) - Modular Fuel Cells

Advanced Exploration Systems (AES)
Modular Power Systems (AMPS)

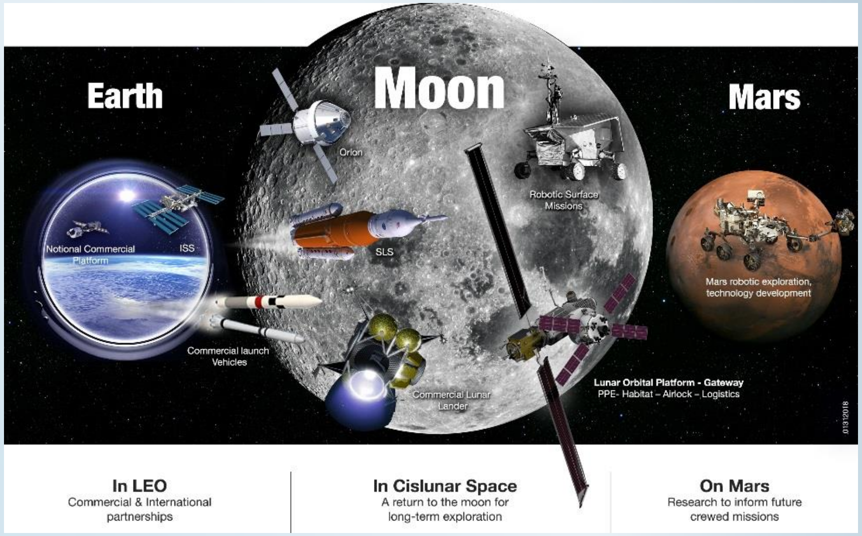
Domain: Vehicle Systems

Lead Center: GRC

PM: Karin Bozak

Chief Technologist: Jim Soeder

- AMPS will infuse new technology into power systems and components and prove their capabilities through exploration-based ground demonstrations
- AMPS will develop modular power units which, when combined with standardized interfaces, can provide commonality across a variety of space exploration vehicles



AMPS Modular Fuel Cells

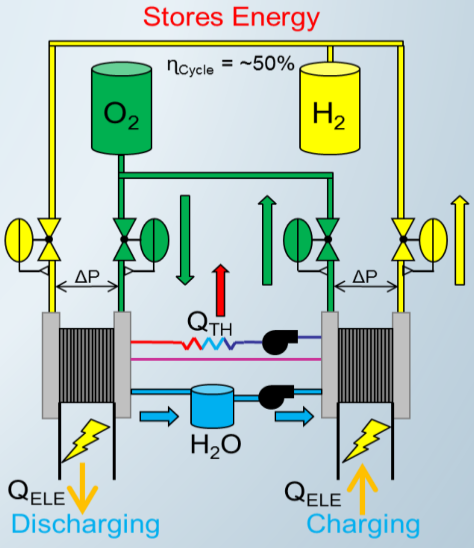
Team Lead: Monica Guzik (216-433-3317)

FY18 Procurement Budget: $75K (including service pool)

FTE Workforce: 2.5 **WYE Workforce: 0.0**

- AMPS Project completed risk reduction vibration testing of several fuel cell stack designs, including flight weight prototypes, to demonstrate the ability of the stacks to survive under Space Launch System Exploration Upper Stage (SLS EUS) qualification-level and acceptance-level loads. This culminated in a presentation of the test results, along with a Fuel Cell Flight Demonstrator proposal, to the SLS EUS Program Office at the Marshall Space Flight Center.
- The regenerative fuel cell (RFC) integrated system model provides a capability to perform trade studies of candidate fuel cell technologies, including both polymer electrolyte membrane and solid oxide, in order to support a multitude of missions. Two RFC model enhancements made this year were the inclusion of multiple electrolyzer types and the ability to perform transient analysis of RFC systems.

