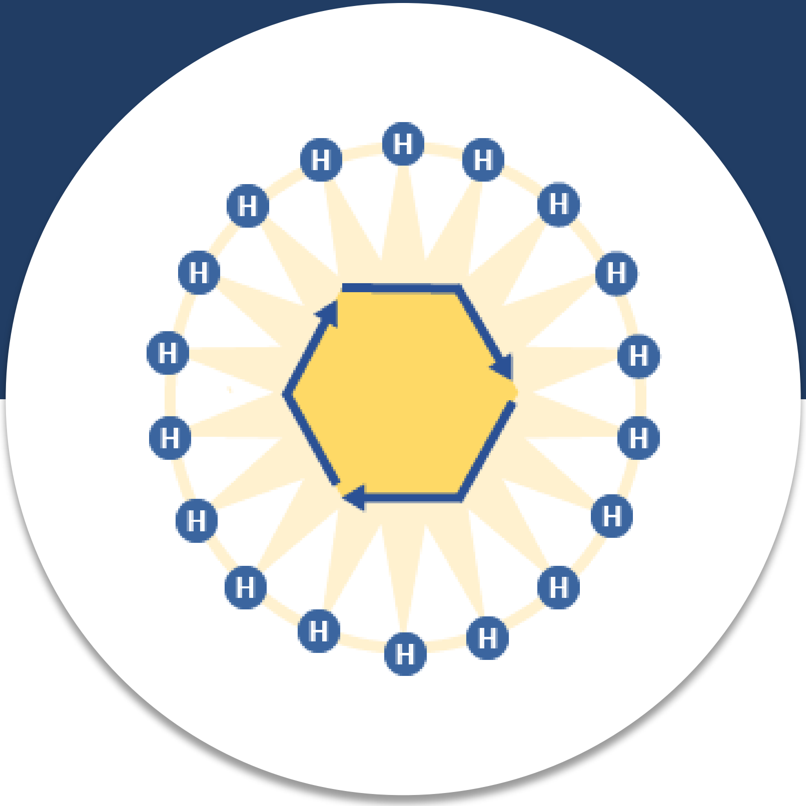
FY21 STTR I: Development of a Direct Fuel Cell for the Perhydrodibenzyltoluene / Dibenzyltoluene Fuel Pair

ENERGY 18H

Safe Hydrogen Clean Energy System



Powering the transition to a net-zero world

Presenter: Guido Pez, Energy 18H, LLC, Principal Investigator
Energy 18H LLC
Project ID#: FC360
DE-FOA-0002360
2022 Annual Merit Review Meeting
June 6-8, 2022

Our plan is to help get the world to net-zero emission, by developing a cost-effective liquid fuel cell to further advance clean energy storage and automotive transportation fuel.

Lab Demonstration

Our zero-emissions direct liquid fuel cell system (DLFC) powered by regenerable liquid organic hydrogen carrier (LOHC) fuel

Value Proposition of Project

- Cost Competitive
- Existing Infrastructure
- Convenient + Safe
- Energy Density (Power)

Scaling renewable energy system

Decarbonizing transportation

Overview

Timeline

Phase I
Project Start: 7/1/2021
Project End: 6/30/2022

Phase II*
Project Start: 8/22/2022
Project End: 8/21/2024

Budget

Phase I:
DOE Allocated
$200,000

Phase II:
DOE Submitted
$1,100,000

Licensed Patent Pending

Proprietary: System and method for electrochemical energy conversion and storage

US 2018/0053957

2/22/18, G. Pez & A. Herring as co-inventors

STTR Agreement

Department of Energy Grant Awardee

Letter of commitment from University of Delaware, Fuel Cell Research Center

IP Agreement with University of Delaware, Fuel Cell Research Center

Private-Sector Partnerships

Letter of Support from Proton-On-Site

VP of R&D shared encouraging letter of support for Proton's potential role in co-creating a commercial electrolyzer for use in Energy 18H system

Memorandum of Understanding with Hydrogenious, LOHC product supplier and developer.

*Submitted Application

Current solutions lack the ability to get us to 100% clean energy.

	Electricity	Transportation
Problem Areas	"It's Not Always Sunny" - Long-term storage viability - Cost-effective distribution methods - Grid inflexibility, unresponsiveness	"Big Rigs Require Big Batteries" - Cost of new fueling infrastructure - Safety concerns - Shipment and cargo efficiency
Why it Matters	25% of GHG emissions in U.S.[1]	29% of GHG emissions in U.S.[1]

Notes:
1. United States Environmental Protection Agency *Total GHG Emissions by Economic Sector* (2019)
2. RE = Renewable Energy; EV = Electric Vehicles

We're developing the key to unlock scaled adoption of clean energy.

What

A zero-emission direct liquid fuel cell system (DFLC)

It uses liquid organic hydrogen carrier (LOHC) technology powered by the regenerable fuel pair of: perhydro-dibenzyl-toluene (PDBT) and dibenzyl-toluene (DBT)

Why

Cost

Leverages liquid fuel infrastructure

1 order of magnitude lower storage capital vs. H2 tubes

2 orders of magnitude lower storage capital than Li-Ion batteries

Safety

Stable liquid (-30°C to +300°C)

