Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

HydroGEN: High Temperature Electrolysis

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Idaho National Laboratory
May 6–9, 2024

Project ID # P148b

STI#: INL/CON-24-77370

DOE Hydrogen Program 2024 Annual Merit Review and Peer Evaluation Meeting

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NREL Transforming ENERGY | BERKELEY LAB Bringing Science Solutions to the World | Sandia National Laboratories | INL Idaho National Laboratory | Lawrence Livermore National Laboratory

HydroGEN HTE Seedling Projects and Lab Collaboration

Project-driven tech transfer, resulting in

- Efficiency
- Yield
- Cost
- Durability
- Manufacturability

HTE Node Labs

Idaho National Laboratory

NREL Transforming ENERGY

Sandia National Laboratories

BERKELEY LAB

Lawrence Livermore National Laboratory

Support through:

Personnel

Equipment

Expertise

Capability

Materials

Data

Interactive HTE Projects

p-SOEC

Seedling FOA projects

Raytheon Technologies

Georgia Institute of Technology

West Virginia University

The UNIVERSITY of OKLAHOMA

COLORADO SCHOOL OF MINES

Lab call projects

INL Idaho National Laboratory

Lawrence Livermore National Laboratory

o-SOEC

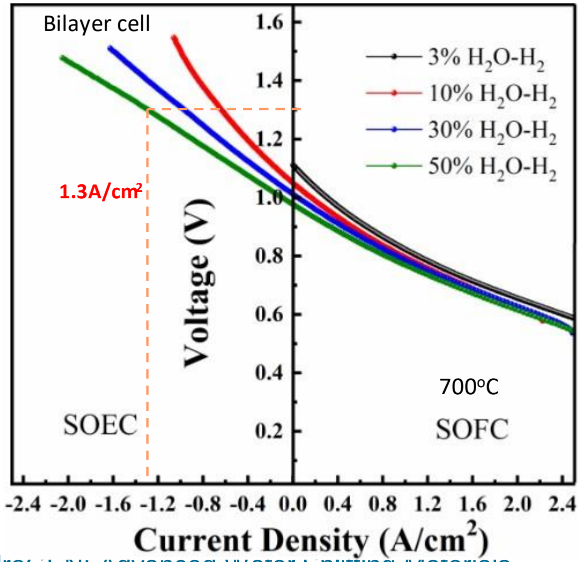
SAINT-GOBAIN

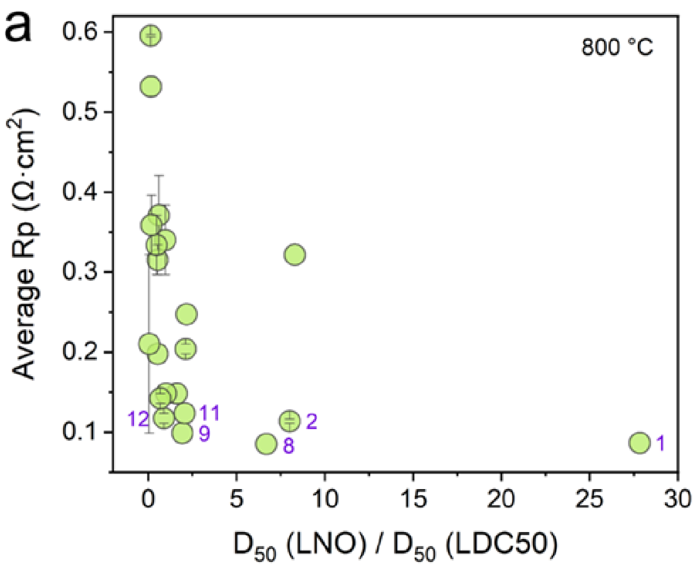
UNIVERSITY OF South Carolina

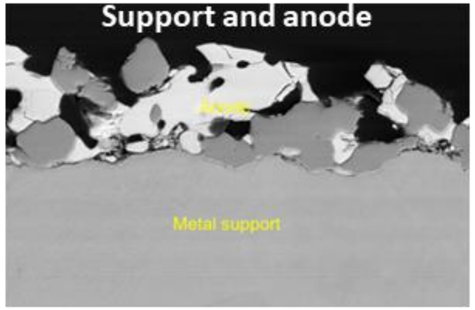
HydroGEN HTE Seedling Projects with Lab Capability Support

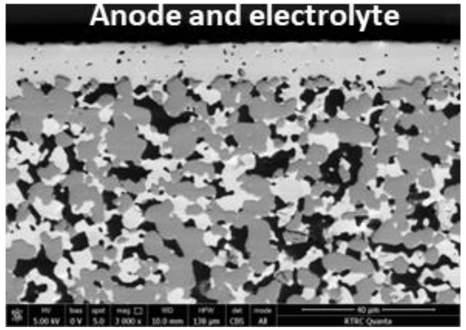
Technical Accomplishment Highlights

- **(USC, INL and NREL) A Multifunctional Isostructural Bilayer Oxygen Evolution Electrode for Durable Intermediate-Temperature Electrochemical Water Splitting:** Solid oxide electrolyzer featuring a bilayer air electrode was evaluated across various H_2O-H_2 ratios. The optimal performance was observed at 50% H_2O-50% H_2, achieving 1.3 A/cm²@1.3V at 700° C.
- **(Saint-Gobain and INL) Development of Durable Materials for Cost Effective Advanced Water Splitting Utilizing All Ceramic Solid Oxide Electrolyzer Stack Technology:** Symmetric cells were used to optimize the particle size ratio of Lanthanum Nickelate and Lanthanum doped Ceria, defining a working range to produce a composite air electrode with low polarization resistance and a tolerance to small batch to batch PSD variations. (p176)
- **(RTRC and INL) Thin Film, Metal-supported High Performance and Durable Proton-Solid Oxide Electrolysis Cells:** p-SOEC metal cells were produced with advanced manufacturing process, showed strong bonding of metal support and electrode with no Cr diffusion at the metal-electrode interface. (p154)









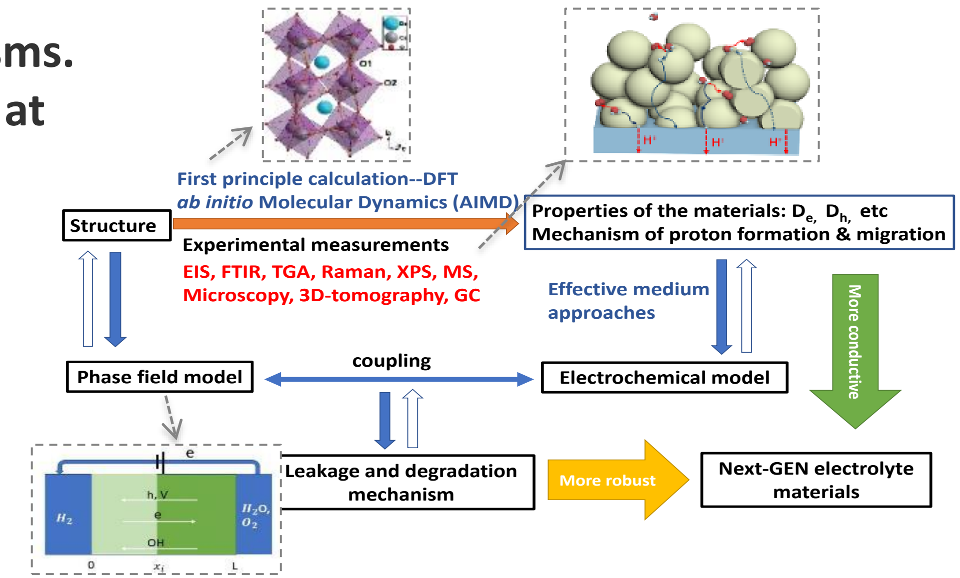
HydroGEN HTE Lab R&D p-SOEC Approach:

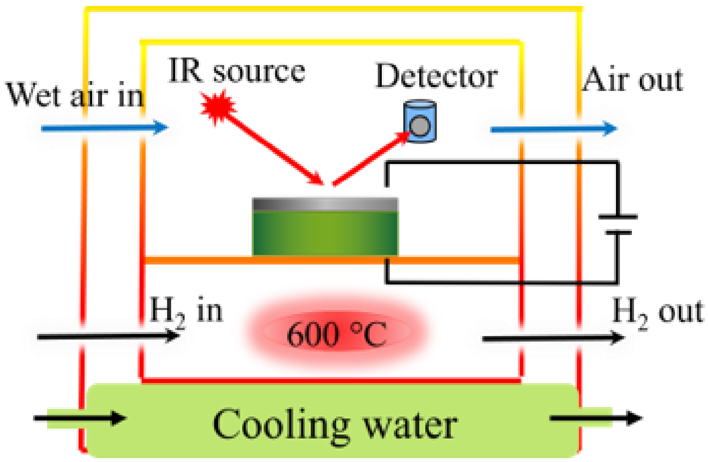
Combine Multi-Scale Computation and Experiment to Improve Faradaic Efficiency

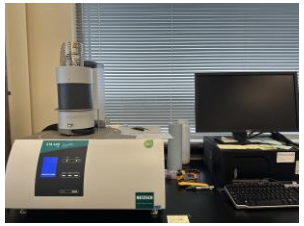
- **Develop effective approaches to suppress electronic leakage by understanding the proton conduction and electronic leakage mechanisms.**
- **Develop a robust, energy-efficient, and reliable electrolyte, for p-SOEC at 500-600°C, achieving high Faradaic efficiency (FE) and long durability.**

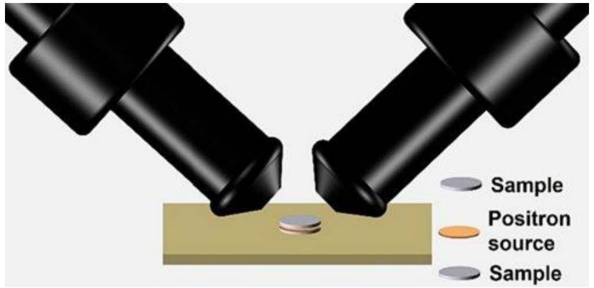
- **Framework:** Established an efficient framework by integrating experiment and multi-scale simulation (DFT/AIMD, phase-field model) for mechanism study in broad time and size scales.
- **Experiments:** Developed advanced characterization techniques to assess electrolytes to disclose thermodynamic information for modeling.

