



Space Technology Mission Directorate Game Changing Development Program

Christian Junaedi (Precision Combustion, Inc) | Ian Jakupca (GRC) | FY22 Propellant Fueled Solid Oxide Fuel Cell (PropFC) TP GCD APR | 09.12.22
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Project Overview



➤ Technology Product Capability

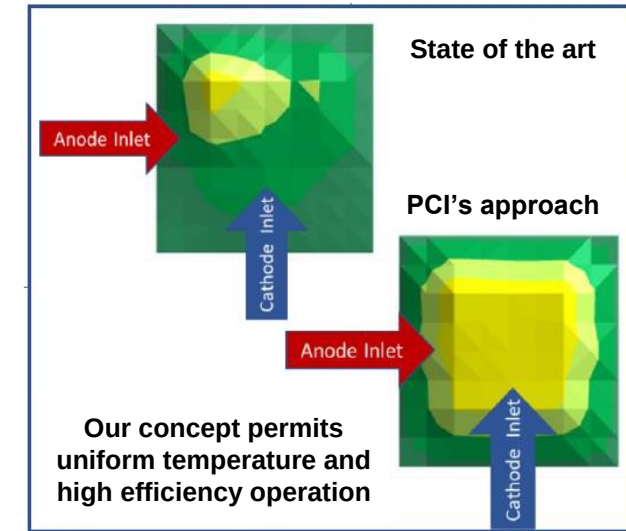
- Generate DC electrical power directly from residual CH_4/LOX propellants to satisfy lunar or Mars mission power and energy requirements within allocated mass budget
- Goal to advance air-independent SOFC stack technology from TRL 4 to TRL 6

➤ Technical Capabilities

- Using residual propellants eliminates dedicated tanks for fuel cell system reactants
- Internal CH_4 reformation eliminates external equipment → reduces mass / improves reliability
- High temperature solid oxide technology operation compatible with high temperature ISRU processes and tolerant of probable ISRU contaminants
- Cryogenic temperature cold-soak capability may provide a pre-positioned power source for crewed missions

