Multi-Scale Ordered Cell Structure for Cost Effective Production of Hydrogen by High Temperature Water Splitting (HTWS)

Project ID: PD144

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PARC - Ranjeet Rao, Yunda Wang. GAIA – Whitney Colella

June 7, 2017

2017 DOE Hydrogen and Fuel Cells Program Review Presentation

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Overview

Timeline

Project Start Date: October 1, 2016

Project End Date: September 20, 2019

Percent Completed: 5%

Barriers

F. Capital Cost

G. System Efficiency and Electricity Cost

I. Grid Electricity Emissions

J Renewable Electricity Generation Integration

Budget

- **Total Project Budget:** $ 1,875,101
  - **Total Recipient Share:** $ 375,130
  - Total Federal Share: $ 1,499,971
  - Total DOE Funds Spent*: $ 151,840

* As of 3/31/17

Partners

PARC: Electrode Feature Mfg Dev

GAIA: Technoeconomic and Lifecycle Analyses

Relevance to DOE Goals

- **Objectives:** Develop and test advanced HTWS stacks to demonstrate the potential pathway to

    1. Meet the FCTO **cost goals for hydrogen production** <$2/kg, excluding delivery, compression, storage, and dispensing, and

    2. Ability to operate on intermittent renewable energy sources for **energy storage** and grid ancillary services applications

- **DOE Mission Relevance**
    - Reduce petroleum use
    - Reduce greenhouse gas and air pollution emissions
    - Reduce market barriers to commercialization

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Relevance to Technical Barriers

- **Cost Goal**
  - Improve stack performance - Lower capital cost
  - Operate at lower voltage - Reduce electric input
  - Increase lifetime - Lower levelized H_2 cost

- **Integration with Renewable Energy**
  - Reduce gas diffusion resistance - Response to transient load
  - Mechanical robustness - Faster heat up/cool down - Thermal cycle capability

- **Pressurized H_2 Delivery**
  - Robust seal - Operation at pressure - Thermal cycle

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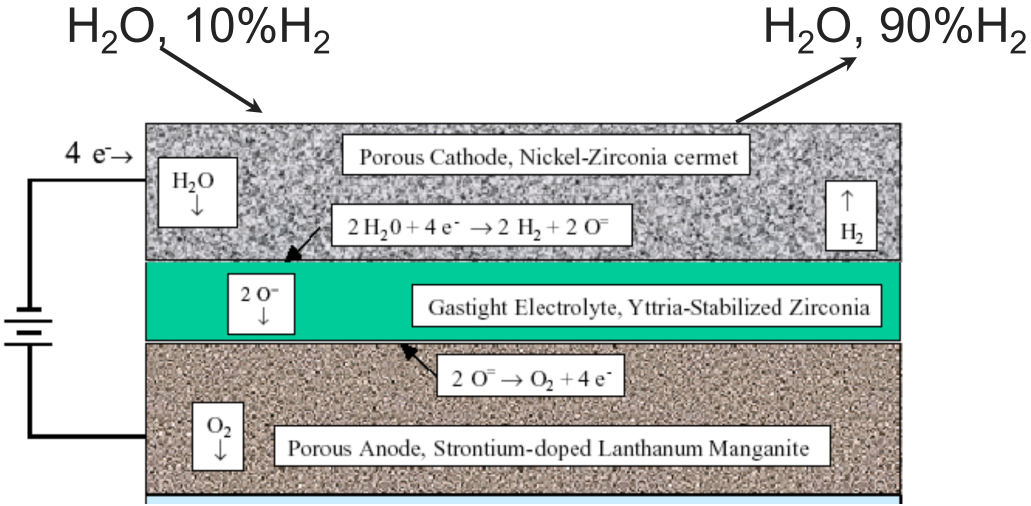
High Temperature Water Splitting



- Conventional Design
  - Electrolyte or Cermet as support
  - Combination of tape casting and screen printing

Approach - Technical Challenges

Performance Limitations	Limiting Factors
• Electrical resistance of cell	Layer thicknesses
• Electrode non-ohmic resistance	Electrode catalytic activity Gas diffusion resistance
• Heat up/shut down, load follow	Mechanical robustness
• Hydrogen purity	Inadequate seal
• Hydrogen delivery at pressure	Seal characteristics
• Lifetime	Electrode chemical instability (Oxygen electrode delam) Electrode physical Integrity (H_2 electrode coarsening)

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Approach – Technical Concept