Low hazard potential, toxicologically harmless, immiscible with water

Performance

Higher net energy density than lithium-ion batteries and compressed H_2

Lower refueling times

Environmental

Zero CO_2 emissions

Regenerable fuel

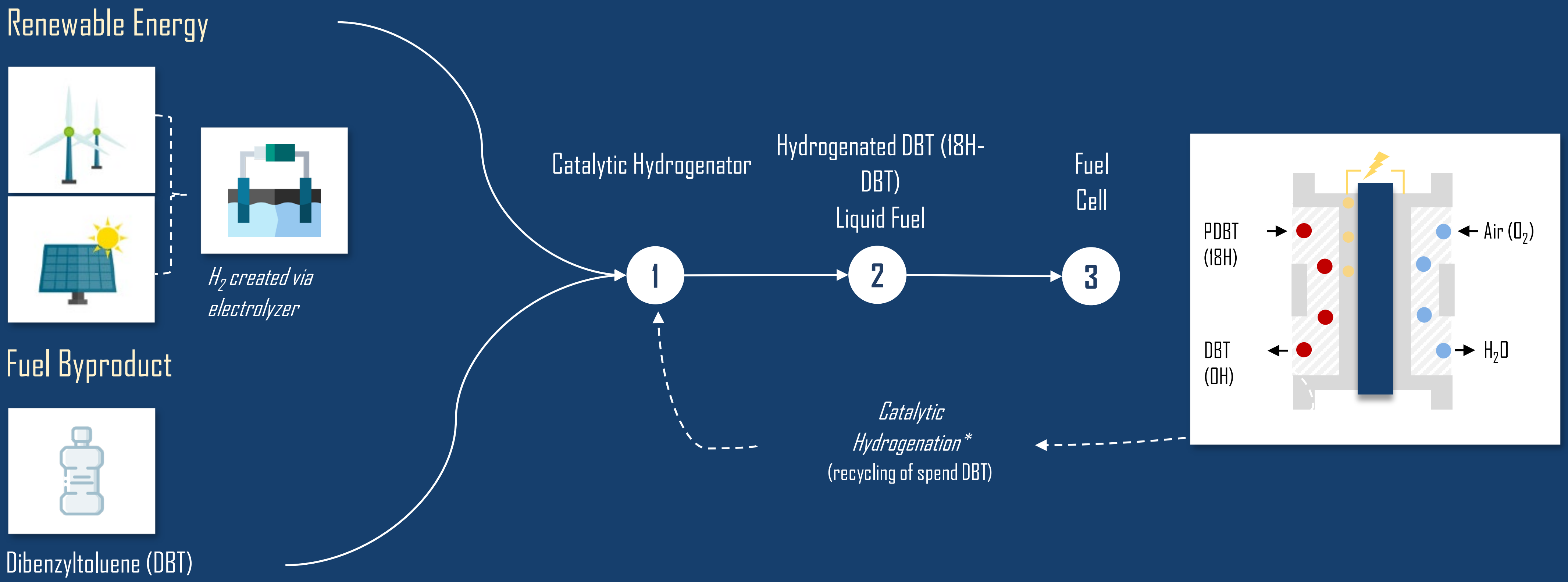
Our bold plan to solve climate change by enabling low-cost and safe renewable energy storage.

A zero-emission direct liquid fuel cell system (DLFC)

Powered by regenerable liquid organic hydrogen carrier (LOHC) fuel

SOLUTION

The direct liquid fuel cell energy cycle



*Regeneration of "spent" DBT fuel by catalytic hydrogenation demonstrated by Hydrogenious Inc.

Energy Sources

North-star vision is to primarily use green hydrogen

LOHC System

Liquid Organic Hydrogen Carrier

DLFC System

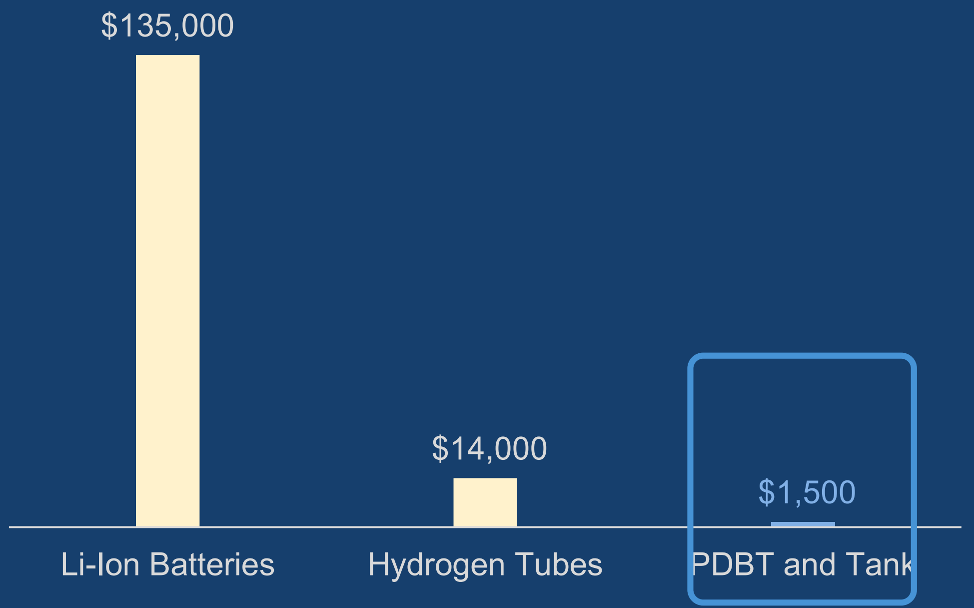
Recycle spent fuel to be re-used

Iconography Sources: Flaticon and Freepik

PDBT: Perhydro-dibenzyltoluene

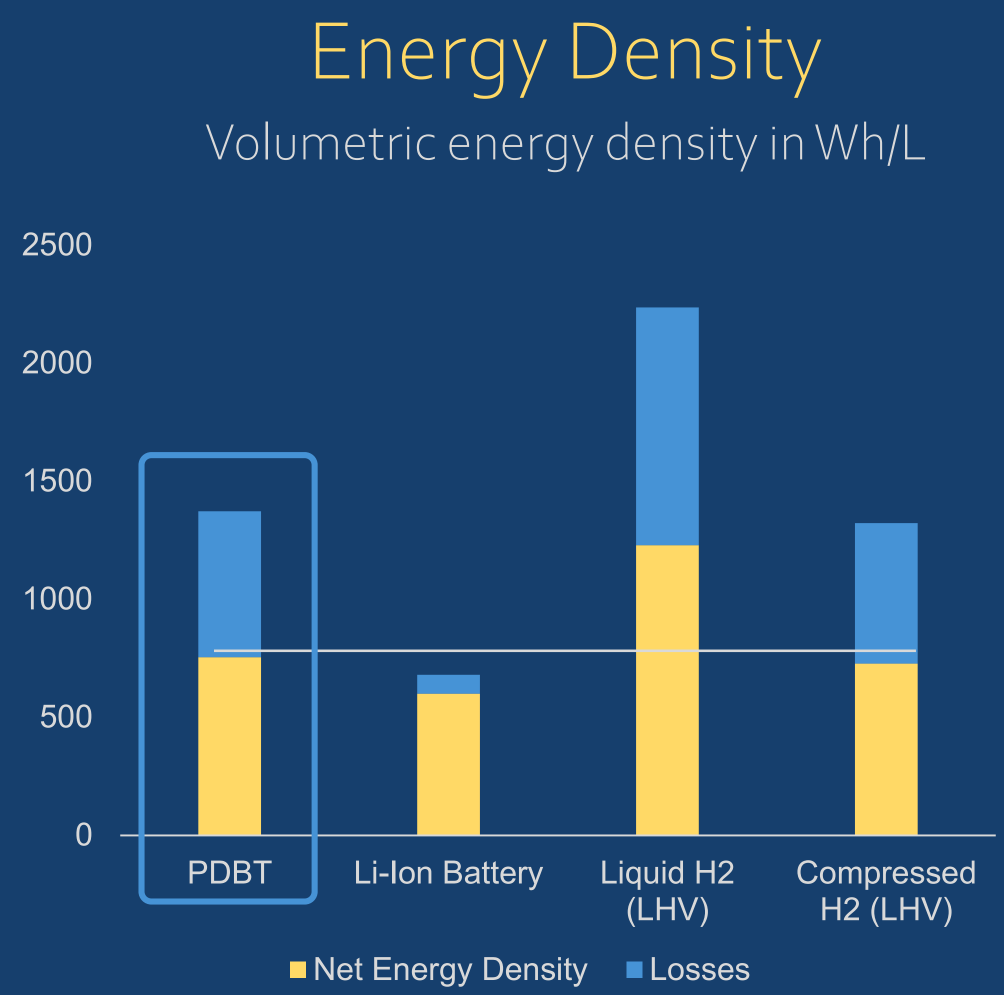
We intend to win on value and ecosystem enablement…

Capital Cost of 1MWH Energy Storage



- Storage capital only - excludes all fuel cell capital (H2 or PDBT)
- Li-Ion Batteries - Bloomberg 2021 average cost
- PDBT – Liquid at $3.5/KG, fuel and spent fuel tank capital

…as well as product differentiation.



