



Space Technology Mission Directorate Game Changing Development Program

Ryan Gilligan (GRC) | Ian Jakupca (GRC) | FY23 Regenerative Fuel Cell (RFC) Annual Review Presentation | 09.20.23

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Project Overview

Technology Development Needs Addressed by Project

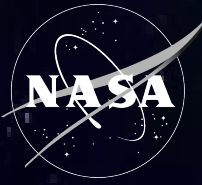
Stakeholder (i.e. HLS)	Energy Storage for Moon & Mars surface exploration, crewed landers, habitats and long-term lunar power infrastructure	STARPort Capability Area(s) and Gap ID(s): Advanced Power (505), Autonomous Systems (1136), ISRU (572, 577), Logistics Management (760)
Stakeholder	Demonstrate regenerative fuel cell (RFC) energy storage system technology for sustained and reliable electrical power for surface missions where PV/Battery or nuclear options are not feasible.	HLS (Lunar Surface)

Project Goals

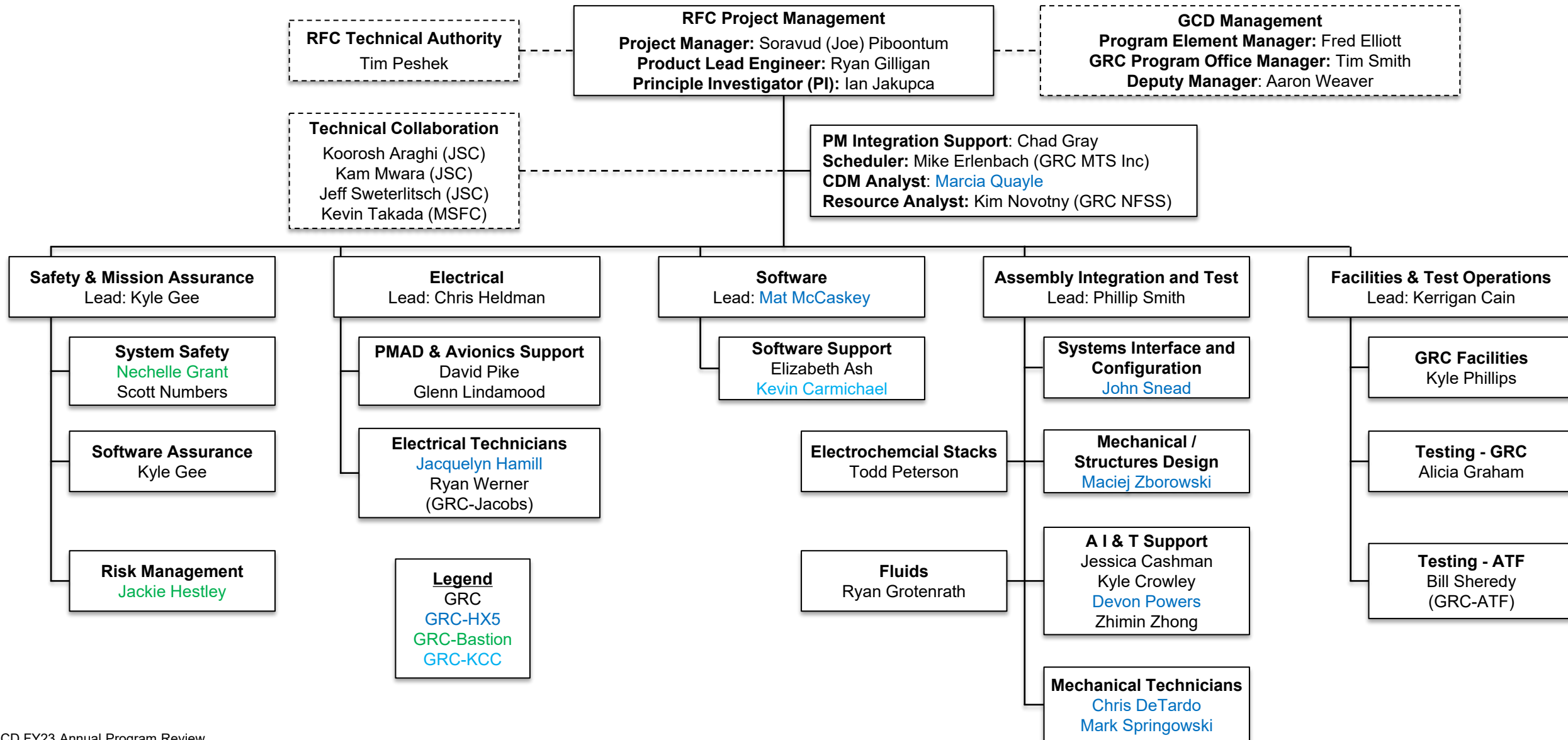
Goal #1	Develop, build, and demonstrate a Breadboard Regenerative Fuel Cell (RFC) energy storage system for lunar surface applications that can provide 2 to 3.4 times the energy storage capability of state-of-the-art packaged lithium-ion battery systems.
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Project Objectives