Mechanism study









- **Electrochemical modeling:** Built framework that leverages experimental measurements, electrochemical modeling and DFT simulation to predict Faraday efficiency of p-SOECs for various of electrolyte materials.
- **DFT/AIMD:** Unraveling factors affecting the mechanical properties of electrolyte at atomic scale.

Approach: Safety Planning and Culture

Top to Bottom Safety Focus

- **Design**
  - HAZOP
  - Subject Matter Expert review
  - Hydrogen and flame detection systems
- **Procurement**
  - Quality procurement program
  - Hydrogen material compatibility awareness
- **Installation**
  - Qualified and trained installation
- **Pre-operational Testing**
  - Inspections and monitoring for hydrogen and other leaks
- **Operation**
  - Alarms and operator aids
  - Routine checks and inspections of operating systems

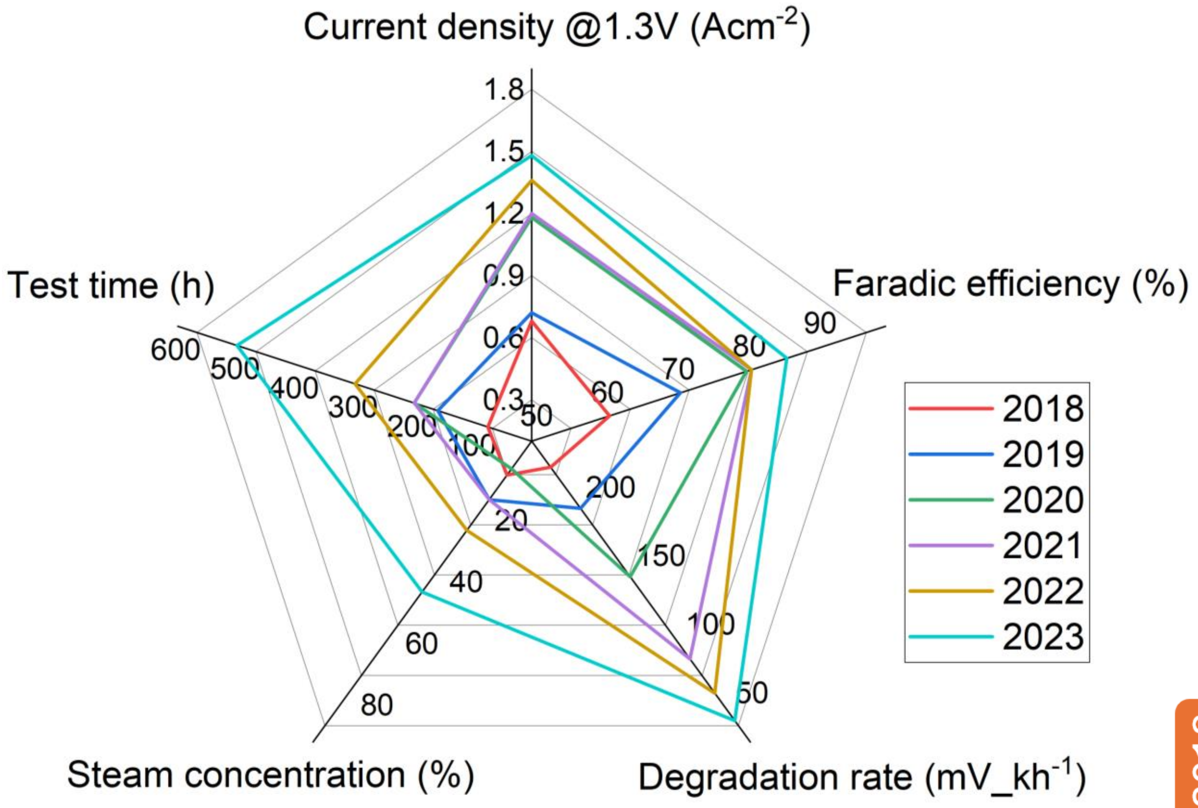
Idaho National Lab Safety

- **Work Control**
  - What is and isn’t authorized
  - Test plan reviews
- **Stop work**
  - If conditions are unsafe, anyone can call for a work stoppage.
- **Questioning mindset**
  - Briefings prior to the start of a new activity
  - Asking what could go wrong?
- **Training**
  - On-site training to facilitate broad institutional awareness of the safety considerations for hydrogen work.
  - NFPA 2 training
- **Flexible electrolysis system test platform**
  - Atmospheric testing with hydrogen recycle
  - Separate “Hot Box” module

HydroGEN Lab R&D p-SOEC Technical Accomplishment:

Overall Progress and Figure of Merits

INL p-SOEC Technical Progress*



- Parameters in each year represent the upper limits we achieved where test time and steam concentration are facility-constrained and have been improved significantly
- INL is focusing primarily on FE and degradation rate for a given current density and steam concentration.

- A p-SOEC metrics target table has been developed, similar to the one H2NEW-HTE initiated, with the additional focus on FE, FE durability and specific metrics on cell scales (e.g. button cells, single unit cells and short stack).
- As an emerging technology, the recognition development and knowledge buildup are advancing, which is valuable to refine and reshape the technology roadmap.
- Increasing inquiries, discussions and licensing needs from industry are good signs for accelerating P-SOEC penetration to the market.
- Timely communication (technically and strategically) with DOE managers and stakeholders are the best practice we learned.

2018 Initiated P-SOEC work with focus on bolstering the current density

2020 FE is critical in P-SOEC where there is a controversy in literature. Document and report to DOE

2022 Electrolyte composition and operation condition influence FE simultaneously. Reached consensus with all seedling PIs

2023 Unrevealed the significance of interface engineering on performance and durability. Develop more specific metrics for P-SOEC

* Data derived from INL internal reports and publicly available publications

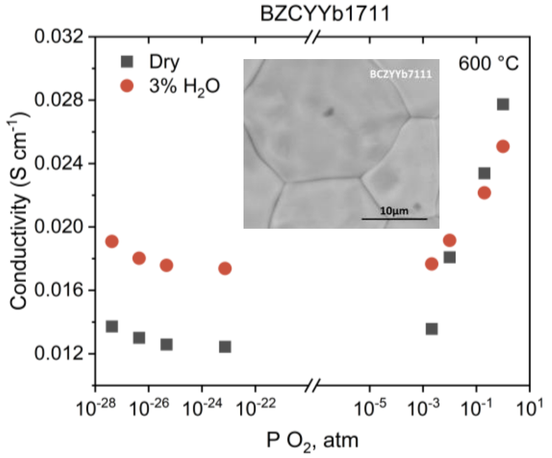
HydroGEN Lab R&D p-SOEC Technical Accomplishment:

Synergies between numerical simulations and experiments to derive Faradaic efficiency

- ✓ Conductivity of the electrolyte material determines the Faradaic efficiency for a given operation condition with some basic assumptions.

- ✓ The framework validated the experimental data from full cell testing well, and provided the FE predictions under extreme conditions

