Advanced Water-Splitting Technology Pathways Benchmarking & Protocols Workshop

Breakout Session Summaries
High Temperature Electrolysis (HTE)

May 3 – 4, 2022

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ASU Arizona State University

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HTE Breakout Sessions

Session ID	Topic	Lead
H1	Priority Research Opportunities - Materials, Components	Scott Swartz (Nexceris)
H2	Priority Research Opportunities - Devices, Testing, Life cycle analysis	Joe Hartvigsen (OxEon)
H4	Favored conditions vs Optimal conditions; durability vs H2 production (efficiency)	Xingbo Liu (WVU)
H5-A	HTE Protocols Published to Date & Plans for Validation; Protocols to be Written	Dong Ding (INL)
H5-B	AST testing protocol development; Protocols to be Written	Mike Tucker (LBNL)
H6-A	Wrap-up: Challenges, Outlook, Action Item Assignment	Nguyen Minh (UCSD)

Session Summary

Session ID: H1
Title: Priority Research Opportunities: Materials, Components
Technology: HTE

Summary

- Need industry input on durability testing conditions.
- R&D needed to identify limits on specific test conditions (temperature, steam content, etc.)
- Need more standardization on cells and testing conditions.
- Discussed electrolytes and barrier layers: desired density, thickness, RE availability, processing cost).

Consensus and/or dissenting opinions

- **C:** Proton conducting ceramic electrolytes have significant potential advantages, but would need at least 10 years to mature.
- **D:** Need to identify testing conditions to make button cell testing results more valuable.
- **C:** Mechanical properties important (e.g., inverse relationship between strength and conductivity);
- **C:** Chemical stability in 100% steam is important.
- **D.** Barrier layers need work or need for them eliminated.

Key Take-Aways

- Spider charts could be used to assess progress.
- Prioritize durability.
- Supply chain for critical materials (Sc, Ni, Co, RE, etc.) need more consideration.
- Cost will drive the design.
- Interconnects materials and coatings need more discussion.

Action Items

- Define details on standard cells (e.g., dimensions) and testing conditions (e.g., current density, steam content, steam utilization).
- Define reproducibility requirements.
- Survey industry for conditions required for performance and durability testing.
- Perform an analysis of critical HTE materials (perhaps national labs working with USGS).

Session Summary

Session ID: H2
Title: Devices, Testing, LCA
Technology: HTE

Summary

- Objective: develop framework for standardized testing at cell, stack, and (perhaps) system level.
- Definitive test condition unclear, as different technologies target very different operating conditions and windows.
- Expanding electrochemical performance tests to techno-economics & life-cycle analysis requires input from broad range of professionals.

Consensus and/or dissenting opinions

- **C**: Drive towards production cost per kg H2.
- **C**: Agreement that "best" technology may be a matter of perspective, as no single metric defines "best"
- **C**: Drive towards performance map for a technology, including cost of H2 production v operating conditions (current density, temperature, voltage).
- **D:** Scope of standardization deemed problematic
- **D:**Cell-level metrics quite different from LCA metrics

Key Take-Aways

- Define scope: standards for cell, stack, and system characterization
- Define "standard conditions" for a set of tests, then "favorable conditions" to illustrate value of a technical approach.
- Define gross metrics:
  - H_2 production rate per unit mass or volume of stack
  - H_2 production efficiency (vs electricity input)
  - Degradation rate (ΔASR khr^{-1})
  - (Many) TEA inputs

Action Items

- Agree to scope of standardization.
- Define standardized output metrics across cells, stacks, and systems, around which testing protocols can be built.
- Create "stake in the ground" to focus efforts – initial standardized test(s) document for review.
- Develop test hardware that ensures uniformity across large-area devices.
- Acknowledge that multiple performance metrics will be produced as a result of standardized testing, with perhaps no clear winning technology.