Objective #1	Develop RFC Energy Storage System Requirements.
Objective #2	Develop a Breadboard RFC Energy Storage System design.
Objective #3	Build a Breadboard RFC Energy Storage System.
Objective #4	Demonstrate the Breadboard RFC Energy Storage System in a laboratory environment.



Team Members / Project Org Slide





Collaborations & Partnerships



➤ Participating Entities

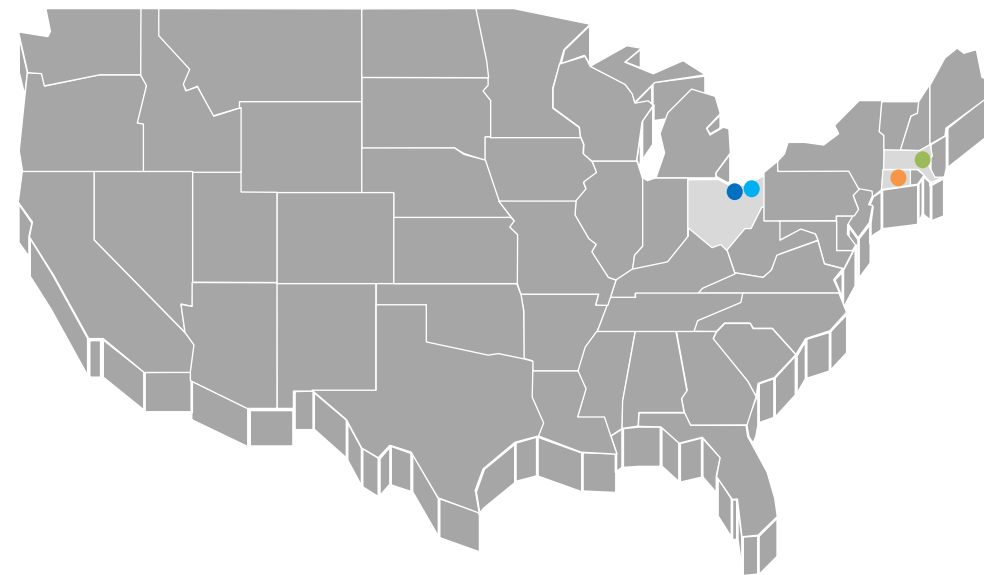
- NASA Glenn Research Center (GRC), Lewis Field (LF)
- NASA GRC, Armstrong Test Facility (ATF)
- Infinity Fuel Cell and Hydrogen, Inc
- Giner, Inc

➤ Stakeholders

- Exploration Systems Development Mission Directorate (ESDMD)
 - Artemis Foundation Habitat Team
 - Human Landing Systems; Human Rovers
- Science Mission Directorate (SMD)
 - Long-duration science landers and rovers

➤ Infusion/transition plan

- Target applications include:
 - Energy storage for Moon & Mars surface exploration and lander operations.
- NASA mission(s) impacted by the technology product
 - Lunar surface missions (e.g. rovers, landers, habitats)
 - Mars surface missions (e.g. rovers, landers, habitats)
 - Potential utility for transit or EDL