Total conductivity measurement

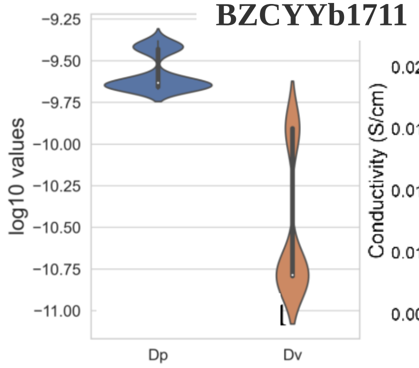


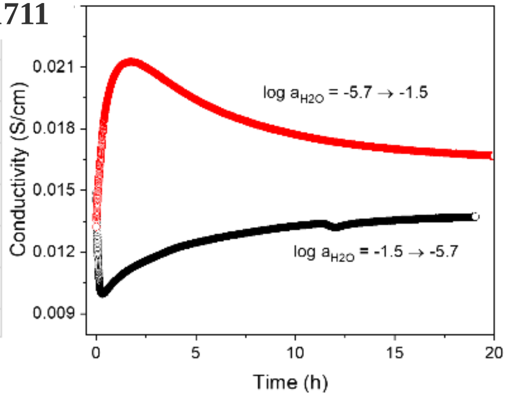
P Zhu, et al. under review

Inform

Parametric model: derive parameters

Verification: ECR experiments





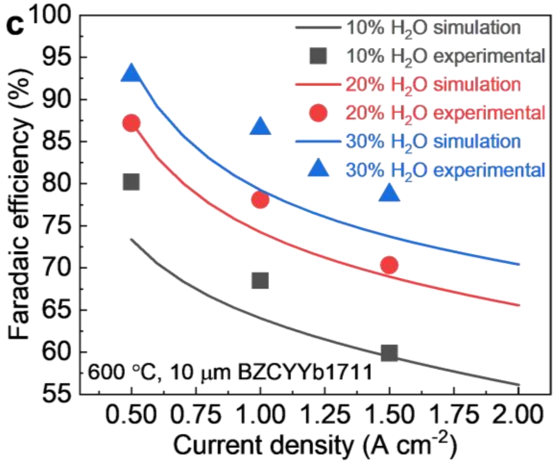
Y Meng, et al. under review

Feed-in

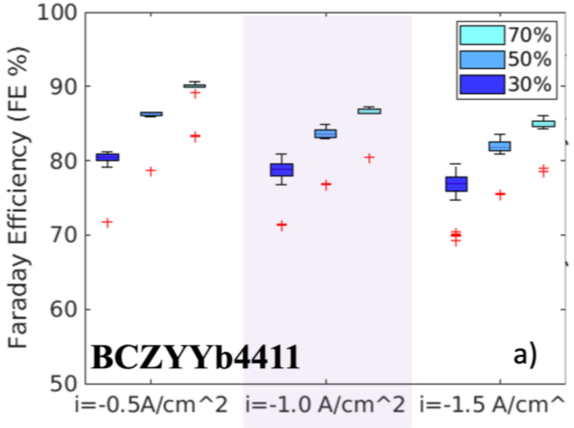
Validation

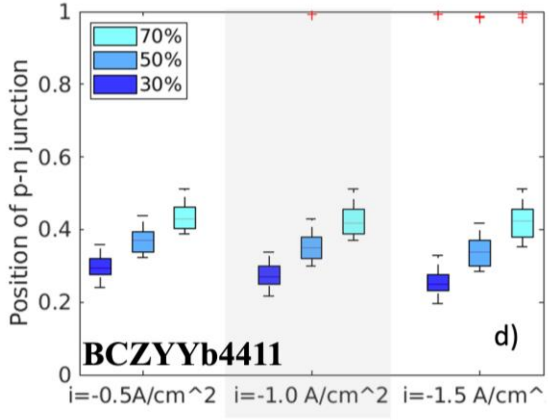
Experimental measurement

Electrochemical model: FE prediction



W Zhang, et al. under review





p-n junction verification: DFT simulation

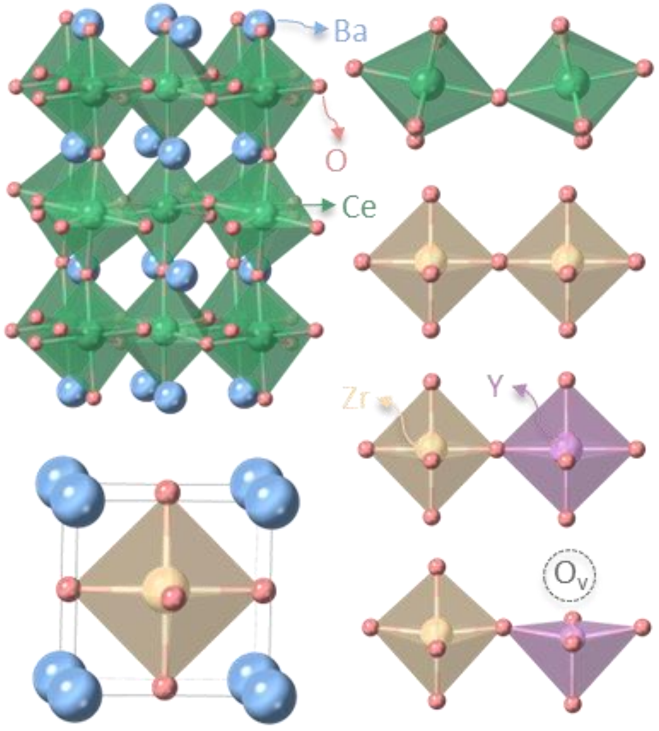
Q Zhang, et al. under review

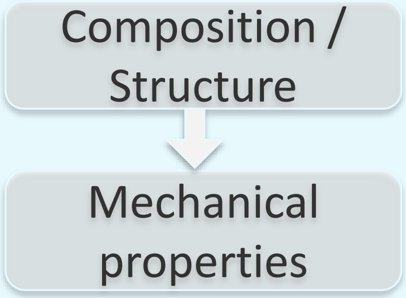
HydroGEN Lab R&D p-SOEC Technical Accomplishment:

Factors Affecting the Mechanical Properties of Proton-Conducting Perovskite Electrolytes

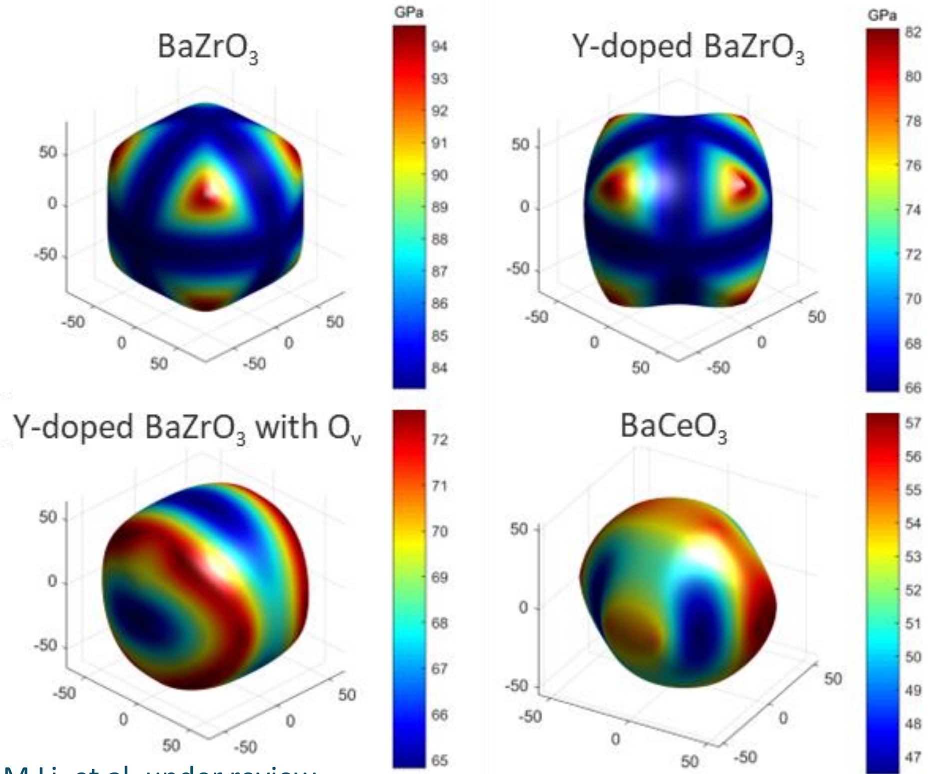
- **Key compositional and microstructural factors affecting mechanical properties**
  - Composition ($BaCeO_3$ vs $BaZrO_3$)
  - Lattice phase (Cubic vs. Orthorhombic)
  - Defect (O_v)
  - Octahedron (w/wo distortion)

- **Mechanical properties from first-principles calculations at atomic scale**
  - Doping and defects create elastic anisotropy and orientation-dependent elastic moduli, which may cause anisotropic fracture propagation and thermal expansion.
  - Reducing lattice symmetry decreases elastic moduli, increasing susceptibility to failure under cycling.





Insights on mechanical properties at atomic scale:
- Deformation
- Fracture behavior
- Fatigue resistance
- Thermal expansion



M Li, et al. under review

HydroGEN Lab R&D p-SOEC Technical Accomplishment (LLNL):

Proton Incorporation and Defect Concentrations in Doped Ba{Zr,Ce}O_3 Electrolytes

Investigated alternative modes of proton incorporation

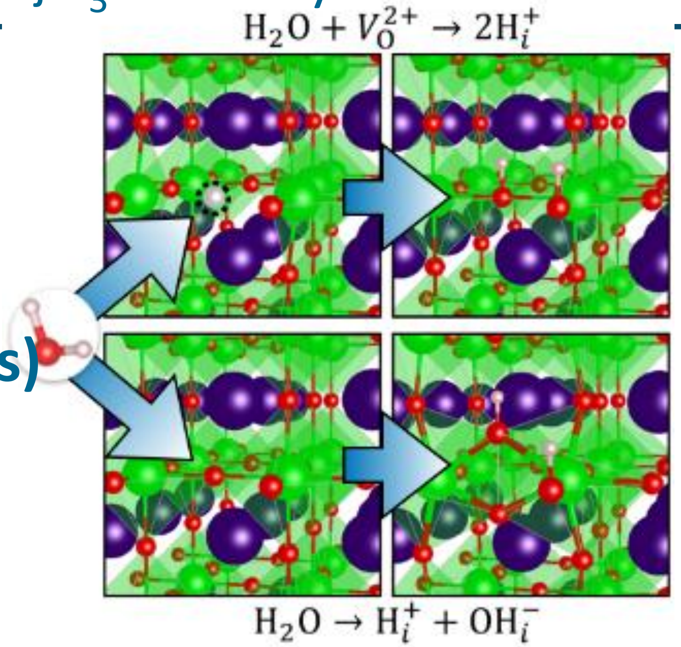
- Proton (H_i^+) incorporation in Y-Ba{Zr,Ce}O_3 more favorable with oxygen vacancies (V_O^{2+}) than without, particularly in $BaZrO_3$

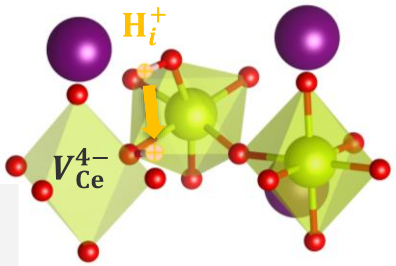
Studied ionic migration near defects (proxy for grain boundaries)

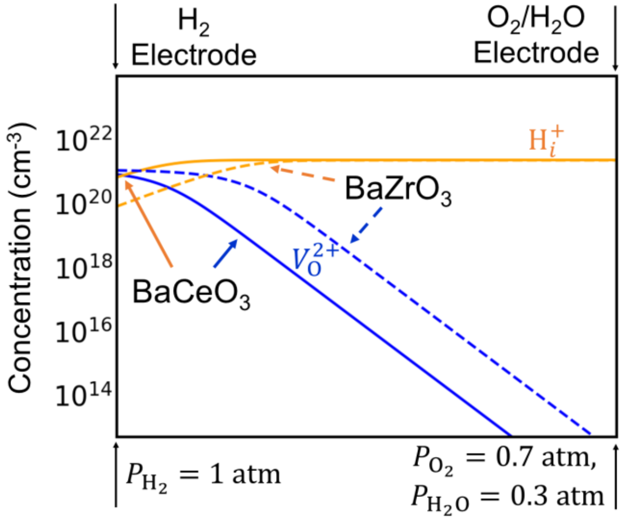
- H_i^+, V_O^{2+} migration slower near (negatively charged) cation vacancies

Modeled defect concentrations for *operando* conditions

- H_i^+ usually the main charge carrier in electrolyte, but V_O^{2+} surpasses it near the H_2 electrode
- Particularly true in $BaZrO_3$ – **supports importance of Ce**
- Polarons/electrical carriers much less prevalent







High ionic conductivity can be achieved through optimizing synthesis conditions to maximize the concentrations of H_i^+, as well as reducing defect-rich regions such as grain boundaries.