Session Summary

Session ID: H4

Title: Favored conditions vs Optimal conditions; durability vs H2 production (efficiency)

Summary of discussion

- Tradeoffs between what customer (e.g., utility) and their customers need as compared to what industry can achieve (e.g., maximum output at odds with long lifetime)
- Significant discussion regarding how research is best done to address industry needs

Consensus/Dissenting Options

- Consensus: Research should represent relevant application space
- Dissension: Freedom to study new science desirable through breakthroughs, but concern that it may not address customer (i.e., funding agency) needs
- Consensus: Protocols for test conditions and post-test analysis are still needed

Key Take-Aways

- Parameters used in published research should be better defined in publications
- Performance mapping will aid understanding of small scale tests over wide range of conditions in commercial stack
- Testing protocols and relevant parameter space needs to be defined and agreed upon by all stakeholders

Action Items

- A revised survey to be sent to stakeholders regarding optimal cell design and test conditions for better standardized testing
- Protocols previously developed will be finalized (e.g., degradation via ASR)
- New protocols identified will be initialized (e.g., steam generation and quantification)

Session Summary

Session ID: H5-A
Title: Protocols Developed & Next Steps

Summary of discussion

- Reviewed the status of protocols developed and identified the pathway moving forward (e.g. make assignments, detail goals for new submissions, etc)
- Discussed the missing protocols that should be prioritized and concurred it should be a constant effort to improve the protocols
- Discussed the strategies for validation of the protocols, probably through round robin test.

Consensus & dissenting opinions

C: Methods for introducing steam, pros and cons; Different requirements for different cell sizes. Best practice from different labs, make it public and disseminate

C: Protocols need to be improved and added gradually and help newcomers to speed faster and more efficiently.

C: Steam purity quantification.

D: Quality control, human factor could not be considered in protocols. Testing station, test protocols, materials standardization. Standards like ISO9000, for everyone to use.

Key Take-Aways

- Publishing the protocols and making them openly accessible with DOI is critical. Further validation/refinement and quick adoption is beneficial to accelerate the HTE development
- Protocol validation is important and could be done with the collaboration among national lab, industry and university.
- Steam supply with accurate control is an important topic for HTE and some best practice and lessons learned should be shared.

Action Items

- 5 more protocols to be submitted soon (Olga, Dong, Mike).
- Reach out to U of SC, OxEon and FCE for new protocols (Olga will send notice to Kevin and Joe)
- Initiate communication with HFTO management and identify the resources for the validation of protocols. (Olga, Dong, Jamie, Richard, and leads at universities)
- Publish a research article of steam supply on SOEC (Kevin)

Session Summary

Session ID: H5-B

Title: HTE Accelerated Test Protocols

Summary of discussion

- Identified primary degradation modes and the operating parameters that control them

Consensus & dissenting opinions

- **C**: Can we use AST to predict long-term result? Yes, Results don't need to be perfect but define the success metric

Key Take-Aways

- Button cells are OK for many testing parameters and degradation modes, but not others (steam utilization, spatial temperature gradient)
- Analysis, diagnostics, and modeling can fill a calendar time gap in testing data (test for few kh, predict to 10's kh)

Action Items

- Academia, industry submit protocols to H2NEW for validation
- Need round robin testing

Session Summary

Session ID: H6A

Title: Challenges and Outlook

Summary of discussion

- **Challenges to reach cost target**: use current state of the art for scaling up of SOEC stack to reduce stack cost; Increase efficiency, and focus on durability issues, scale-up SOE like PEM & AEM to GW level. Reduced electricity cost would be beneficial.
- **Outlook to overcome challenges**: Improve consistency and yield (90%) for industry; Test new material and manufacturing approach; Post analysis and validated modeling are needed.

Consensus & dissenting opinions

C: Leverage learning from SOFC to improve SOEC

D: Innovations needed for lowering operating voltage

D: Interconnect material is important to reduce the overall cost. It degrades with time.

C: Proper TEA is needed. Current analysis was not validated and was based on extrapolations

C: Compared to LTE, HTE have low material cost because of low operating voltage and high efficiency, even with lower current density. Thermoneutral voltage current density is a critical parameter for SOE performance.

Key Take-Aways

- Manufacturing: draw the line for the size of the SOE stack for massive production and focus on further cost reduction.
- Companies should focus more on manufacturing, not solely on R&D to compete with universities and national labs.
- 500cm^2 SOE stack manufacturing with automatic operation using robots has been proved to be effective by Fuel Cell Energy to increase the yield and limit variability.
- OE needs to be improved for higher performance and better durability.

Action Items

- More system cost analysis to help identify cost reduction drivers.
- Benchmarking and validation of performance of the state-of-art design by national lab are needed, so industry and university could use as comparison.