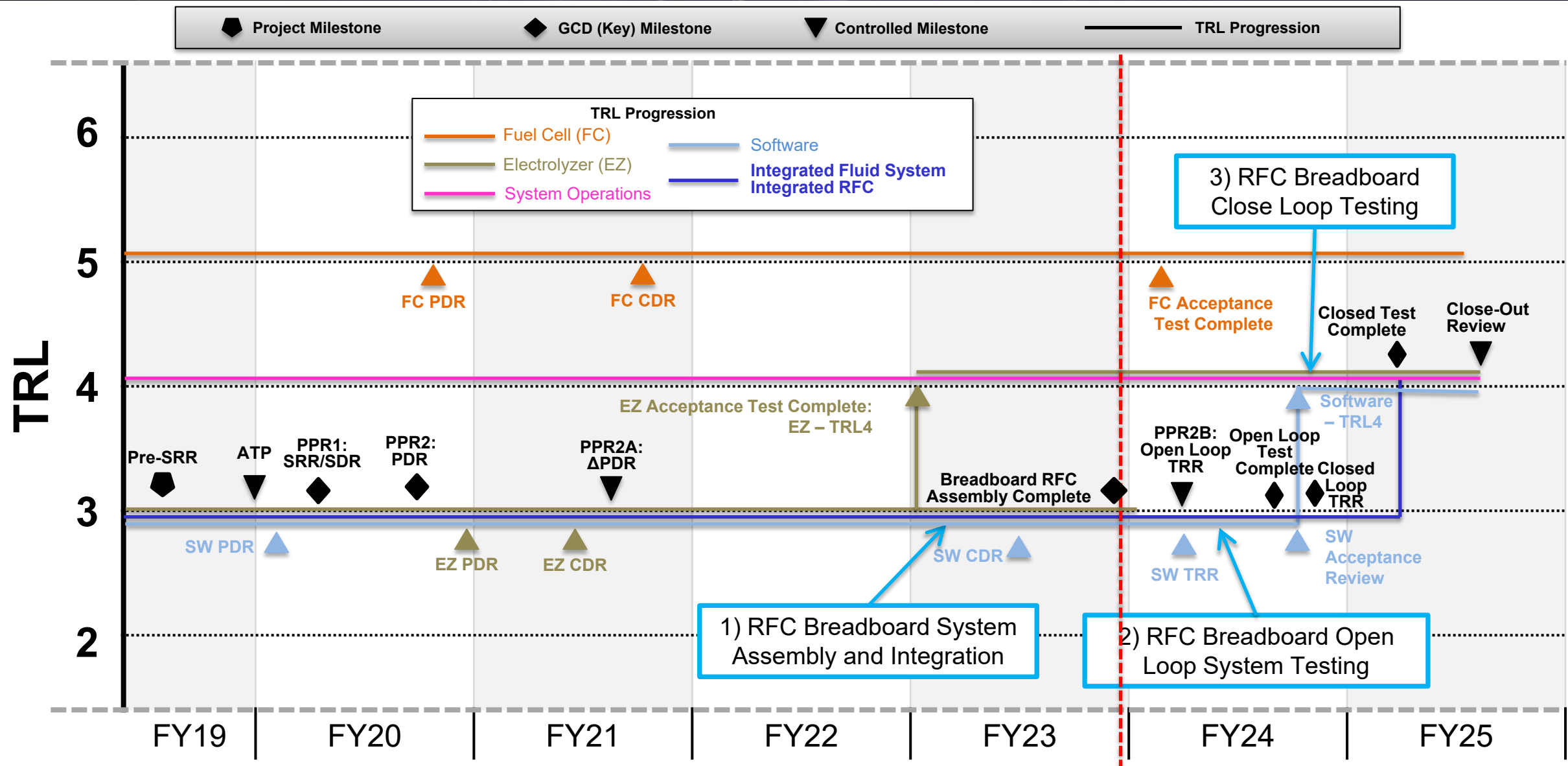




RFC Project



Technology Maturity Schedule / Project Life Cycle Milestones





Accomplishments

➤ Programmatic

- Re-baselined project with updated milestones and scope of work to fit available budget
- Started developing Technical Task Agreement for closed-loop H_2/O_2 testing
- Discussed potential RFC Technology Infusion with internal and external entities at Outreach and technical events