Notes:
* Losses assumes LOHC direct fuel cell system (PDBT/DBT) and H2 fuel cell system operate at 55%. Further development required for DBT fuel cells to achieve parity with H2 fuel cell efficiency.

FY 2021-2022 Milestones & Status

Work in budget period was focused on defining the lab research requirements and determining practical feasibility of research program.

MILESTONES	STATUS
Transfer Fuel Cell (FC) Test Equipment to UD	Transfer and Setup Completed
Design & Implement Catalyst Synthesis Apparatus.	Completed
Prep. & TEM of Pt, Co Nanoframe Cat. Precursor.	Completed
FC Experiments with cyclohexane model fuel	Completed
Design and Implementation of FC feed system for involatile liquid fuels	Completed
FC Experiments with 18-H DBT; varying flow fields and diffusion layers.	In Progress
Scale-up Pt,Co Nanoframe catalyst, evaluate in FC.	Phase 1 goal by project end date

FY 2021-2022 Milestones & Status – Phase I TEA – Techno-Economic Analysis of Class 8 Trucks

Work in the budget period was focused on understanding the economics of a direct liquid fuel cell for truck transportation.

MILESTONES

- Model energized DBT fuel cost vs. alternative fuels.
- Model total cost of ownership of class 8 trucks using a DBT fuel cell vs. alternative powertrains.
- Calculate sensitivities of fuel and truck cost assumptions.
- Complete a break-even analysis of fuel cell parameters.
- Develop a technical roadmap.
- Complete and document a report.

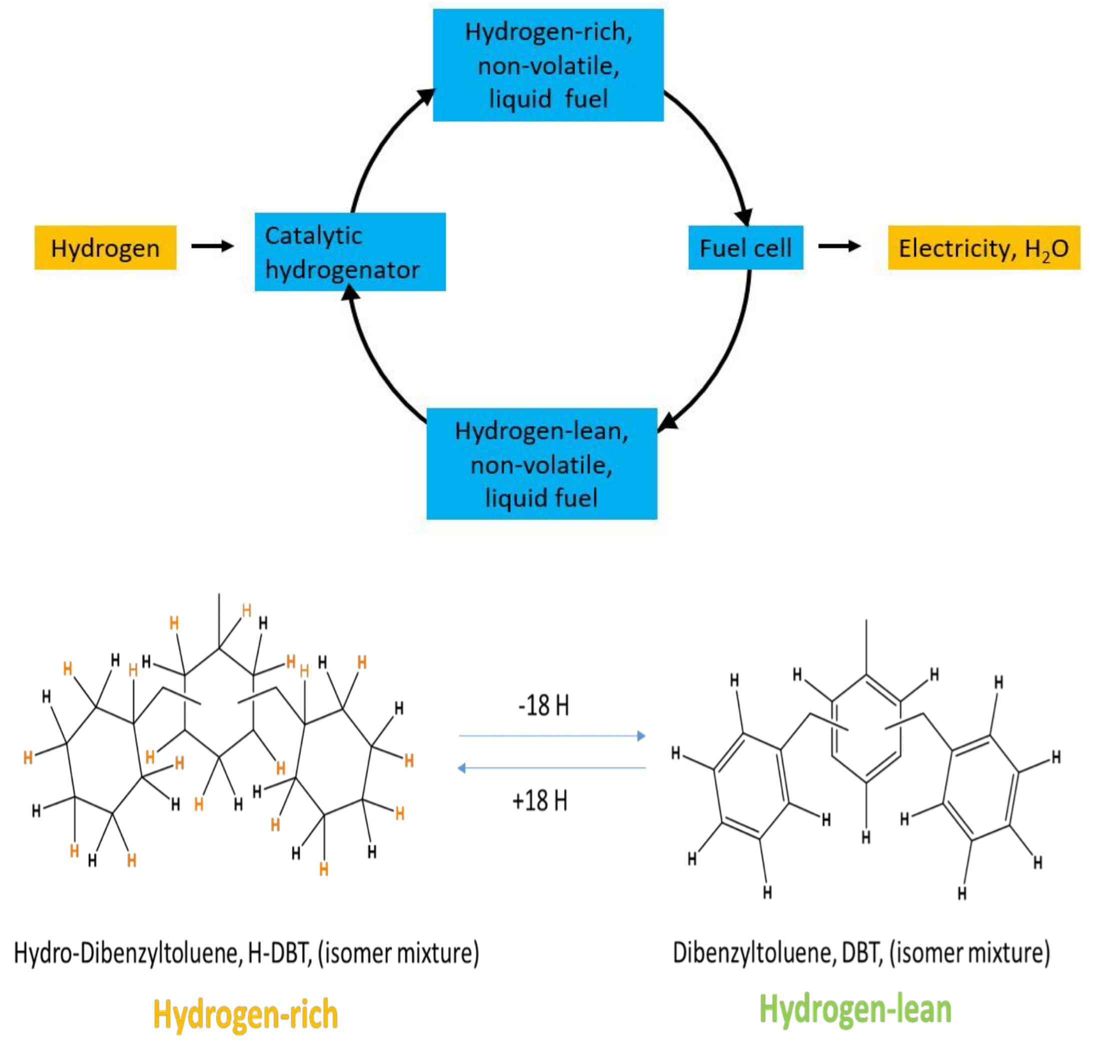
STATUS

- Completed
- Phase I goal by project end date
- Completed for fuel cost
- Phase I goal by project end date
- Phase I goal by project end date
- Phase I goal by project end date

RESEARCH & DEVELOPMENT

- Selection of the fuel pair
- Preliminary hypotheses testing completed at Colorado School of Mines labs (CSM Golden, CO)
- US Patent Pez, Herring (CSM), US 2018/00539570
- Conceptual and fuel test construction work - Kai Landskron, Lehigh University (to 7/1/2021)
- STTR Award to Energy 18H / University of Delaware
- Transfer of equipment and STTR award FC work to Ajay Prasad, Dept. of Mechanical Engineering, University of Delaware, Fuel Cell Research Center
- Preparation of catalyst material and MEA for testing with PDBT
- Conducting research of the fuel cell, MEA, and catalyst through partnership with University of Delaware

CHEMISTRY AND FUEL CYCLE



RESEARCH & DEVELOPMENT – TEA Results to Date

- Modeling of H-DBT fuel cost indicates structurally lower cost vs hydrogen alternatives
- Elimination of fuel station compression and high-pressure storage tubes drives lower costs than H2 options
- Equivalent energy basis assumes H2 in H-DBT at 24 KWH/KG H2 (gas H2 at 31.5 KWH/KG)
- Fuel cell capital and efficiency will be included in the final truck TCO analysis (not included).

