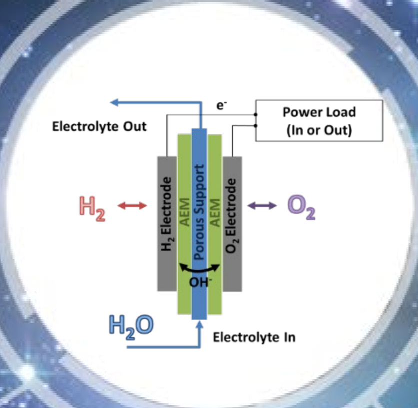


National Aeronautics and
Space Administration

Space Technology Mission Directorate

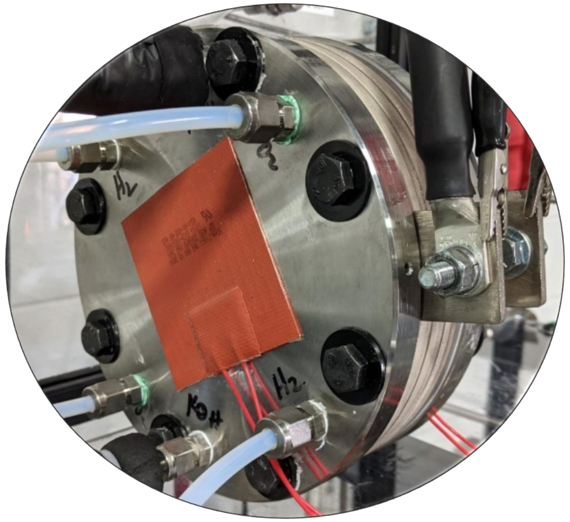
Game Changing Development Program

Ian Jakupca (GRC) | Paul Matter (pH Matter) | FY23 BRACES-TP Annual Review Presentation | 09.20.23

Name/Email POC: Ian Jakupca, ian.j.jakupca@nasa.gov

Project Overview

- Technology Product Capability
  - pH Matter is developing a highly integrated and novel "unitized" reversible fuel cell (URFC) system that enables reliable, long-duration energy storage and can generate hydrogen and oxygen from locally sourced water. Reversible fuel cells can store energy at 3 times higher energy density than conventional systems and don't require recycle blowers or compressors.
- Technical Capabilities
  - Highly-integrated unitized reversible fuel cell (URFC)
  - Patented hybrid liquid/membrane alkaline cell
  - Goal of moving from TRL 3 to TRL 4 with the system designed and built for a potential future thermal vacuum (TVAC) test
  - Technology will be commercialized for remote energy storage and production of green hydrogen
- Exploration & Science Applicability
  - Technology will support NASA's mission to establish a human presence on the moon
  - Conversion of *in situ* derived water (extracted or byproduct) into oxygen and hydrogen
  - The gases will be used for energy storage and propellants, oxygen will be used for life support
  - Fuel cell reactants provide "keep alive" or operational power during sunlight eclipse periods



Project Overview

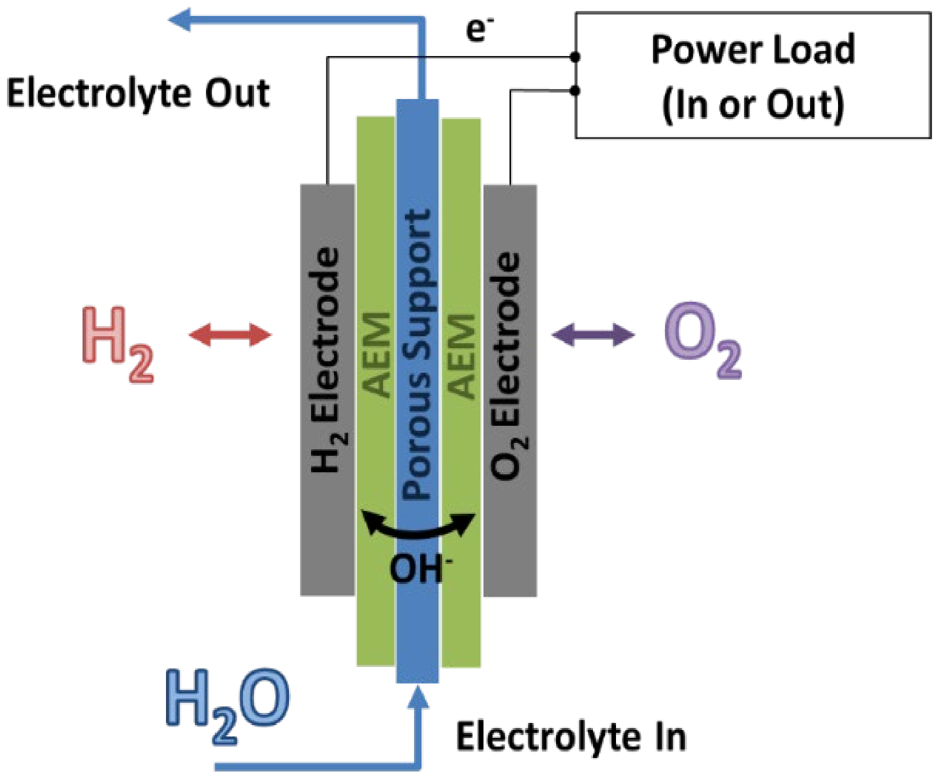
- Benefits to NASA Missions
  - For a 10-kW equatorial lunar base, 22,000 kg of lithium-ion batteries (160 W-h/kg) would be needed to survive the 354-hour lunar night
  - At the minimum Reversible Fuel Cell (RFC) system specific energy of 320 W-h/kg, launch mass would be cut in half, resulting in massive savings
    - RFCs can store energy at 5X higher energy density than battery systems
  - The energy density of RFC systems for long-duration storage are dominated by gas tank storage mass, which is directly proportional to round-trip efficiency; volume/mass is strongly impacted by storage pressure
  - This project targets advancing the state of the art for (1) efficiency by operating the fuel cell at high pressure, (2) storage pressure by integrating the RFC in a carbon fiber vessel, and (3) reliability/simplicity through process intensification

Value	NASA RFC Goal	SOA Discrete PEM System (AIRS)	Proposed URFC Approach
Nominal Current Density (mA/cm^2)	N/A	200 (each stack)	160
Round-Trip Efficiency (RTE)	54% [4]	~55%	55%
Specific Energy (Wh/kg)	> 320	360-850	> 1,000*
Water Purity Required**	TBD	Deionized	ppm
Mode Change Speed	Seconds	Minutes	< 5 s
Number of Cell Cycles	>79***	30,000	> 1,000
Reliability / # of Moving Parts****	No Failure for >5 yrs	Blowers (2), Pump	Pump (1)