➤ Technical Accomplishments

- Completed mechanical assembly of RFC Breadboard test article
- Began functional verification of RFC Breadboard test article
- Continued facility modifications for open-loop H_2/O_2 testing





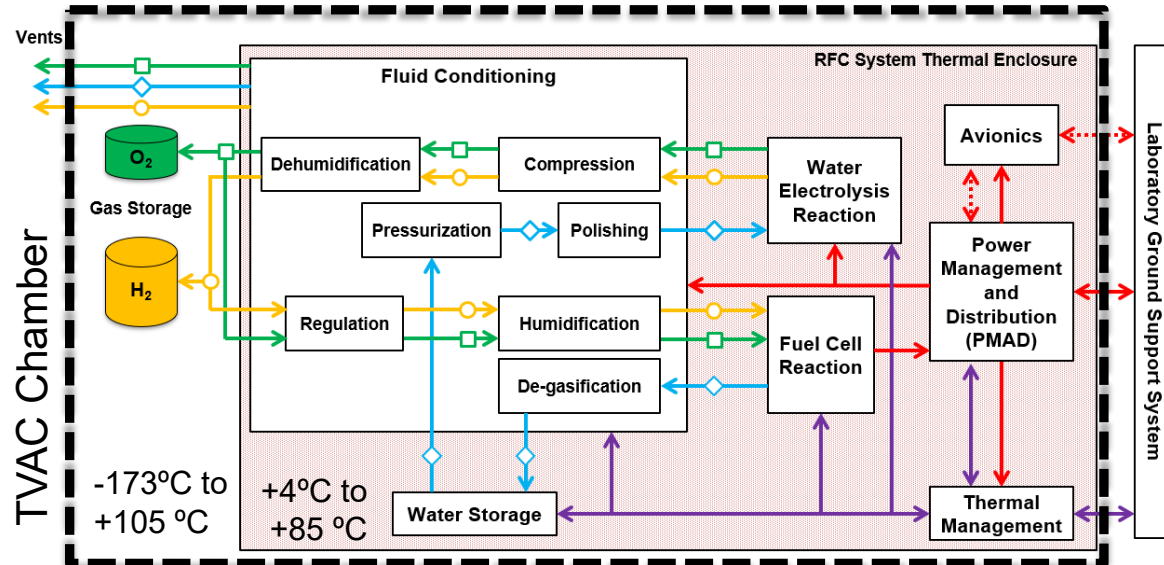
RFC Project Update

Initial Test Plan

Environment :

- TVAC chamber simulating lunar surface pressure and Temperature

- Target TRL: 5



KPP:

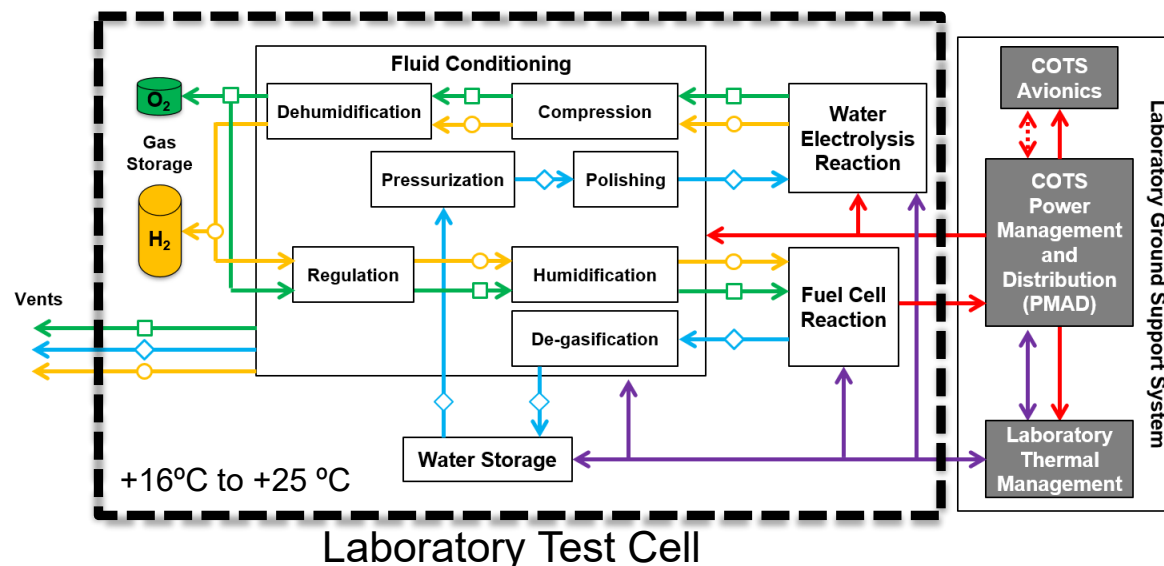
- Specific Energy
 - ❖ Threshold = 320 W•hr/kg
 - ❖ Goal = 550 W•hr/kg
- Round-trip efficiency
 - ❖ Threshold = 50%
 - ❖ Goal = 55%