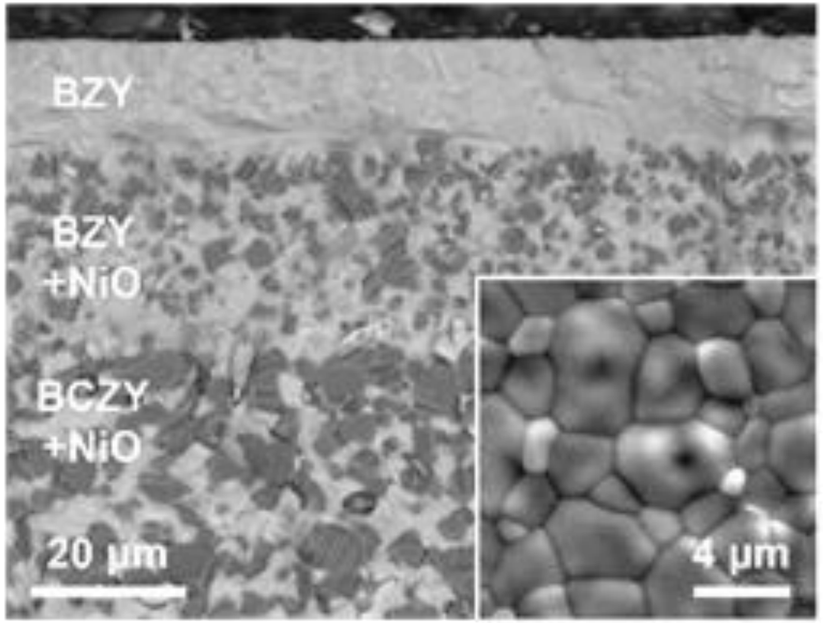
A. Rowberg, M. Li, T. Ogitsu, J. Varley. Mater. Adv., 2023.

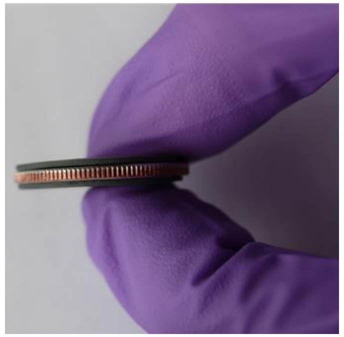
HydroGEN Lab R&D p-SOEC Technical Accomplishment:

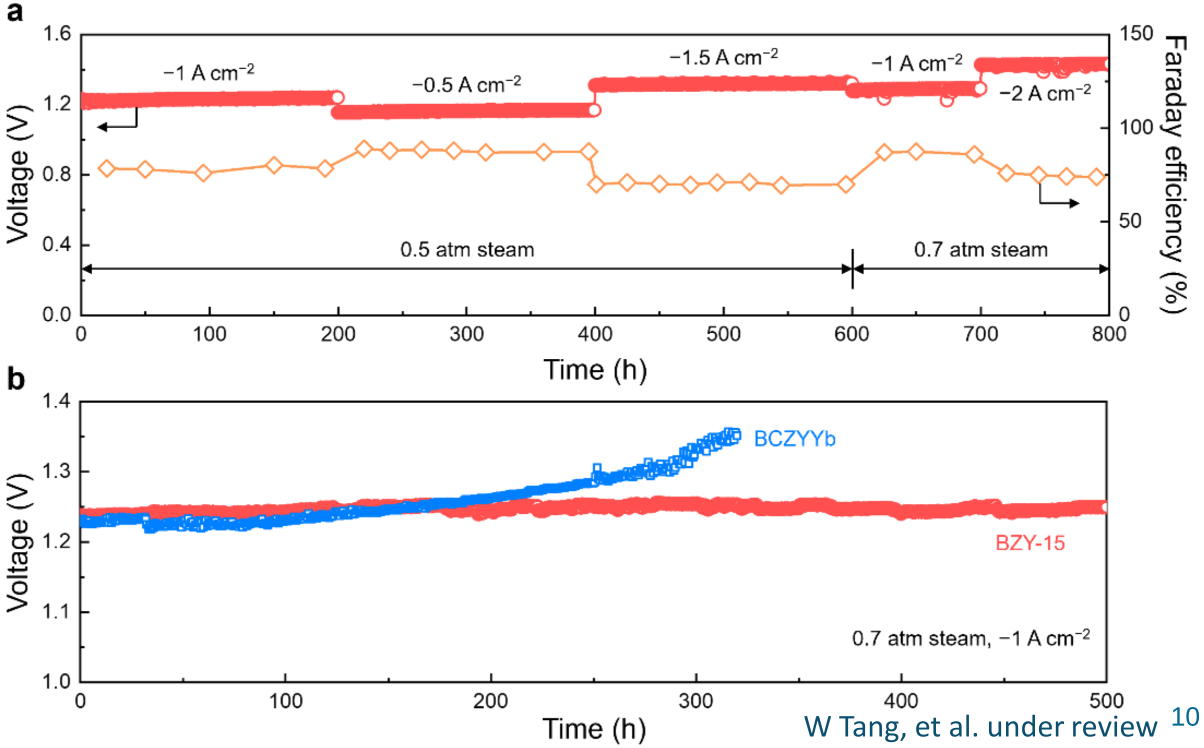
Benchmarked BZY cells with enhanced electrolysis stability and Faradaic efficiency

Performance and durability of p-SOEC is equally important for its advancement and adoption by the market.

- Additional effort is placed on the full cell durability, especially under some extreme conditions.
  - Benchmarked electrolyte BZY is employed
  - Cells successfully underwent different current densities (up to 2 A cm^{-2}) and steam concentrations (up to 70%)
- New fabrication methods suppressed Ce effect on electrolyte and enabled the flat cells with clean grains.
- The Faradaic efficiency can be maintained at ~ 90% at −1 A cm^{-2} with 70% stream concentration at 600^{o}C with a durable operation (single condition >500 hrs and multi-conditions > 800 hrs). Combined with the modeling prediction conducted under 99% steam concentration, it suggested the completion of the annual milestone (FE >95% and tested for 500 hrs)







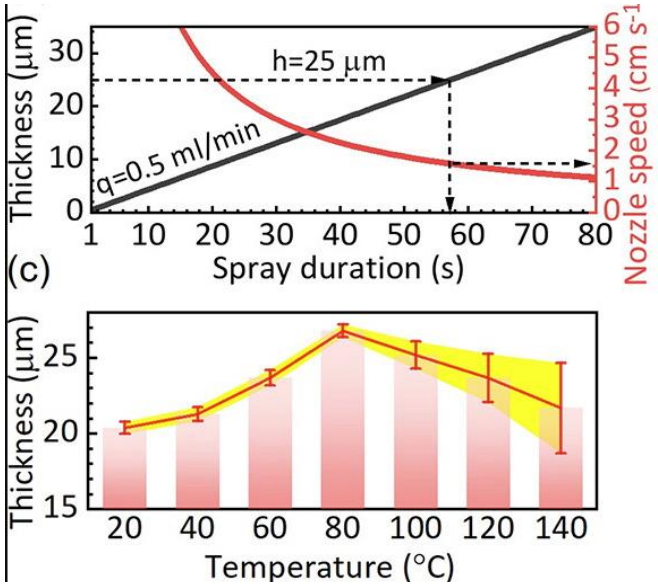
W Tang, et al. under review

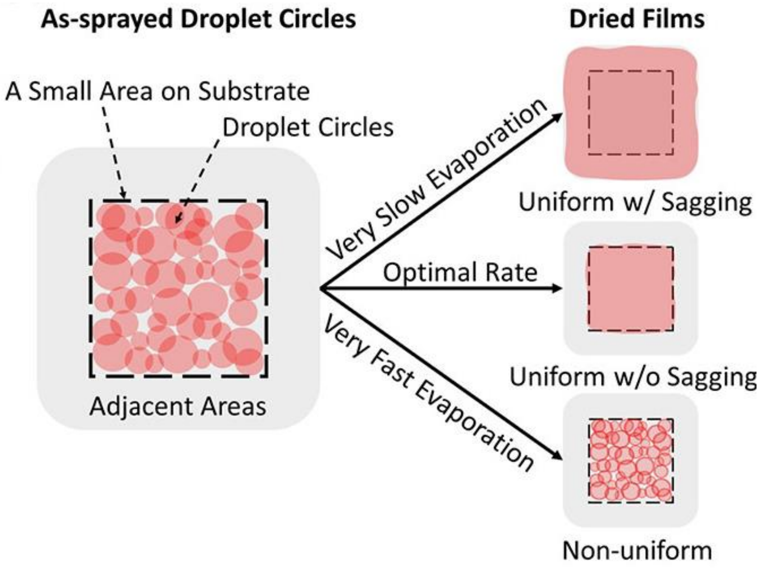
HydroGEN Lab R&D p-SOEC Technical Accomplishment:

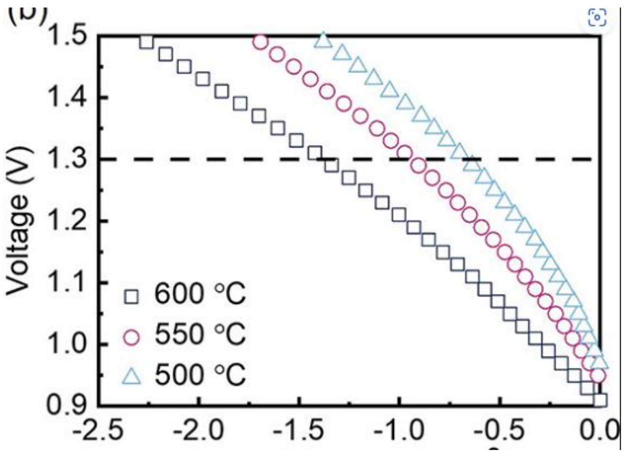
Surface engineering enhances electrolyte layer uniformity

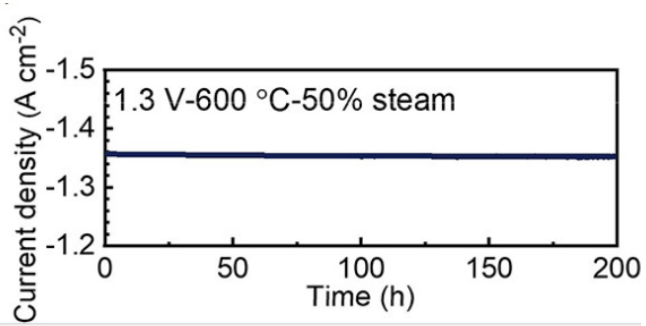
Electrolyte uniformity and quality affects cell performance substantially

- Proposed a facile and systematic parameter optimization for thin layer deposition, satisfying the requirements for throughput, thickness, and uniformity, simultaneously.
    - Thin electrolyte film with 30 μm thick PNC oxygen electrode by layer-by-layer deposition.
    - Full cell validation show current density of 1.36 A cm^{-2} at 1.3 V in the electrolysis mode, with minimal degradation over a period of 200 h.