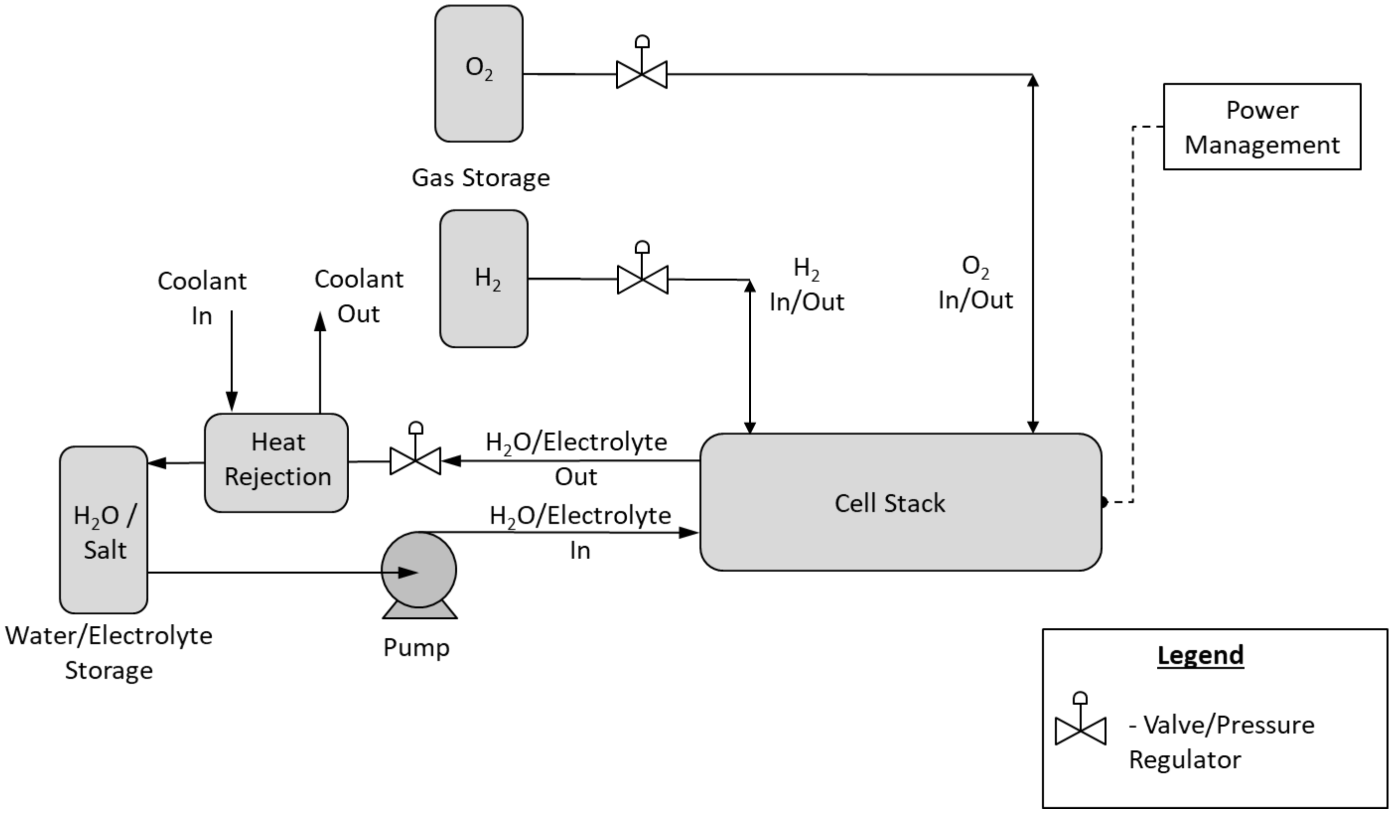
** Without thermal system and assuming locally sourced water (the proposed URFC would be 850 Wh/kg if water mass is included)*
*** PEM systems require D.I. water free of metal ions; proposed approach was demonstrated with ppm metal ion impurities (Ca, Mg, Fe, and Ni)*
**** Based on 5-years between maintenance, 700-hour cycles*
***** System reliability is poor for system with blowers and/or compressors*

URFC Technology Overview

Technical Approach:



Unitized Reversible Fuel Cell (URFC) Overview



Integrated URFC System Diagram

Project Goals and Objectives

Technology Development Needs Addressed by Project

Stakeholder	Energy Storage for Moon & Mars surface exploration, crewed landers, habitats and long-term lunar power infrastructure	STARPort Capability Areas and Gap IDs: Advanced Power (505), ISRU (546, 573), 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)

