FARADAY TECHNOLOGY, INC.

CO_2 Reduction to Hydrocarbons via Copper Gas-Diffusion Electrocatalysts

DOE SBIR-STTR 2017 Phase I Release 1 Webinar

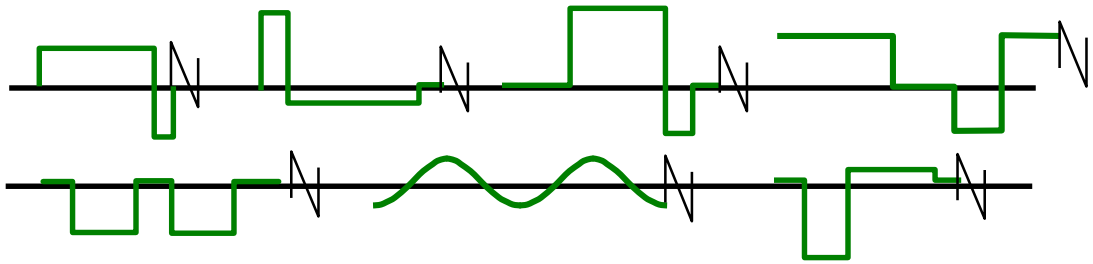
Carbon Capture & Carbon Utilization

Brian Skinn
Faraday Technology, Inc.

Sponsored by:
US DOE
Contract No. DE-SC0017199

12 May 2017

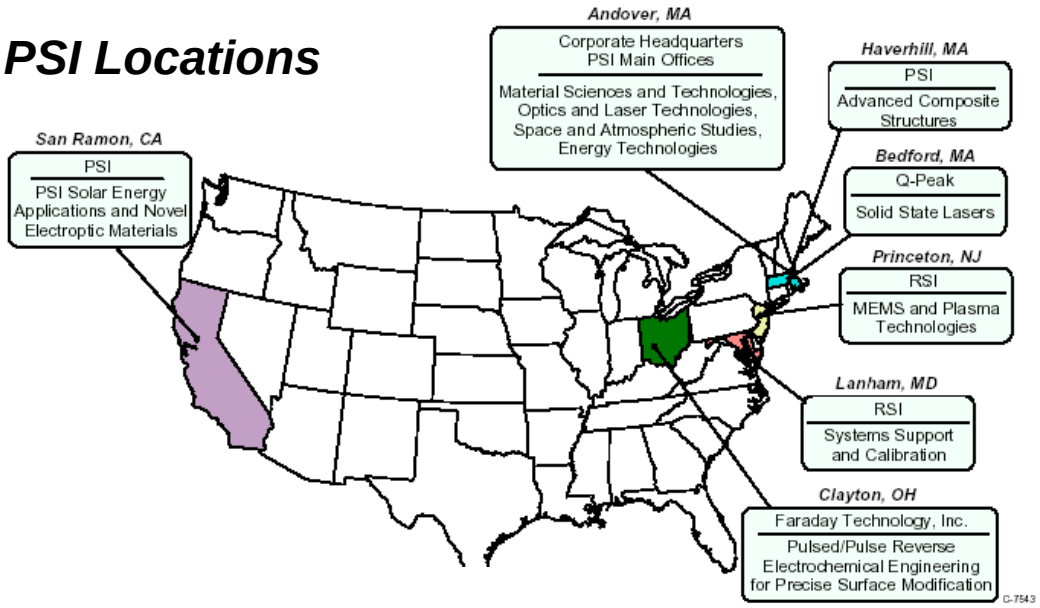
Introduction to Faraday Technology, Inc.

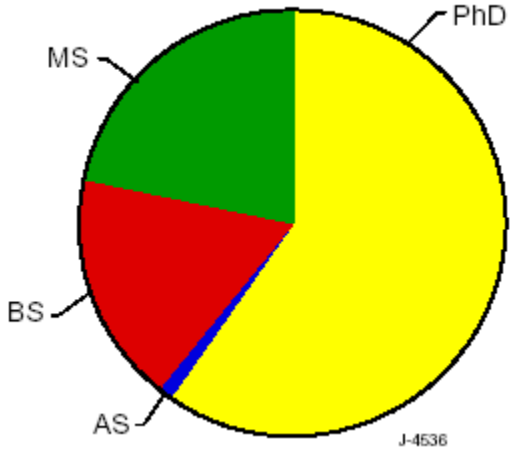


FARADAY TECHNOLOGY, INC.