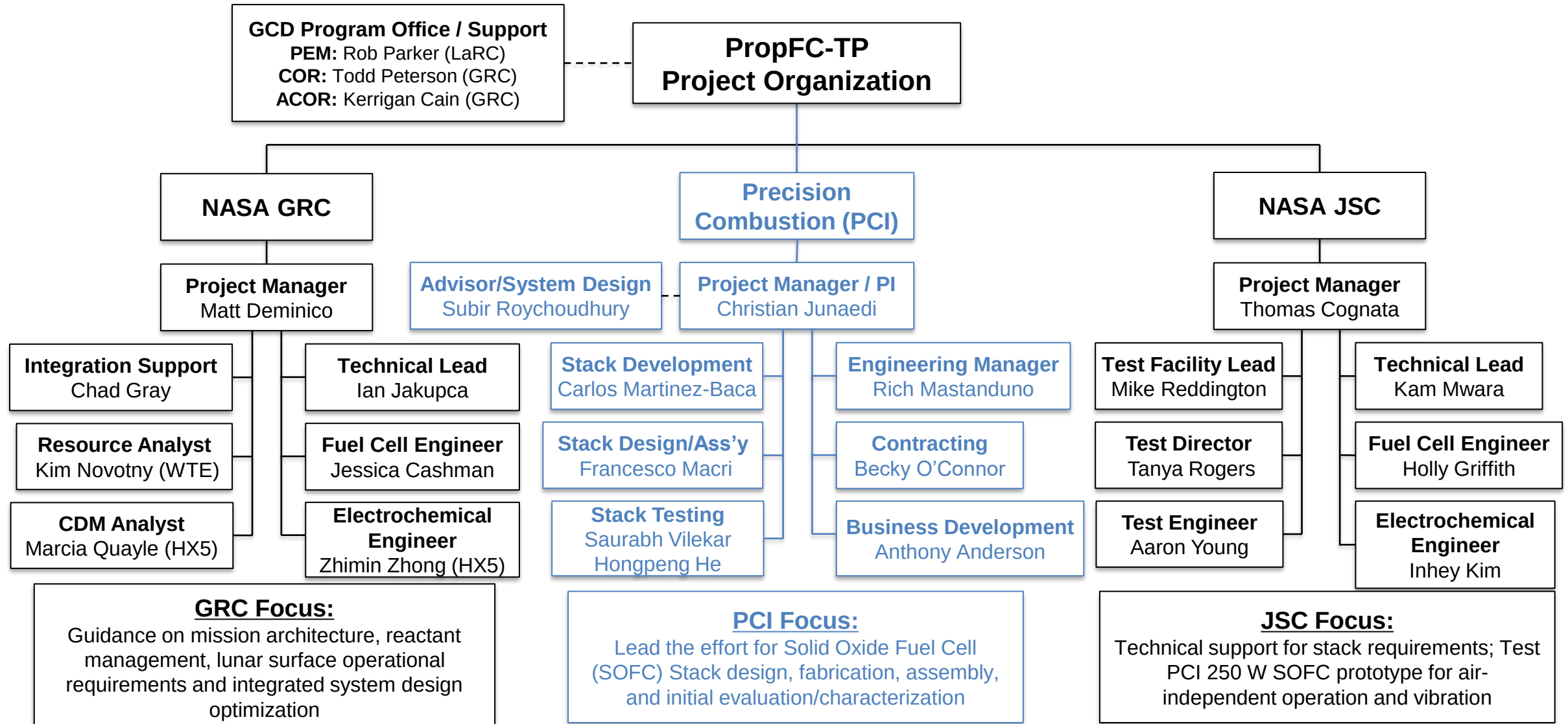
➤ Exploration & Science Applicability

- Technology will support NASA's mission to establish a human presence on the moon
- Power In-Situ resource utilization (ISRU) hardware used in space applications
- Enabling sustainable surface power for lunar missions



Thermal measurements show a more uniform temperature distribution

Team Members / Project Org Slide



Mission Infusion & Partnerships



➤ Participating Entities

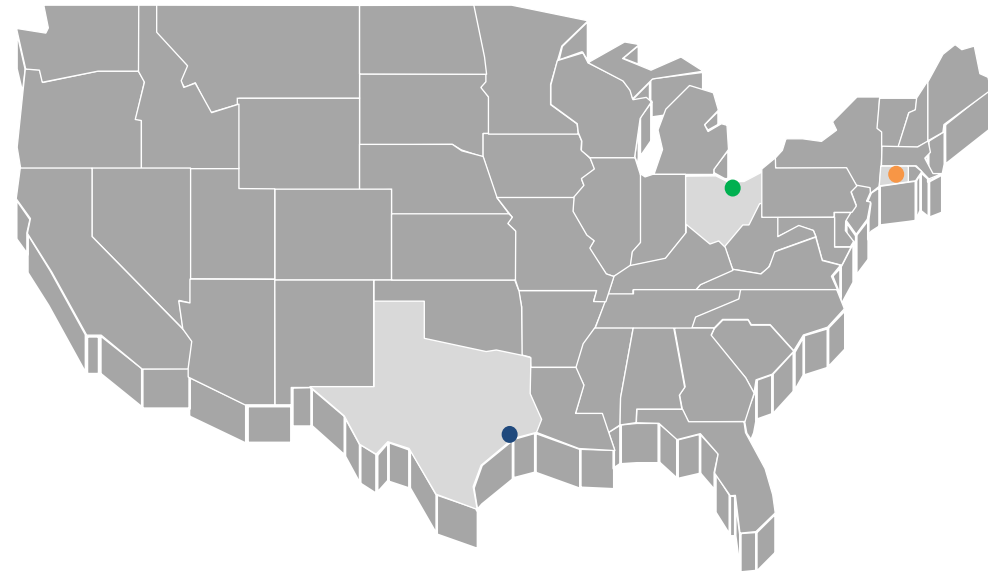
- NASA Johnson Space Center (JSC)
- NASA Glenn Research Center (GRC)
- Precision Combustion, Inc (PCI)

➤ Stakeholders

- Artemis Foundation Habitat Team
- ESDMD
 - Robotic & Human Landing Systems
 - Robotic and Crewed Rovers
- Commercial Industry

➤ Infusion/transition plan

- Target applications include:
 - Primary power for high energy missions using methane / oxygen propulsion
 - Energy storage for Moon & Mars surface exploration, lander operations, and upper stage long-term power
- Detail NASA mission(s) impacted by the technology product
 - Crewed spacecraft transiting cis-lunar space, traversing between the surface and orbit, surviving a lunar night
 - Lunar / Mars surface missions (e.g., rovers, landers, habitats)