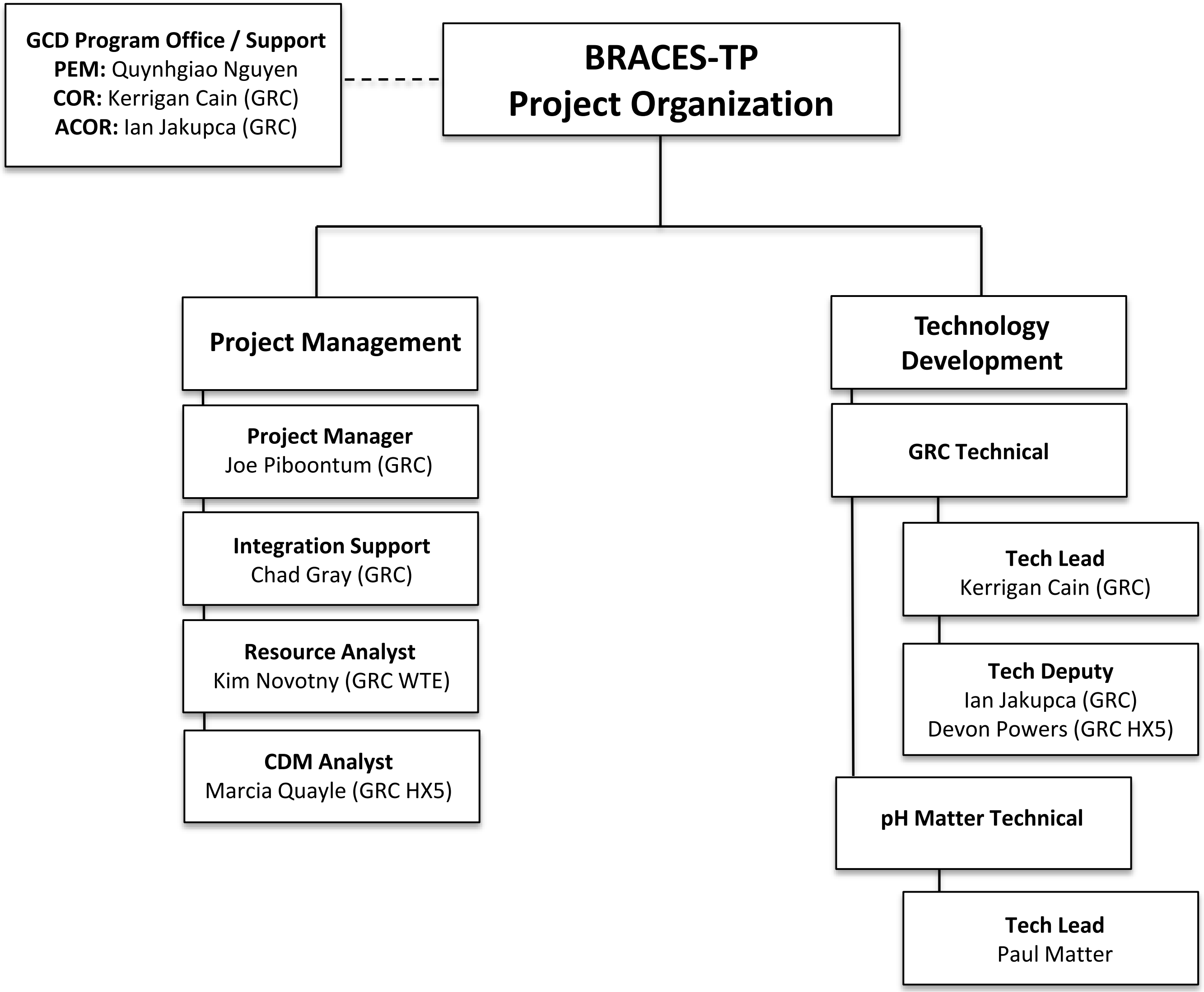
Technology Goals

Goal #1	Design and demonstrate the reversible fuel cell technology in a full-scale 2-kW electrolysis / 1-kW fuel cell breadboard prototype system, increasing the technology from TRL 3 to TRL 4
Goal #2	Demonstrate a brassboard URFC system in relevant environments, including shock and vibration to increase the technology to TRL $\geq$ 4 for lunar surface applications

Project Objectives

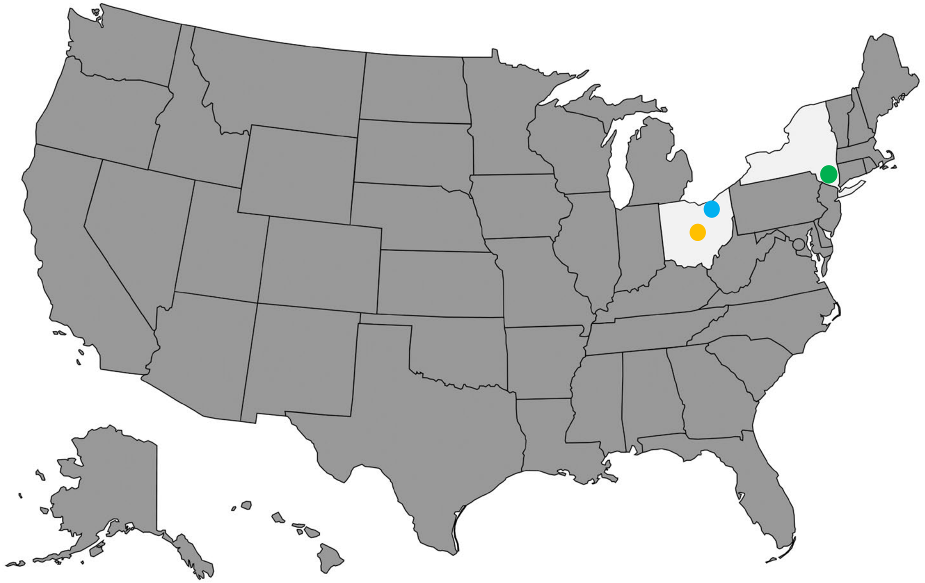
Objective #1	Demonstrate cell operation at 250-bar to enable high system energy density through storage of compressed hydrogen and oxygen
Objective #2	Design and demonstrate a cell stack module at the scale necessary for 2 to 10-kW systems
Objective #3	Integrate the stack with gas storage and controls in an instrumented breadboard system and demonstrate the system under simulated operating conditions for lunar energy storage applications
Objective #4	Design and build an integrated prototype 2-kW electrolysis reversible system and demonstrate under Thermal Vacuum (TVac) and Shock/Vibe testing to achieve TRL $\geq$ 5. Thermal vacuum will simulate lunar surface conditions

BRACES-TP Organizational Chart

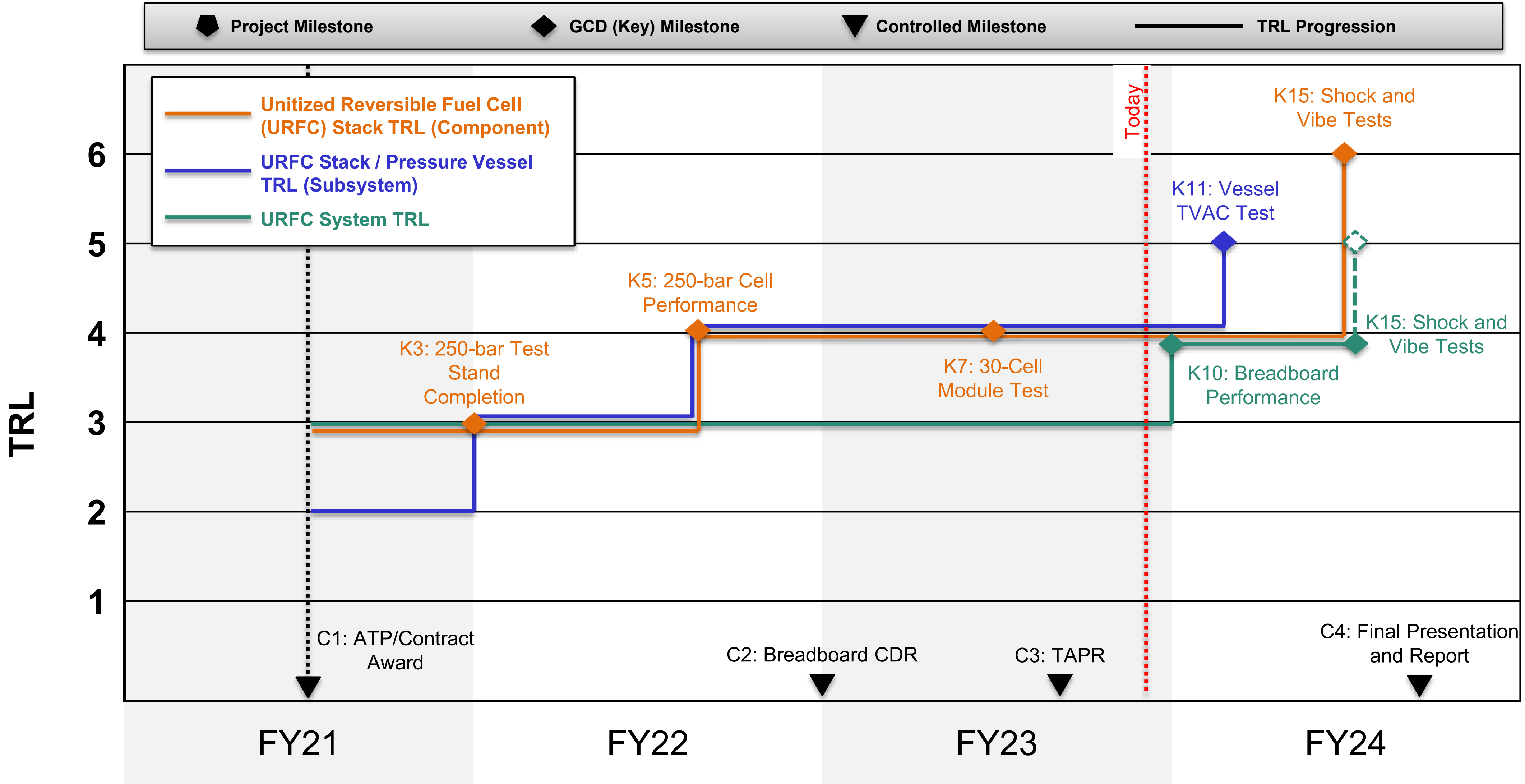


Collaborations & Partnerships

- Participating Entities
  - pH Matter
  - NASA Glenn Research Center (GRC)
  - Bettergy Corp.
- Targeted NASA Missions
  - Energy storage for Moon and Mars surface exploration (e.g., rovers and habitats)
  - Lander operations
  - Long-term power
  - Generating propellant and cabin oxygen