- Performance Improvement
  - Cell Design: Multi-scale Ordered Cell Structure
    - Thin, high conductivity electrolyte (low electrolyte resistance)
  - Macro-scale features as mechanical support on air electrode
    - Eliminate steam diffusion limitation of fuel support
  - Micro-scale ordered hydrogen electrode
    - Improve electrode performance by increasing density of reaction sites for electrochemical reduction of water

- Lifetime Improvement
  - Thermochemically stable electrode compositions
    - Oxygen electrode – stability of stoichiometry
    - Hydrogen electrode – high steam stability

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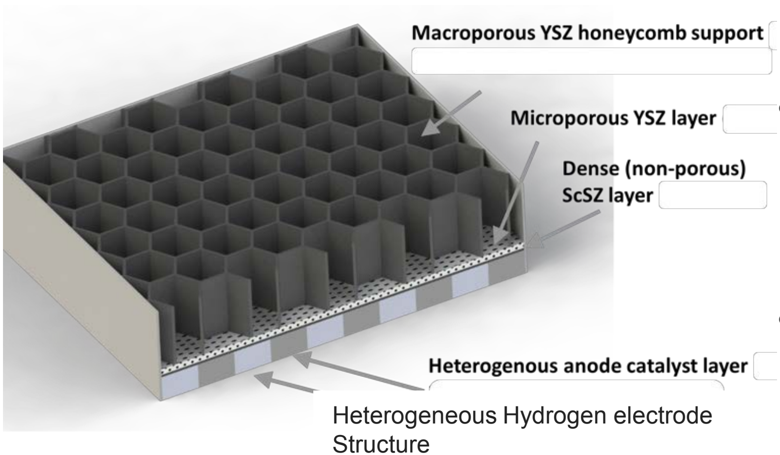
Approach – Performance Improvement



Not to scale

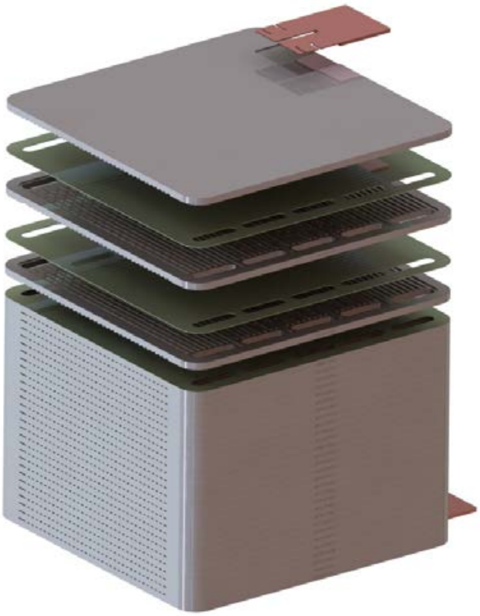
- Higher conductivity electrolyte (Scandia doped)
- Mechanical support on oxygen evolution side
  - Macroporosity reduces gas diffusion resistance
- Structured hydrogen electrode
  - Control of composition and reaction site density
  - Thinner electrode eliminates H_2O/H_2 diffusion resistance

Approach – Technical

- **Cell fabrication development**
  - Thin, high conductivity electrolyte — Tape casting, lamination (Ceramatec)
  - Ordered electrode structure — 3D Printing (PARC)
  - Mechanical Support — 3D Printing (PARC)
  - Seal — Glass (Ceramatec)

- **Materials Selection**
  - Stable dopant in oxygen electrode to eliminate delamination and cation mobility
  - Glass seal to limit gas cross over for hydrogen purity and pressurized operation
  - Inert oxide dispersion to make hydrogen electrode (nickel) coarsening resistant in high steam conditions

Approach – Stack Fabrication



Notional Stack Design

- Interconnects and cell joining layers from ongoing NASA CO_2 electrolysis project
- Typical ASR ~ 0.8 – 1.0 ohm-cm^2 at 800°C

  (0.6 – 0.7 ohm-cm^2 when corrected for activation polarization and CO_2 conversion)

Approach – Milestones & Go/No-Go

Major Technical Tasks

- Baseline materials set to identify largest contributors to cell resistance
- Develop process for novel cell structure that addresses resistance contributors
- Button cell testing of new cell structure
- Production of full-scale cells
- Stack production development with new cells
- Stack testing to prove targets of 1 kg H_2/day production
- Modeling of GHG emissions vs. SMR
- Levelized cost model for target of $<\$2$/kg H_2