- Electrochemical engineering
  - ~29 Issued Patents and ~15 Pending Patents in this area
  - www.FaradayTechnology.com
- Subsidiary of Physical Sciences, Inc. (Boston, MA)
  - www.psicorp.com
- Collective employment ~160; ~90 MS/PhDs
- Annual revenue of ~ $60 million
- ~ 100 patents company-wide in numerous fields

PSI Locations





PSI Employees by Education

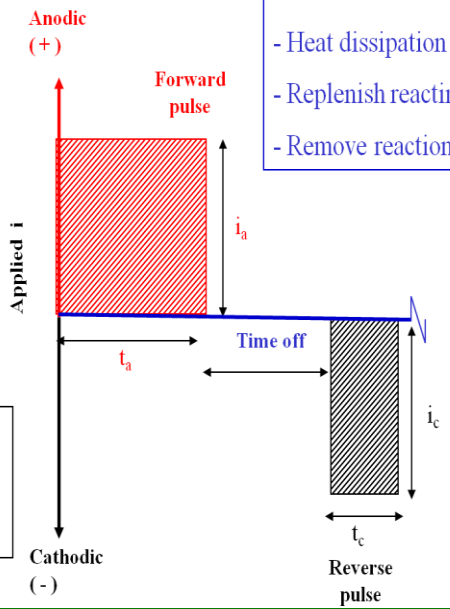
VISION - TECHNOLOGY PLATFORM

"…to be known as the company that changed the focus of electrochemical engineering from the art of complex chemistries to the science of pulse/pulse reverse electric fields…"

Electrochemical Machining, Polishing, Deburring, Through-Mask Etching

Anodic Pulse "Tuned" to:
- Control current distribution
  - ➔ Eliminates need for viscous, low water content electrolytes

Off-Time "Tuned" to:
- Heat dissipation
- Replenish reacting species
- Remove reaction products



Cathodic Pulse "Tuned" to:
- Reduce oxide/depassivate surface
  - ➔ Eliminate need for HF

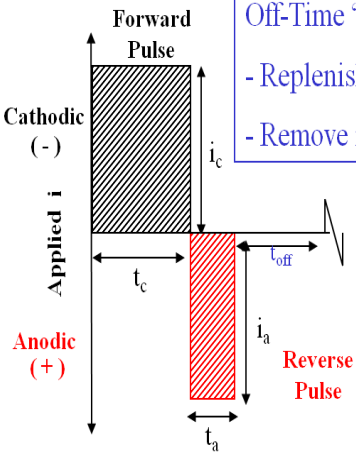
- 2008 Blum Scientific Achievement Award for Pulse Reverse Surface Finishing
- 2016 R&D 100 Finalist for HF-Free Nb SRF Cavity Polishing

Electrodeposition/Plating

Cathodic Pulse "Tuned" to:
- Enhance mass transfer
- Control current distribution
  - ➔ Simplify chemistry

Anodic Pulse "Tuned" to:
- Remove H_2 effects
  - ➔ Acidify interface

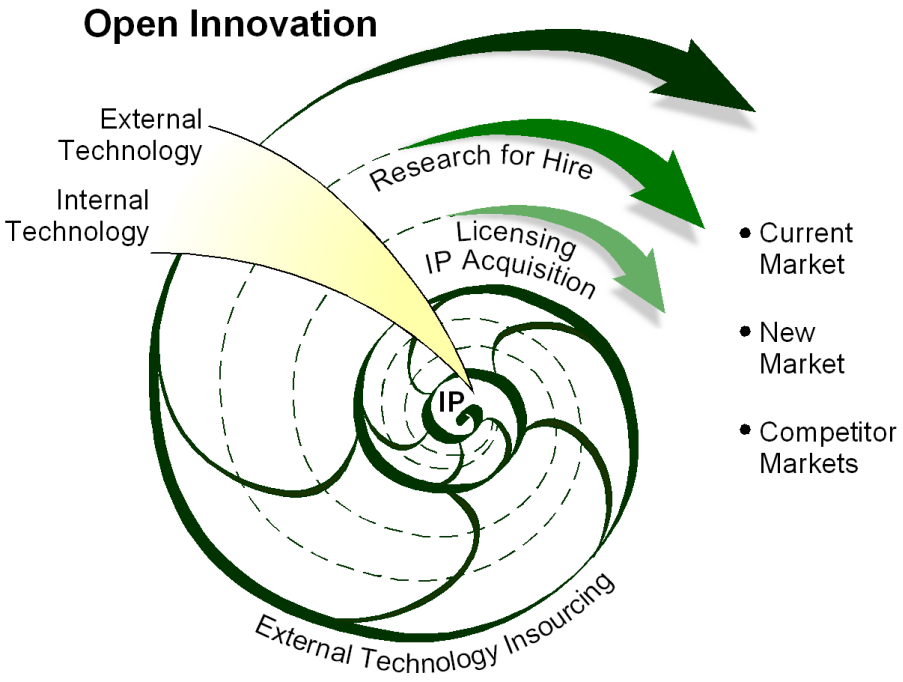
Off-Time "Tuned" to:
- Replenish reacting species
- Remove reaction products