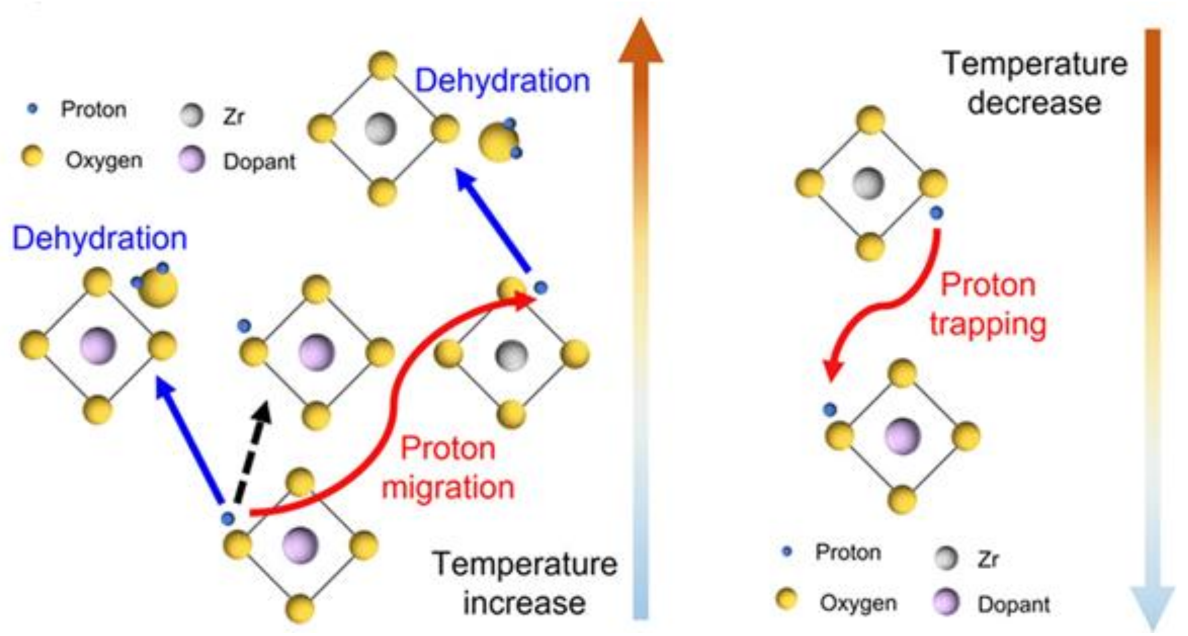
W Feng, et al, ACS Applied Materials & Interfaces, 2023

HydroGEN Lab R&D p-SOEC Technical Accomplishment:

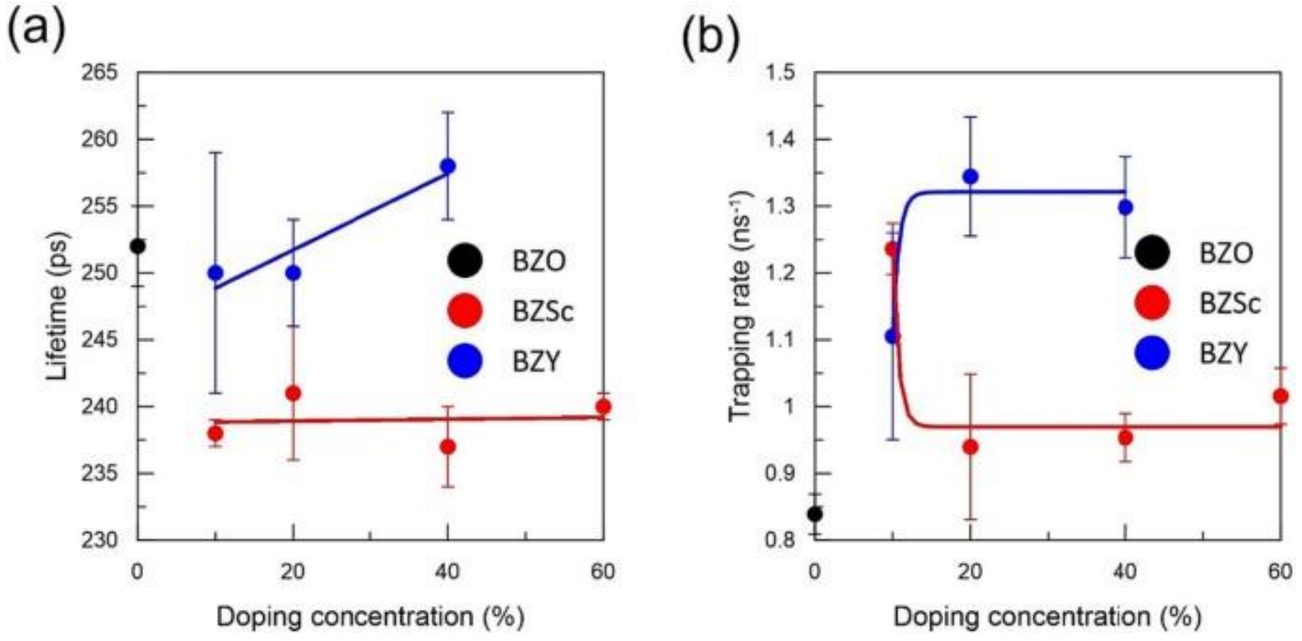
Improving proton conductivity in perovskites and positron annihilation lifetime spectroscopy

Varying the dopant and concentration level in PCOs affects the hydration ability

- Scandium doping reduces the activation energy for proton migration and improves hydration of the material, both conditions may increase the proton conductivity in comparison to yttrium doped materials, suggesting it may be a good electrolyte candidate.
- Positron annihilation lifetime spectroscopy (PALS) is proven to be a powerful tool for studying the proton-trapping behavior and the defect chemistry of proton ceramics.



C. Regalado Vera, et al. Chemistry of Materials. 2023



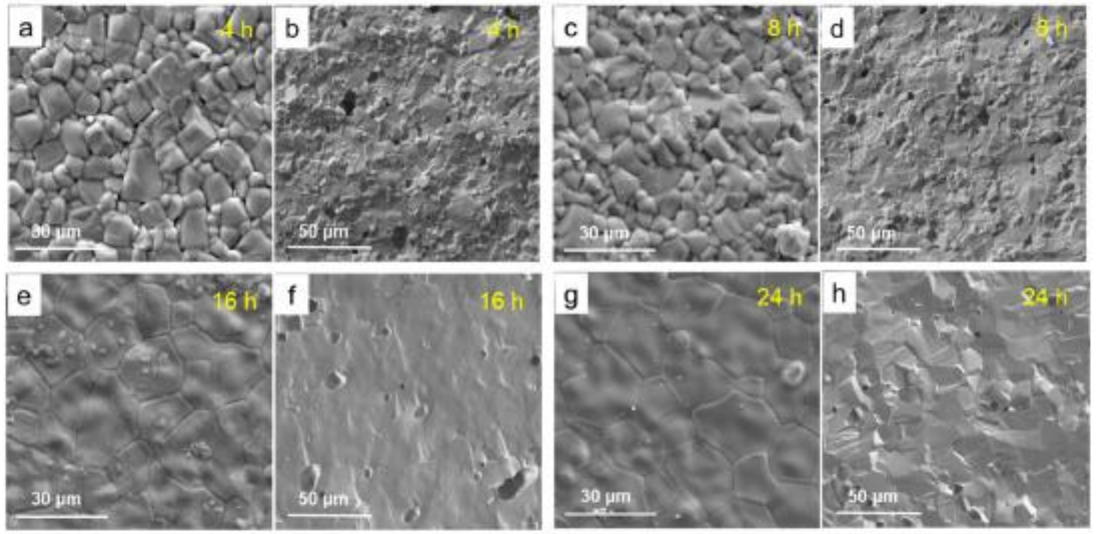
J Urban-Klaehn, et al. Solid State Ionics. 2023

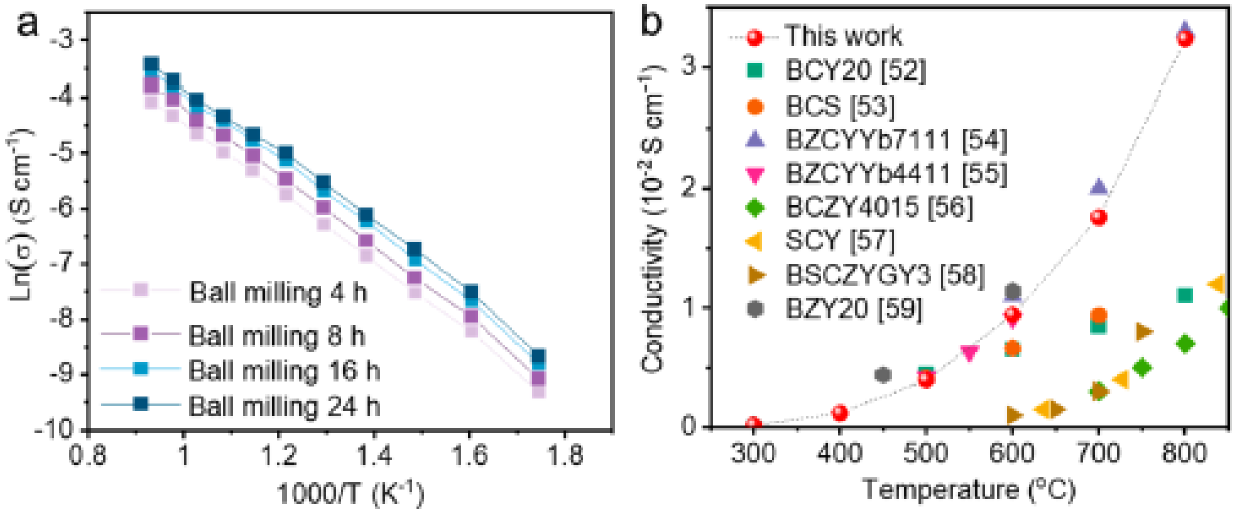
HydroGEN Lab R&D p-SOEC Technical Accomplishment:

Improved solid-state reaction method for synthesis of electrolyte materials

Synthesize high performance and cost-effective protonic electrolyte materials with reliable protocols

- The conventional solid-state reaction (SSR) method suffers from tedious synthesis procedures and low phase purity of the materials involved
- Improved SSR (i-SSR) method can produce high phase-purity electrolyte material $BaZr_{0.4}Ce_{0.4}Y_{0.1}Yb_{0.1}O_{3-\delta}$ (BZCYYb4411)
    - The ball-milled precursor powders are pelletized prior to calcination to reduce the length of the diffusion paths during perovskite phase formation.
    - The synthesis procedure and calcination temperature are carefully optimized based on the powder crystallization behavior.