<table>
<tr><th colspan="7">Estimated Fuel Prices Across Supply Options</th></tr>
<tr><th>Fuel Supply Node</th><th>Units</th><th>H-DBT Direct FC</th><th>H-DBT Dehydro Reactor to H2</th><th>H2 TT</th><th>Pipeline</th><th>Diesel</th></tr>
<tr><td>H2 Feedstock - Ref Only</td><td>$ / KG H2</td><td>5.34</td><td>7.49</td><td>5.34</td><td>5.34</td><td rowspan="5">N/A</td></tr>
<tr><td>Logistics Cost</td><td>$ / KG H2</td><td>0.99</td><td>3.47</td><td>2.64</td><td>0.34</td></tr>
<tr><td>Station Cost</td><td>$ / KG H2</td><td>0.00</td><td>7.93</td><td>5.76</td><td>7.55</td></tr>
<tr><td>Total Price - H2 Wt. Basis</td><td>$ / KG H2</td><td>6.33</td><td>18.89</td><td>13.73</td><td>13.23</td></tr>
<tr><td>Total Price, Equivalent Energy Input Basis</td><td>$ / KG H2</td><td>8.28</td><td>18.89</td><td>13.73</td><td>13.23</td></tr>
<tr><td>Total Price, Equivalent Energy Input Basis</td><td>$ / KWH</td><td>0.26</td><td>0.60</td><td>0.44</td><td>0.42</td><td>0.09</td></tr>
</table>

Our path to commercialization is fueled by strategic partnerships.

2021 | 2022 | 2023 | 2024 | 2025

Phase 1 | Research & Development

Phase 1: Awarded

Phase 2: Application Pending

Current Partners

Department of Energy (DOE) | University of Delaware Fuel Cell Research Center
Small Business Technology Transfer (STTR) Grant | *Hydrogen and Fuel Cells*

Research Partnerships

Seeking research partnerships across complimentary companies and potential customers

Phase 2 | Sales & Marketing

Commercialization

Ramp up commercialization efforts, including starting pilot programs

To be addressed in FY 2022 - 2024.

Generally, on improving the performance: the output power (mW/cm^3) and stability / lifetime of the fuel cell.

To the extent that its performance in individual 50 cm2 test cells would elicit sufficient interest to FC Companies for a further development of the technology; building FC stacks, etc.

Additionally, to prepare the commercialization of proprietary Membrane Electrode Assembly.

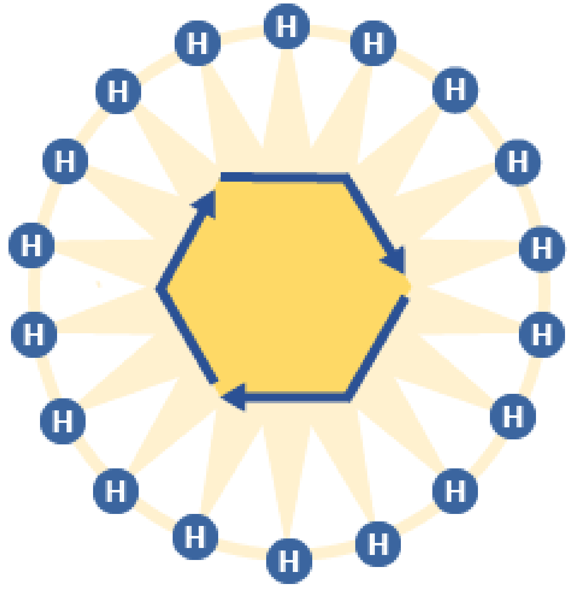
To be addressed in FY 2022-2024

Work in budget period 2 will focus on Improving the performance: the output power and stability/ lifetime of the fuel cell.

MILESTONES

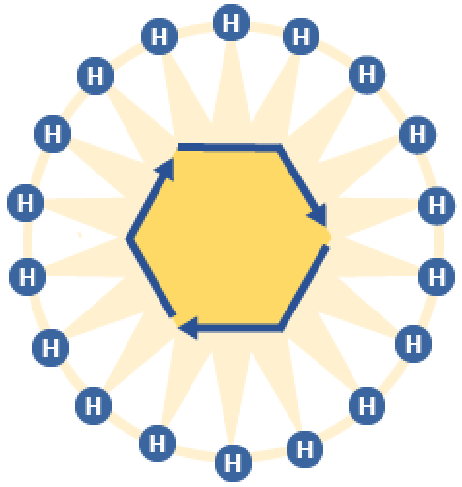
- Optimize the Pt,Co nanoframe 'binderless' catalyst layer for overall cell performance. Provide mass, energy balance data.
- Continue with study on the effect of varying flow fields –particularly the interdigitated FF which has been shown to be particularly effective in flow cells.
- Investigate the FC lifetime as a function of the anode potential relative to that of a standard electrode.
- Run exploratory FC tests with closely related 'fuel pairs': Perhydro benzyl toluene (DBT)/benzyl toluene (BT) and methyl cyclohexane/toluene.
- Q8 Go / No-Go decision to move to manufacturing

Thank You!



