



Space Technology Mission Directorate Game Changing Development Program

Matt DeMinico (GRC) | Ian Jakupca (GRC) | FY22 Regenerative Fuel Cell (RFC) Annual Review Presentation | 09.12.22

Name/Email POC: Matt DeMinico, mathew.r.deminico@nasa.gov



RFC Project Overview



➤ Technology Product Capability

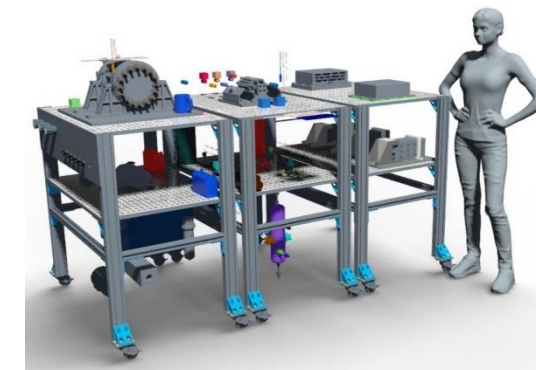
- Develop regenerative fuel cell (RFC) energy storage system technology to provide sustained and reliable electrical power for surface and near-surface missions where PV/battery or nuclear options are not feasible; advance RFC from TRL3 to $\geq$ TRL5

➤ Technical Capabilities

- Integrated system performance of key components in the challenging thermal/vacuum environments for required duration:
 - Oxygen & hydrogen vapor-liquid separators
 - High pressure lift and recirculation pumps
 - Solenoid valves
 - Electrolyzer
 - Fuel Cell
- Demonstrate reliable operation over identified number of Lunar Day/Night Cycles in a relevant pressure and thermal environment

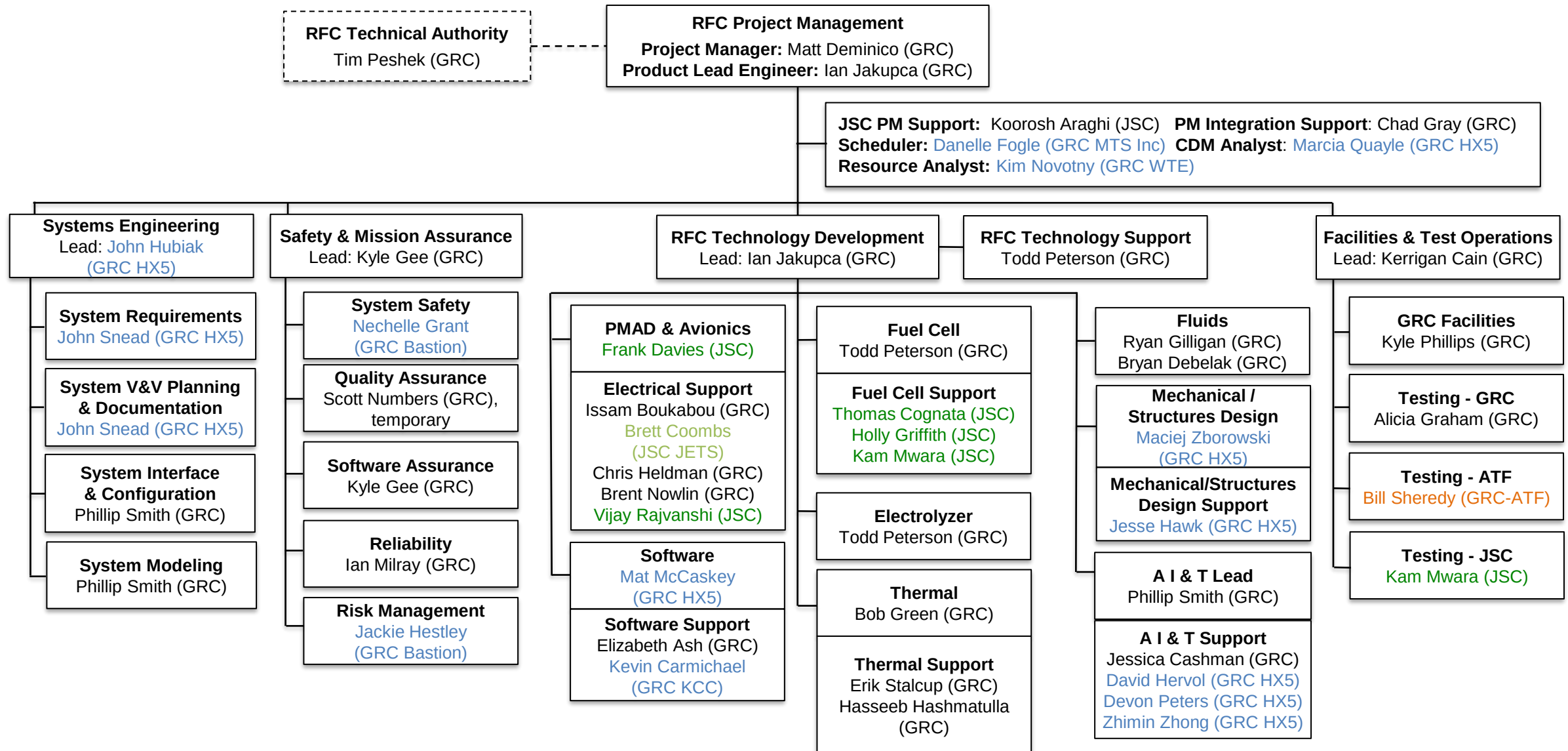
➤ Exploration & Science Applicability

- Energy storage for Moon & Mars surface exploration, lander operations, and upper stage long-term power
- Lunar / Mars surface missions (e.g., rovers, landers, crewed habitats)
- Potential utility for transit or Entry, Descent, & Landing (EDL)