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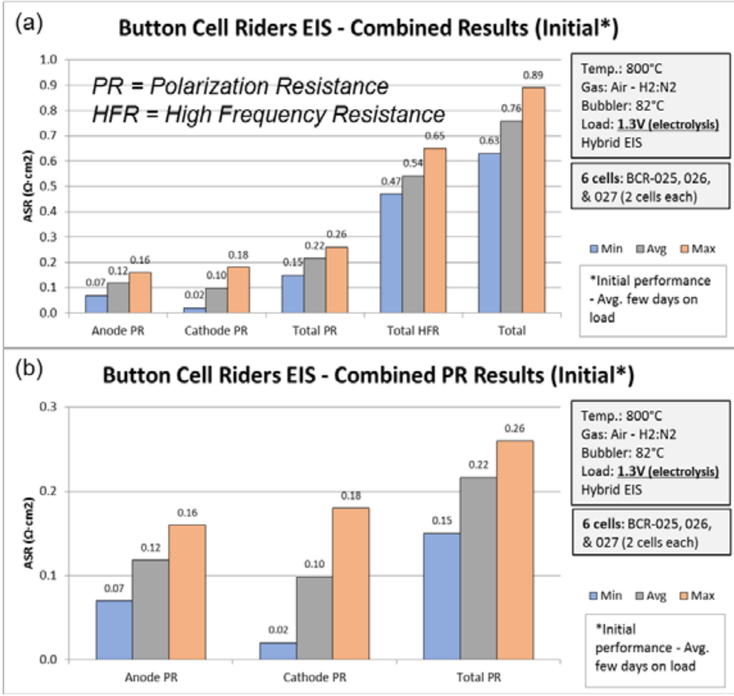
Approach – Milestones & Go/No-Go

Milestone/Go-NoGo Description	Anticipated Completion Date	% Complete
M1.0.1: Finalized Cell Design, Fabrication Process	12/17	100
M2.2.1: Cathode Ink Formulated	3/17	90
M2.4.1: Anode Ink Formulated	3/17	90
M3.2.1: Micro-patterned Cathode Films Fabrication	6/17	10
M3.3.1: Support Structure Fabricated	9/17	
Go/NG: Button Cell Structure Tested ≤ 0.4 ohm-cm²	**9/17**	
M5.0.1: Button Cell ASR measured	9/17	
M6.2.1: Patterning Developed for Support	3/18	
M6.4.1: Cell Fabrication	6/18	
M7.0.1: Seal Demonstrated	9/17	
M8.0.1: Verification Short Stacks	6/18	
G/NG: Short Stack ASR of 0.4 ohm-cm²	9/18	
M9.0.2: Stack capable of 1 kg H_2/day	9/19	
M10.0.1, 2, 3: GHG Emissions of HTWS vs SMR Comparison	9/17,9/18,9/19	
M10.2.1, 2, 3: Levelized production cost <$2/kg H_2	9/17,9/18,9/19	

2 quarters of effort completed

ACCOMPLISHMENTS – Baseline Testing

- Button cell testing of baseline components
  - Target to reduce Electrode Polarization resistance to 0.1-0.2 ohm-cm^2 range
  - Baseline results include thick electrolyte
  - ASR is the sum of HFR (ohmic) and PR (electrode)



Baseline electrodes average polarization resistance ~ 0.2 - 0.25 ohm-cm^2
Further reduction possible with micro-featuring

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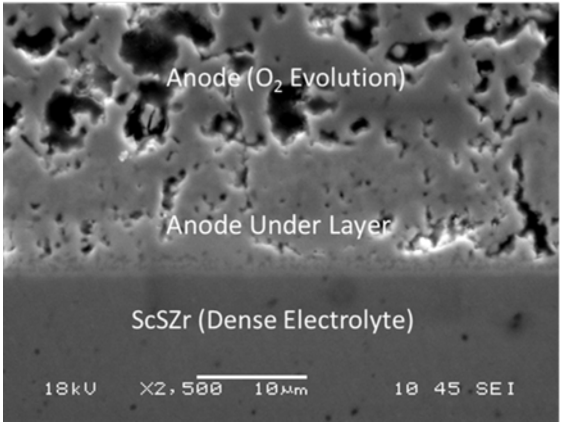
Oxygen Electrode Symmetric Cell



- Prior typical current density 0.3 to 0.4 A/cm^2
- High Current Density (1 A/cm^2) operation shows no delamination after 300 hours