BRACES-TP TRL Progression



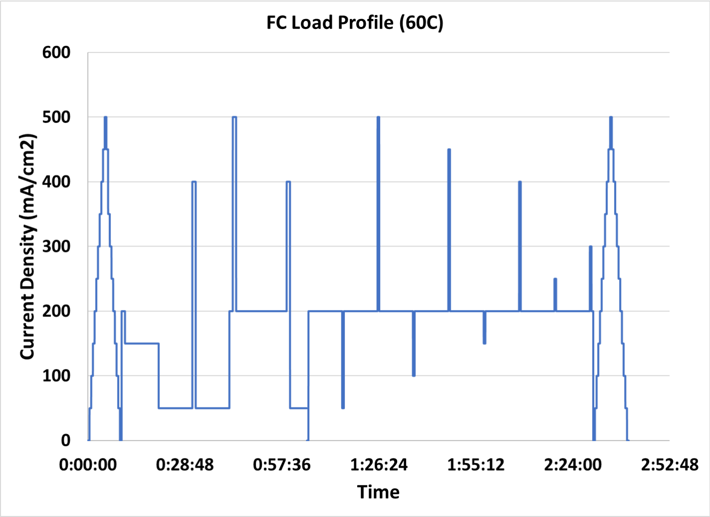
Integrated URFC System TVAC testing was de-scoped due to facility availability & budget issues.

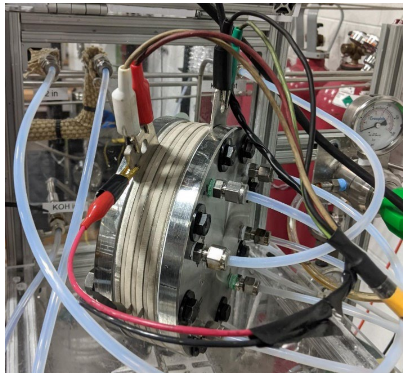
Dashed line indicated potential TRL progression with TVAC testing completed.

Accomplishments

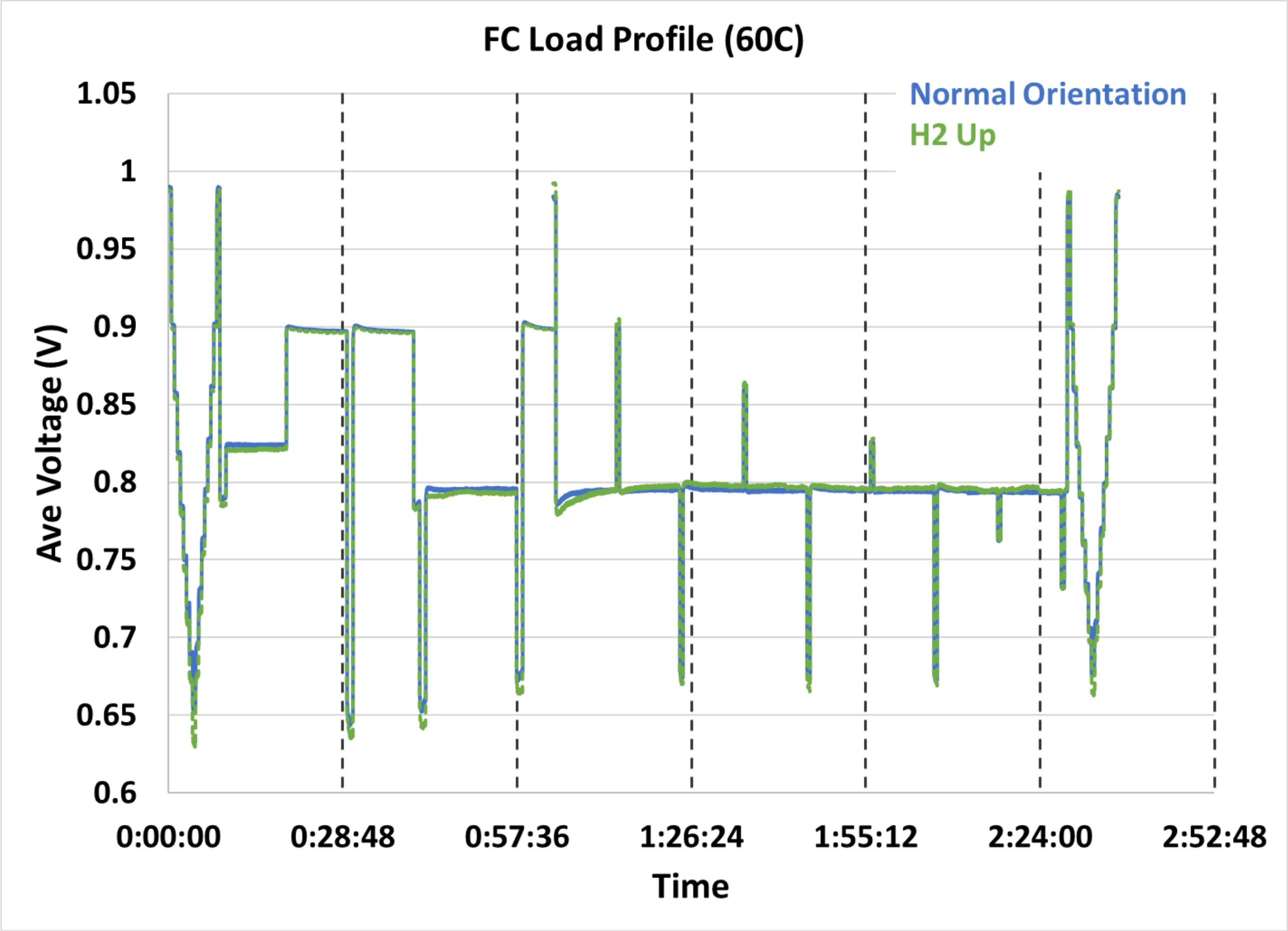
Stack Testing:

- Internal testing on 3-cell stack with the NASA fuel cell load profile





3 bar (Gas Pressures)
60° C electrolyte
5 M NaOH



Accomplishments

30-cell Stack Tests:

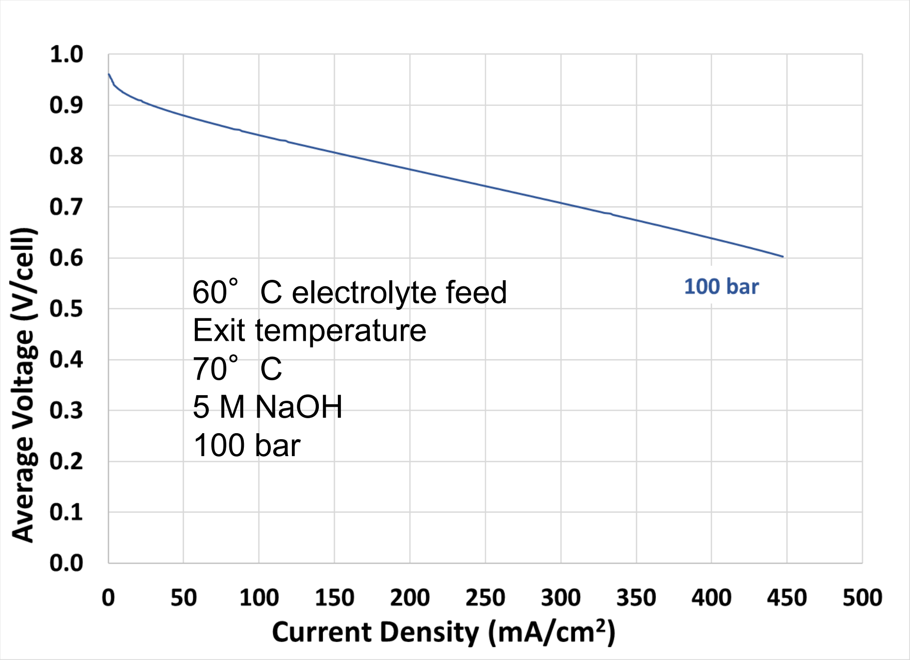
- Improved the cell alignment process during assembly
- Adopted thicker endplates for wider margins on compression forces
- Sealing improved, stack was demonstrated in pressure vessel; demonstrated 50% RTE_{Stack}

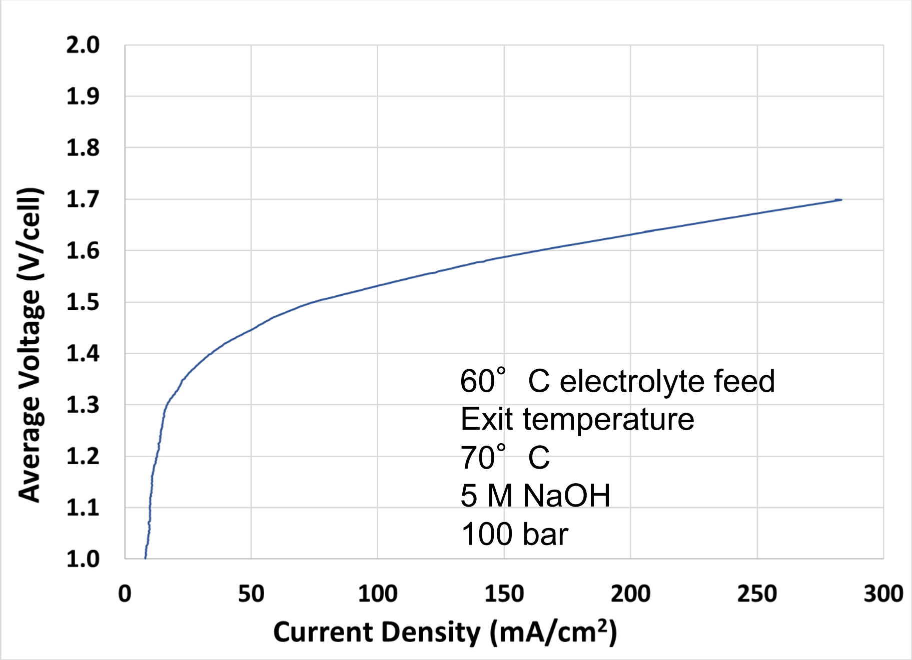
Stack RTE

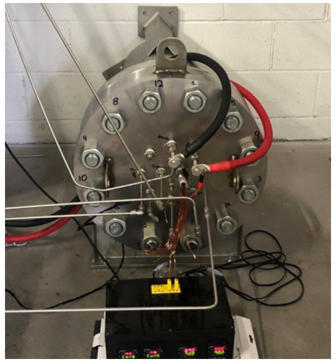
Stack Size	Pressure (bar)	Electrolysis Voltage, V_{EZ}	Fuel Cell Voltage, V_{FC}	RTE_{Stack}*
10 cells	100	1.54/cell	0.84/cell	54.5%
30 cells	100	1.59/cell	0.80/cell	50.3%

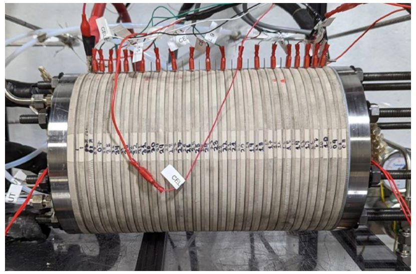
*$RTE_{Stack} = V_{FC}/V_{EZ}$ measured at 160 mA/cm^2

Efficiency improvement expected with new 30-cell stack build in the breadboard testing





