PROVIDING ENERGY. IMPROVING LIVES.

A Highly Efficient and Affordable Hybrid System for Hydrogen and Electricity Production

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DE-FE0031975

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Outline

- Project Overview
- Project Objective
- Technical Approach
- Project Progress
    - Electrolyte Development
    - Air Electrode and Catalyst Development
    - Button Cell Performance
    - Powder Synthesis Scale up and Large Cell Fabrication
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Overview

- **Project Title:** A Highly Efficient and Affordable Hybrid System for Hydrogen and Electricity Production
- **Award No.:** DE-FE0031975
- **Project Timeline:** 09/27/2020 – 09/26/2023
- **DOE/NETL Program Manager:** Andrew O'Connell

Phillips 66	Ying Liu (PI) Imona Omole Denay Huddleston Byunghyun Min	Mingfei Liu Mark Jensen Miranda Rine Sarah Bushyhead	• Powder synthesis • Large cell manufacturing • Stack fabrication and testing • System design and operation
Georgia Tech	Meilin Liu (Co-PI) Yucun Zhou Xin Qian	Gyutae Nam Nick Kane Conor Evans	• Cell materials development • Catalyst development • Button cell evaluation

Phillips 66 SOFC R&D

Company Overview

- Diversified manufacturing and logistics company
- Portfolio includes Midstream, Chemicals, Refining, and Marketing & Specialties businesses
- Process, transport, store, and market fuels and products globally
- #23 on the Fortune 500 list

SOFC Program

- Launched in 2010
- Proprietary high-performing materials
- Cost-effective fabrication methods
- Unique stack designs
- Fully automated control systems
- Full spectrum of cell/stack manufacturing and testing facilities

Fabrication and Testing Facilities

Tape Caster

Spray Coater

High Power Laser

High Temp Furnace

Stack Tester

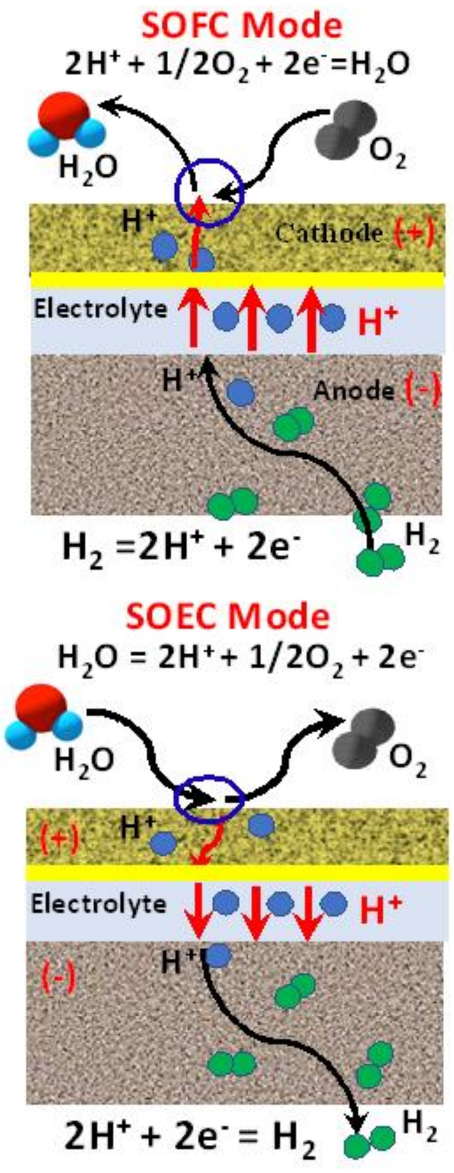
System Testing Enclosure

- >10,000 sq. ft. floor space
- 20+ fuel cell and stack test stations
- Fuel (H_2, CH_4, pipeline NG) processing and treatment
- Steam generation and control
- Large load banks and power supplies
- System instrumentation, control and communication

Project Objectives

- To design, fabricate, and demonstrate a robust, highly efficient, and affordable reversible solid oxide cell (rSOC) system based on a proton conducting electrolyte membrane for hydrogen and power generation.

- The 1-kW prototype system will meet the following technical specifications:
  - Operate the system in a real-world environment.
  - ≥50% electrical efficiency (LHV of H_2) at 0.5 A cm^{-2} in fuel cell mode on H_2 at 650 °C.
  - >85% electrical efficiency (LHV of H_2) in electrolysis mode at ≤ 650 °C.
  - Demonstrate the potential to < $2/kg hydrogen.