Team Members / Project Org Slide





Mission Infusion & Partnerships

➤ Participating Entities

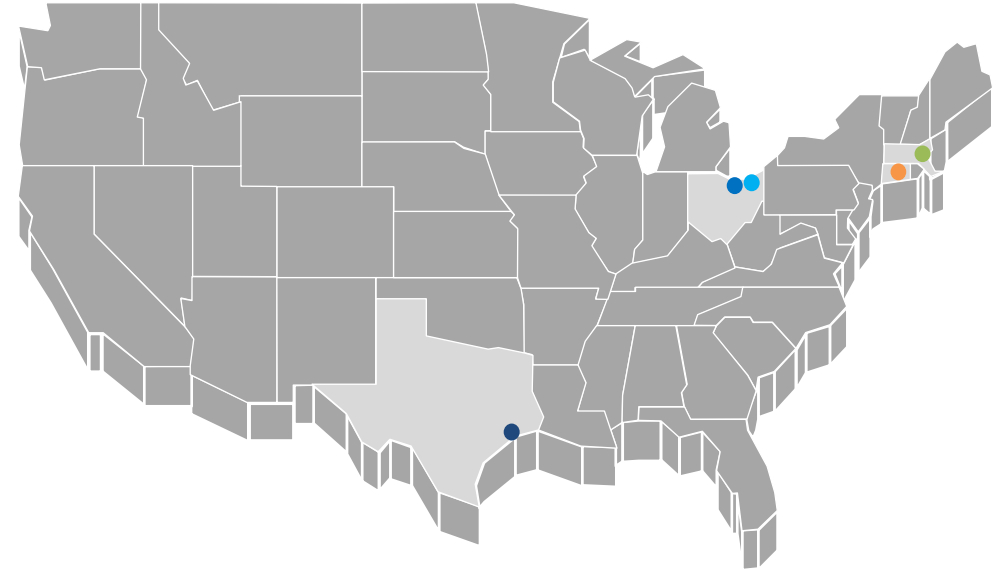
- NASA Glenn Research Center (GRC)
- NASA Johnson Space Center (JSC)
- NASA Armstrong Test Facility (ATF)
- Infinity Fuel Cell and Hydrogen, Inc
- Giner, Inc

➤ 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, lander operations, and upper stage long-term power.
- Detail NASA mission(s) impacted by the technology product
 - Lunar surface missions (e.g. rovers, landers, habitats)
 - Potential utility for transit or EDL
 - Mars surface missions (e.g. rovers, landers, habitats)





Regenerative Fuel Cell Technology Goals & Project Objectives

Technology Goals

Goal #1	Develop and demonstrate Regenerative Fuel Cell (RFC) energy storage system technology for lunar surface applications that can provide 2 to 3.4 times the energy storage capability of the state-of-the-art packaged lithium-ion battery system.
Goal #2	Advance aerospace RFC system technology from TRL3 to TRL5 or greater to enable infusion of the technology into NASA exploration missions.

Project Objectives

Objective #1	Develop RFC energy storage system technology that demonstrates a packaged system specific energy capability of at least 320 W•hr/kg.
Objective #2	Demonstrate operation of an RFC system for at least 1 lunar day/night cycle through ground testing in a simulated lunar surface environment.

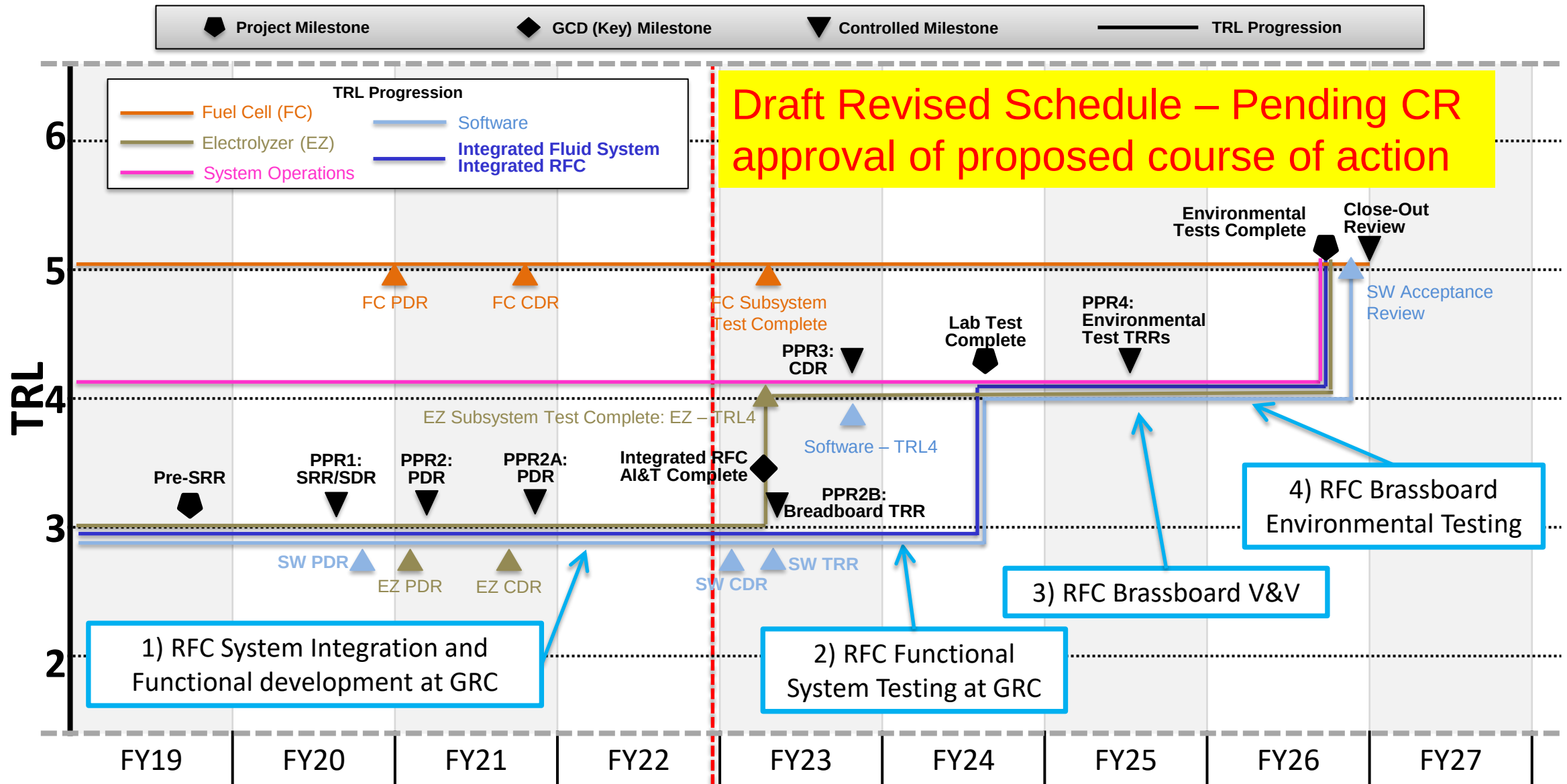
From the RFC Project Plan (GCDP-02-PLN-19015)