Revised Test Plan

Environment :

- Ambient laboratory

- Target TRL: 4



KPP:

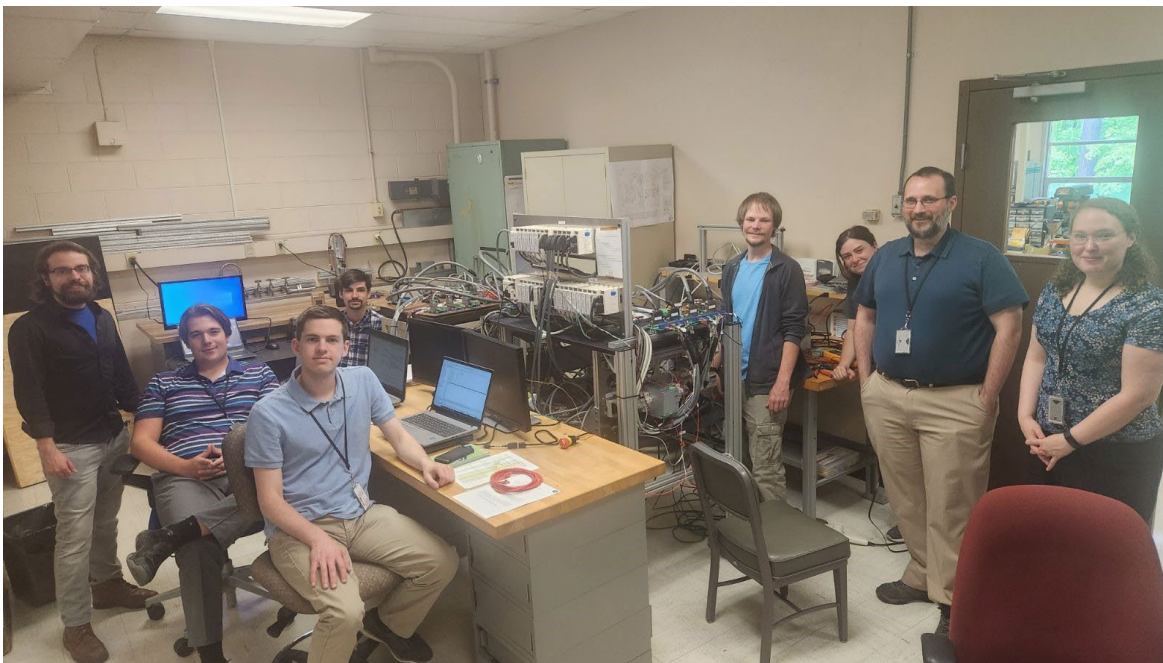
- Specific Energy
 - ❖ Threshold = 320 W•hr/kg
 - ❖ Goal = 550 W•hr/kg
- Round-trip efficiency
 - ❖ Threshold = 50%
 - ❖ Goal = 55%

Changes shown in Blue

Accomplishments

➤ Avionics/Power Management and Distribution (PMAD)

- Completed soft-baseline of PLC architecture, settings, and configurations
- Completed assembly and programming of PLC modules
- Electrical drawings of as built system completed
- Software functional check-outs with Hardware Emulator
- Electrical interfaces design completed, electrical wiring of RFC breadboard near completion



The Power and Avionics team of engineers and technicians, and Software Team perform functional checkouts of the software and PMAD/Avionics cart.