Min Wang et al. ACS Appl. Energy Mater. 2023.

Technology Transfer: p-SOEC

- **Exclusive license option agreement executed with a U.S. based start-up for multiple technologies supported by HFTO in 2023.**
  – Market focus for this company is green hydrogen production.
  – Negotiations to convert the option into an exclusive license are expected to conclude mid 2024.
- **Expanded patent portfolio for p-SOEC (details see “Intellectual Property” slide).**
  – 1 Granted Patent
  – 1 PCT Application
  – 1 Provisional Application
  – 1 Invention Disclosure Record (IDR) submitted and elected for patent filing.

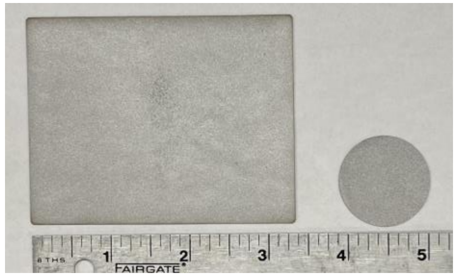
HydroGEN HTE Lab R&D Technical Accomplishment:
LBNL Metal-Supported Solid Oxide Electrolysis Cell (MS-SOEC)

Project targets at 700°C, 50:50 $H_2O:H_2$

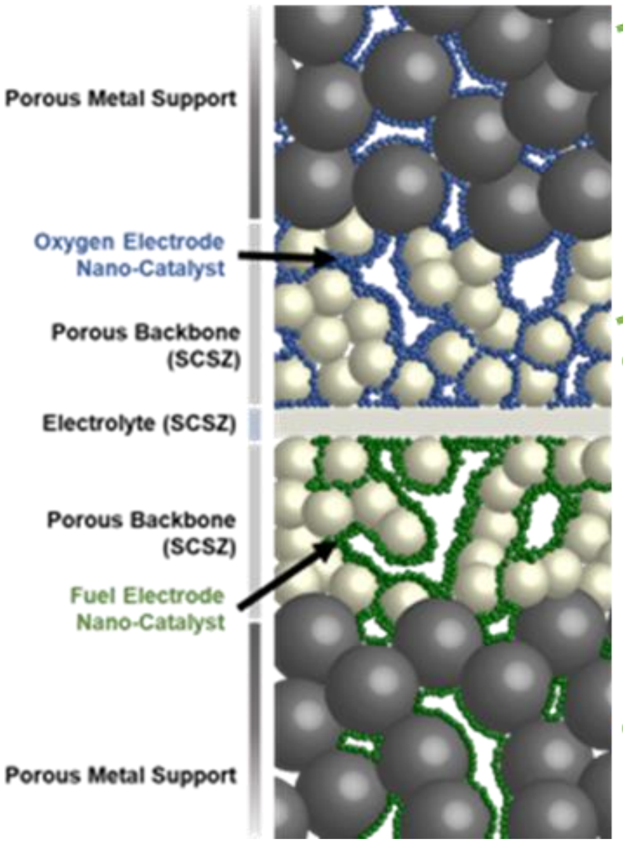
Cell size (complete)
Target: >40 cm^2
FY23 status: 5 cm^2
FY24 Status: 50 cm^2

Performance (complete)
Target: > 1.0 A/cm^2 at 1.4V
FY23 Status: 1.2 A/cm^2 at 1.4V
FY24 Status: 1.3 A/cm^2 at 1.4V

Durability (ongoing)
Target: <5%/kh
FY23 Status: 13%/kh at 0.5 A/cm^2
FY24 Status: 11%/kh at 0.5 A/cm^2



Approaches to improve performance and durability



Protective coatings to block Cr
- Particle size
- Composition
- EPD deposition parameters
- Sintering protocol

Catalyst composition and processing
- Alternative OER catalysts
- Coatings to prevent LSCF-ScSZ reaction
- Micron-scale Ni to prevent coarsening

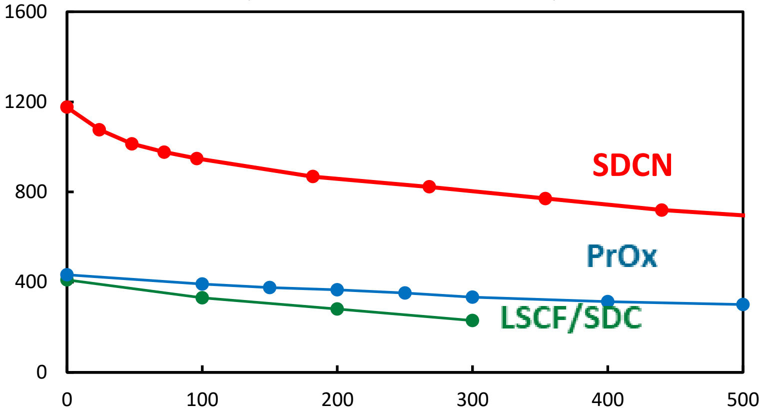
Cell structure and processing
- Processing in air to allow high-T sintering of catalysts

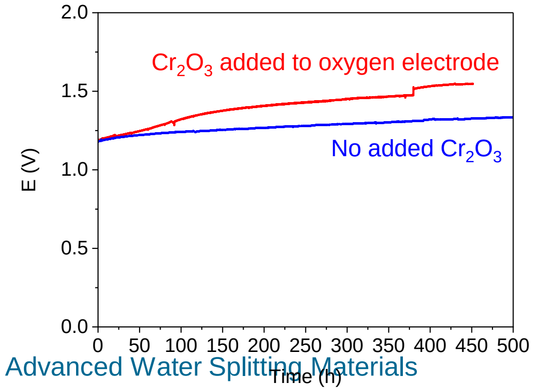
Diagnostics and model cells
- Symmetric cells to isolate each electrode
- Cr dosing
- Pre-oxidize metal support
- Refresh catalyst after long-term operation
- Post-mortem at 0, 100, 300, 1000h

MS-SOEC Model cells to assess degradation modes

Symmetric cells

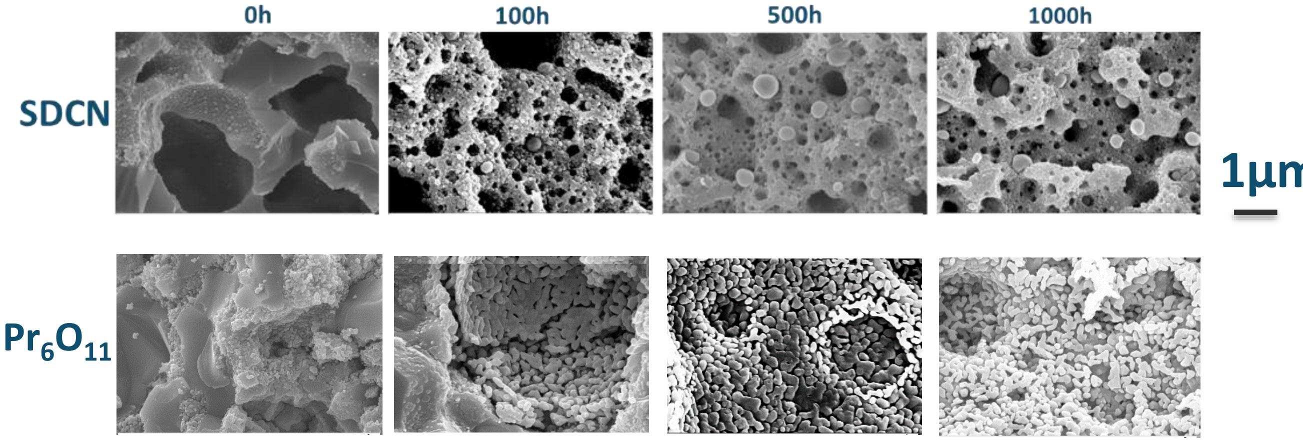
Oxygen catalysts dominate
- lower performance and durability than SDCN





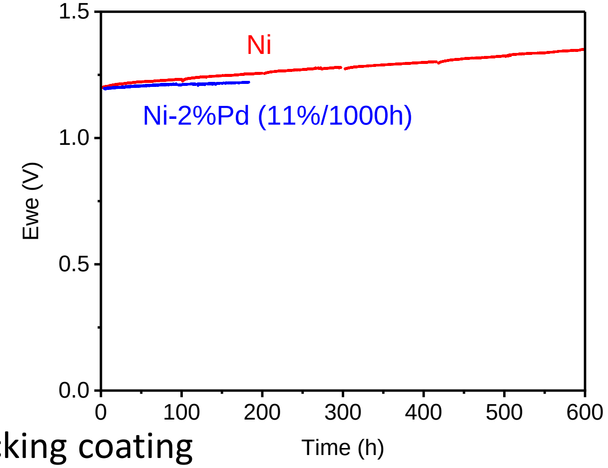
Detailed post-mortem analysis

Separating break-in and long-term degradation phenomena



Ni alloy

2% Pd doping increases stability
- suggests less expensive alloys may be fruitful