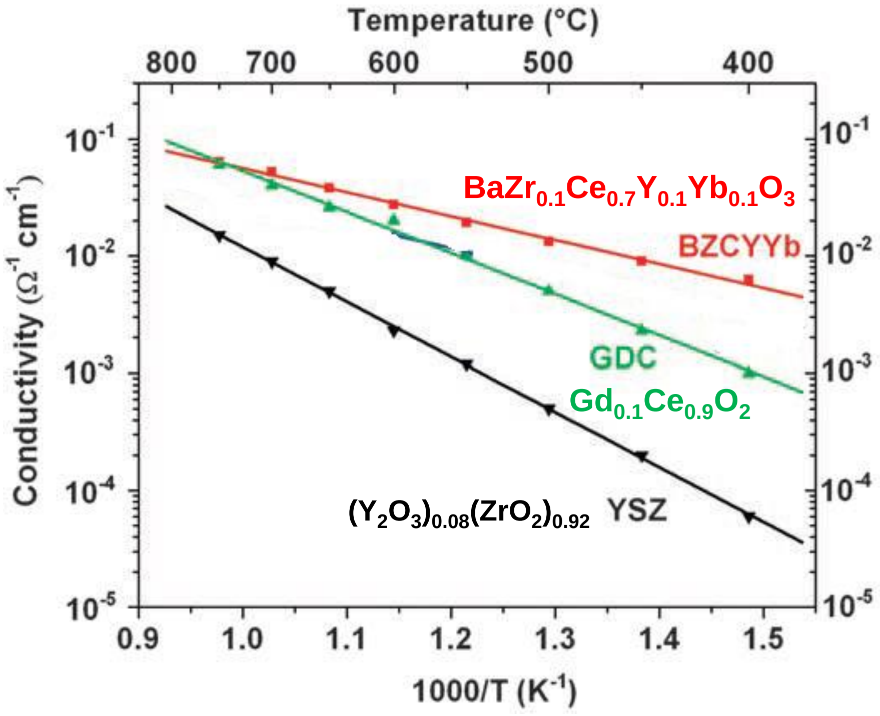
Technical Approach

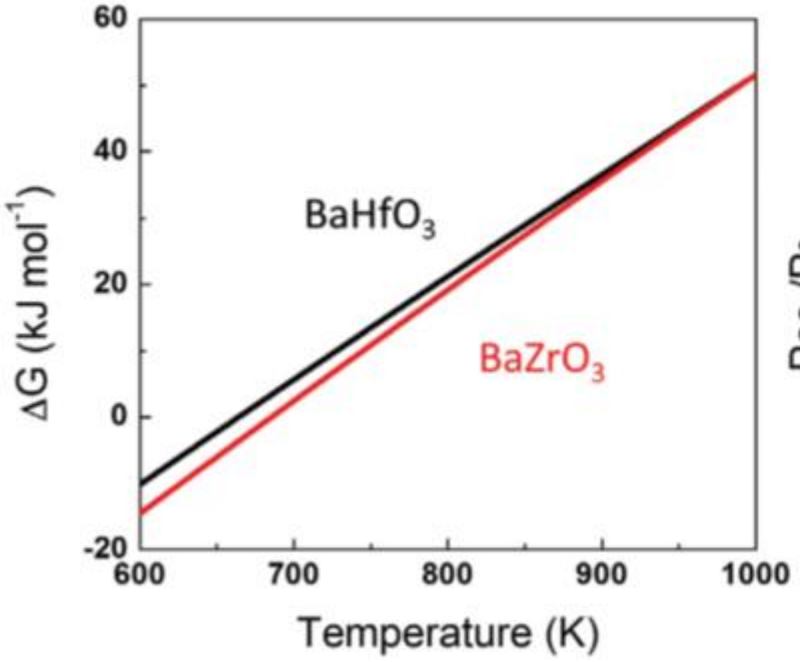
Major Tasks	Action Plan
Materials Development	• Modify composition of state-of-the-art $BaZr_{0.1}Ce_{0.7}Y_{0.1}Yb_{0.1}O_{3-\delta}$ electrolyte • Develop air electrodes with high ORR/OER activities and excellent tolerance to H_2O and Cr-poisoning
Cell Fabrication	• Scale up powder synthesis to >1 kg /day • Fabricate button cells showing higher performance and good durability • Fabricate 10 cm $\times$ 10 cm cells by low cost and scalable methods
Stack Assembly	• CFD assisted stack design • QC for stack components and assembly • Demonstrate high stack performance in both SOFC and SOEC modes
System Demonstration	• Design a 1.0 kW autonomous system with cloud-based control and data communication • Evaluate system performance and achieve efficiency, lifetime and cost targets • Techno-economic analysis to demonstrate $2/kg H_2

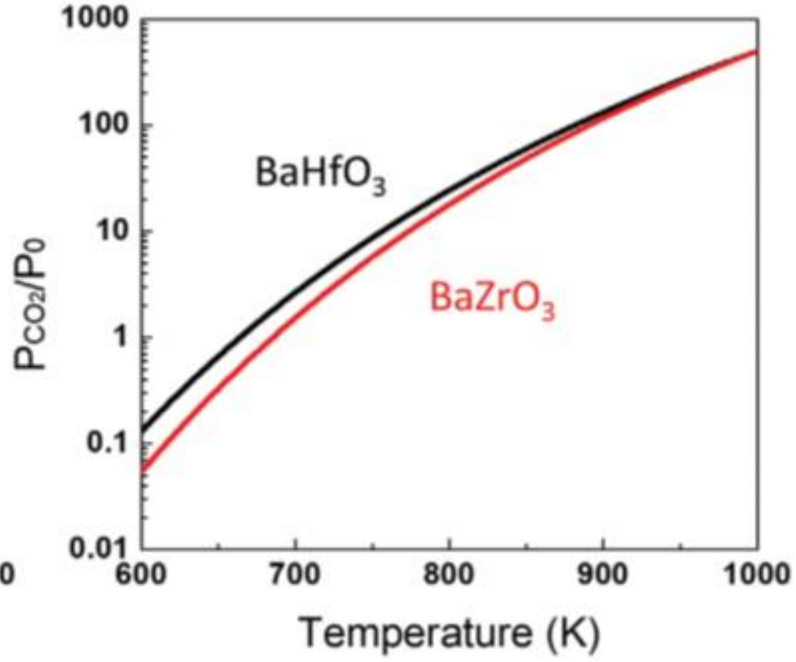
Project Progress

Timeline	Milestone	% Complete
12/31/2020	Electrolyte conductivity >0.01 S cm^{-1} and ionic transference numbers >0.95 at 600 ºC.	100%
12/31/2020	Electrolyte degradation rate <2%/1000 h at 600 ºC.	100%
03/31/2021	Air electrode with catalysts polarization resistance <0.2 Ω cm^2 at 600 ºC.	100%
06/30/2021	Air electrode with catalysts degradation <2%/1000 h at 600 ºC under H_2O and Cr.	100%
07/30/2021	Scale up ceramic powder synthesis to > 1.0 kg per day	100%
09/30/2021	Button cells 1 W cm^{-2} at 0.7 V and 600 ºC in fuel cell mode, 1.5 A cm^{-2} at 1.3 V and 600 ºC in electrolysis mode, and a Faradaic efficiency of 95%.	100%
03/31/2022	Button cells degradation <2%/1000 h at ≤ 650 ºC	50%