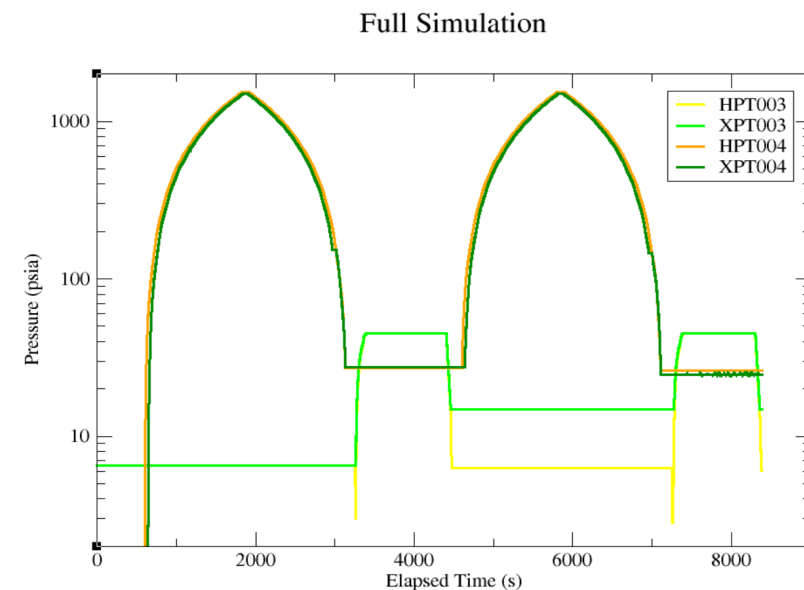


Accomplishments



➤ Software

- Successfully ran full fault test in a Hardware-in-the-Loop configuration.
 - Test ran over all operational modes, channels, and faults in the Fault Tables
 - 97% of the faults were successfully triggered
- Debriefed Code Quality and Reliability Assessment (CQRA) results with Independent Verification and Validation Facility at GSFC
 - RFC software risk score: 1.88 / 5 (1 = low risk, 5 = high risk)
 - Implementing CQRA Review recommendations to reduce Performance Risks



Pressure plot generated during full day/night cycle simulation using hardware emulator



Accomplishments

➤ Electrochemical Stacks

- Electrolyzer Stacks
 - Received contract deliverables from Giner that included 2 electrolyzer stacks with acceptance data package showing successful testing to RFC requirements
 - Executed electrolyzer stack storage maintenance protocols at GRC
- Fuel Cell Stacks
 - Stack assembly
 - ❖ FC Stack #1 developed an anomaly during assembly verification test
 - ❖ FC Stacks #1 and #2 being serviced before restarting internal verification testing
 - ❖ FC Stack #1 scheduled for delivery to NASA by the end of October 2023
 - Fuel Cell Life Test
 - ❖ Test station undergoing functional verification testing prior to starting life test of FC Stack #2
 - ❖ 5,000-hour Life Test with FC stack #2 scheduled to start October 2023