Regenerative Fuel Cell



Additional Near Term NASA Power Focus

- Power for small satellites and CubeSats
- Lunar Power Systems
  - Lunar Landers
  - Lunar Surface Power
    - Photovoltaics, Fuel Cells, Batteries, Energy Transfer
- Advanced Battery Development
  - Strong Aeronautics pull
  - Energy density, Battery safety, new chemistries/materials
- Fuel Cell Development
  - Lunar RFC Ground Test
  - Development/certification of RFC in microgravity
  - In-situ resource utilization (ISRU)
- Power Systems for Mars

Acknowledgements

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Thank you

Back-up Slides

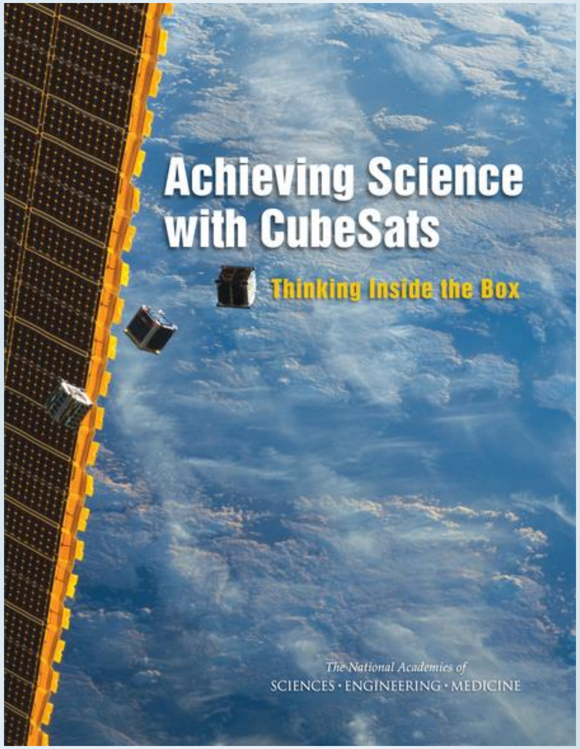
SMD CubeSat/SmallSat Approach

National Academies Report (2016) concluded that CubeSats have proven their ability to produce high-value science:

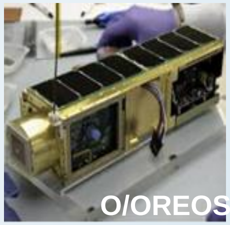
- Useful as targeted investigations to augment the capabilities of larger missions
- Useful to make highly-specific measurements
- Constellations of 10-100 CubeSat/SmallSat spacecraft have the potential to enable transformational science

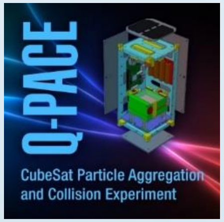
SMD is developing a directorate-wide approach to:

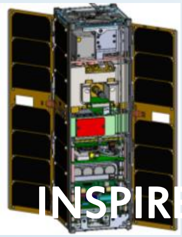
- Identify high-priority science objectives in each discipline that can be addressed with CubeSats/SmallSats
- Manage program with appropriate cost and risk
- Establish a multi-discipline approach and collaboration that helps science teams learn from experiences and grow capability, while avoiding unnecessary duplication
- Leverage and partner with a growing commercial sector to collaboratively drive instrument and sensor innovation



SMD Planetary CubeSat Missions







Spacecraft	**O/OREOS**	**MARCO**	**Q-PACE**	**INSPIRE**	**LunaH-Map**
PI	Ricco	Asmar	Colwell	Klesh	Hardgrove
Size	3U	6U (2)	3U	3U	6U
Goals	Investigate how microorganisms and organic molecules respond to the space environment	Provide real-time data relay using two redundant 6U CubeSats during InSight EDL at Mars.	Investigate properties of low-velocity particle collision in microgravity	Demonstrate deep space CubeSat in Earth-escape orbit; Demo operations, communications, and navigation in deep space.	Create detailed map of the moon's water content at lunar South Pole in preparation for exploration.
Science Area	Planetary Science; microgravity	Planetary Science / technology demo	Planetary Science	Planetary Science	Planetary Science
Status	Launched Nov. 2010; Mission Success	In Development; LRD May 2018 with Insight to Mars	In Development; LRD Dec. 2017	In Development; LAUNCH: TBD, selected by the Cubesat Launch Initiative, awaiting manifest	In Development; LRD Nov 2018 onboard SLS/EM-1

SIMPLEx solicitation is out now to select the next SmallSat (<180 kg) planetary science mission.