- 2011 R&D 100 for Co-Mn Alloy Plating
- 2013 Presidential Green Chemistry Challenge Award for Cr^{+3} Plating

FARADAY TECHNOLOGY, INC.

FARADAY'S BUSINESS MODEL: OPEN INNOVATION



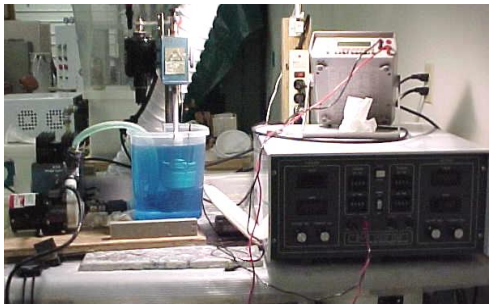
- Establish IP (29 issued U.S. patents + know-how)
- Leverage Federal SBIR opportunities as non-equity technology funding
  - Retain IP rights
- Collaborate with universities and government laboratories
- Develop electrochemical engineering solutions based on PC/PRC processes
- Transition technology & competitive advantage to large companies via
  - Field-of-use licenses
  - Patent sale (8)
- Direct transition to interested government entities

Detailed mechanistic understanding is not required;
Development of robust process is critical!

FARADAY'S TECHNOLOGY DEVELOPMENT

Technology development begins conceptually and is demonstrated at the bench-scale and developed through α/β-scale validation.

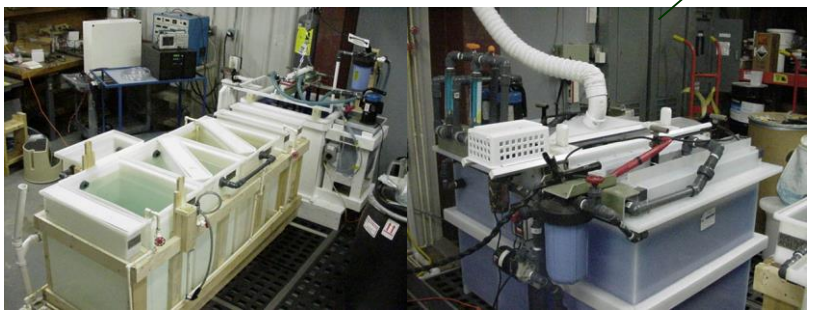
Technology/IP Alignment

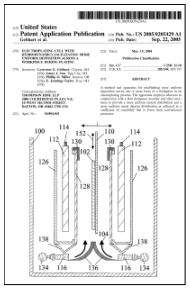


Bench-Top Feasibility

Cell Design

Pilot-Scale Validation



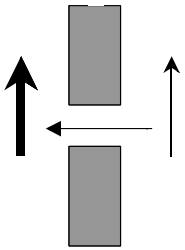


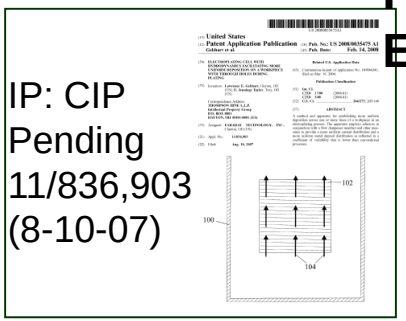
IP: Issued 7,553,401 (6-30-09)