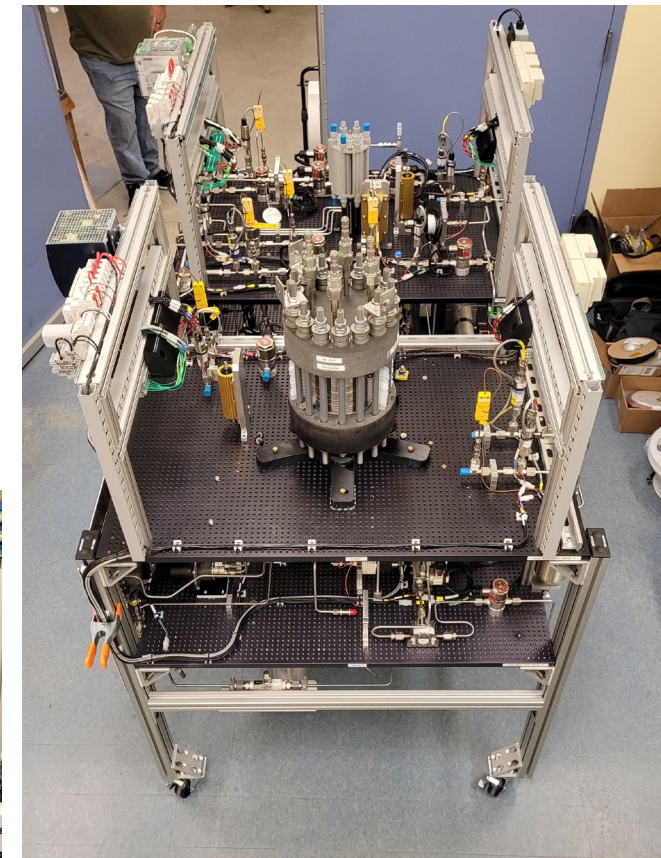


RFC project Liquid Anode Feed Water Electrolyzer manufactured by Giner on 3D printed support fixture at GRC

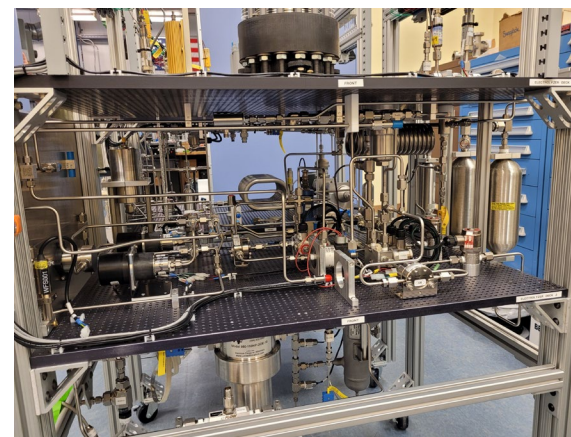
Accomplishments

➤ Fluids

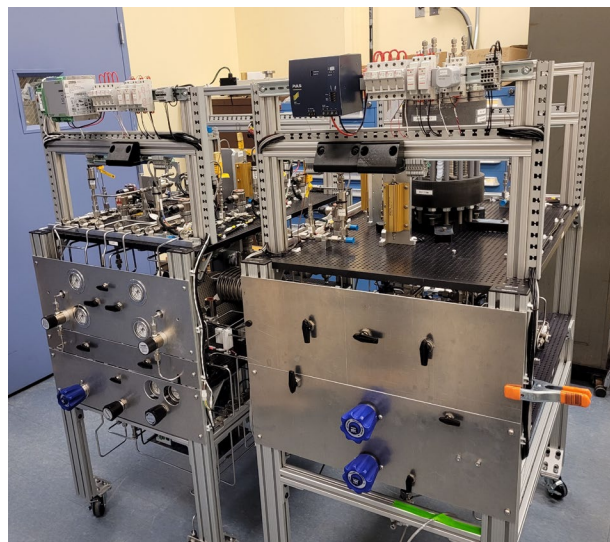
- Completed oxygen-in-hydrogen catalytic recombiner test
- Updated hazards analysis and materials compatibility assessments to support Safety and Engineering Review Board
- Onboarding new fluids engineering support to backfill project member transitioning off project to new position (delayed due to personnel availability)



RFC Breadboard test article
without Electrical Cart



Middle Deck of RFC
Breadboard Electrolyzer Cart



RFC Breadboard Fuel Cell test
article without Electrical Cart



Middle Deck of RFC Breadboard
Fuel Cell Cart

Accomplishments

➤ Test Facilities

- Electrolyzer verification test stand mechanically and electrically assembled
- Reimbursable Space Act Agreement (SAA) testing H_2/O_2 fuel cell stacks in B334 paused
 - Assessing schedule impacts of required facility changes
 - Leveraging opportunity to train NASA staff
- Formalizing Technical Task Agreement with Armstrong Test Facility
- Developing requirements and specifications for climate-controlled ConEx box to be installed at ATF
- Began B334 test facility performance and required modifications
 - Installation of new H_2/O_2 vent lines
 - Installation of new oxygen supply panel