(pending Change Request guidance from GCD due to FY22 budget cut – see slide 7 for summary)



Regenerative Fuel Cell (RFC)

Technology Maturity Schedule / Project Lifecycle Milestones





Accomplishments - Programmatic



➤ Programmatic

- Change Request (CR) proposed to update project schedule and budget in response to FY22 budget cuts
 - Pending a future Program Control Board (PCB) to decide between multiple courses of action (COA) for RFC CR
 - COA's include: Split into two phases, restore out-year budget, or eliminate TVAC design, build, and test
- Revised RFC Technical Assessment, Technology Readiness Level (TRL) and the Advanced Degree of Difficulty (AD²) using the Technical Readiness Assessment Insight Template (TRAIT) spreadsheet tool
- Evaluating courses of action to close agency-wide risks related to availability of fuel cell test capabilities

➤ Published Technical Memorandums

- Proton Exchange Membrane Fuel Cell Transient Load Response (NASA/TM-20210018094)
- Aerospace Regenerative Fuel Cell Fluidic Component Design Challenges (NASA/TM-20210024659)
- Lunar Equator RFC Efficiency Analysis (NASA/TM-20210014627)
- Lunar South Pole RFC System Efficiency Analysis (NASA/TM-20220010931)



Accomplishments – Systems Engineering



➤ Completed Major Engineering Reviews

- Electrolyzer Contractor Test Readiness Review
- Fuel Cell Contractor Critical Design Review

➤ Maintained project documents

- Engineering Documents (5): Concept of Operations (ConOps), Systems Engineering Management Plan (SEMP), Systems Requirement Document (SRD), System Definition Document (SDD) / Interface Control Document (ICD), integrated Master Equipment List (MEL) / Powered Equipment List (PEL) / Bill of Materials (BoM), Process and Instrumentation Drawings (P&ID), State and Fault tables
- System Test Plans (4): GRC Laboratory Test, Armstrong Testing Plan, JSC Temperature-Vacuum (TVAC) Test, Life Test, and Assembly, Integration and Test (AI&T) Plan
- Component Test Plans with procedures (6): RFC Fuel Cell Test Plan, Non-Flow-Through (NFT) Fuel Cell Test Using the Common Test Bed (CTB), RFC Project Component Development Plan, RFC Adsorption Dryer Subsystem Test Plan, RFC Coalescing Filter Subsystem Test Plan, RFC Catalytic Recombiner Test Plan and the RFC Phase Separator Subsystem Test Plan



Accomplishments – Assembly / Integration / Testing

➤ Subsystem testing

- Set up and continuing coolant pump and solenoid valve life and orientation tests
- Operated solenoid valve spike and hold testing to determine most energy efficient valves
- Set up and completed pressure test, began operation of water pump subsystem (2 different pumps installed so far)
- Performed testing on water deionization media required to produce deionized (DI) water
- LLFC project prepared the GRC Building 334 systems (FC Common Test Bed, plus facility) for FC testing and RFC checkout testing in FY23. This included updating the Fuel Cell (FC) / Electrolyzer (EZ) qualified operator training checklist

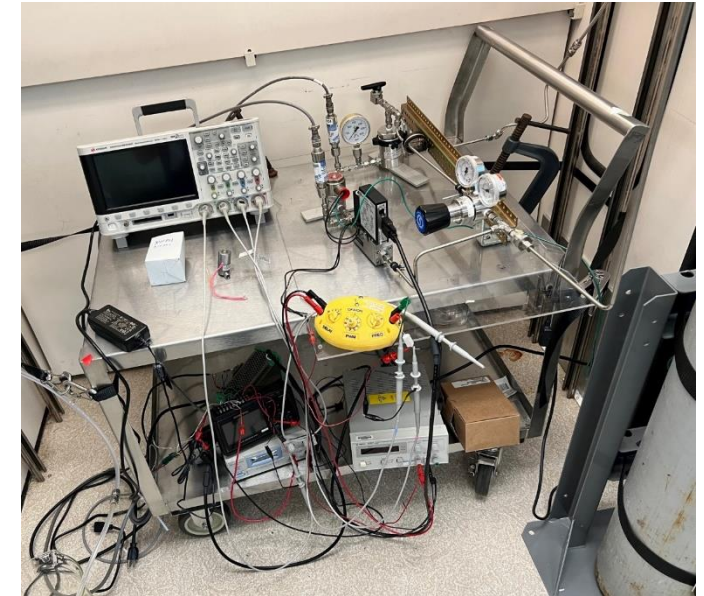
➤ RFC components

- Purchased high temperature water deionization media (2 sources)
- Procured a custom flexible plastic storage bladder for the water storage vessel

Accomplishments - Fluids

➤ Risk Reduction Testing

- Designed & built “solenoid valve spike and hold” subsystem test
 - Integrated simulated Power Management and Distribution (PMAD) hardware
 - Collected efficiency data for 5 valves so far with additional valves to test
- Designed & built pump flow test system for testing candidate pumps
 - All candidate pumps require modifications to meet TVAC requirements
 - Successfully collected data for 2 candidate pumps
 - Cole-Parmer Chemical Dispenser Pump (0-2000 psi, 0-100°C, 0.01 to 10 mL/min, 5 kg)
 - Eldex metering pump (0-5000 psi, 0-200°C, 1 to 144 mL/min, 14 kg)
 - Remotely controlled pumps over a representative RFC operational profile
- Designed & built system to test deionization resins at RFC temperatures
 - Successfully collected preliminary test data
 - Testing continues