Electrolyte Development







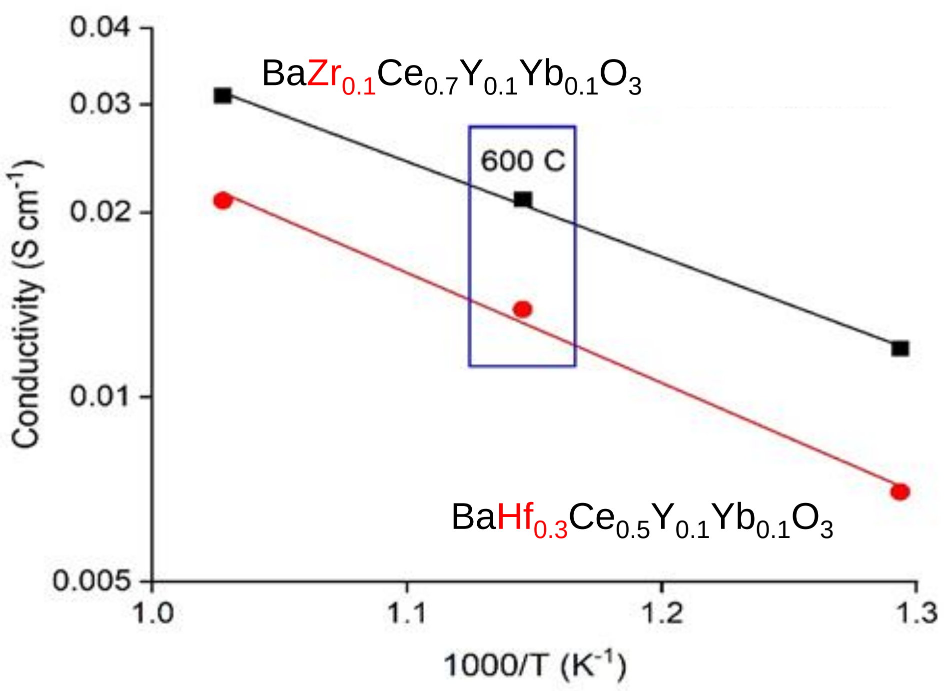
Limitations

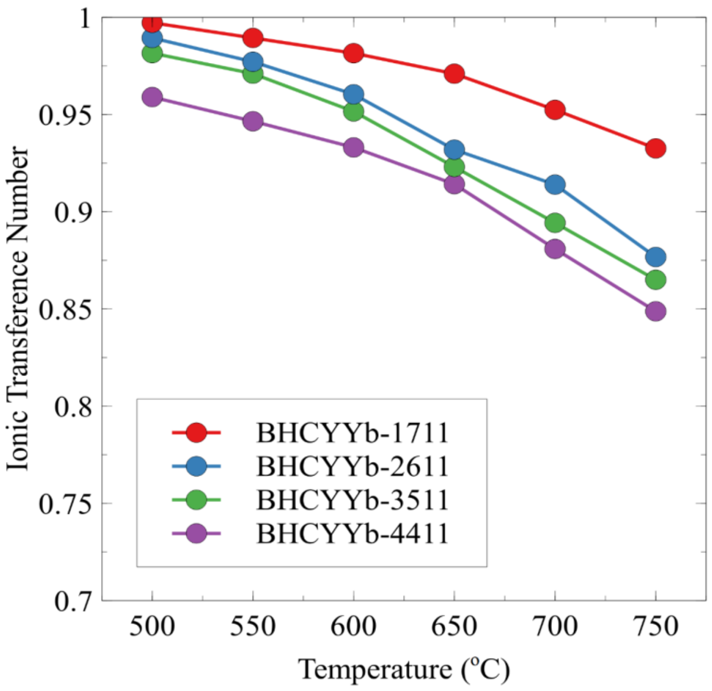
$BaMO_3 + H_2O \rightarrow Ba(OH)_2 + MO_2$