www.energy18h.com | Guido Pez

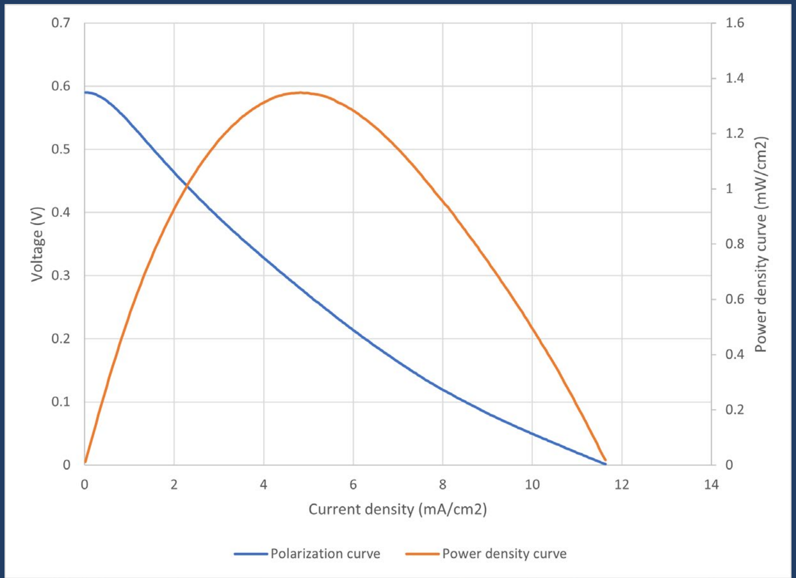
Additional Technical Information

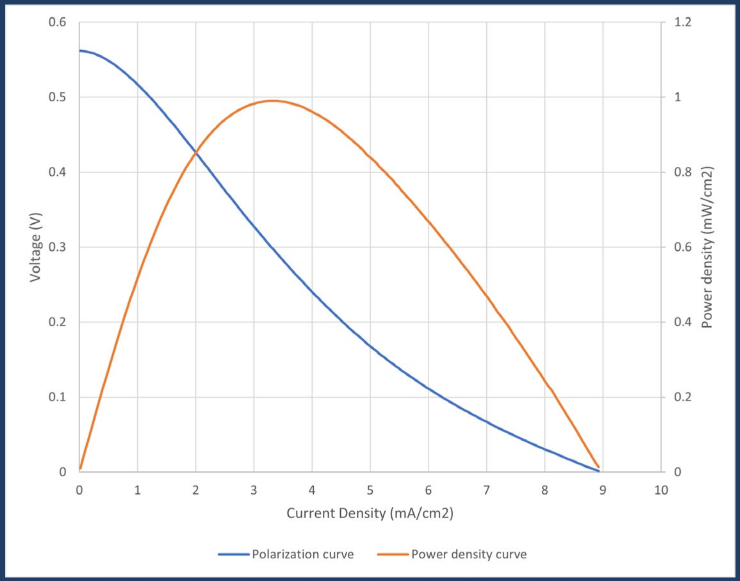


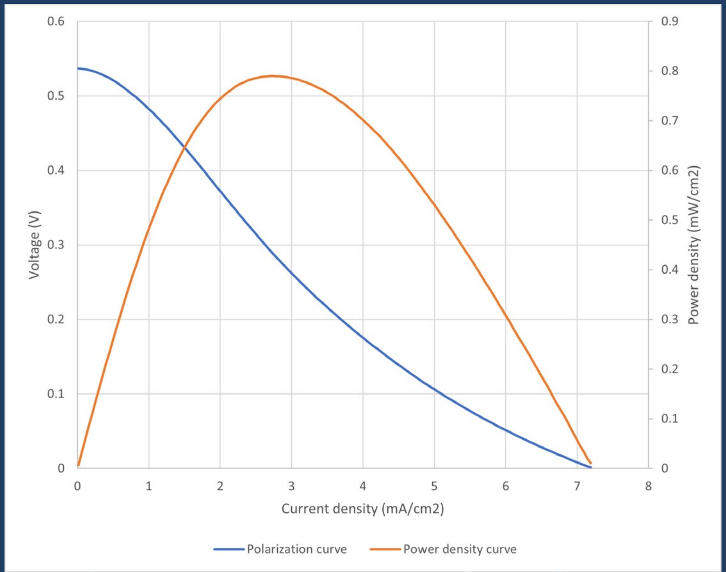
Fuel Cell Experiments with Perhydro Dibenzyltoluene, 18H-DBT

Polarization Curves (blue) taken over ca. 30 min. of FC operation from start of fuel/N2 injection.

Pt 4mg/cm2, Feed and cell at 160 deg C.







Fuel,0.1ml/min+N2 fed at 200sccm,32psia.
Oxygen,200sccm. Scan rate 2mA/sec.

Pale mist emitted from the anode outlet.

Same conditions, after 15 min.

Mist and dripping fuel from anode outlet

At 37 min., liquid feed shut off, continuing N2 flow.

No visible output from anode outlet

Fuel Cell Experiments

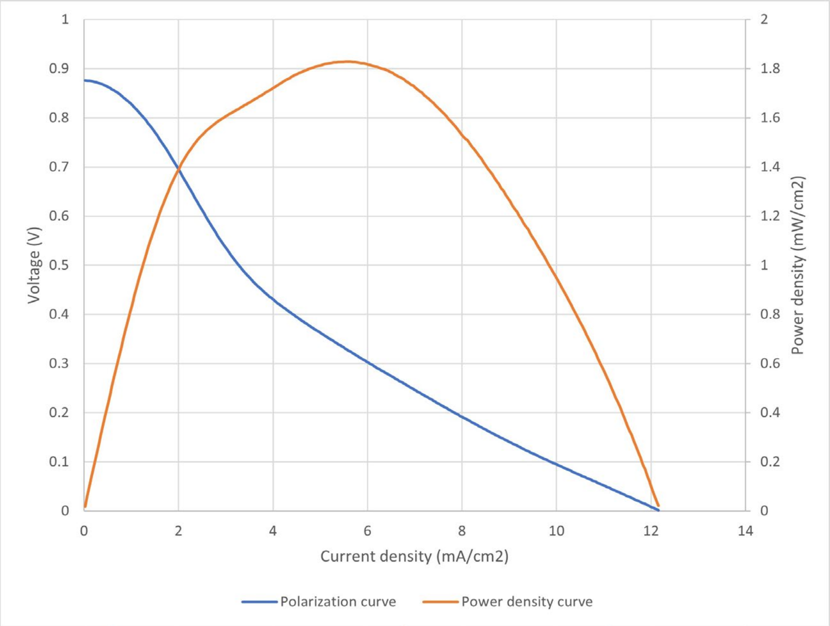
Done at University of Delaware – Fuel Cell Research Center

1. The cyclohexane/benzene 'fuel pair': The simplest six-membered ring system for which there is prior data. Refs. (1)&(2) (practically not viable because of the toxicity of benzene)

Employed a Danish Power Fuel Cell, a 25cm2 Dazapol MEA with a Polyimidazole (PBI) membrane, Pt/Co catalyst, 4mg/cm2 Pt

The performance is much poorer than the (optimized) 35mW/cm2 value from Kariya (1), but a little better than that reported by Ferrel (2). Both used a Nafion™ membrane at ca. 100 deG C, but very different fuel feed systems.

Underlines the importance of FC architecture!