This is an open call – SMD expects to fly SmallSats as secondary payloads on all future missions.

Autonomous Regenerative Fuel Cell Power System for Lunar Surface Exploration

Ian Jakupca

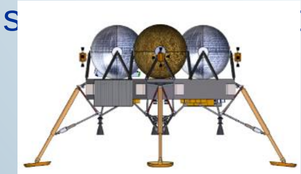
20 July 2018

Problem/Need – The Importance of the Idea (or So What?)

- Design and build an autonomous Regenerative Fuel Cell (RFC) energy storage system operationally validated within a thermal-vacuum environment
- RFC offers up to 3.4X energy storage for the same mass as batteries
  - Extends Lunar exploration mission duration in, or range into, shaded areas
  - **Enables** Lunar night survivability with low mass penalties and no regulatory complications
- The Problem
  - Current energy storage technologies insufficient for NASA Lunar exploration missions
  - Access to flight-qualified fuel cells ended with the Space Shuttle Program
- The Need
  - Delivers an enabling technology suite providing sustained and reliable electrical power for surface and near-surface missions where PV/battery or Nuclear options are not feasible
  - This technology development addresses multiple cross-cutting technologies:
    - Fuel Cell Technology enables missions in DRM 7, 9, and 9a per NASA Roadmaps TA03 (3.1 and 3.2)
    - RFC energy storage specified in TA03 (3.2.3)

The Concept

- Overall Proposal Concept
  - Advance the TRL from TRL 3 to TRL 6 by building a **fully integrated autonomous RFC system** packaged for vacuum operation.
  - Low-mass nominal 100 W_{ele} class RFC system to meet power/energy storage requirements for medium-class Lunar landers
    (Net energy storage ≥110 kW•hr)
  - System to be validated by continuously operating within a thermal-vacuum chamber for at least two-(2) Lunar day/night cycles (>1,344 hours)<re-work to include "mission Profile>
  - Leverage applicable Terrestrial technologies to avoid development costs
- Technologies to Enable the Concept
  - Aerospace fuel cell technologies
  - Relevant pressure electrolysis for aerospace applications
  - High s orage



1,000 kg Payload Lander

Develop RFC System Requirements

↓

Build RFC Engineering System

↓

≥ 2 month autonomous closed-loop test under laboratory conditions → High Pressure EZ for ECLSS and ISRU

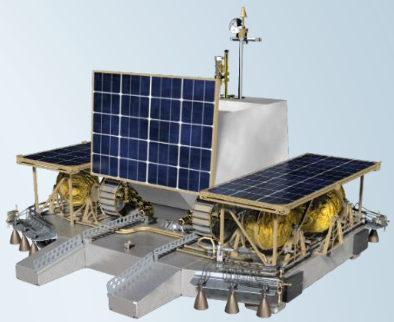
↓

≥ 2 month autonomous closed-loop test in a Relevant Environment

↓

Define parameters for Lunar Flight Demonstrator → RFC for Surface Power

Lunar Pallet Lander



The Benefit

- Demonstrates aerospace RFC power architectures needed for surface missions with energy storage to survive the Lunar night
- Advances RFC TRL level through thermal-vacuum demonstration
- Goals and Objectives
  - Develop and demonstrate an RFC energy storage for the Lunar surface within thermal-vacuum chamber
  - Demonstrate relevant pressure aerospace electrolyzer technology for energy storage and ECLSS needs
- Quantitative Impact
  - RFC provides mass reduction over battery storage
    - Packaged RFC system(1) up to 3.4X specific energy of batteries(2
  - Provides a relevant pressure (>1,500 psi) aerospace electrol technology
    - Enables RFC high specific energy storage
    - ECLSS and ISRU have applications requiring pressurized reactants

NOTES:
1 = 320 W•hrs/kg to 550 W•hrs/kg per AES/AMPS 2017 Lunar RFC Trade Study
2 = 100 W•hrs/kg to 160 W•hrs/kg per Eric Darcy, JSC