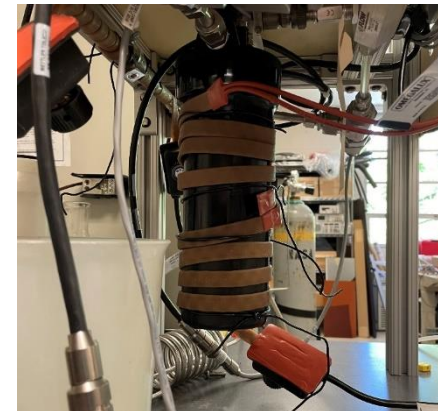
Solenoid spike and hold test system



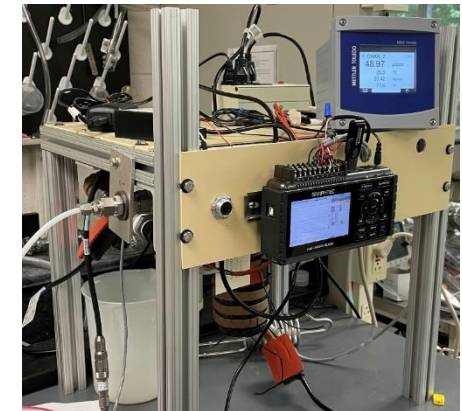
Resin (New)



Resin (Used / Filled)



Resin Housing



Resin Test Stand

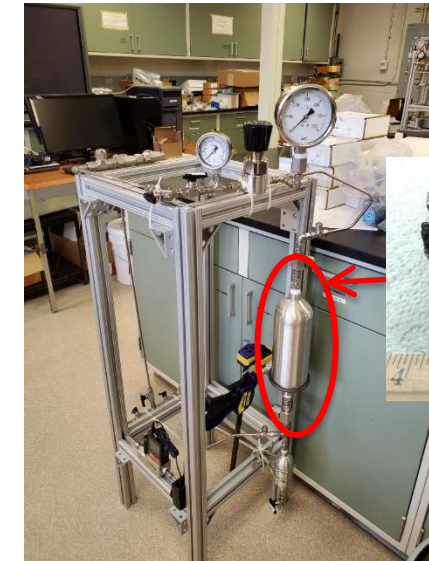
Accomplishments - Fluids

➤ Risk Reduction Testing (cont.)

- Designed and built catalytic recombiner test bed to safely test H₂ / O₂ mixtures up to 125 psig at ambient temperature
 - Procured pre-mixed supply gases with concentrations of 0.01 – 1.5 mol % H₂-in-O₂ and 0.01 – 1.5 mol% O₂-in-H₂
 - Using residual gas analyzer to evaluate effectiveness
- Developed in-house pneumatic test capability (hardware, procedures, approval work-flow) for RFC fluid systems

➤ Breadboard system component procurement

- Finished specifying and procuring majority of fluidic hardware required for RFC breadboard system build-up. Significant procurements include water storage vessel, water/oxygen phase separator, and fittings



Recombiner Test Stand

Knitted Wire Catalyst



Oxygen/water phase separator



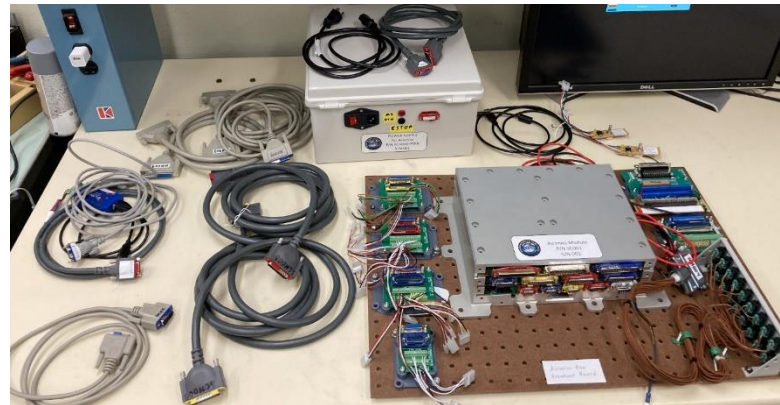
Accomplishments - Thermal

- Updated RFC Level 2 thermal system model of the RFC system Brassboard
 - Thermal geometry model of the RFC was updated to the latest mechanical design of the 2-bay, dual-deck RFC Thermal Enclosure interior along with placing RFC components in their revised locations
 - A preliminary thermal model of the Variable Conductance Heat Pipes (VCHPs) was developed based on design equations in the literature
 - Individual (Level 3) component thermal models of the fuel cell and electrolyzer stacks were completed in order to compute lumped thermal property values needed for the simplified thermal geometry FC and EZ models in the Level 2 system model
- Initiated study to assess the radiator interface options for implementing the heat rejection function for the RFC TVAC test
 - Developed and presented RFC radiator interface options and qualitative impacts and considerations of each option on the Bldg 334 check-out testing, ATF test, and TVAC test
 - Submitted a Risk on the Radiator Interface Option Evaluation/Selection, per recommendation in the Thermal RFA from PDR2 on this topic
 - Investigated chiller or other heat removal facility options for Radiator Interface options study. Received initial quote on chiller/recirculating bath that meets temperature range and heat rejection rates for this application

Accomplishments – Avionics and PMAD

➤ FY22 Accomplishments (JSC)

- Shipped full set of RFC Avionics and PMAD hardware to GRC
- Visited GRC as part of equipment commissioning
- Built second set of RFC Avionics and PMAD hardware as spares to be kept at JSC
- Delivered test support electronics to conduct Risk Reduction Testing
- Developed initial build drawings and as-built redlined drawings
- Delivered check-out documentation (process shown on next slide)
- (GRC) Developed initial drivers and other interface routines for avionics operating software