$BaMO_3 + CO_2 \rightarrow BaCO_3 + MO_2$

R. Murphy et al., *Adv. Funct. Mater.* **2020**, 30, 2002265

Electrolyte Development, BHCYYb

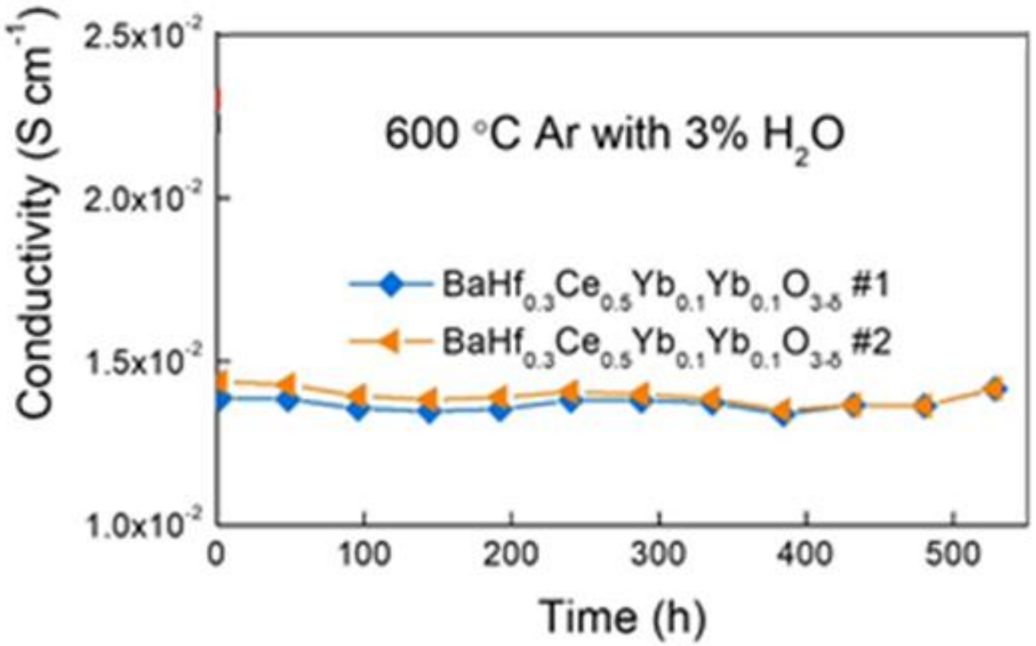


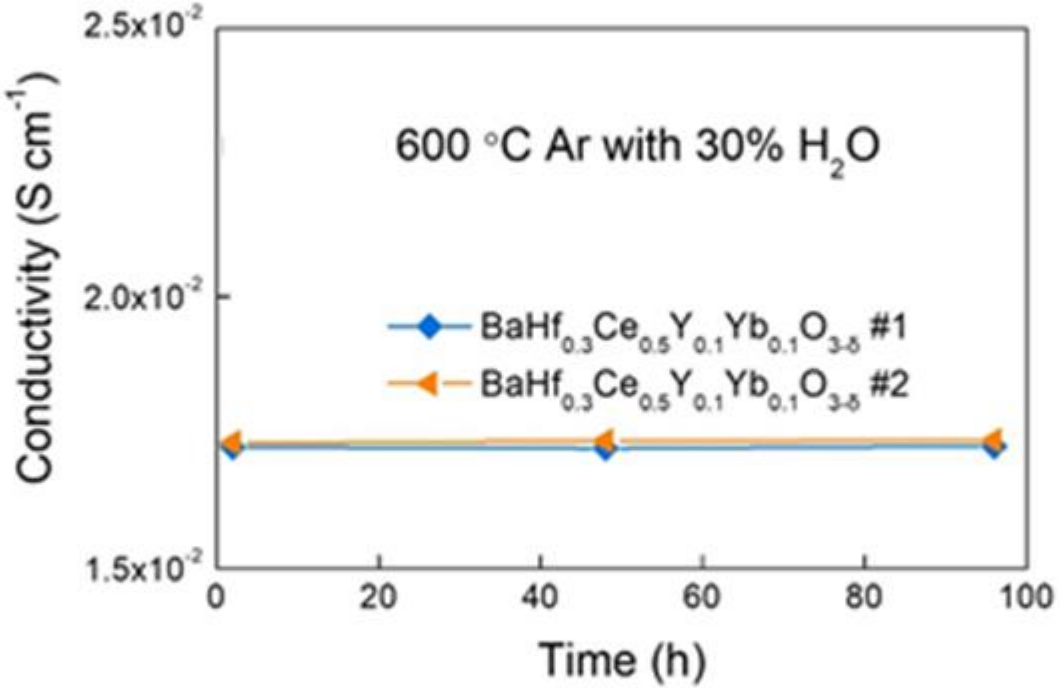


H_2 with 3% H_2O//ambient air

- **Hf** based electrolytes show conductivity >**0.01 S cm^{-1}** at 600 °C (3%H_2O-Ar)
- Ionic transference number >**0.95** at 600 °C

Electrolyte Development, BHCYYb

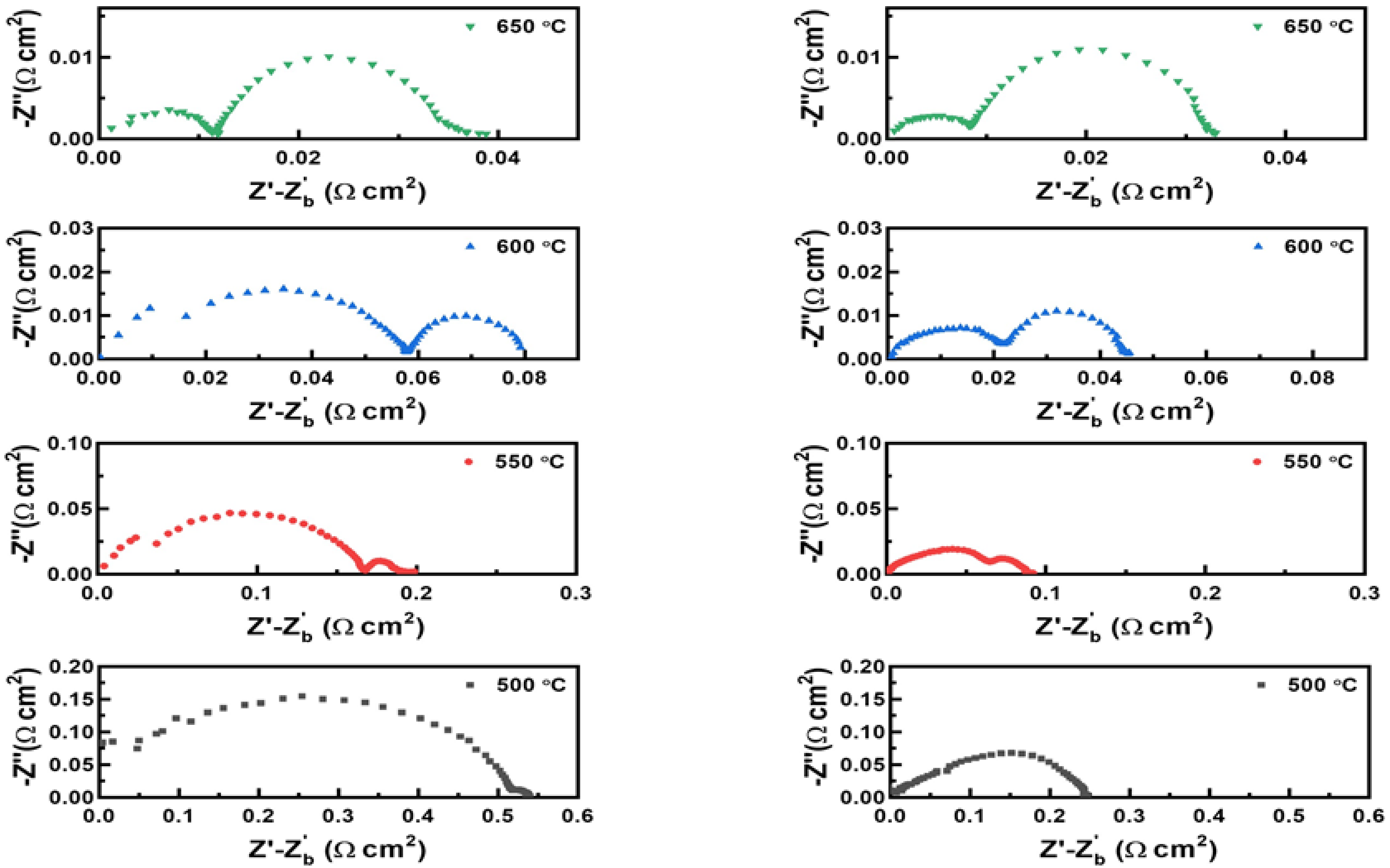




No observable degradation in water in short-term testing

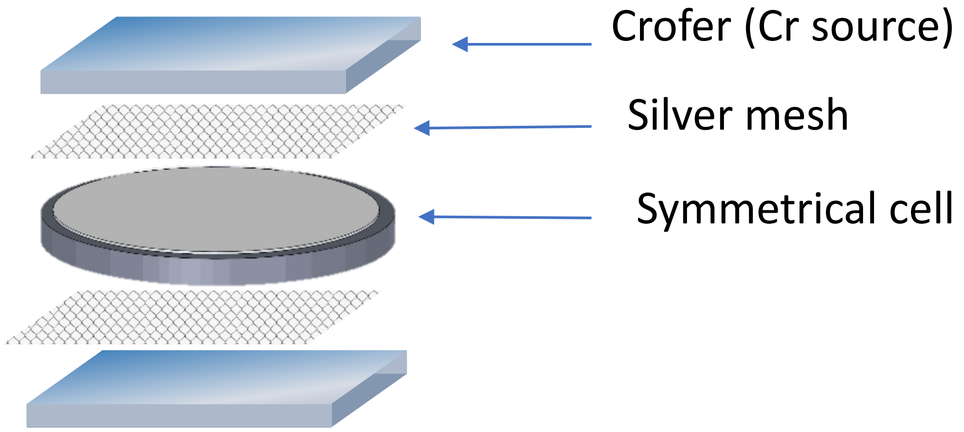
High-Performance Catalyst Coated Air Electrode