Production-Scale Validation

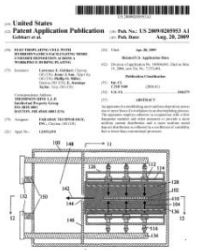
Novel Flow

Further IP Enhancement





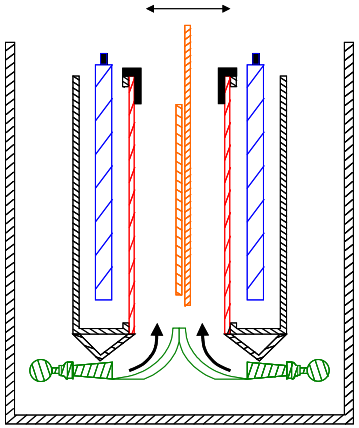
IP: CIP Pending 11/836,903 (8-10-07)

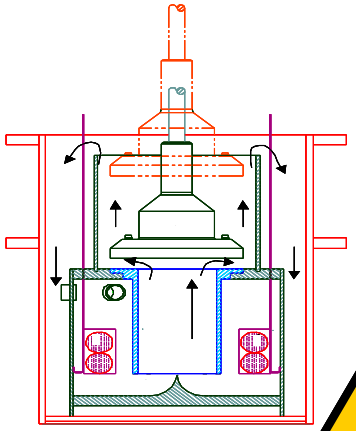


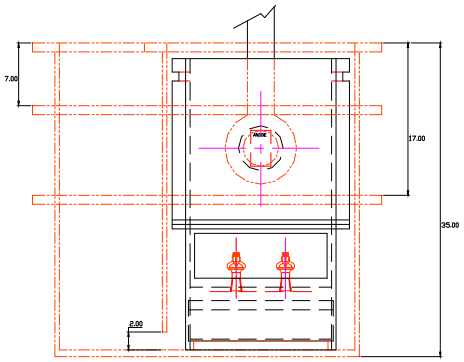
IP: Pending 12/431,030 (4-28-09)

FARADAY TECHNOLOGY, INC.

APPARATUS – PROCESS







Cell Geometry

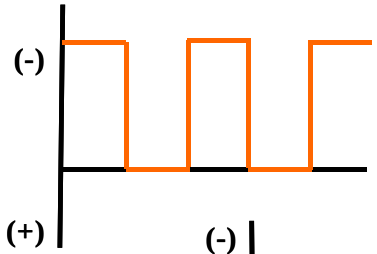
Secondary and Tertiary Current Distribution:
Chemistry/Waveform Parameters, Temperature

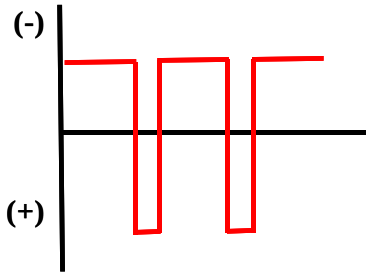
→ ***Throwing Power, Feature Size/Shape***

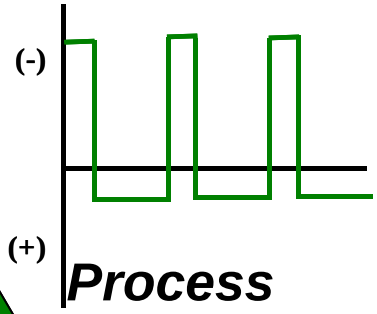
Primary Current Distribution:
Agitation, Anode-Cathode Design and Spacing

→***Panel Uniformity***

→***Must be Optimized Before Implementing Process***



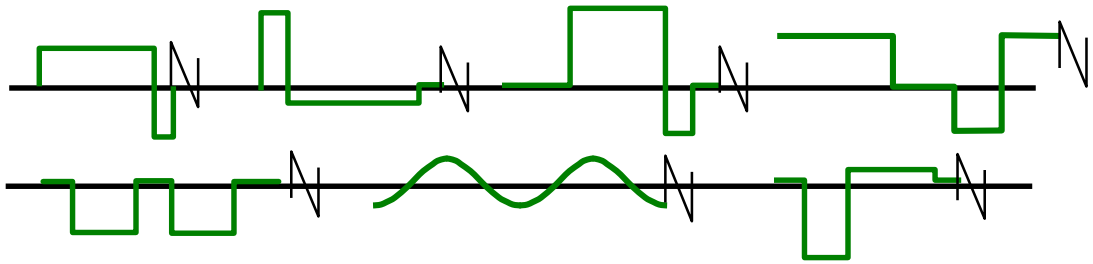




Process Parameters

FARADAY TECHNOLOGY, INC.