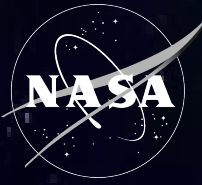
B334 Fuel Cell Test Laboratory Build-up
for the RFC Breadboard Test



Accomplishments

➤ Safety and Mission Assurance

- GRC Safety Engineering Review Board (SERB) held 7/31 to reduce risk of Safety-imposed changes resulting from poor communication
 - Implemented multi-layered safety approach
 - Completed NFPA 70 justifications to support SERB
 - Project received approval to proceed with Safety Permit Application without additional actions
- De-escalated Personnel Availability Issue down to a 4x4 Risk



Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year					Technical – Technical team continued test preparation activities for the RFC Breadboard system by starting facility modifications, assembling test articles and addressing safety permit issues Cost – The FY22 RFC budget reduction resulted in a scope reduction significantly challenging the ability to reach TRL 5 within the adjusted budget allocation Schedule – Milestone dates were unaligned following project re-scoping Programmatic – Project team performing task reviews for pending Change Request (CR). The project CR incorporated staffing and scheduling adjustments
Annual					The RFC project was re-baselined per GCDPO direction; GCDPO approved the updated Project Plan (Rev B) on June 29, 2023.



Plans Forward and Transition / Infusion Plan

➤ Plans Forward

- Complete Breadboard RFC assembly (Sep 23)
- Complete Breadboard RFC Open-loop testing (May 24)
- Complete Breadboard RFC Closed-loop testing (Oct 24)

➤ Infusion

- No NTRs submitted to date
- Currently funded RFC Project ends with RFC at TRL 4; additional development work required to raise TRL

➤ Collaboration

- Project supported multiple lunar trade studies by providing RFC performance metrics and design parameters
 - Lunar Surface Habitat (Artemis) with preliminary design studies of available volumes within the Artemis Habitat which could host an RFC-based energy storage system
 - Lunar Power Architecture Team (SAC23) to support development of potentially viable integrated lunar surface power systems
 - Pressurized Rover trade studies investigating options to survive the lunar night within mass budget allocation
- Continued collaborating with ECLSS and ISRU communities on water electrolysis
- Sharing RFC technology status updates and RFC Project Lessons Learned through multiple HLS activities



Education/Public Outreach

EPO Involvement

- American Astronautical Society Fifth Annual John H. Glenn Memorial Symposium, Cleveland, OH, July 17-19
- LSIC Lunar Proving Grounds Definition Workshop, JHU/APL, July 12-13
- LSIC Power Systems Reliability Workshop (virtual), July 26-27
- Power Sources Conference, June 26-30
- Fuel cell and Electrolysis Technologies presentation at the CLPS Program Office Technical Workshop (Virtual); April 20th, 2023
- Lunar Surface Innovation Consortium at Johns Hopkins University Applied Physics Lab; April 24-25, 2023
- Hydrogen and Fuel Cell Seminar; Long Beach CA; Feb 7-9;
- Flight Software Workshop; California Institute of Technology; March 20-23,
- Hydrogen and Fuel Cell Seminar. February 7-9
- Supporting four interns from the University of Toledo
- Thermal and Fluids Analysis Workshop (TFAWS), NASA Goddard Spaceflight Center, 21-24 Aug 2023

EPO Calendar Outlook (High Priorities):

6 Month Look-Ahead	
LSIC Fall Meeting	10-11 Oct 2023
LSIC Path to Sustainable technologies in the Lunar Surface	7 Nov 2023
AIAA SciTech Forum and Exposition	8-12 Jan 2024
Hydrogen and Fuel Cell Seminar	March 2024



Summary

➤ Accomplishments for the Year

- Re-baselined project with updated milestones and scope of work to fit available budget
- Completed mechanical assembly of RFC Breadboard test article
- Began functional verification of RFC Breadboard test article

➤ Demonstrating closed loop operation of a breadboard RFC will raise the TRL of this technology from 3 to 4

- Project deliverables include a functional breadboard system, final report and data package, technology road map for component and system development required to further increase TRL