Polarization curve (blue) for cyclohexane. Feed at 0.1 ml/min, vaporized at 160 deg C. Cell at 160 deg C. Scan rate 2mA/sec, sample period 0.5 sec. Max. Power Density (PD) : 1.8 mA/cm2

(1) N. Kariya, A. Fukuoka and M. Ichikawa. *Phys. Chem. Chem Phys.*, 2006, 8 1724-1730

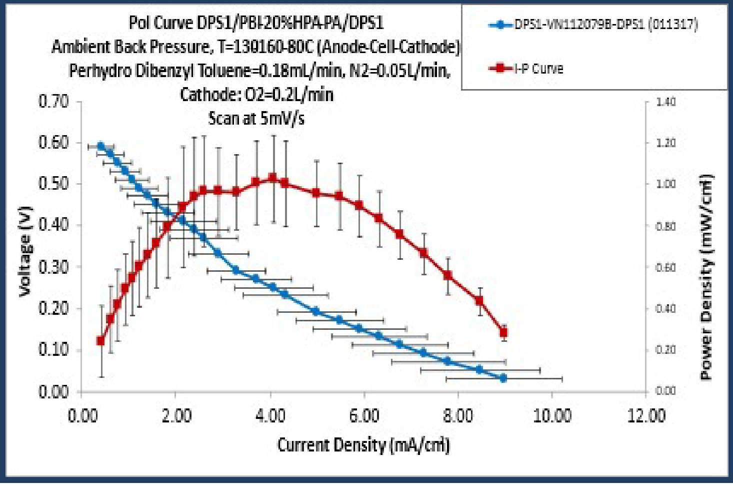
(2) J. Ferrell III, S. Sachdeva, T. A. Strobel, G. Gopalakrishnan, C. A. Koh, G. Pez, A. C. Cooper, and A. M. Herring. *Journal of the Electrochemical Society, 159 B371-B377 (2012).*

Discussion on polarization curves sequence for 18H –DBT. Comparisons with prior work at CSM

1. There was clearly a build-up of fuel in the cell
 Could be mitigated by introducing a more N2-diluted
aerosol of the fuel. Or a more reactive catalyst, or another flow field. (work in progress)

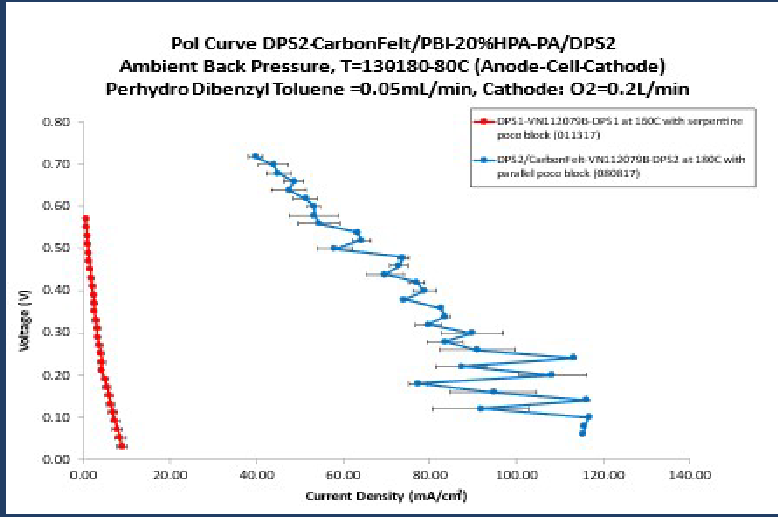
2. The initial performance of the cell is strikingly similar
to that from the prior work by the team at CSM. (Ref. US 2018/0053957) The corresponding Pol. Curve, at similar conditions is shown as Fig 1 on right. Their PBI/H3PO4 membrane contained a heteropoly acid (HPA) stabilizer, which it seems did not greatly impact the performance.

Fig.1



3. The CSM team saw a dramatic, more than an order of magnitude improvement in performance, by using a different cell architecture: a parallel flow field, a felt diffusion layer and operating at 180 deg. C. Fig. 2 shows, for comparison, a new plot of the Pol. Curve of Fig 1, (red curve on left) and of the new data (blue curve), both on the same x axis.

Fig. 2



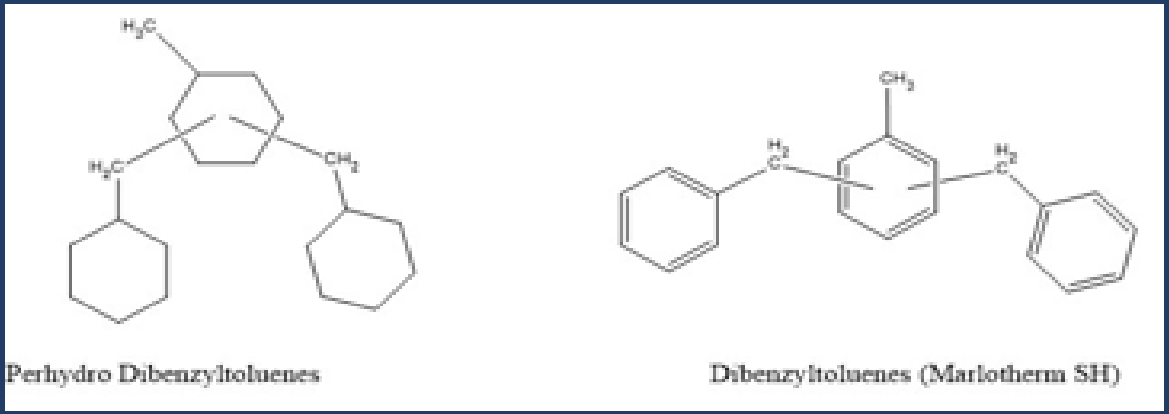
This much improved performance provides the encouragement to not only emulate, but with a better understanding, provide a pathway to ultimately, a commercial device,

- Specific technology transfer activities, and any potential patentable features, as well as licensing opportunities, have yet to be determined.
- Patent: Proprietary: System and method for electrochemical energy conversion and storage, US 2018/0053957 - 2/22/18, G. Pez & A. Herring as co-inventors
- Plan for future funding are in progress with a VC firm and a due diligence process is being executed.
- Marketing strategies and options are being developed with potential partners.

This project is developing a Direct Liquid Fuel Cell and associated energy storage and distribution equipment. Development will advance key technology needed for high demand energy storage and clean energy distribution system. The aim is to meet the relevant DOE targets.