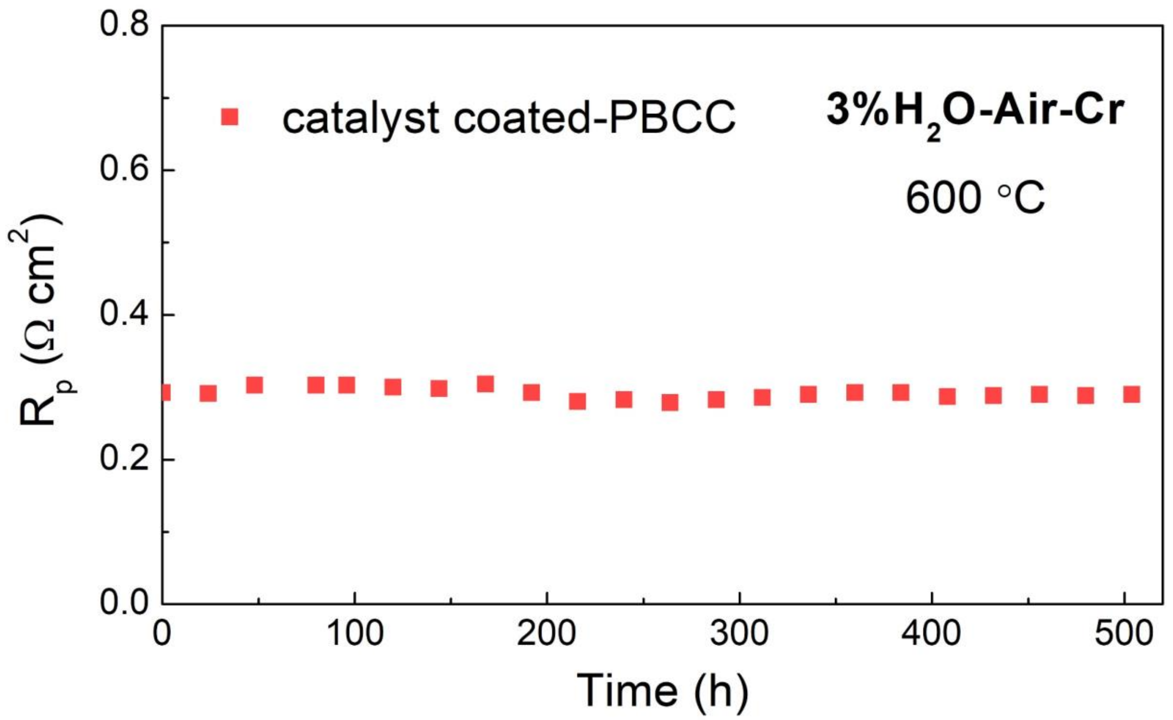
Bare PBCC | **Catalyst-coated PBCC**



Catalyst coated $PrBa_{0.8}Ca_{0.2}Co_2O_{5+\delta}$ (PBCC) air electrodes show **<0.05 Ωcm²** R_p at 600°C in air w/ 3% H_2O.

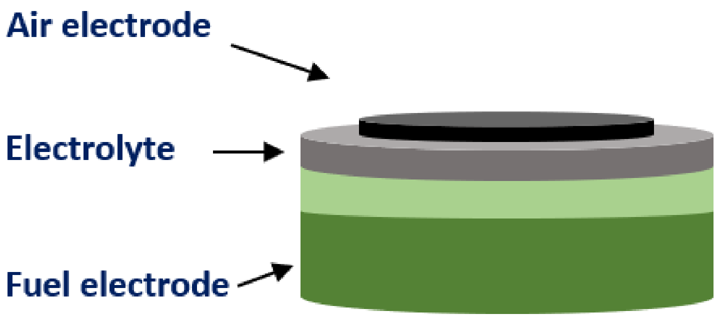
Stable Catalyst Coated Air Electrode

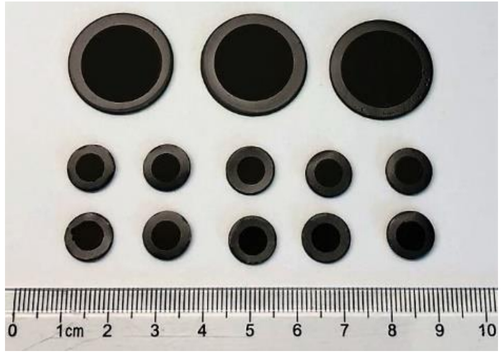


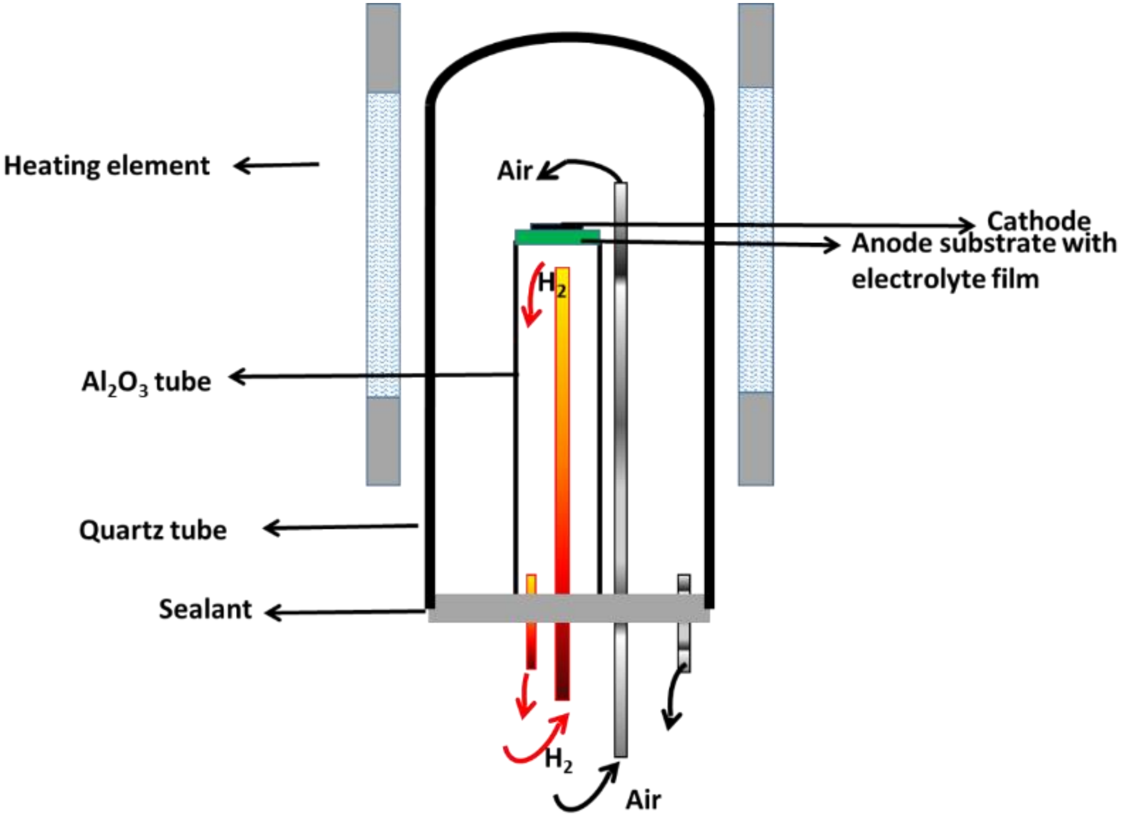


Catalysts coated $PrBa_{0.8}Ca_{0.2}Co_2O_{5+\delta}$ (PBCC) air electrodes show a low degradation rate of **<1% pre 1000 h** in H_2O and Cr environment