Project Goals & Project Objectives



Project Goals

Goal #1	Generate electrical power from Oxygen / Methane propellants
Goal #2	Convert solid oxide fuel cell stack technology cathode reactant from air to pure oxygen

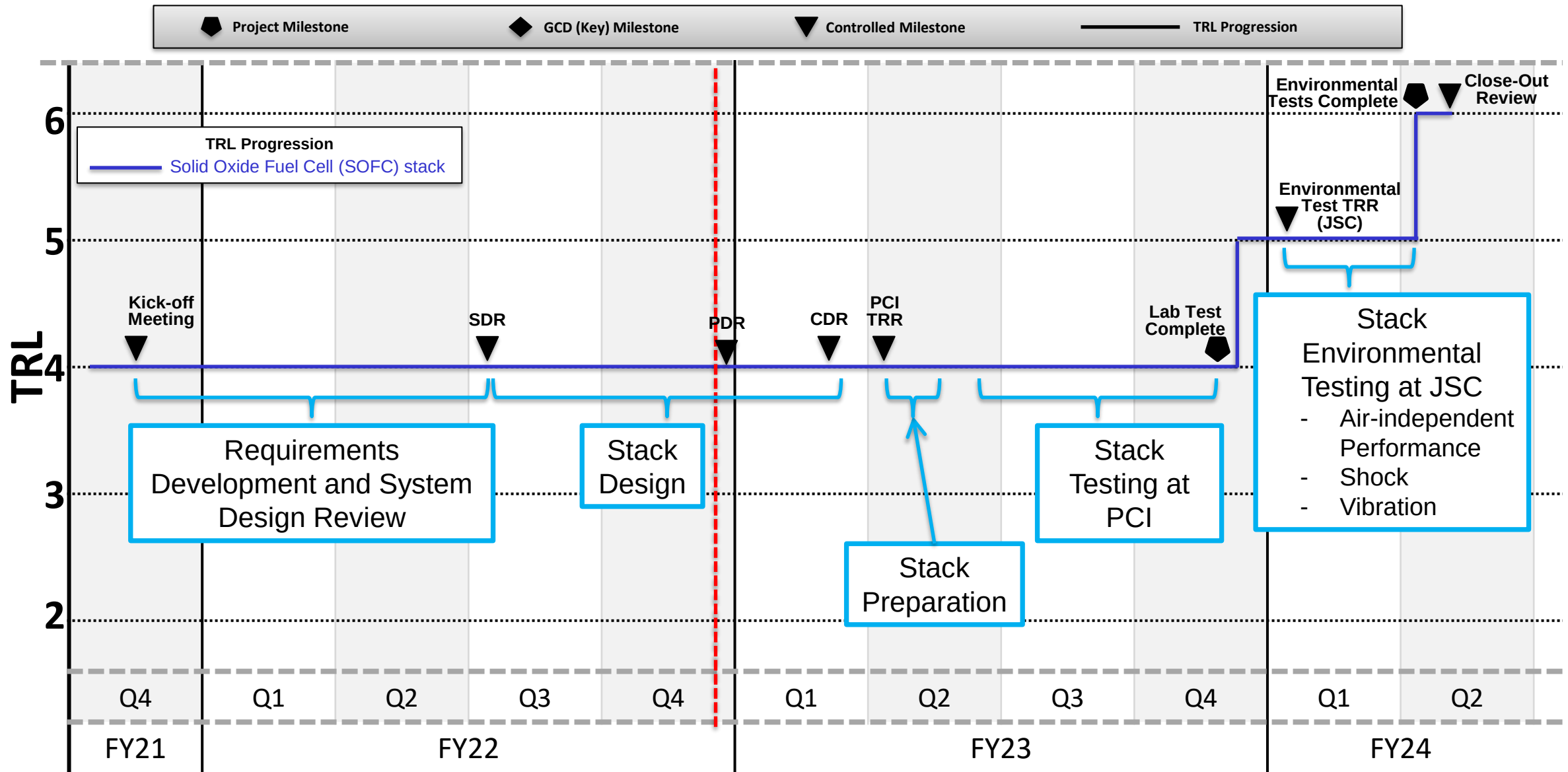
Project Objectives

Objective #1	Demonstrate operation of 250 W Solid Oxide Fuel Cell (SOFC) stack using propellant-grade oxygen and methane reactants
Objective #2	Advance stack TRL by conducting shock and vibration environmental testing of prototype 250 W SOFC stack

Note:

The contract covering this work is in place. The Project Plan is under development.