2. The perhydro dibenzyltoluene (18H- DBT)/ Dibenzyltoluene (DBT) Fuel Pair.

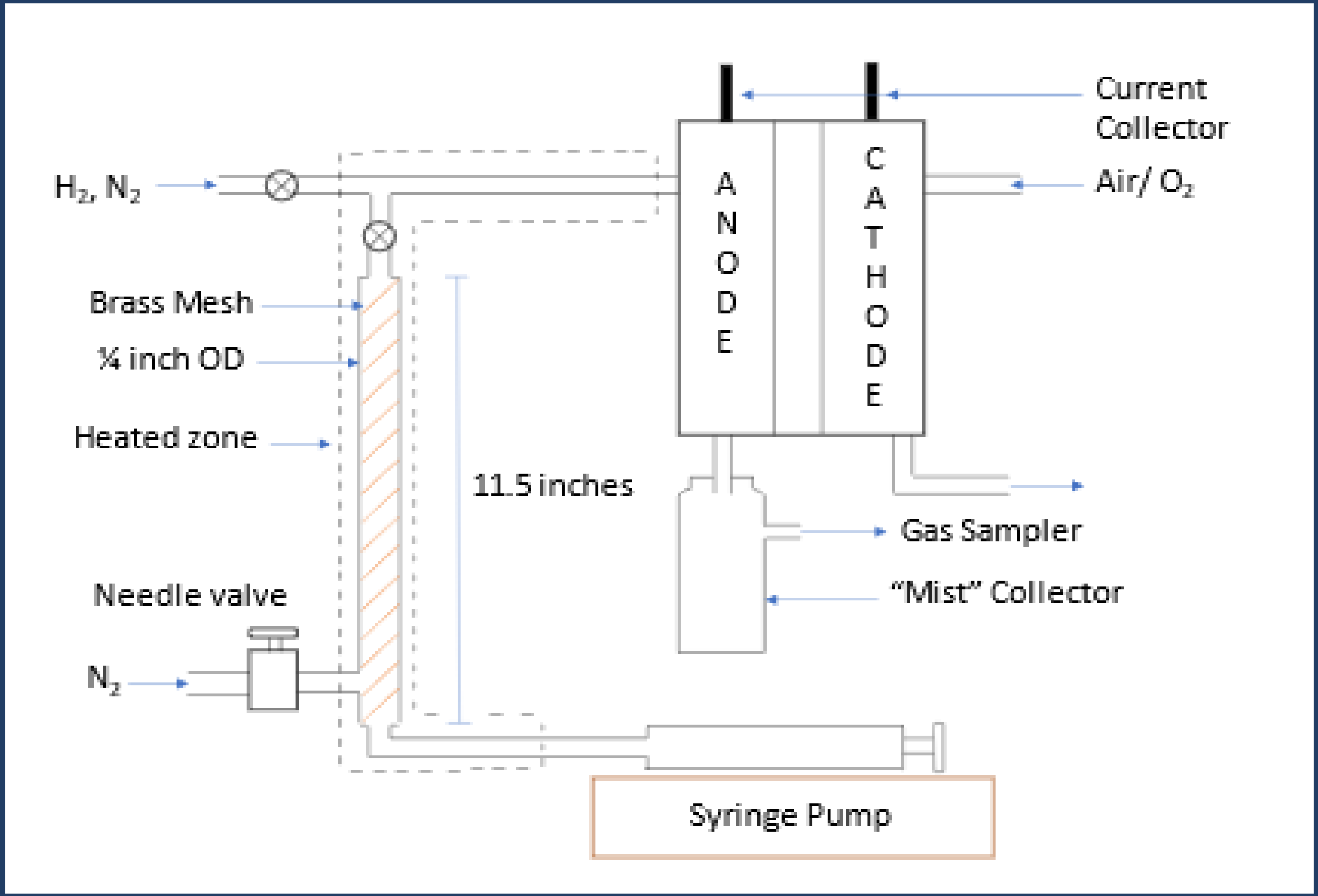
Both 18H-DBT and DBT are colorless light oils, and essentially involatile, electrically non-conductive liquids at the 160 deg C, Fuel Cell operating temperature.



Faced an uncommon situation: Noting that in most direct (e.g. Methanol) FC's, the liquid feed is in the vapor phase at the membrane-catalyst interface.

The concern was that the 18-H fuel would 'flood' the anode limiting access-and electrical conduction to the active interface. Needed a way to 'dilute' the fuel.

The CSM team used a combination of the fuel and nitrogen. We elaborated on this concept by 'blending' the fuel with N2 to controllably provide a fuel/N2 aerosol which appears as a light mist from the outlet of the cell.



Fuel Cell Apparatus for entering Low-Volatility Liquid Fuels.

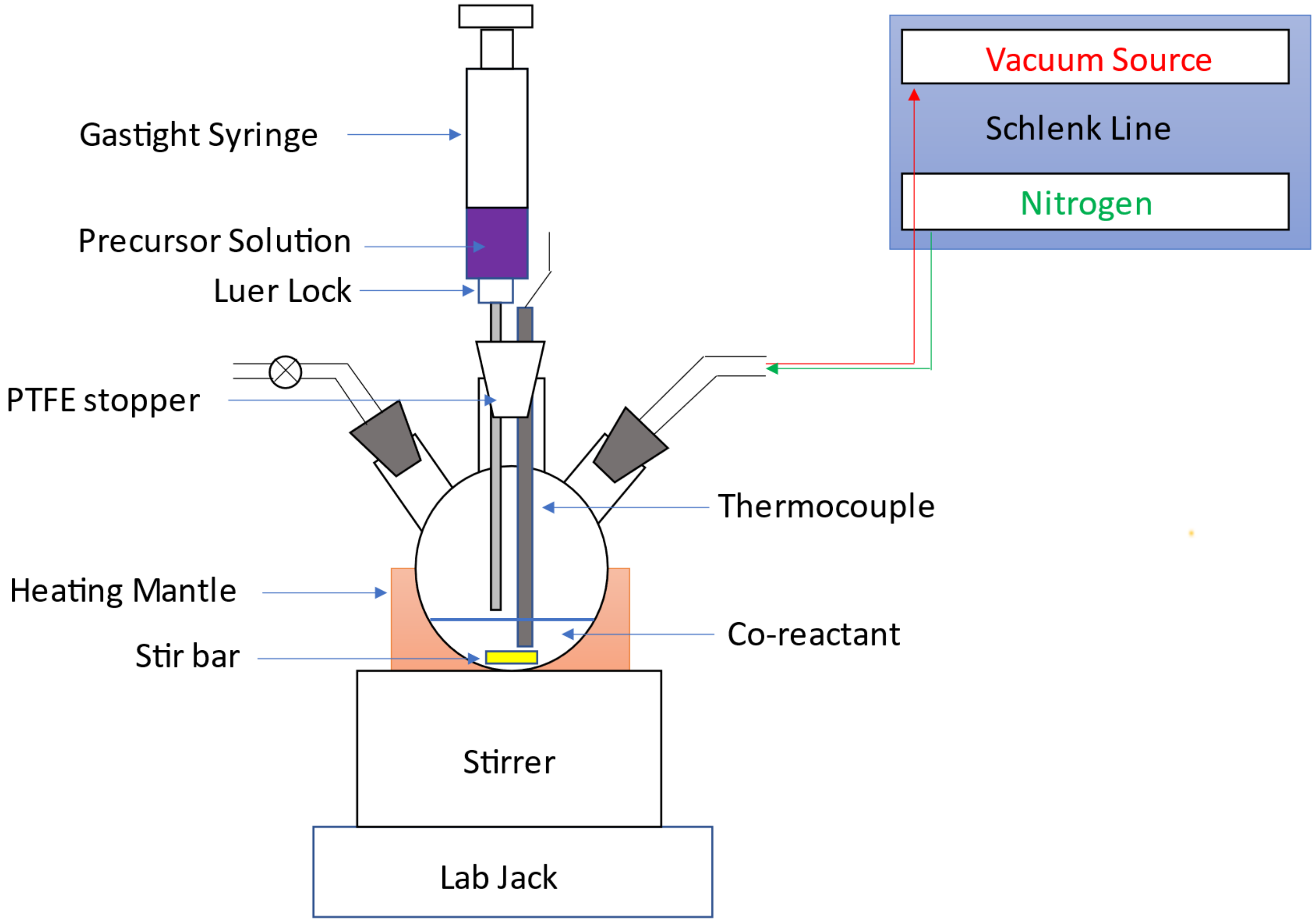
Nitrogen at a controlled pressure and flow rate is used to disperse the liquid, resulting in an N2/ liquid fuel aerosol feed to the cell.