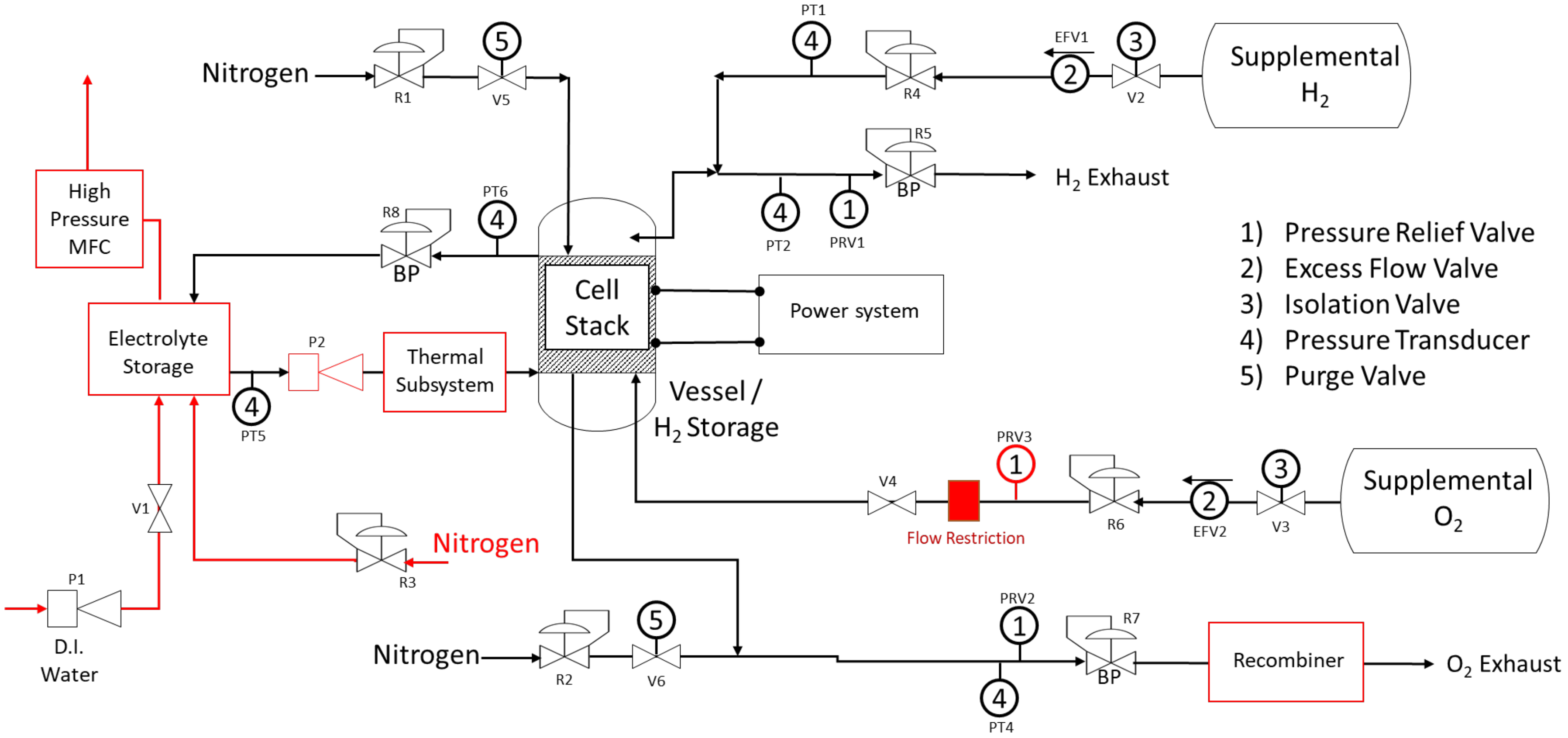




Accomplishments

Completed Breadboard Preliminary and Critical Design Reviews, addressed all RFAs:

Breadboard High-level PFD – Planned Additions to Existing High-Pressure Test Stand

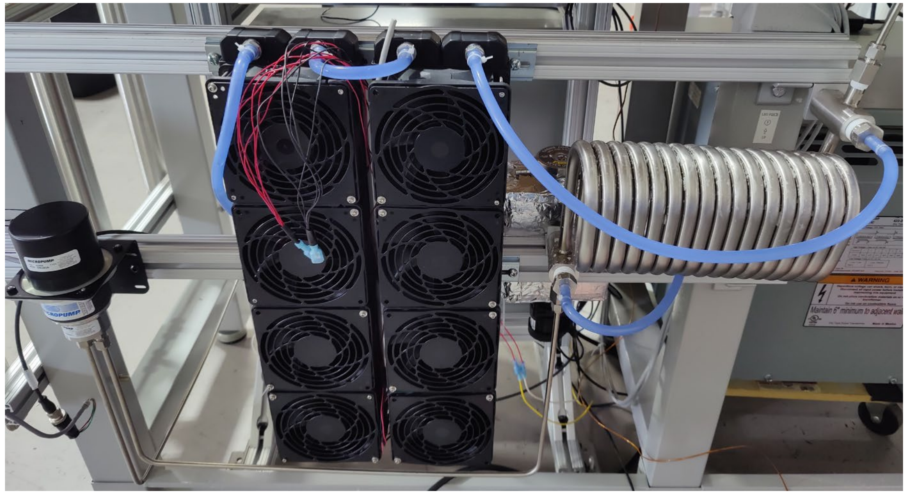


Accomplishments

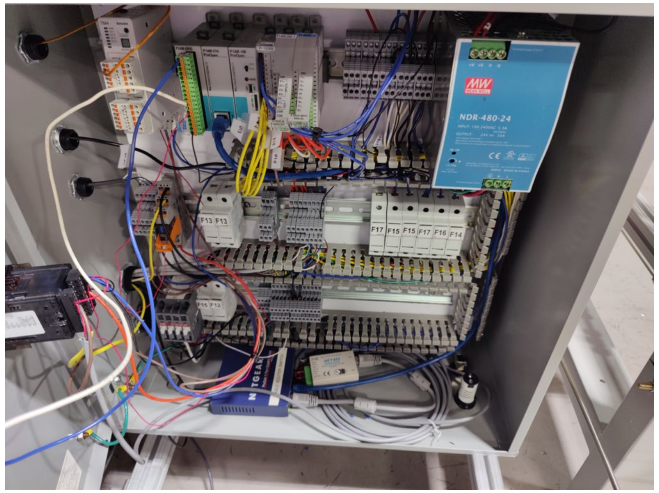
Built Breadboard System:

- Includes controls sub-system module, thermal controls module, and electrolyte storage with gas analysis to high-pressure test stand
- Completed shakedown tests on each module operation