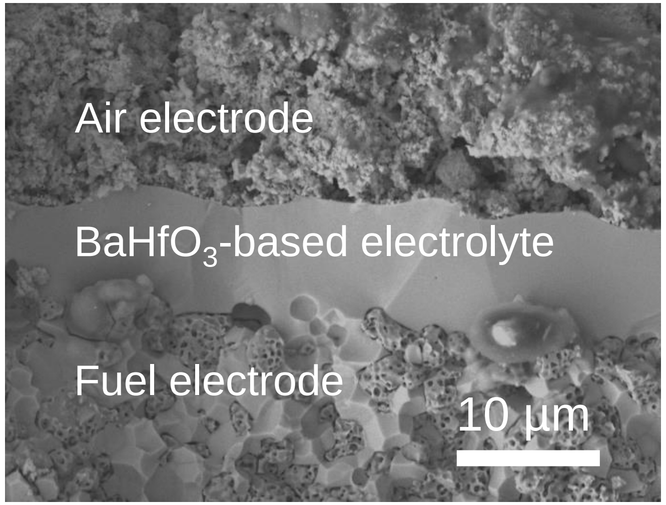
Cell Configuration and Testing Setup

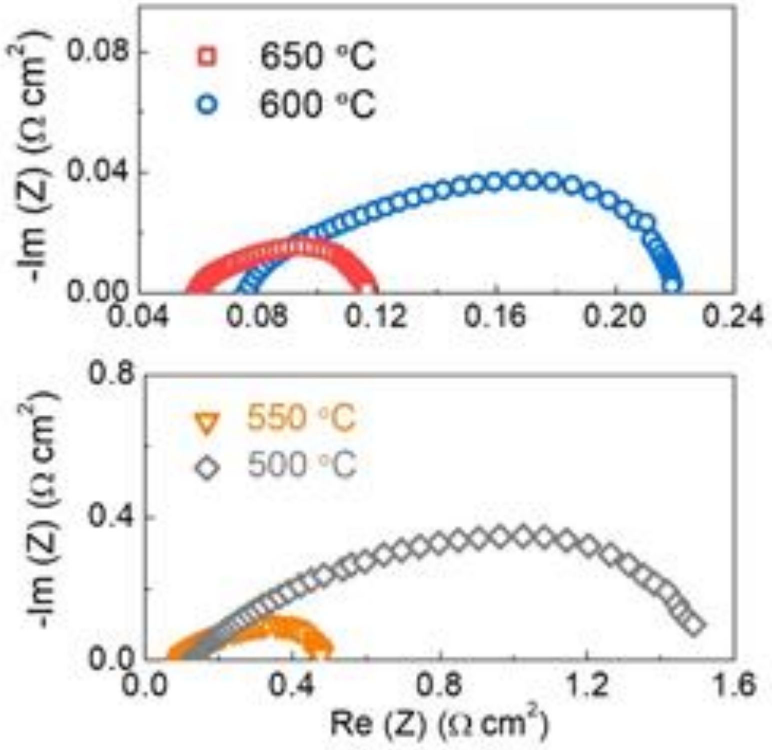


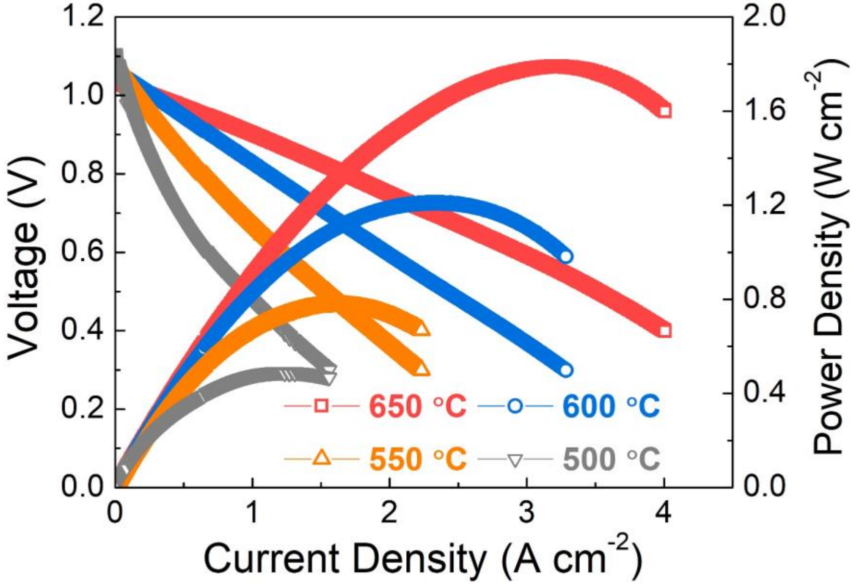




Performance of Single Cells in Fuel Cell Mode

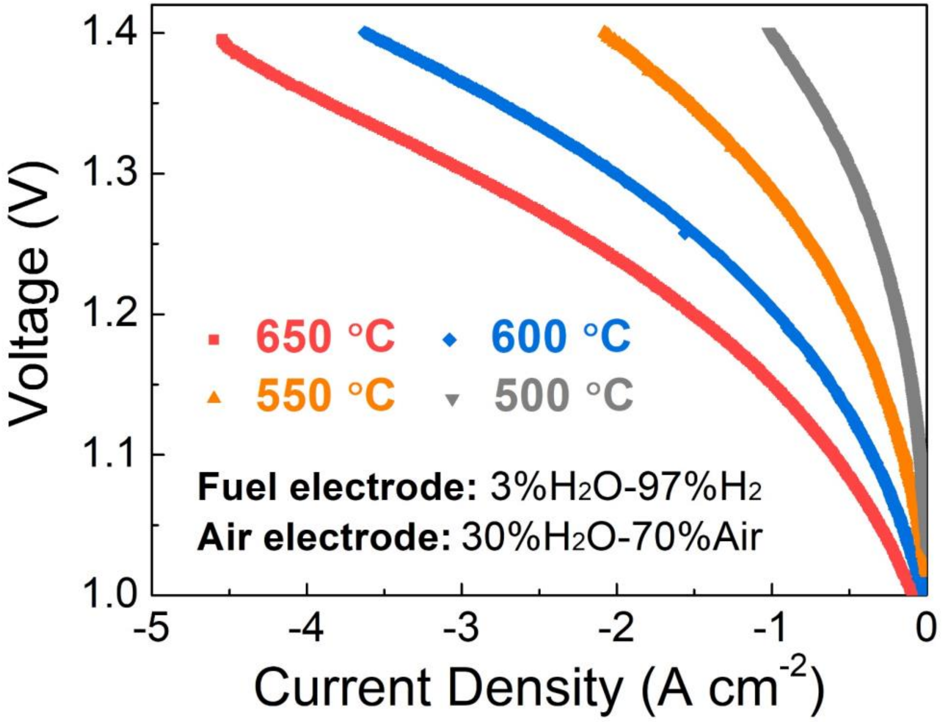