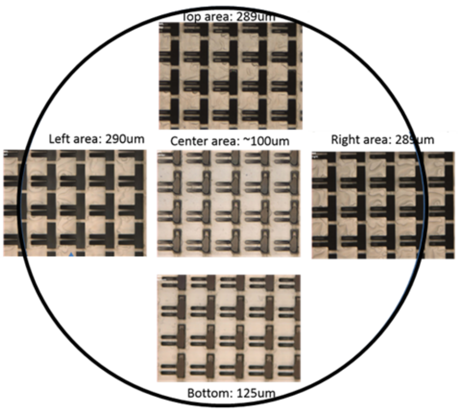
Accomplishments
Tape Casting Trials; Print Ink Formulation

- Thin tape casting trials (Ceramatec)
  - Tape formulation evaluation for compatibility
    - With featured electrode
    - Support structure
    - Sintering multi-layer structure

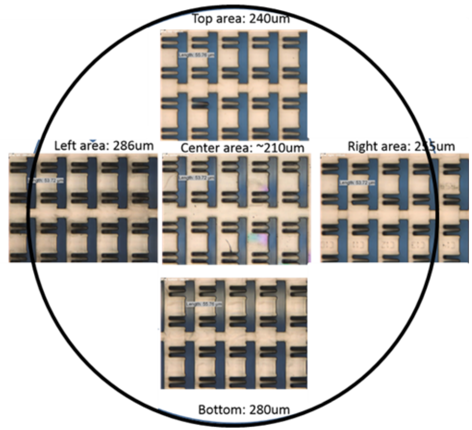
- Electrode/Support Structure Inks (PARC)
  - Ceramic powder (Ceramatec)
  - Ink viscosity, solvent boiling point, rheology control
  - Formulation developed

Accomplishment – Patterning
Ink Formulation for Oxygen Electrode Support

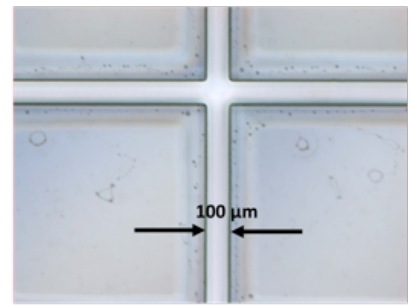
- Advanced Printing Techniques for Cell Design
  - Use of existing tooling for process development



Early result



Improved result



Wet layer

  - Thickness variation reduced from ±90 µm to ±40 µm by controlling baking process
  - New mask design in progress

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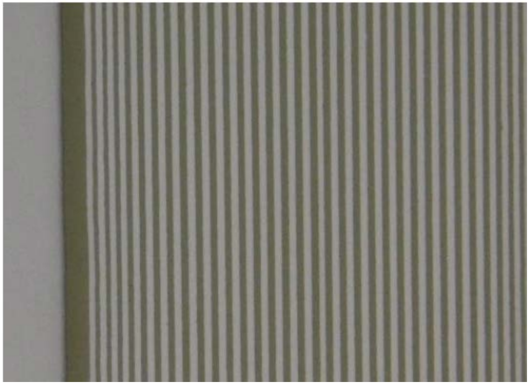
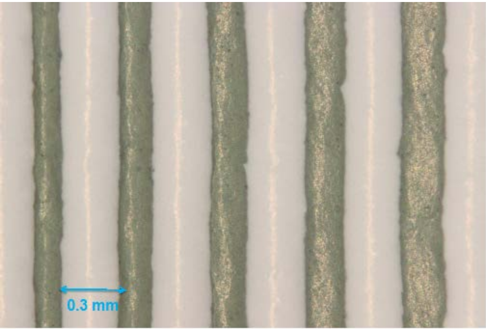
Accomplishment – Micropatterning Hydrogen Electrode





- As printed hydrogen electrode
- Awaiting sintering trials

Magnified Image

Control of line thickness, pitch and composition possible

COLLABORATIONS

- Prime: Ceramatec
  - Ionic Ceramic device focused industry
  - Division of CoorsTek
- Sub: PARC
  - Development and commercialization of Printing technology
  - Division of Xerox Corporation
- Sub: GAIA
  - Technoeconomic and life cycle analysis models
  - Economically disadvantaged women owned small business (EDWOSB)

REMAINING CHALLENGES/BARRIERS

- Fabrication of new cell design
  - Lamination/Printing Compatibility
  - Sintering of multi-layer cell structure
- Button cell Area Specific Resistance <0.4 ohm-cm^2
- Stack assembly
  - Joining materials compatibility with new cell structure
  - Cell flatness for stacking
  - Stack ASR 0.4 ohm-cm^2
  - Seal integrity for pressurized operation
- 1 kg/day production
- Manufacturing cost verification to support <$2/kg H_2