Thermal Subsystem



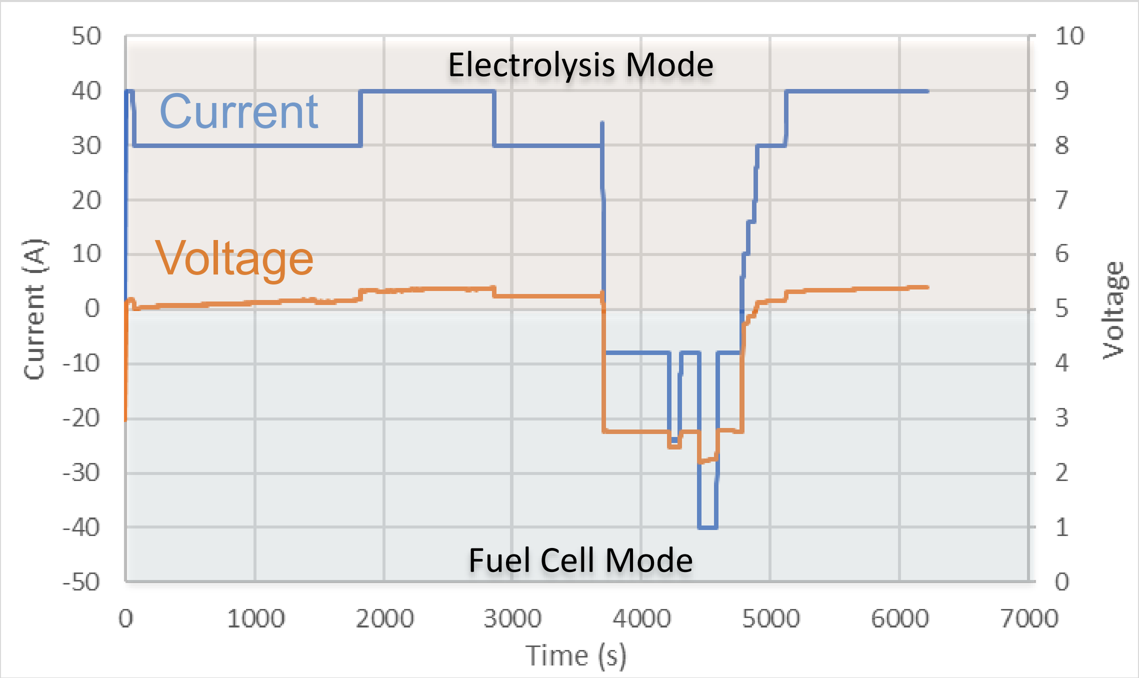
Controls Module

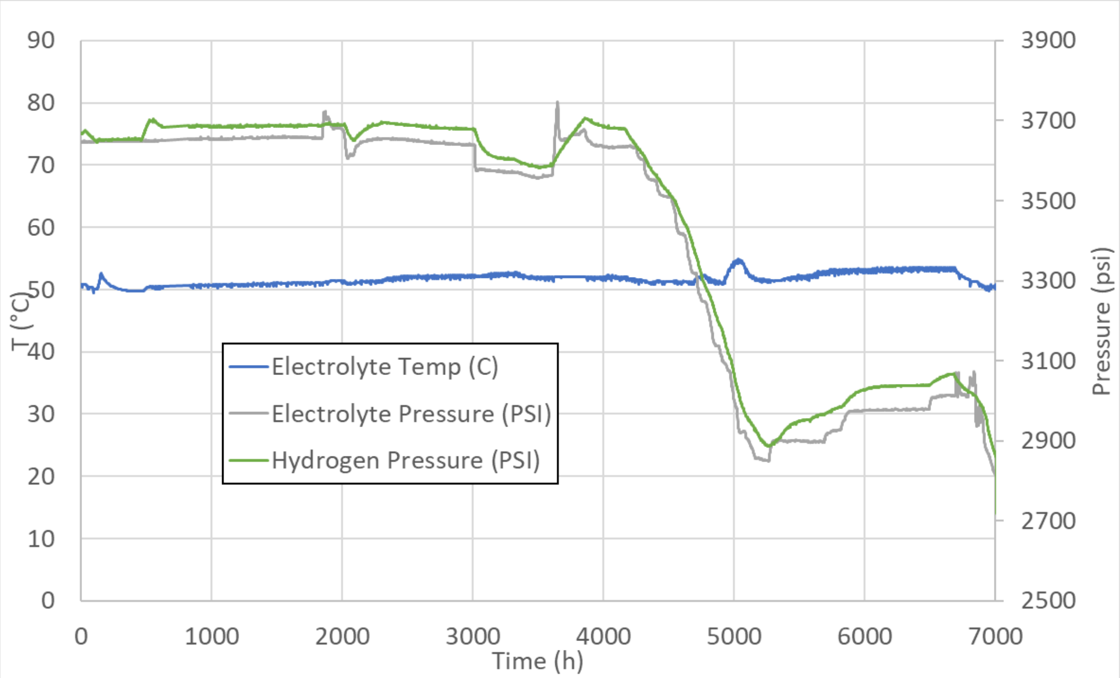


Electrolyte Storage

Began testing breadboard operation at 250-bar:

- Demonstrated min and max electrolysis currents in 3-cell stack
- Demonstrated cycling from electrolysis to fuel cell and back to electrolysis
- Tested at baseline fuel cell and fuel cell power spikes

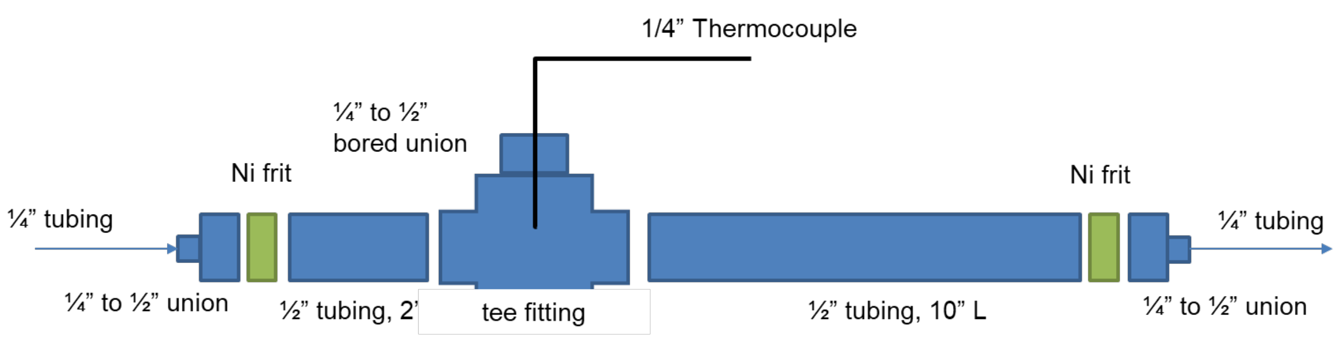




Accomplishments

<u>Developed high pressure recombiner design:</u>

- Designed for worst-case failure scenario; procured parts
- Integrated flame arrestor into the recombiner
- Quote obtained for qualification testing from WHA International
- Completed shakedown tests at low-pressure operation



Test #	Total Flow (slpm)	% H2	Top Temp (°C)	Midpoint Temp (°C)	Bottom Temp (°C)
1	12.5	1.0%	104	73	52
2	12.5	2.0%	127	89	57
3	12.5	3.0%	171	111	77
4	9	1.0%	103	66	50
5	9	2.0%	121	76	54
6	9	3.0%	155	92	60
7	6	1.0%	102	56	40
8	6	2.0%	109	64	41
9	6	3.0%	133	68	42