Propellant Fueled Solid Oxide Fuel Cell (PropFC) Technology Maturity Schedule / Project Lifecycle Milestones





Accomplishments - PCI



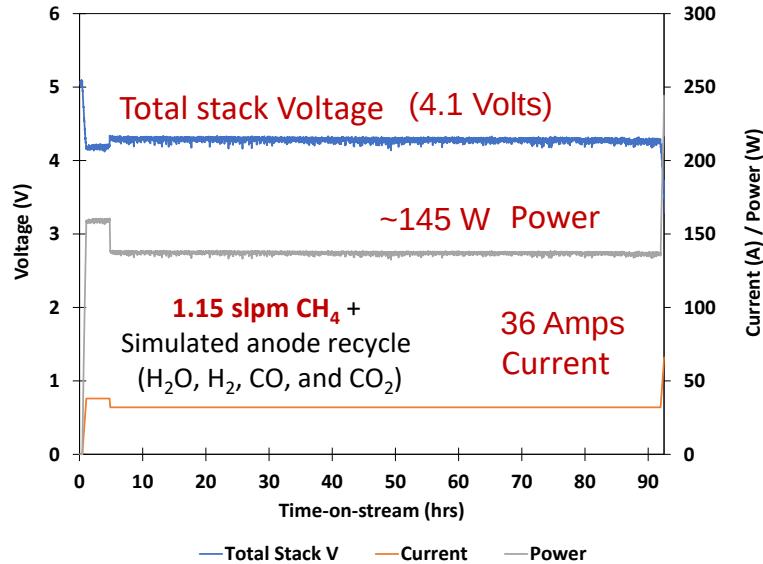
- Summary of PCI's activities since the start of the Tipping Point effort:
 - Completed SOFC stack & system requirements/interface document
 - Completed System Design Review (SDR); addressed SDR RFA's
 - Discussed interface & safety requirements of NASA test facility with JSC team
 - Developed preliminary SOFC operations concept; discussed with JSC team
 - Completed preliminary stack design via CFD analysis (flow manifolding) & FEA/stress analysis (stack components)
 - Finalized vibration isolation materials & design
 - Developed a modular stack design for scale-up based on prototype evaluation
 - Preparation for Preliminary Design Review (PDR)
 - Finalized materials selection with inputs from GRC & JSC teams
 - Setup test equipment for SOFC evaluation at PCI, including flow controllers, furnace, safety protocols, current/load bank, voltage readout, temperature readout, and gas sample analyzer

Ongoing activities on the system requirements/design model (w. GRC), test facility requirements (w. JSC), & preparation for PDR

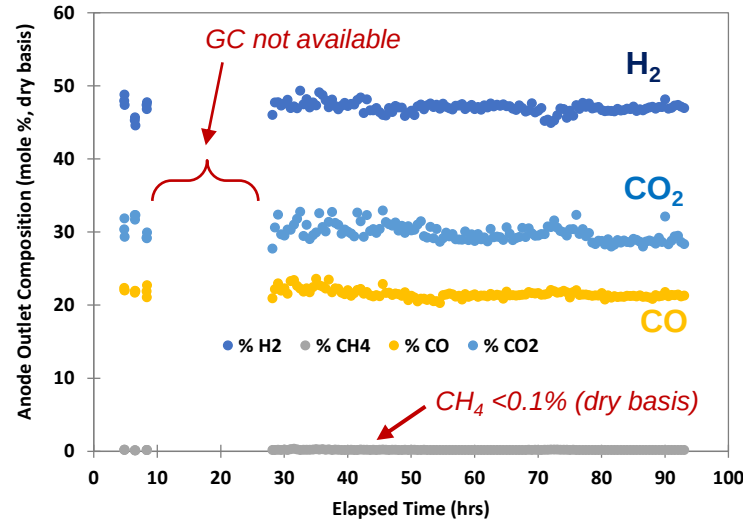
Results from Proof-of-Concept CH₄/Air SOFC Stack Operation