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PROPOSED AND FUTURE WORK

- Remainder of FY17:
  - Produce structured button cells for testing
    - Demonstrate <0.4 ohm-cm^2 performance
  - Begin scale up to full cell size
  - Demonstrate glass seal capability

- FY18 Tasks
  - Short stack testing
    - Demonstrate 0.4 ohm-cm^2 performance

- FY19 Task
  - 1 kg H_2/day stack test
- LCA & TEA with increasing fidelity

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Technology Transfer Activities

- Internal planning for manufacturing development in progress
- Integration and optimization of combining Ceramatec and PARC processes

SUMMARY

- Key objective is to develop HTWS stack technology to meet
    - Performance and cost goals

- Tasks are designed to improve stack performance
    - Use of multi-scale ordered structure to address performance limiting factors

- Fabrication development well underway
    - Materials selection completed
    - Tape cast process development underway
    - Printing ink development complete
    - Printing process development underway

- Button cell testing planned for end of year 1
    - Task on schedule

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Thank you

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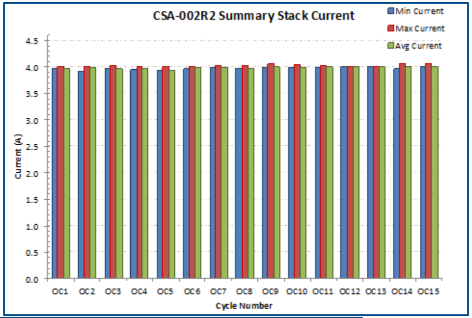
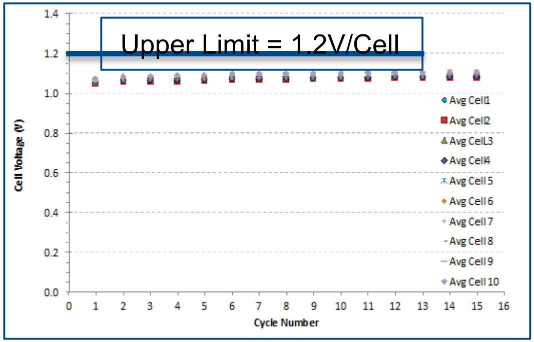
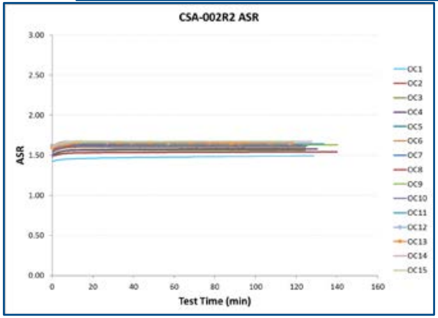
TECHNICAL BACK-UP SLIDES

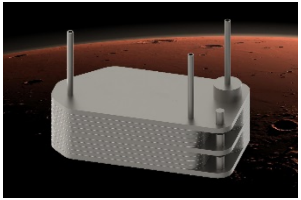
Materials set developed for NASA Mars Project will be used
MOXIE: Operational Cycle Testing

- Cycle life testing on **dry CO_2**
  - 120 minute operational cycles
- No significant cycle to cycle degradation
- Excellent Cell-to-Cell Voltage Grouping