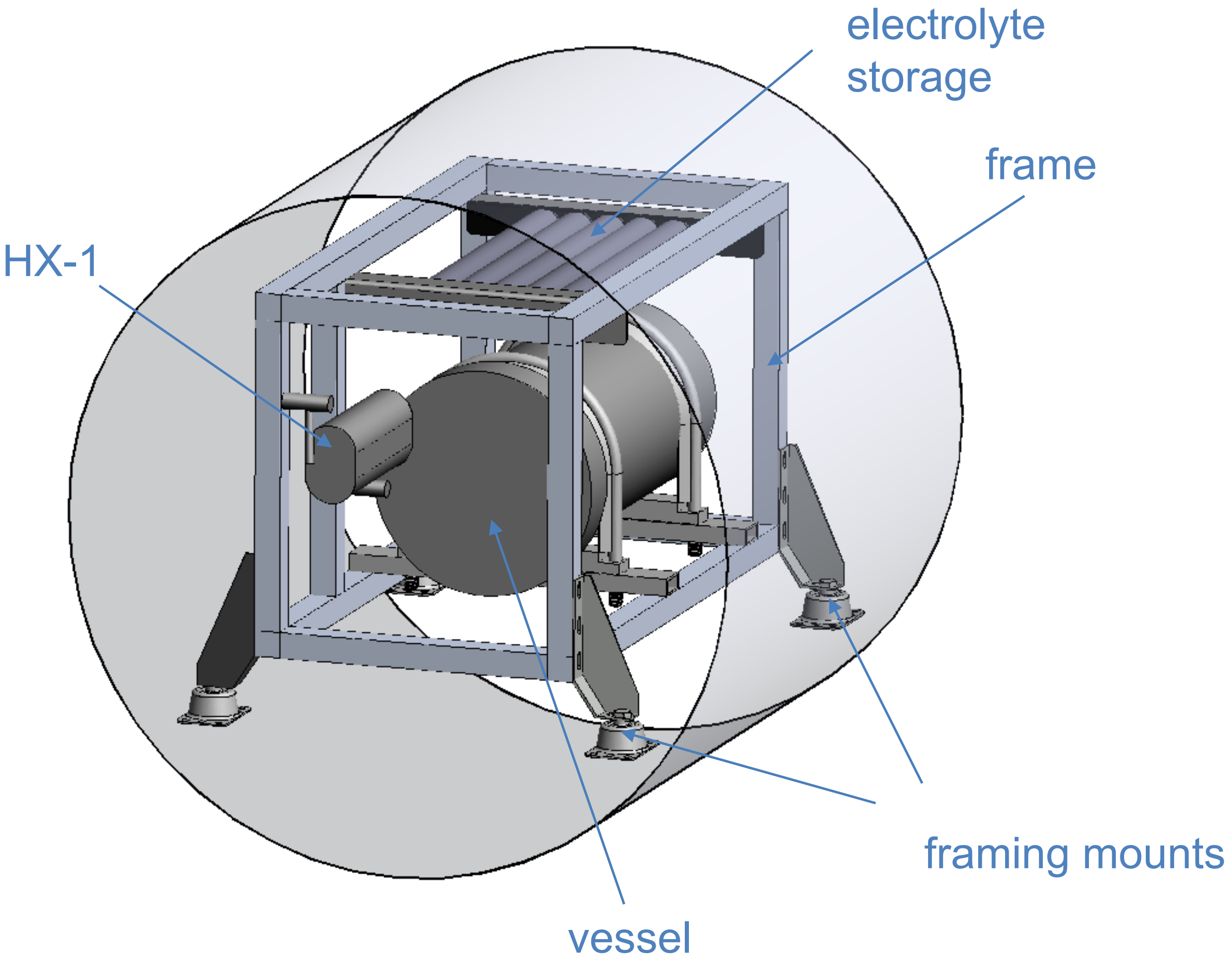
Accomplishments

Brassboard DDR:

- Updated requirements for brassboard
- Packaged system design
- Developed test plan
- Completed design review

Breadboard versus Brassboard Design Changes

Subsystem / Component	Breadboard	Brassboard
Cell Stack	30-cell	30-cell
Power Supply	OTS	OTS
Controls	OTS	OTS, less instrumented
Thermal	Stack TC	Stack + Enclosure TC
Water/Electrolyte	1 Orientation	3 Orientations
Recombiner	1 Orientation	3 Orientations
H2 Storage	Test Vessel	Smaller Vessel
O2 Storage	<470 mL	<470 mL
Frame/Structure	Test Stand	Enclosure



Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year					**Cost** – No issues **Schedule** – Milestones K7 and K8 delayed due to leaking issues in the URFC stack **Technical** – 30-cell stack testing completed up to 100 bar; leaks observed at higher pressure. **Programmatic** – No issues
Annual					**Cost** – No issues **Schedule** – Milestone K10 delayed due to leaking issues in the URFC stack. Milestone K11 delayed until safety permit approved to conduct vessel TVAC test. **Technical** – Breadboard assembled and completed checkout testing with a 3-cell stack. Full verification testing to begin once leaks in 30-cell stack are resolved. **Programmatic** – TVAC testing descoped and funding rephased to return ~$300k

Plans Forward and Transition / Infusion Plan

- BRACES-TP and related GCD AARC-ACO projects demonstrate technology for energy storage, primary power, and In-Situ Resource Utilization (ISRU) applications
  - pH Matter to partner with aerospace system integrators to develop flight systems for commercial and NASA missions (Signed first commercial MOU with aerospace system integrator to develop flight system in March 2023)
  - Target NASA applications include:
    - Energy storage for Moon and Mars surface exploration (e.g., rovers and habitats)
    - Lander operations
    - Long-term power
    - Generating propellant and cabin oxygen
- Related ARPA-E SEED project awarded-focused on integrating stack into Type V composite tank
- Spin-out company, Power to Hydrogen (P2H2), developing products for terrestrial commercial applications
  - Partners/customers include Shell, Automotive OEM, and Electric Utilities
  - Pilot agreements signed with Enel Green Power, American Electric Power (AEP), and Free Electrons Partners (ESB, EDP, E.On)
  - Additional development agreement opportunities for off-shore energy storage

Plans Forward and Transition / Infusion Plan

- Commercial MOU with aerospace integrator
  - pH Matter to provide both electrolysis and URFC stacks
  - Integrator to develop aerospace systems for energy storage and propellant generation
  - Non-exclusive commercial rights to use stacks in aerospace systems
- Information exchanges with additional target partners
  - Planning for future proposals
  - Desire to source fuel cell stacks, electrolyzers, and URFCs
- P2H2 developing products for terrestrial commercial applications:
  - Automotive OEM for distributed refueling and home energy storage
  - Pilot agreements signed with Enel Green Power for electrolysis
  - Free Electrons Partners (AEP, ESB, EDP, E.On):
    - 10-kW electrolysis
    - 2-kW URFC demonstration

Education/Public Outreach

EPO Involvement

- Ohio Fuel Cell and Hydrogen Coalition Symposium, October 13, 2022, North Canton, Ohio
- Free Electrons winner from the electric utility consortium (AEP, ESB, EDP, E.On), November 2022
- Enlit Europe, November 29, 2022, Frankfurt, Germany
- OhioSci Podcast
- CERA Week, March 7, 2023, Houston, Texas
- ARPA-E Innovation Summit, March 22-24, 2023, Washington, D.C.
- Energy.Media Podcast, June 20, 2023
- Powering Manufacturing in a Sustainable Future, Panel Discussion, BRITE, June 29, 2023
- Newsworthy Events for NASA.gov:
    1. Free Electrons 2022 award winner from six global electric utility companies (out of 700 applicants)
    2. Pilot demonstrations with utilities (AEP, ESB, E.On, EDP, and Enel)
    3. Advancing the state-of-the-art with first ever demonstration of 250-bar high-pressure unitized reversible fuel cell stack, and highest-known round-trip efficiency

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

- Demonstrated a 30-cell URFC stack up to 100 bar with 50% RTE_{Stack}
- Designed, procured, and assembled breadboard system
- Breadboard checkout testing completed with a 3-cell URFC stack
- Designed a high pressure recombiner
  - For safety precautions, testing completed at low pressure; high pressure testing to be outsourced when funding is available
- Completed a delta design review to incorporate changes from the breadboard to the brassboard URFC system
- Hardware testing scheduled to conclude by April 2024

Upon conclusion of this project, the URFC system will be at a TRL of 4 with hardware capable of being tested in a TVAC environment