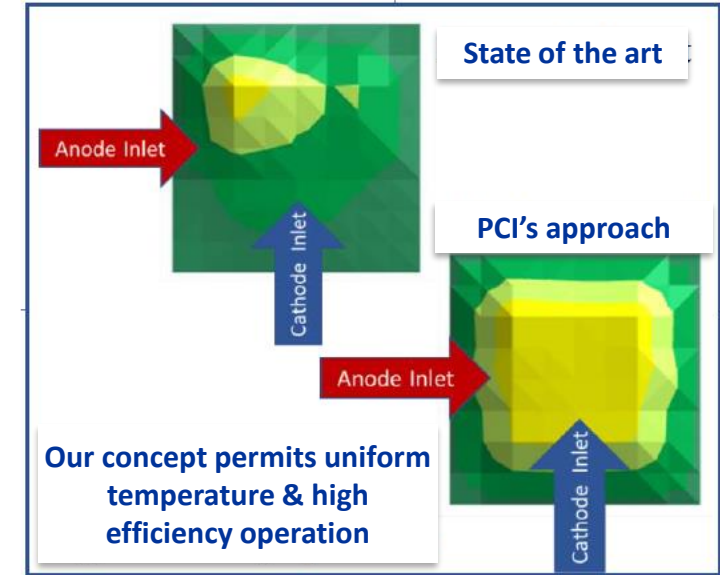
(1) Stack voltage & power vs. time at 700° C (90+ hrs)



(2) Anode Exhaust Composition (dry basis) vs. time



(3) Enhance temperature uniformity within cell



- Operated SOFC stack w. mixture of CH₄ & simulated anode recycle (@ H₂O/CH₄ of 2) with stable performance
- Observed near complete & stable CH₄ conversion (Anode internal reforming elements converted ~100% CH₄ into H₂ & CO)
- H₂ & CO produced in the anode side were consumed via electrochemical reaction providing thermal balance within the stack
- Post-test analysis was performed & indicated no noticeable carbon formation (coking) in the stack components

PCI's CH₄-fueling approach of SOFC results in improved temperature distribution, higher fuel utilization & carbon avoidance

Completed FEA/Stress Analysis for SOFC Stack

Completed properties assignment, design features, springs, loading & meshing geometry

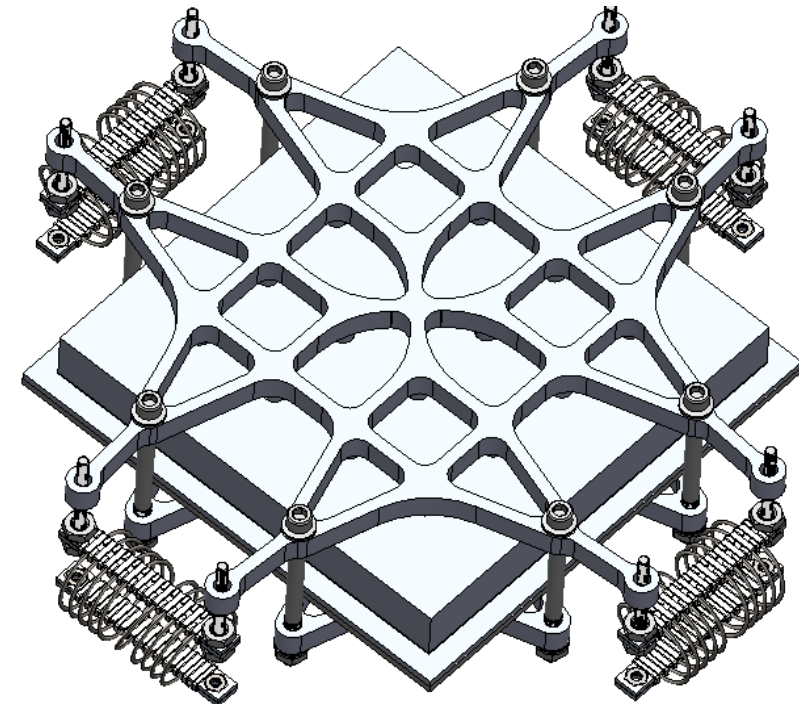
Developed 3D finite element model for the SOFC stack for structural & thermal analysis (ANSYS).