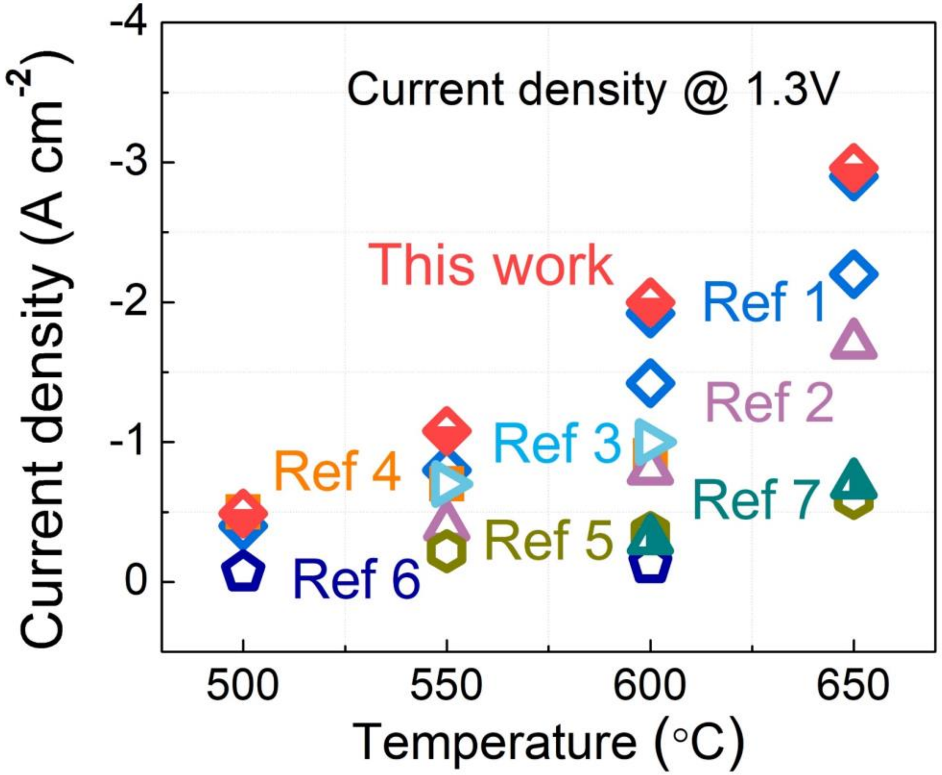




Single cells demonstrated peak power density of **1.2 W cm^{-2} at 600 °C**.

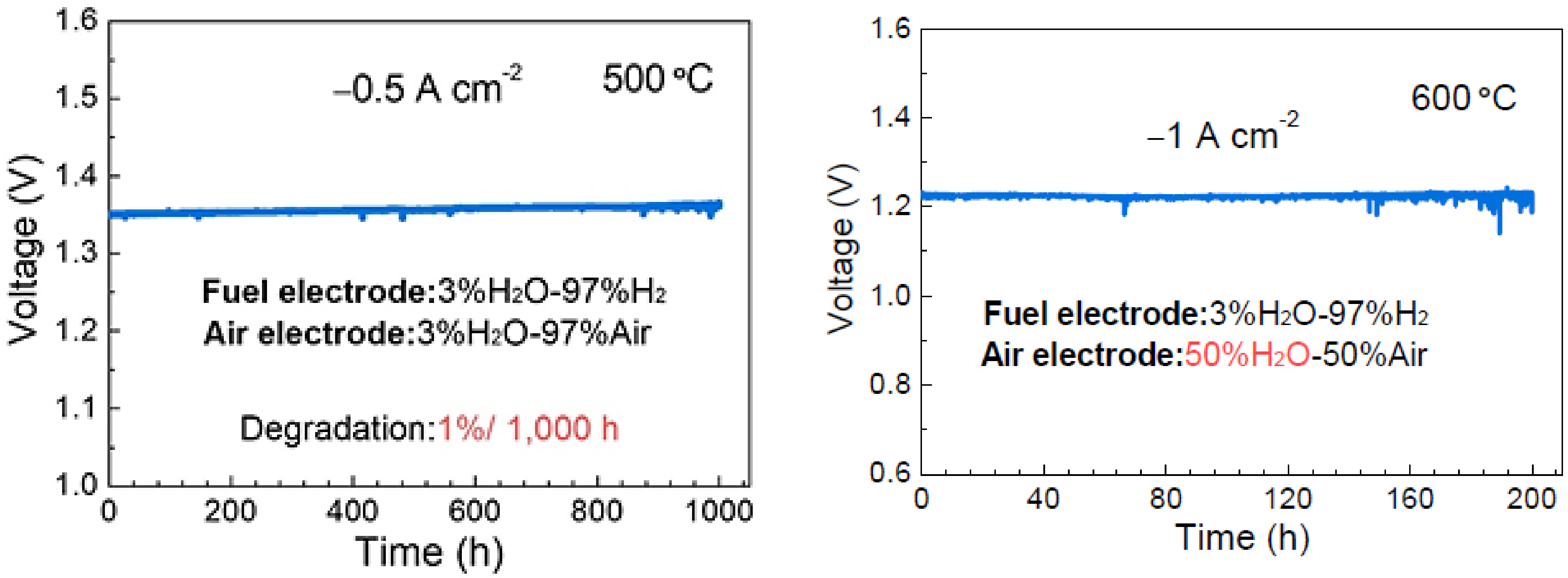
Cell Performance in Electrolysis Mode





- Single cells demonstrated **2 A cm^{-2} at 600 °C in the H_2O electrolysis mode**