Program Overview



Program Overview

- **Timeline**
  - Start date: 21 Feb 2017
  - End date: 20 Nov 2017

- **Challenges**
  - Copper deposition optimization
  - Catalyst performance evaluation

- **Partners**
  - MIT (Fikile Brushett)

Project Team Members

- **Faraday**
  - Brian Skinn (PI)
    Phone: 937.836.7749
    Email: brianskinn@faradaytechnology.com

- **DOE**
  - TPOC: I. A. Aurelio
    isaac.aurelio@netl.doe.gov

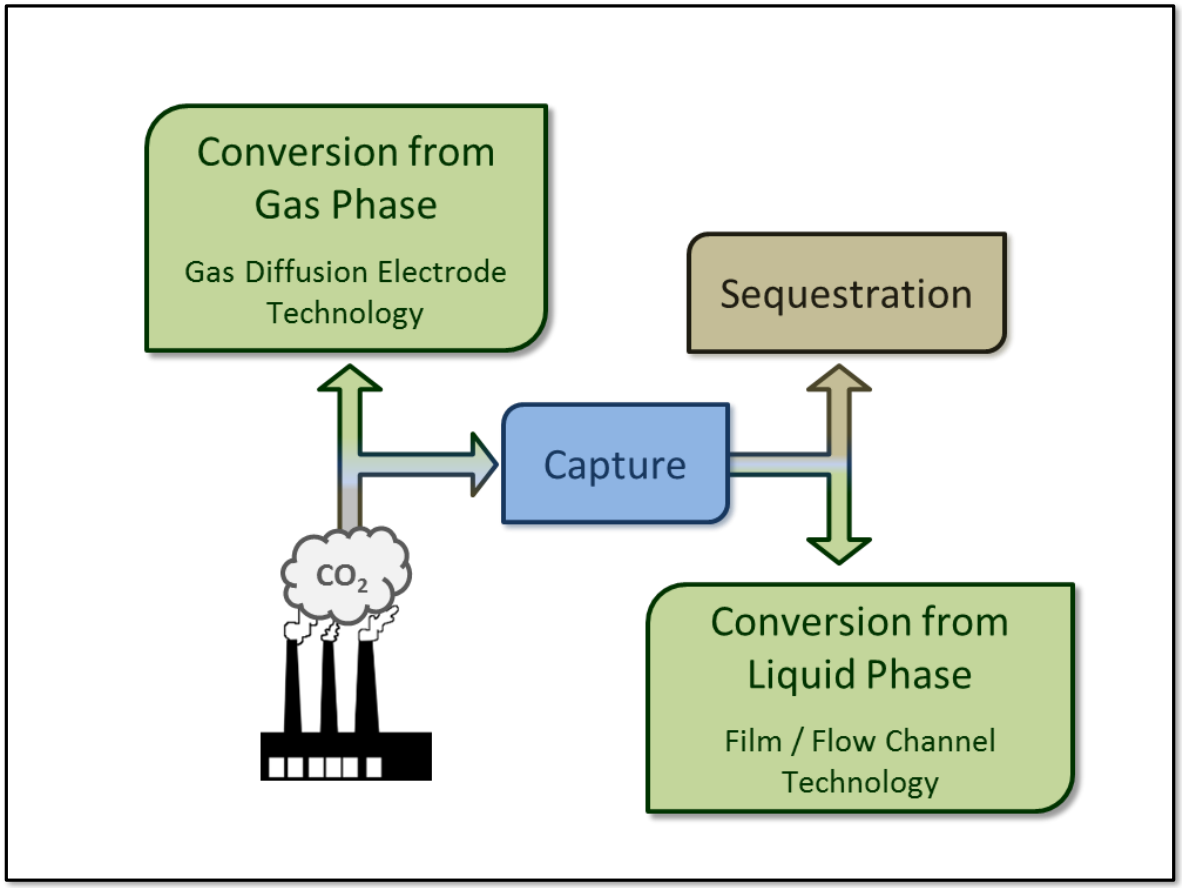
- **Massachusetts Institute of Technology**
  - Fikile Brushett
    - Ph: 617.324.7400
    - Email: brushett@mit.edu

Problem or Opportunity

- **Problem**
  - Development of conversion/utilization technologies for transforming captured CO_2 to value-added products are needed to enhance the cost proposition of carbon capture technologies.