Analysis:

- Pressure: Operating & Burst
- Shock: Per NASA specifications
- Random Vibration: Per NASA specifications
- Thermal: ground & flight operation
- Thermal Stress: SOFC stack & hardware preloaded
- Modal

Iteration on:

- Compression 'waffle' frame design
- Materials of construction
- Component sizing/thickness



SOFC Stack Support Structure (Iterative Design)

Detailed FEA/mechanical analysis results were presented to NASA team; and a summary will also be presented during the upcoming PDR

Accomplishments - JSC



➤ System Design Review (SDR)

- Completed Milestone and material for SDR data package
- Identified concerns in SDR that impact scope of effort, including of test facility and test campaign
- All SDR RFA's are in closure process
 - Final RFA closure paperwork being processed
 - Resolution to RFA4 being implemented in JSC documentation

➤ JSC Test Facility Requirements and Specifications document

- Basic version is released
- Revision A is in progress incorporates SDR information and feedback



Slip table for x- and y- axis vibration



Solid Oxide Technology Test Stand and Kiln

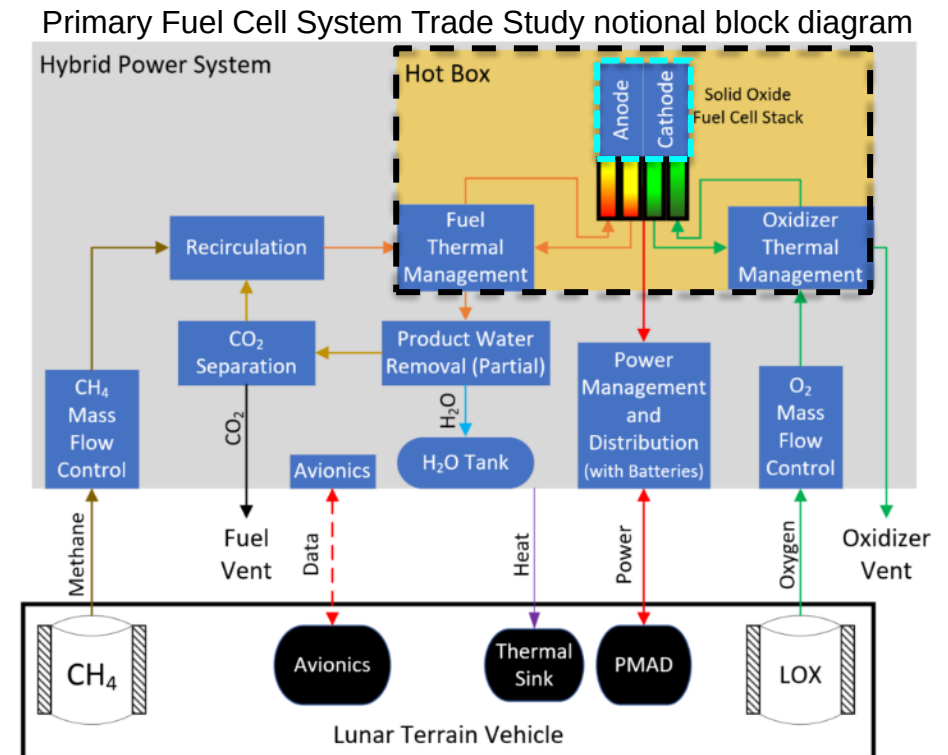
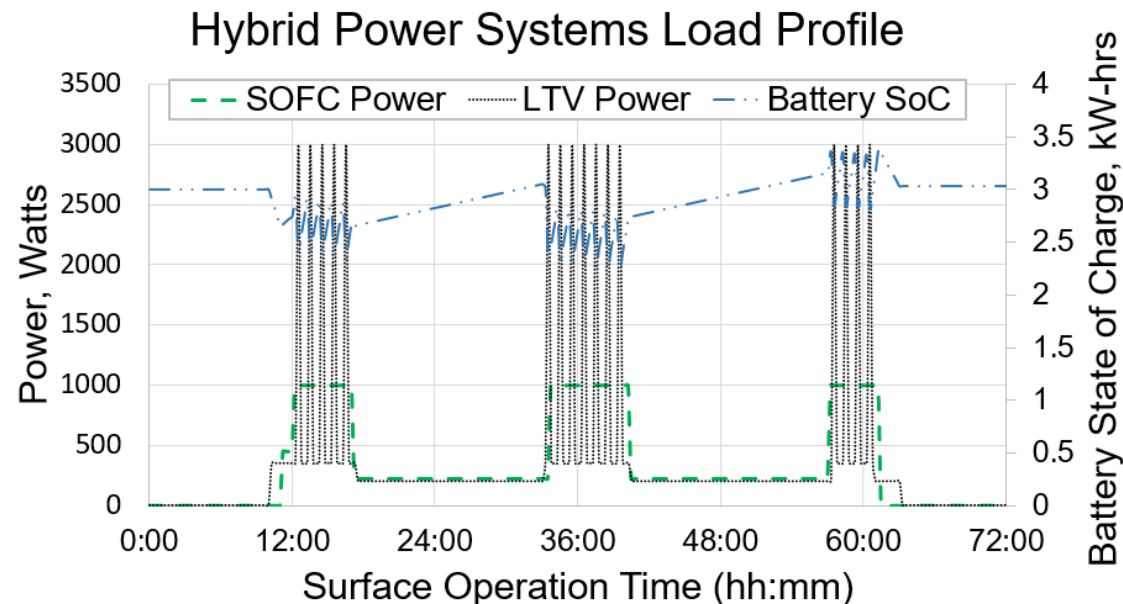