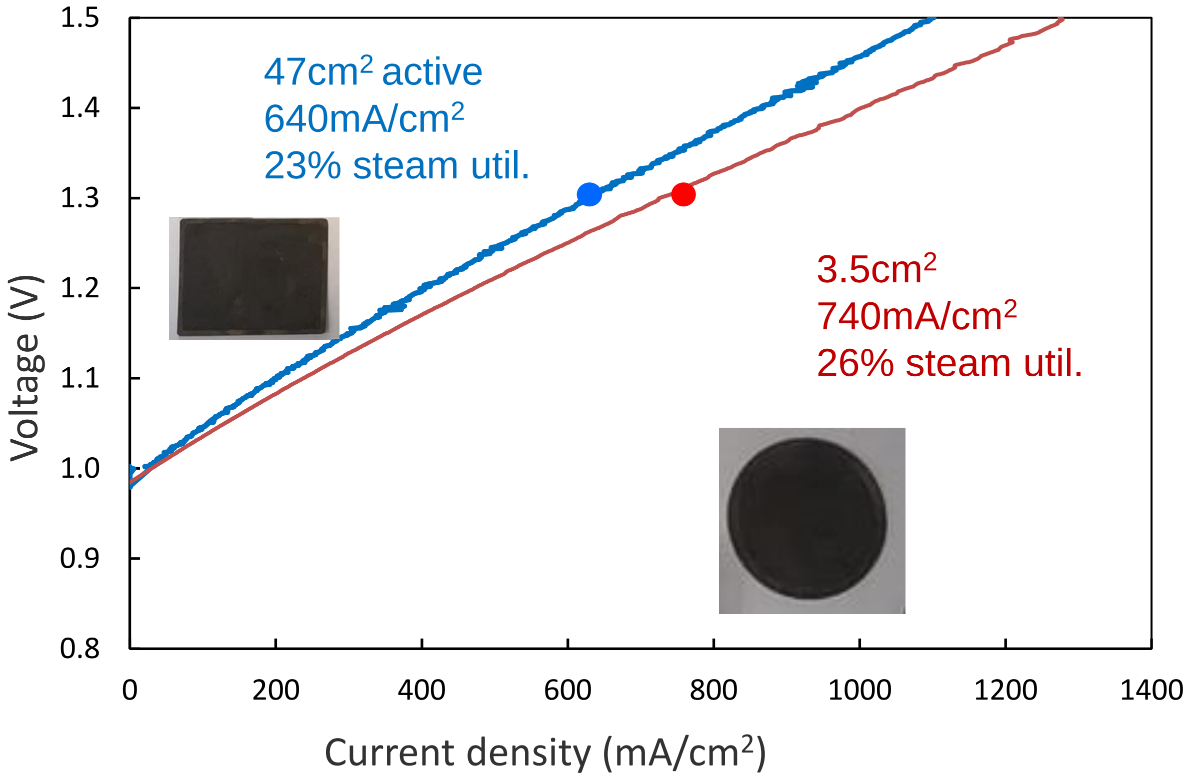
Conclusions

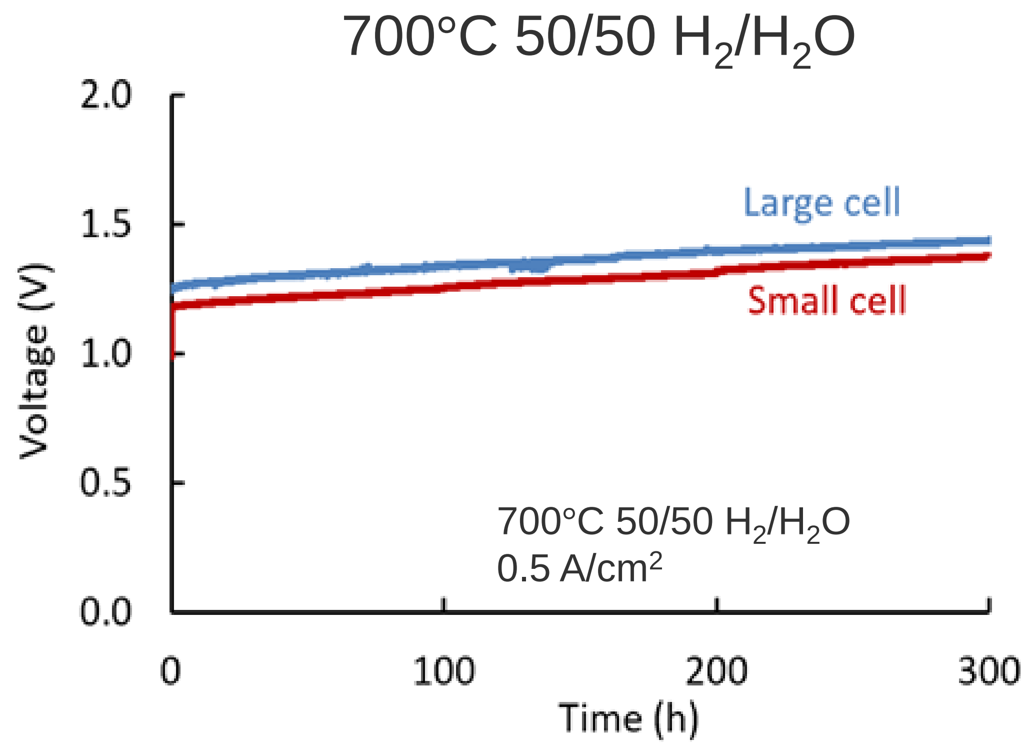
- Oxygen electrode limits performance and durability
  - Cr poisoning is significant in SOEC mode
- Ni coarsening is complete at <500h
- PrOx coarsening is complete at 100h
- SDC coarsening is minor

Priorities

- Cr-blocking coating
- Increase Ni and LSCF/Pr particle size
- Alternative to infiltrated catalysts
  - Ni alloy or exsolution
  - conventional OER catalyst

MS-SOEC Scale-up to 50 cm^2 cell size



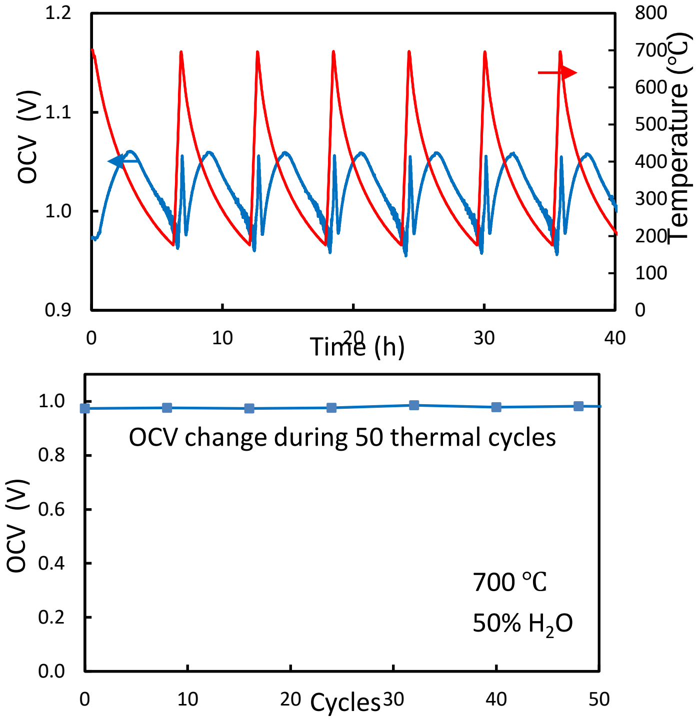


- Good performance for large planar cell
- Performance and durability is similar to button cell

- 86% of button cell current density at 1.3V (exceeds target of 75%)

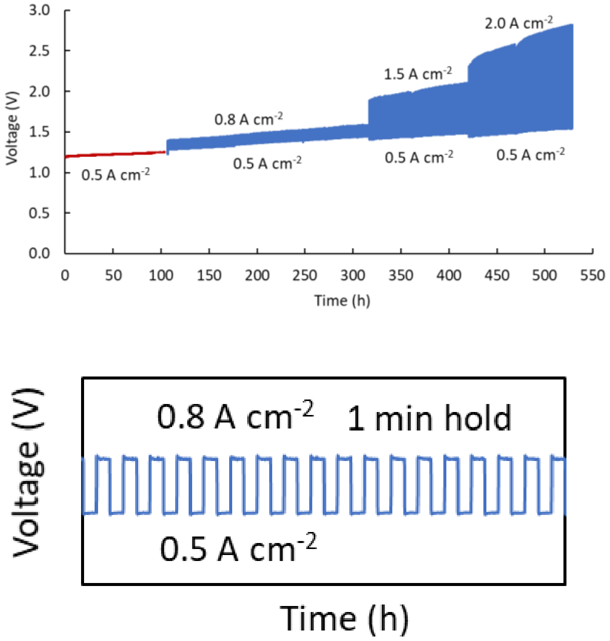
MS-SOEC Dynamic Operation at 700°C

Thermal Cycling



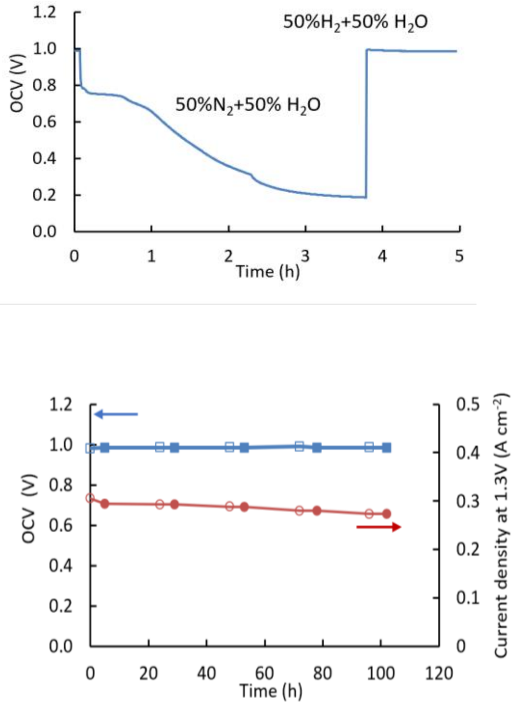
50 cycles from
160°C to 700 °C

Current Cycling



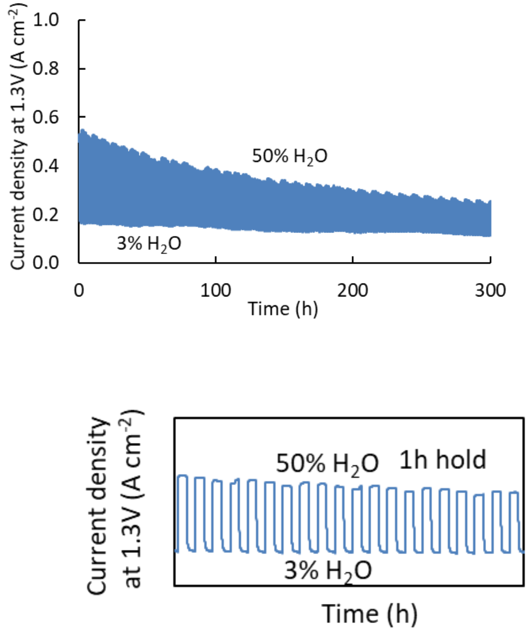
13,500 cycles between
0.5 A/cm^2 and 0.8-2 A/cm^2