Avionics module + cables and test hardware



PMAD module, cables and test hardware



Cold plates for PMAD and Avionics modules

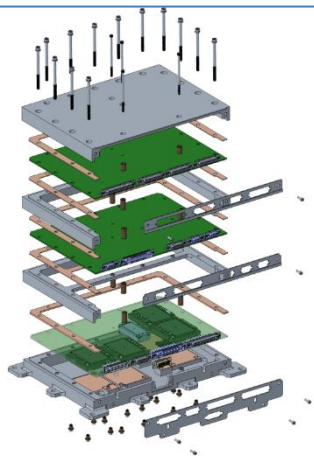


Solenoid test box

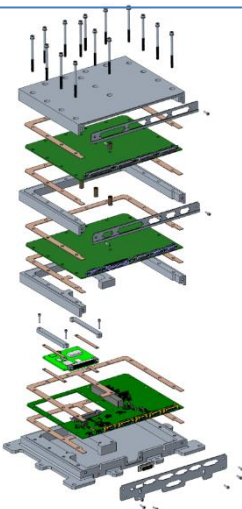


Accomplishments – Avionics and PMAD

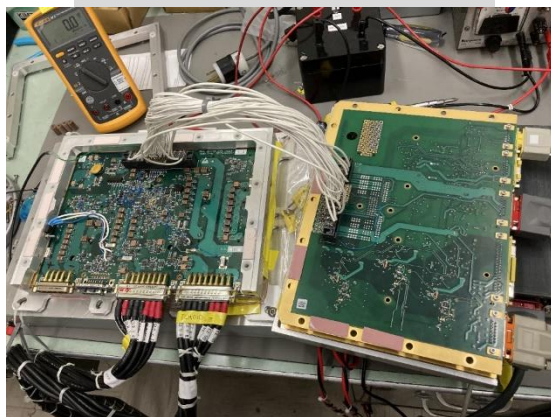
PMAD exploded view



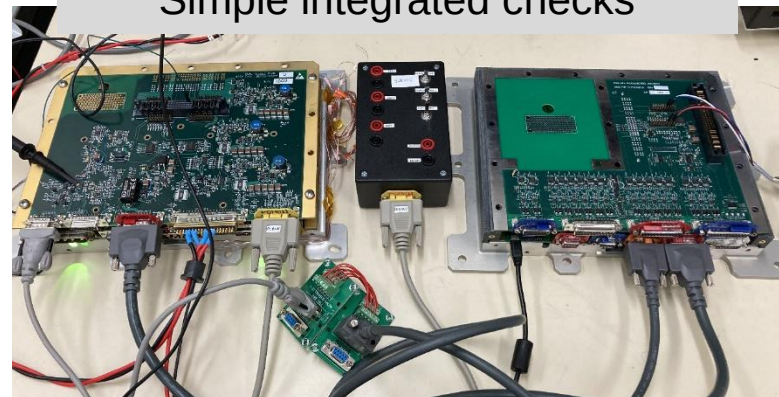