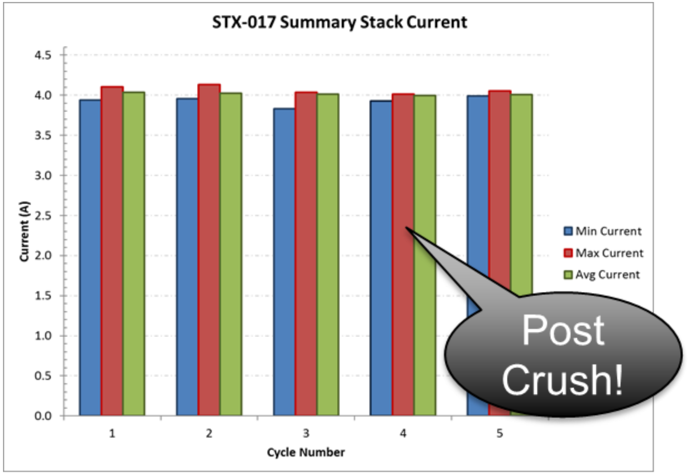






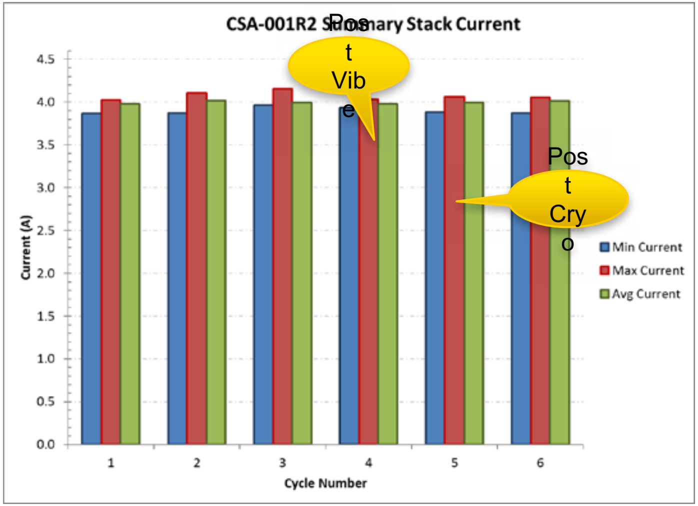
MOXIE: Performance and Stability

- Mechanical Requirements
  - **Structural Testing: Must withstand compressive forces required for entry, descent, landing packaging design**
    - Multiple stacks tested to 10kN compressive force and then operationally cycled with no leakage or degradation
    - No leakage at 25kN on multiple stacks, only failure at 62.7 kN

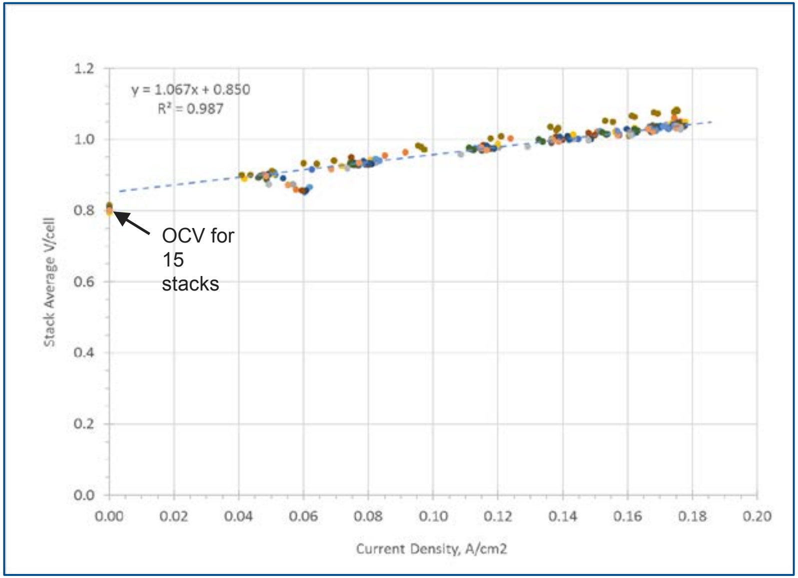


MOXIE: Performance and Stability

- **Mechanical Requirements**
  - **Shock and Vibe**
    - Maintained Performance
    - Maintained O_2 purity > 99.9%
  - **Cryo Testing: Must withstand thermal cycles down to -65**
    - 3 cycles from ambient to -55°C
    - 40 cycles to -40°C
    - 1 cycle to -65°C



MOXIE: Reproducibility



20+ consecutive stacks had identical performance on Dry CO_2 electrolysis

MOXIE: Summary

Baseline Performance

- 15 consecutive stacks built with *aerospace quality standards and traceability* having a maximum baseline performance of 1.6 ohm-cm^2 dry CO_2 and 99.9%+ O_2 purity

Cycling Performance

- 3 stacks with 21 cycles of varying cycle-to-cycle flow rates and final cycle averages of 10.11 g O_2/hr production and 99.8% purity – Targets exceeded

Structural Stability Testing

- **No leak or significant performance change after 10kN crush testing**
- Stacks tested to 25kN force with no leakage
- *Only failure required 62.2kN (>30 margin of safety from design)*

Shock/Vibe Testing

- Stacks vibrated at JPL and post vibe tested at Ceramatec
- **No leak or significant performance change post vibe!**
- **No leak after shock testing, retest for performance underway**

Cryo-Cycling

- Vibe stack cryo-cycled to -40°C (40 cycles), -55°C (3 cycles), -65°C
- **Stack performance and purity unchanged in operational cycling post test**