Redox Cycling



5 cycles from
Ni to NiO

Steam Content Cycling



150 cycles from
3% to 50% H_2O:H_2 ratio

MS-SOEC tolerates aggressive dynamic operation conditions
First report of MS-SOEC dynamic operation

Collaboration and Coordination

- Interfacing between HydroGEN and existing seedling projects.
- Interfacing between HydroGEN and H2NEW for exchanging information.
- Interfacing between HydroGEN and industry for benchmarking, technology transfer, and potential collaborations

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Future Work

- Continue leveraging the lab node support for the existing and upcoming FOA projects.
- Benchmark and develop the p-SOEC electrolyte materials that have higher proton conductivity, better stability, less electronic leakage, and better chemo-mechanical properties.
- Develop MS-SOEC with further improved durability; Develop alternative cell architecture and fabrication approaches

Any proposed future work is subject to change based on funding levels

Summary of Accomplishments

- **Lab capability support:** Effective collaborations between the seedling projects and the lab nodes, significantly accelerating both o- and p-SOEC technology advancement.

- **p-SOEC Lab R&D**: Investigated the fundamentals of protonic ceramic electrolytes and emphasized equal importance in performance and stability of p-SOEC with improved Faradaic efficiency, based upon the benchmarked electrolyte materials.

- **MS-SOEC Lab R&D** : Demonstrated robustness of MS-SOEC to dynamic operation; scale-up to cell size 50 cm^2; systematic analysis of degradation phenomena; screening of concepts to improve durability.

Responses to Reviewers

Comments: Some work, such as the Chemours project and HTWE, overlaps with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) scope of work.

Response: Lab work has a clear distinction where p-SOEC is within HydroGEN while H2NEW covers o-SOEC work. It makes sense that some o-SOEC seedling projects were funded through HydroGEN prior to H2NEW.

Comments: Proton-conducting solid oxide electrolysis cell (P-SOEC) Faraday efficiency should increase with current density (slide29).

Response: Our discoveries revealed that the overpotential has more significant impact on Faradaic efficiency (FE) which caused the FE decrease with current density. It is consistent with the observations from the WVU and RTRC seedling projects as well as those reported by other groups and companies in US and Europe.

Comments: Metal-supported SOEC should address Cr poisoning under high steam conditions, and the operating temperature of 700C seems too high for metal support.

Response: i) Under normal operating conditions, Cr evaporation is prevalent on the oxygen side but is not expected on the steam side. At very high steam concentrations, volatile chromium oxyhydroxide may form. We plan to address this mechanism in the future via post-mortem study and direct measurement of Cr transpiration. ii) Oxidation of the metal support is temperature-dependent. Recently, we have studied oxidation of porous stainless steel in SOEC conditions in the temperature range 600-800C. In the case that the metal support is preoxidized and coated with catalysts (standard procedure), the oxidation rate at 700C is acceptable for long-term integrity of the metal support.

Intellectual Property

- Dong Ding, Hanping Ding, Wei Wu and Chao Jiang. Electrochemical cells for hydrogen gas production and electricity generation, and related structures, apparatuses, systems, and methods. US Patent (No. 11,557,781), 2023
- Wei Wu, Dong Ding, Zeyu Zhao. Methods for forming an electrochemical device. US Patent Provisional Application (63/602,818), 2023
- Dong Ding, Wenjuan Bian, Wei Wu. Facile methods to rejuvenate electrolyte surface for high-performing protonic ceramic electrochemical cells. PCT Patent Application (PCT/US23/60386), 2023

Publications

1. Puvikkarasan Jayapragasam, Yeting Wen, Korey Cook, Jacob A. Wrubel, Zhiwen Ma, Kevin Huang, and Xinfang Jin, “Crack Growth Rate at Oxygen Electrode/ Electrolyte Interface in Solid Oxide Electrolysis Cells Predicted by Experiment Coupled Multiphysics Modeling”, **Journal of the Electrochemical Society**, 2023, **170**, 054509. DOI 10.1149/1945-7111/acd4f1.
2. Clarita Y. Regalado Vera, Hanping Ding, Jagoda Urban-Klaehn, Meng Li, Frederick Stewart, Hanchen Tian, Xingbo Liu, Yanhao Dong, Ju Li, Meng Zhou, Hongmei Luo, Dong Ding. Improving Proton Conductivity by Navigating Proton Trapping in High Scandium Doped Barium Zirconate Electrolytes. **Chemistry of Materials**. 35 (2023) 5341-5352
3. Wuxiang Feng, Wei Wu, Zeyu Zhao, Joshua Gomez, Chris Orme, Wei Tang, Wenjuan Bian, Cameron Priest, Frederick Stewart, Congrui Jin, Dong Ding. Mathematical Model-Assisted Ultrasonic Spray Coating for Scalable Production of Large-Sized Solid Oxide Electrochemical Cells. **ACS Applied Materials & Interfaces**. 15 (2023) 31430-31437.
4. Min Wang, Wei Wu, Yingqian Lin, Wei Tang, Guanhui Gao, Haixia Li, Frederick F. Stewart, Hanping Ding, Micah J. Casteel, Fanglin Chen, Yingchao Yang, Dong Ding. Improved Solid-State Reaction Method for Scaled-Up Synthesis of Ceramic Proton-Conducting Electrolyte Materials. **ACS Applied Energy Materials**. 6 (2023) 8316-8326
5. Jagoda Urban-Klaehn, Clarita Y. Regalado Vera, Radoslaw Zaleski, Hanping Ding, Hongmei Luo, Dong Ding. Hydrated Doped-BaZrO3 Proton Conductors Studied by Positron Annihilation Lifetime Spectroscopy. **Solid State Ionics**, 402 (2023) 116365.
6. Yeting Wen and Kevin Huang, “Predicting the Rate of Degradation Related to Oxygen Electrode Delamination in Solid Oxide-Ion Electrolyzers”, **Journal of the Electrochemical Society**, in revision.

Presentations

1. J. Pietras, B. Oistad, X. Qian, S. Gopalan, Y. Zhong, W. Li, “Development of Durable Materials for Cost Effective Water Splitting”, 244th ECS Meeting (October 8-12, 2023)
2. Yeting Wen and Kevin Huang, “exploring the safe operational current density for high temperature solid oxide electrolyzers”, ICACC2023, January 22-26, 2023, Daytona Beach, FL.
3. X. Jin , P. Jayapragasam, and Y. Shoukry, Multiphysics Modeling for Solid Oxide Electrolyzer Cell with Heterogenous Synthetic Microstructure, 243rd ECS Meeting, Boston, MA, 05/28/2023-06/02/2023.
4. X. Jin, and Y. Shoukry, Current Leakage and Faradaic Efficiency Simulation of Proton-Conducting Solid Oxide Electrolysis Cells, 243rd ECS Meeting, Boston, MA, 05/28/2023-06/02/2023.
5. P. Jayapragasam , Y. Wen, X. Jin, and K. Huang, A 3D Simulation of DC-Biased Electrochemical Impedance of Solid Oxide Electrolysis Cell: Effects of Delamination, 243rd ECS Meeting, Boston, MA, 05/28/2023-06/02/2023.
6. Y. Wen and K. Huang, Predicting Lifetime of Solid Oxide Electrolytic Cells through Oxygen Electrode Performance, 243rd ECS Meeting, Boston, MA, 05/28/2023-06/02/2023.
7. K. Huang, annual project AMR meeting, June 5-7, 2023, Washington DC.
8. Dong Ding. Intermediate Temperature Solid State Energy Conversions by Protonic Ceramics: A Key for Cost-Effective Decarbonized Economy Invited Presentation. 48th International Conference and Expo on Advanced Ceramics and Composites (ICACC2024). Daytona Beach, January 28-Feb 2, 2024.
9. Dong Ding. Advancement of Proton Conducting Solid Oxide Electrolysis Cells (p-SOEC) for Hydrogen Production at Idaho National Laboratory. Invited Presentation. The 243th ECS conference. Boston, May 28-June 2, 2023.
10. Qian Zhang, Clarita Y. Regalado Vera, Hanping Ding, Wei Tang, Wei Wu, Scott Barnett, and Peter Voorhees, Dong Ding. Dependence of Faraday Efficiency on Operation Conditions and Cell Properties for Proton Ceramic Electrolysis Cells. Oral Presentation. The 243th ECS conference. Boston, May 28-June 2, 2023.

Presentations Cont'd

- Yuqing Meng, Qian Zhang, Haiyan Zhao, Dong Ding. Operando Characterizations of Proton Exchange in Proton Conducting Solid Oxide Electrolysis Cells (p-SOECs). Oral presentation. The 243th ECS conference. Boston, May 28-June 2, 2023.
- Weilin Zhang, Qian Zhang, Dong Ding. Improve the Electrochemical Performance and Long-Term Durability of Protonic Ceramic Electrochemical Cells. Oral presentation. The 243th ECS conference. Boston, May 28-June 2, 2023.
- Yuchen Zhang, Zeyu Zhao, Quanwen Sun, Wei Wu, Jianhua Tong, Dong Ding. Effects of Preparation Conditions of Precursor Powders on Sinterability of Green Bodies and Performance of Protonic Ceramic Electrochemical Cells. Oral presentation. The 243th ECS conference. Boston, May 28-June 2, 2023.
- Quanwen Sun, Wenjuan Bian, Hongmei Luo, Meng Zhou, Dong Ding. Well-designed Oxygen Vacancy in Ni-doped PrCoO3 for Protonic Ceramic Electrochemical Cells. Oral presentation. The 243th ECS conference. Boston, May 28-June 2, 2023.