Avionics exploded view



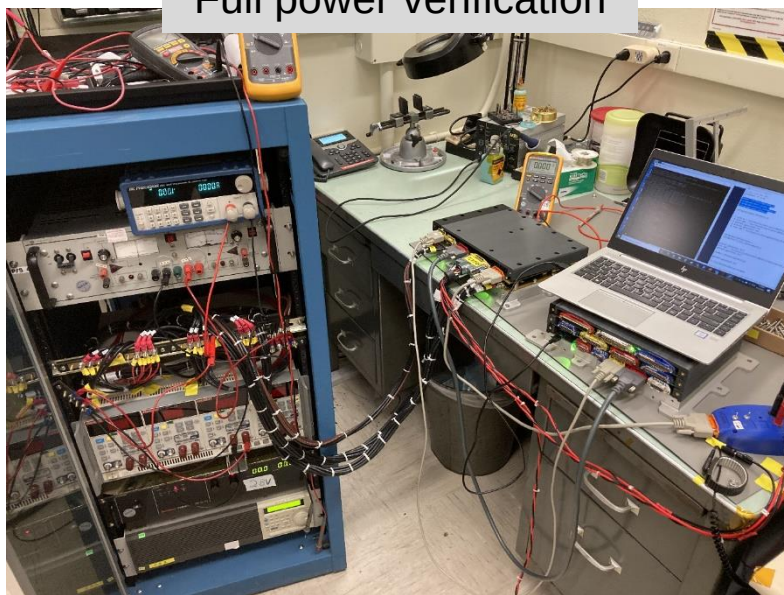
PCB level checks



Simple integrated checks

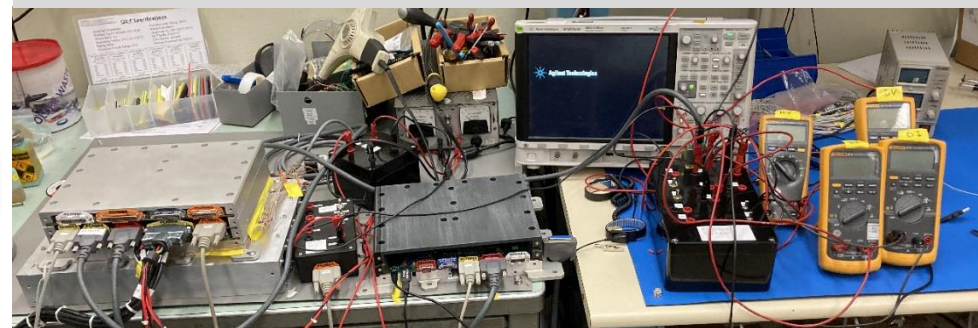


Full power verification



Software device drivers
developed and checked
concurrently at these stages

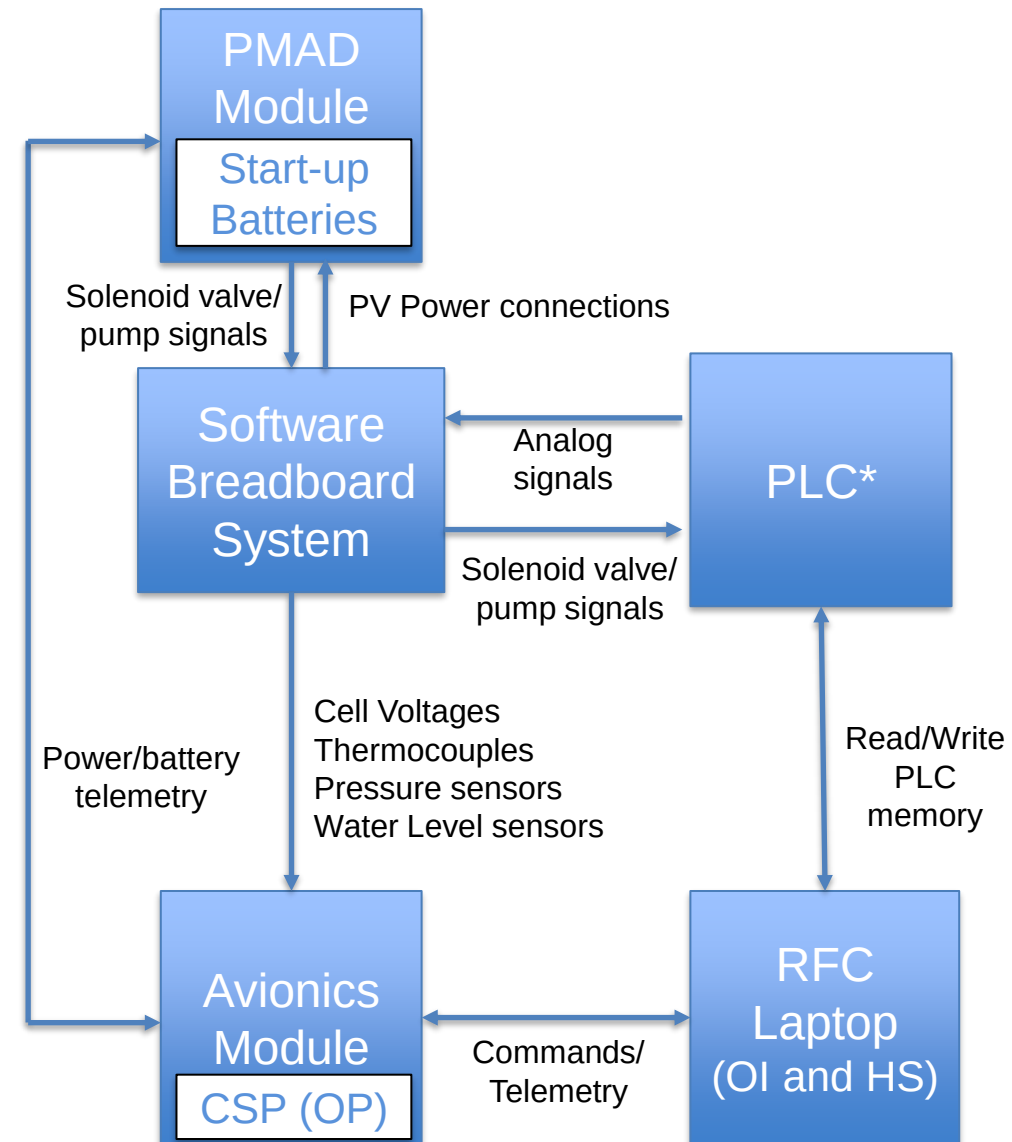
Checks with test boxes emulating RFC Balance of Plant