Accomplishments

- <u>Preparation of Pt,Co Nanoframe Catalyst.</u>
- The STTR Proposal speaks to using this catalyst, in a ‘binder-less’ electrode for maximum performance.
- The Pt, Co catalyst was prepared following the method as detailed by S,Chen*et al.
- The designed special apparatus for the above is shown schematically (in the next slide) as Figure 1.
- Figure 2, on the following slide is the TEM image of the Pt-Co RD product.

* S. Chen, M. Li, M. Gao, J. Jin, M. A. Van Spronsen, M. B. Salmeron and P. Yang. *Nano Lett.* 2020, 20, 1974-1979

Figure1. Pt,Co – Nanoframe Catalyst Synthesis Apparatus.



TEM of Pt-Co RD Nanoframe Catalyst Precursor

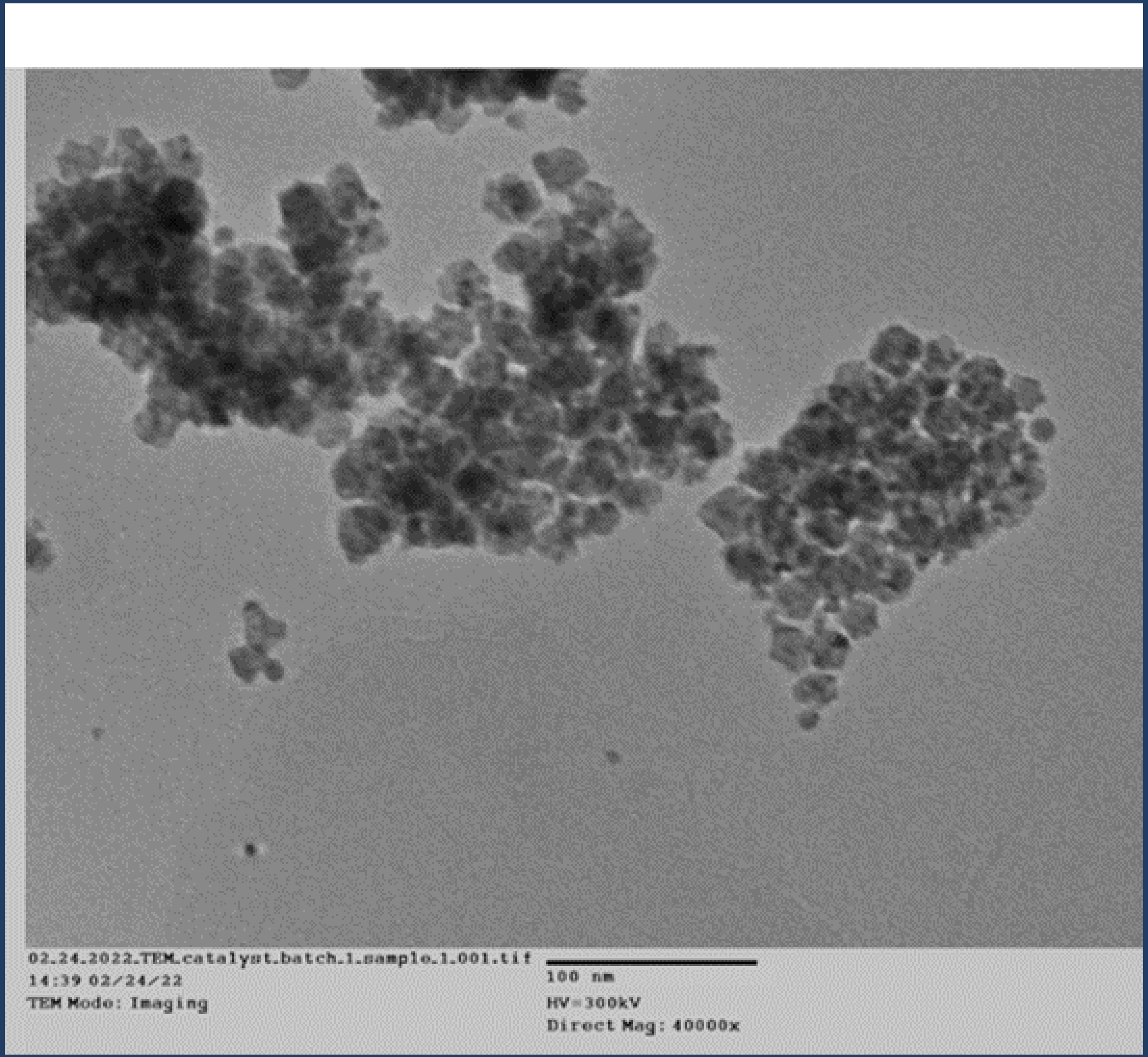


Image is consistent for the Title composition, as in S. Chen et al, Reference. (in previous slide)

Summary

PART A. Experimental Work-in progress, Summary and Path Forward.

1. Equipment: Installed, made operational the fuel cell test equipment at UD.
2. Designed and built the specialized catalyst synthesis apparatus. Employed for the synthesis of the precursor to the desired Pt,Co nanoframe catalyst and characterized by TEM. Etching away some of the Co with nitric acid (in progress) .
3. A cursory Fuel cell study of the cyclohexane/benzene ‘fuel pair’ provided an instructive entry to using H2-regenerable organic liquid fuels.
4. Faced the unique challenge of providing an involatile, viscous, water insoluble liquid to a fuel cell. For which we developed a method and apparatus for providing nitrogen-fuel aerosol (fine mist) to the cell.
5. This enabled the first experiments with 18H- DBT, the desired fuel. Which gave a similar performance as in prior work by CSM. And from comparisons with their data, it provided the confidence that we could greatly enhance our cell’s performance, by changing its architecture e.g., varying the flow field and diffusion layer.
6. Employing the Pt,Co nanoframe catalyst, for enhanced activity will require preparing a ‘binderless’ electrode. From tests with a commercial catalyst we found that this should indeed be possible.

PART B. TECHNO-ECONOMICS STUDY

1. Fuel H-DBT and H2 fuel costs were studied across multiple supply chain scenarios.
2. Sensitivity calculations are underway.
3. Total cost of ownership study for class 8 truck scenarios has begun.
4. A final report with TCO sensitivities is planned to be completed by end June, the Phase I deadline.