Round head expander for Z-axis vibration

Accomplishments - GRC



- Mission Architecture Insight Report
 - Submitted Mission Architecture Insight Report containing notional mission requirements including environmental conditions and power/energy levels to guide development of stack requirements
- Advanced primary fuel cell system trade study
 - Hybrid battery / SOFC power system using residual LOX/methane propellant
 - Defining preliminary mission objectives and requirements, system architecture, and assumptions



Project Assessment Summary



Project Name	Performance				Comments
	C	S	T	P	
Mid Year					<u>Technical</u> – GRC developing stack requirements. JSC completed Facility Environmental Test Requirements and Specifications. PCI completed SDR and scheduled PDR for 9/27/2022 <u>Cost</u> – JSC revised budget for conducting environmental testing of the PCI test article <u>Schedule</u> – Contract on schedule <u>Programmatic</u> – Contract modified to reflect the revised schedule of the GRC deliverables delayed by personnel changes
Annual					<u>Technical</u> – PCI, JSC, and GRC processing closure documentation for all SDR RFAs <u>Cost</u> – Contract currently on budget <u>Schedule</u> – GRC Trade Study did not make planned progress since the support service contract left NASA in January. The replacement skillset started 7/21/2022 <u>Programmatic</u> – Team closed the one programmatic SDR RFA

Plans Forward and Transition / Infusion Plan



- The SOFC technology is being evaluated for lunar surface power generation directly from CH_4/LOX propellants, which will support NASA's mission to establish a human presence on the moon
- Targeted NASA applications include future power generation systems & ISRU concepts for lunar or Martian landers & bases with NASA's STMD as a potential customer
- For non-NASA applications, PCI is in discussion with multiple commercial entities in the field of distributed power & Hydrogen generation for transitioning the technology for this market. PCI is also working with U.S. DoD for potential transition/infusion of the SOFC system as Primary Fuel Cell for various Unmanned Vehicles

Education/Public Outreach



EPO Involvement

- Presented NASA solid oxide technology status at the Ohio Fuel Cell Consortium Solid Oxide Fuel Cell Forum on October 21st in Columbus, Ohio
- Advanced Power Systems for Deep Space Exploration (APS4DS) Aug 30 thru 1 Sept 2022 (Presentation title: “High Power Density, Methane-Fueled, Solid Oxide Primary Fuel Cell”)

EPO Calendar Outlook (High Priorities):

6 Month Look-Ahead

No Activities Planned	N/A
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Summary



➤ Accomplishments for the Year

- Delivered Mission Insight Report identifying near-term NASA missions that could implement this technology
- Completed preliminary Key Performance Parameters (KPP)
- Developed Environmental (Air-independent and shock/vibration) test facility interface and specification documentation to augment PCI's test requirements development
- Developed draft JSC Operation & Configuration Control Plan (OCCP) for environmental testing at JSC
- Completed System Design Review (SDR); preparing for Preliminary Design Review (PDR)

➤ PropFC Technology Maturation End State

- Project to demonstrate electrical power (DC) from LOX/Methane propellants by operating a 250 W SOFC stack on propellant-grade O_2/CH_4
- Advance SOFC stack component to TRL 6 by conducting environmental testing of 250 W SOFC stack
- Deliver preliminary requirements for integrated O_2/CH_4 SOFC primary power system to power spacecraft or surface platforms supporting lunar or Mars exploration missions