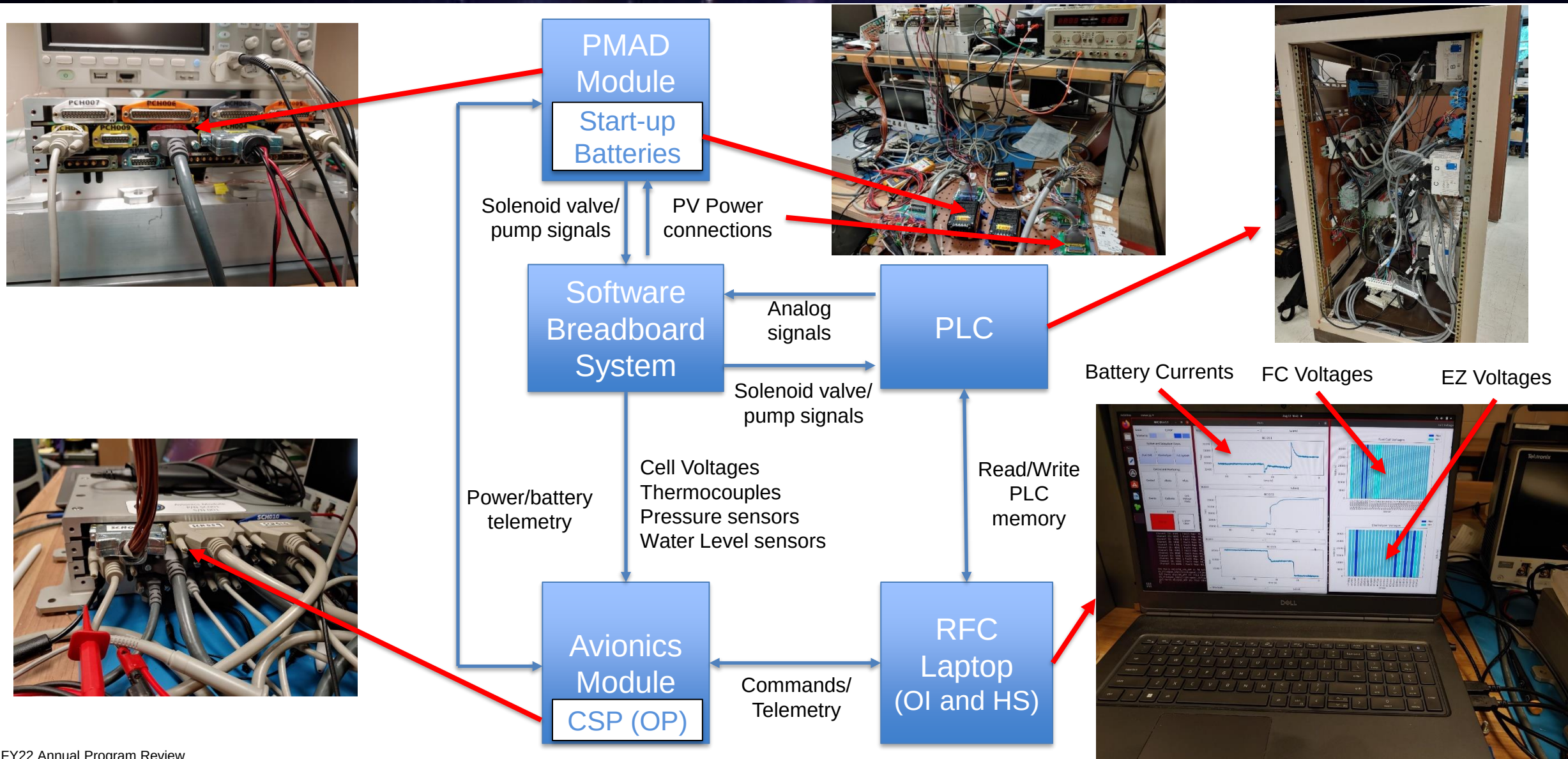
Accomplishments - Software

➤ Hardware/Software Integration Efforts:

- Assembled and verified instrumentation and actuator simulator required to functionally verify Avionics and PMAD hardware and RFC system software independent of fluidic and electrochemical hardware
- Conceptual Hardware-in-the-Loop Design
 - Hardware Simulator (HS) drives the PLC system
 - PLC generates analog signals and reads solenoid valve/pump signals
 - Signals between Programmable Logic Controller (PLC) and the PMAD/Avionics modules are connected through the software breadboard system
 - Avionics Module contains the CSP board running the Operational Program (OP)
 - Laptop runs the Operator Interface (OI) to receive telemetry and send commands



Accomplishments - Software





Accomplishments - Software



➤ Verification and Validation

- Developed a Software Test Plan document and held an inspection with other RFC members
- Developed a functional testing framework to automate some of the more tedious V&V procedures. The framework executes a predefined sequence of commands to the OP and HS
 - Fault Testing: This test will loop over the fault modes (Safe, Standby, Normal FC, and Normal EZ), fault channels, and fault types (Caution/Warning/Alarm Low/High) to test that the OP has the appropriate response for all entries in the Fault Tables
 - State Machine Command Testing: This test will loop over all the different mode transitions in the state machine. For each state within each transition, this test will send all possible mode transition commands to test which commands are valid or invalid for a given transition based on the whole state machine
 - Developed unit tests for the OI

➤ Unique Code Development

- Solenoid cycling algorithm: Periodically cycles binary actuators rapidly between states (e.g. closed / open). This mitigates “sticktion” whereby an actuator fails to change state when not exercised frequently
- Lift pump control: Cycles lift pump operation to meter electrolysis water feed rate based on water level sensor feedback
- Output checking: Satisfy some of the safety critical requirements given by NPR 7150.2C by verifying actuator commands based on the current state in the state machine



Accomplishments – Electrolyzer

- Giner designed, built, and tested two high pressure electrolyzer cell stacks
 - Two electrolyzer stacks fully assembled in June 2022
 - Liquid anode feed electrolyzer
 - Up to 1800 psia (2500 psia max) balanced pressure, capable of survival of 2500 psia differential pressure
 - 60–80°C operating temp (nom.) Rated for 4–85°C
 - 13 g/hr H₂ and 100 g/hr O₂ production rates
 - Lightweight carbon fiber endplates
 - Electrolyzer stack #1 final acceptance testing nearing completion
 - Electrolyzer stack #2 final acceptance testing near 50% complete
 - Both electrolyzer stacks will be delivered to GRC by the end of September 2022
 - Contract No-Cost-Extension mod issued to extend Period of Performance (PoP) until 10/15/22

Cell Stack 1 being prepared for vacuum testing



Cell Stack 2 during 300 hr nominal test





Accomplishments – Fuel Cell

➤ Stack Hardware (Infinity Fuel Cell & Hydrogen)

- Fuel cell TRR held 10/5/21
- Two fuel cell stacks fully assembled in October 2021
- A parallel project discovered fuel cell technical issues in early April 2022 which also impacted the RFC fuel cell design
 - Corrective actions identified and tested (April – August 2022)
 - Both fuel cell stacks to be disassembled and reassembled with corrective actions implemented
- Fuel Cell #1 to be acceptance tested and then delivered to GRC in mid-December 2022
- Fuel Cell #2 to be delivered to GRC in January 2024 after acceptance testing and after the 5,000-hour life test is completed

➤ Contract details

- Implemented 5,000-hour life test risk reduction contract mod in early April 2022



Fuel Cell Stacks 1 and 2



Accomplishments - Packaging



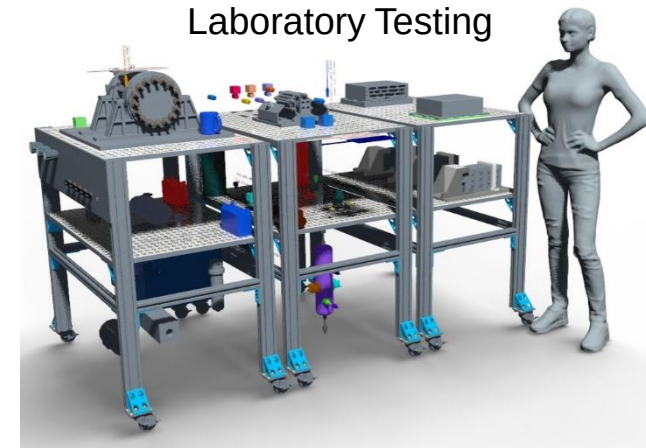
➤ Breadboard System

- Includes all components except for gas storage and thermal insulation elements
- Completed design pivot to laboratory breadboard configuration
 - System will be constructed across three portable carts each with two deck layers to attach components
 - Carts will be fluidically and electrically interconnected
 - Initial build-up and check-out testing to be performed in GRC B309 Fuel Cell Laboratory with final demonstration occurring in GRC B334 Fuel Cell Test Facility
- Initiated buildup of breadboard configuration
- Completed logistical fit-checks for the breadboard