Stability Testing

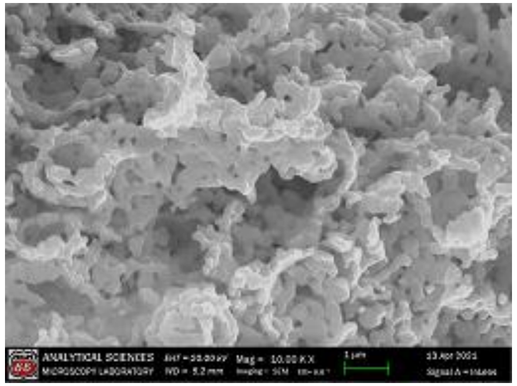


Single cells demonstrated a low degradation rate of **1%/1,000 h**.

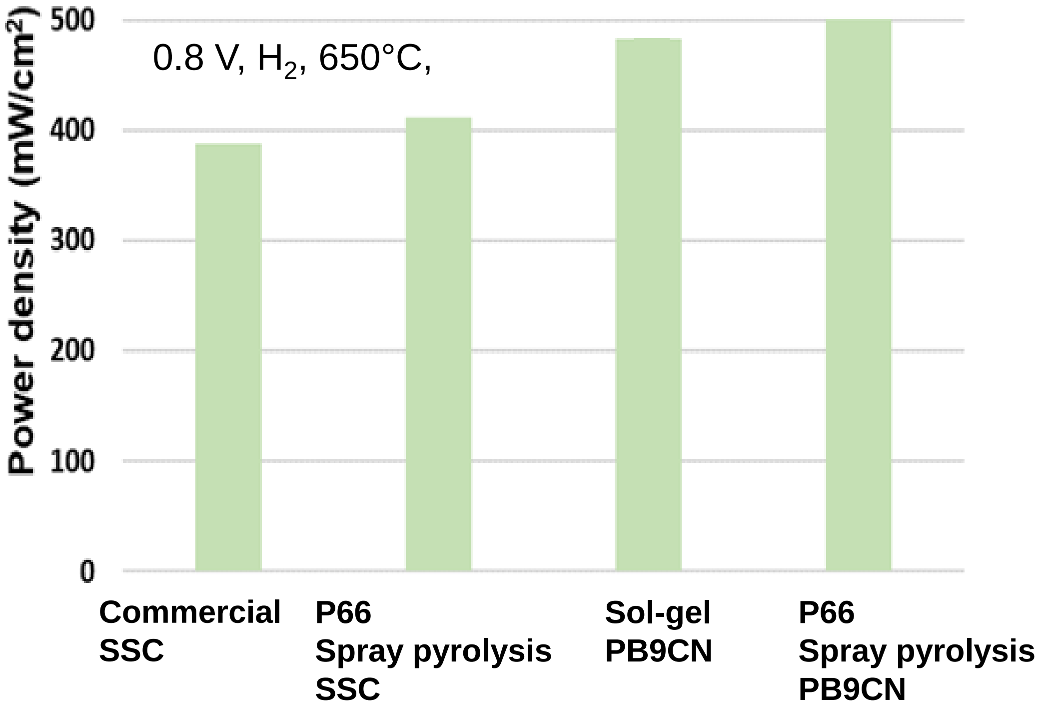
Powder Synthesis Scale-up

Spray Pyrolysis

Ball Mill



Cathode Powder



SSC: $Sm_{0.5}Sr_{0.5}CoO_3$ **PB9CN:** $PrBa_{0.9}Co_{1.96}Nb_{0.04}O_5$

- Continuous or batch synthesis process
- Narrow particle size distribution, d_{50} <0.5 μm.
- Homogeneous composition
- Easy to scale-up
- Up to 1000 g/day powder production rate.

Summary

- Developed proton conducting electrolyte **$BaHf_{0.3}Ce_{0.5}Y_{0.1}Yb_{0.1}O_3$**
  - Conductivity >**0.01 S cm^{-1}**
  - Good stability in H_2O and CO_2 in short term testing
- Developed catalyst coated $PrBa_{0.8}Ca_{0.2}Co_2O_{5+\delta}$ (PBCC) air electrode
  - Polarization resistance R_p <**0.1 Ω cm^2**, 600 ºC
  - No obvious degradation in 3% H_2O at 600 ºC for over 500 h
- Fabricated reversible button cells
  - Peak power density of **1.2 W cm^{-2}** at 600 °C in fuel cell mode
  - Current density of **2 A cm^{-2}** at 1.3 V, 600 °C in electrolysis mode
  - 1,000 h operation at 500 °C with a degradation rate of **~1% per 1,000 h**
- Established ceramic powder synthesis capability up to **1000 g / day**

Proposed Future Work

Date	Milestone	% Complete
03/22	Complete durability evaluation of the button cell for at least 1000 h with a degradation rate of <2% per 1000 h at ≤ 650 ºC	70%
06/22 ***Go/No-Go Decision Point***	Complete the fabrication of 10x10 cm^2 cells (with an effective area of 81 cm^2) with ≥70% roundtrip efficiency at 0.5 A cm^{-2} in both SOFC and SOEC modes at ≤ 650 ºC. Complete durability evaluation of the 10x10 cm^2 cell for at least 1000 h with a degradation rate of <2% per 500 h at ≤ 650 ºC.	50%
09/22	Complete the stack design and components development	Not started
12/22	Complete the fabrication and evaluation of up to 3 short stacks (< 0.25 kW).	Not started
03/23	Complete 1 kW stack testing with ≥55% fuel cell at 0.5 A cm^{-2}, and >90% electrolysis at ≤ 650 °C, <2% per 1000 h degradation.	Not started
05/2023	Complete the system design and integration, complete a thermodynamic analysis.	Not started
07/2023	Complete evaluation of the 250 W system with ≥50% fuel cell efficiency at 0.5 A cm^{-2}, and >85% electrical efficiency at ≤ 650 °C.	Not started
09/2023	Demonstrate the potential to produce hydrogen at a cost of $2 per kilogram based on a cost of electricity of $30 per MWhr.	Not started
09/2023	Evaluate 1.0 kW rSOC system performance at the relevant operating conditions and model: efficiency, durability, degradation, life of electrolysis cell.	Not started

Acknowledgment

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Reference List for Slide 16

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