➤ Lunar Surface Habitat (Artemis)

- Initiated preliminary design studies of available volumes within the Artemis Habitat (current iteration) which could host an RFC-based energy storage system

Updated Breadboard System for Laboratory Testing



Fuel Cell



Lunar Habitat Mock-up at GRC with representative fuel cell stack assembly



Accomplishments - Testing

➤ Testing

- HW/SW Integration Efforts: Started putting together a software breadboard system:
 - The CubeSat Space Processor (CSP) board runs in the Avionics module provided by JSC
 - PMAD module provides power through the startup batteries or PV simulator
 - Power supply acting as a PV simulator, and resistor load action as an electrolyzer
 - PLC system generating all of the FC and EZ cell voltages as well as the water level sensor signals (so far)
- Demonstrated ability to route power from photovoltaic (PV) simulator through PMAD module to the EZ. PV array can also directly power the Avionics module rather than from startup batteries
- Incorporated Emergency Stop (E-Stop) circuit monitoring. Thus, software can trigger an E-Stop event and the software can detect if the external E-Stop switch has been flipped
- Developed Operational Program (OP) modules to startup and run the CSP watchdog timer
- Developed HS modules to control the PLC system. Modules read/write PLC memory registers to read PLC inputs and set PLC outputs (e.g. FC/EZ voltages, pressure sensor values, etc.)
- Incorporated new core flight applications to handle automatic or operator-controlled file transfer between the CSP board and RFC laptop



Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year					<u>Technical</u> – GRC performed component risk reduction testing and worked on contract modifications for fuel cell stack risk reduction testing <u>Cost</u> – Project to incorporate budget deviations in project CR. Deviations resulted from issues at JSC, pace of on-site work due to COVID restrictions, and an increase in hardware costs <u>Schedule</u> – Trend will improve upon approval of RFC re-baselining, and reduction of COVID restrictions <u>Programmatic</u> – Continuing project CR to capture revised work phasing, schedule, and budget
Annual					<u>Technical</u> – Continued component risk reduction testing and required facility modifications, started Software integration and check-out, started assembling system structure <u>Cost</u> – Project captured budget deviations and FY22 reductions in project CR <u>Schedule</u> – GRC pace accelerating with increased on-site presence <u>Programmatic</u> – Working with JSC and GRC management to mitigate budget issues. Project CR to capture revised work phasing, schedule, and budget. Contracts modified to incorporate changes to vendor schedule and cost for both electrochemical stacks



Plans Forward and Infusion Plan

Draft – Pending CR Approval

FY	Activity or Milestone
FY22	• RFC project rephasing data package
FY23	• Receive Fuel Cell and Electrolyzer stacks from vendors • Receive Balance of Plant components • Breadboard RFC system assembled • PPR2B: Breadboard RFC system Test Readiness Review (TRR) package • Brassboard RFC system Preliminary Design Review #3 (PDR#3) package
FY24	• Breadboard RFC system closeout data package • PPR3: Brassboard RFC system Critical Design Review (CDR) package • Brassboard RFC Life Test system assembled; TRR package; Life test start
FY25	• Brassboard RFC TVAC system assembled • Brassboard RFC TVAC system Open-Loop TRR package at GRC • Brassboard RFC TVAC system Closed-Loop TRR package at ATF • PPR4: Brassboard RFC TVAC system TRR package & test start
FY26	• Fully tested (laboratory and TVAC) autonomous regenerative fuel cell energy storage system • Final report package containing Technology Gaps and RFC system technical descriptions, procedures, test reports, lessons learned, and technical drawings to enable future tech utilization

*Gray denotes potential impact due to budget cut and decision on COA's



Education/Public Outreach



EPO Involvement

- 39th annual Space Power Workshop 26-29 April
- LSIC Spring Meeting in Laurel, MD on May 4th
- Government Agency Networking Program at the ARPA-E Innovation Summit in Denver, CO May 23rd thru 25th
- Department of Energy's (DOE's) Advanced Research Projects Agency-Energy (ARPA-E) Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH) – 28 June 2022
- Ohio Federal Research Network (OFRN) Quarterly Review – 30 June 2022
- Energy Storage Panel at the American Astronautical Society (AAS) Glenn Symposium on Energy Storage. 20 July 2022
- OFRN / Ohio State University H₂ Fuel Cell Workshop. August 15, 2022

EPO Calendar Outlook (High Priorities):

6 Month Look-Ahead

Ohio Fuel Cell Symposium	Oct 12-13, 2022
CLPS 2022 Survive the Night Workshop	Dec 6-8, 2022
Fuel Cell Seminar	Feb 7-9, 2023

- Advanced Power Systems for Deep Space Exploration (APS4DS) Aug 30 thru 1 Sept 2022
- Robert D. Green, S. Elango Elangovan, and Fanglin Chen, "Perspective—Solid Oxide Cell Technology for Space Exploration", Journal of The Electrochemical Society, Volume 169, Number 5, 2022, 054528



Summary

- Started assembling Breadboard RFC system for laboratory testing
 - JSC delivered Avionics and PMAD modules to GRC with supporting accessories
 - Software functional testing begun using hardware simulators and emulators
 - Started assembling Breadboard system for laboratory testing
- Electrochemical stacks fabricated
 - Electrolyzer stacks in final verification testing at the vendor
 - Fuel cell stacks scheduled to start verification testing in November
- Component Risk Reduction testing began
 - Many existing components incompatible with TVAC environment
- Armstrong Test Facility integrated into the project to provide closed-loop testing capability
- Continued coordination of RFC technology development across the agency
 - Actively supported in situ resource utilization (ISRU) water electrolysis projects (Advanced Alkaline Electrolyzer (AAE), ISRU-derived water purification and Hydrogen-Oxygen Production (IHOP))
 - Actively supported Environmental Control and Life Support Systems (ECLSS) electrolysis teams at JSC and MSFC
 - Began RFC system assessment with Artemis Surface Habitat Logistics and Maintainability analysis team
 - Technical team members serving as CORs for Phase I / II / II-E / III STTRs/SBIRs in relevant technology areas
- Evaluating options to mitigate and recover from impact of FY22 budget cuts