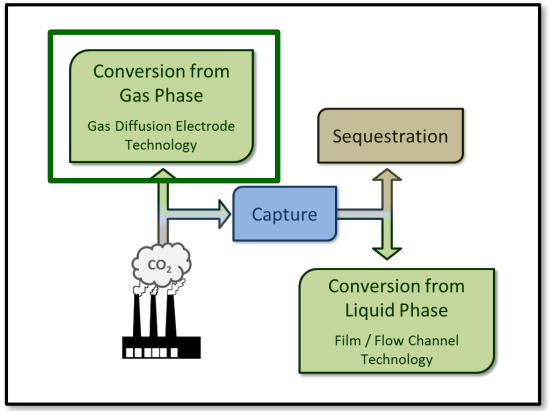
- **Opportunity**
  - Demonstrate potential for tailored micro-/nanoparticulate Cu GDE electrocatalysts fabricated by FARADAYIC® ElectroDeposition in combination with state-of-the-art MIT GDE electroreactor system to enable cost-effective CO_2 conversion to hydrocarbons such as ethylene.

Problem or Opportunity



Objective of Program

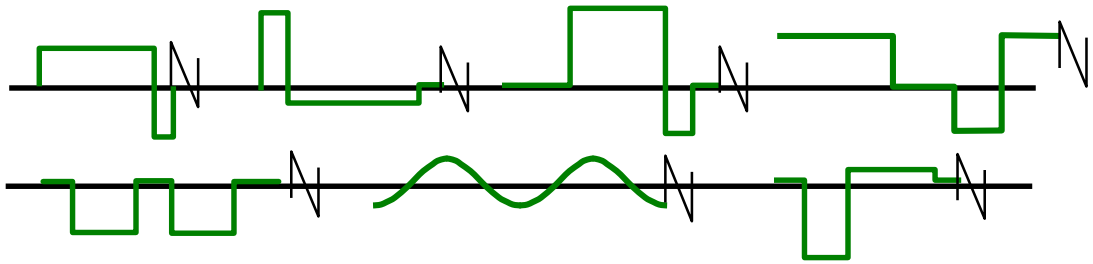
- The objective of the program is to develop an electrocatalytic system for economical conversion of CO_2 to ethylene, encompassing:
  - FARADAYIC® ElectroDeposition of Cu electrocatalyst with tuned microstructure and other properties onto GDL substrates
  - State-of-the-art electroreactor technology incorporating modern gas-diffusion electrode (GDE) materials



Technical Approach

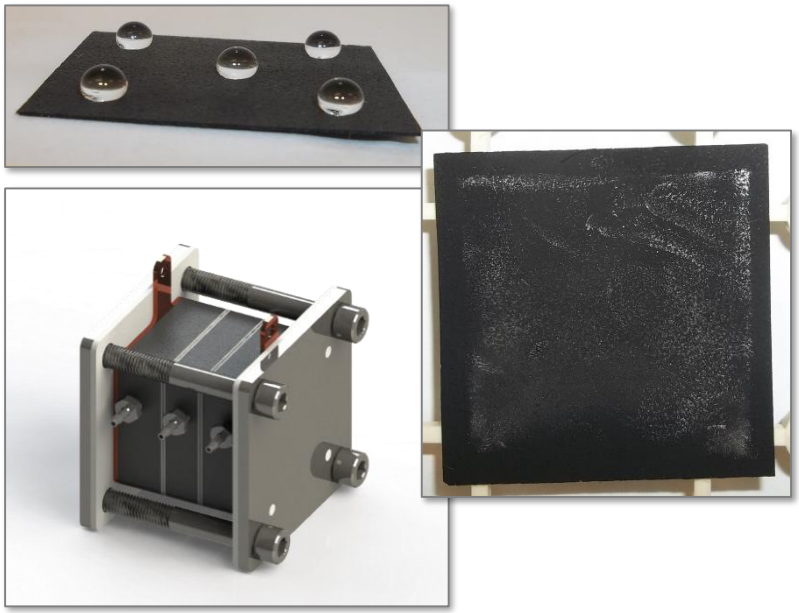
- For the Phase I program **Faraday** will:
  - Construct a benchtop FARADAYIC® ElectroDeposition Cell
  - Develop candidate FARADAYIC® ElectroDeposition protocols
  - Perform a preliminary techno-economic analysis of the electrocatalytic system
- For the Phase I program **MIT** will:
  - Evaluate/analyze Cu electrocatalysts
  - Build/Retrofit demonstration-scale electroreactor
  - Perform electrocatalysis tests & products analysis

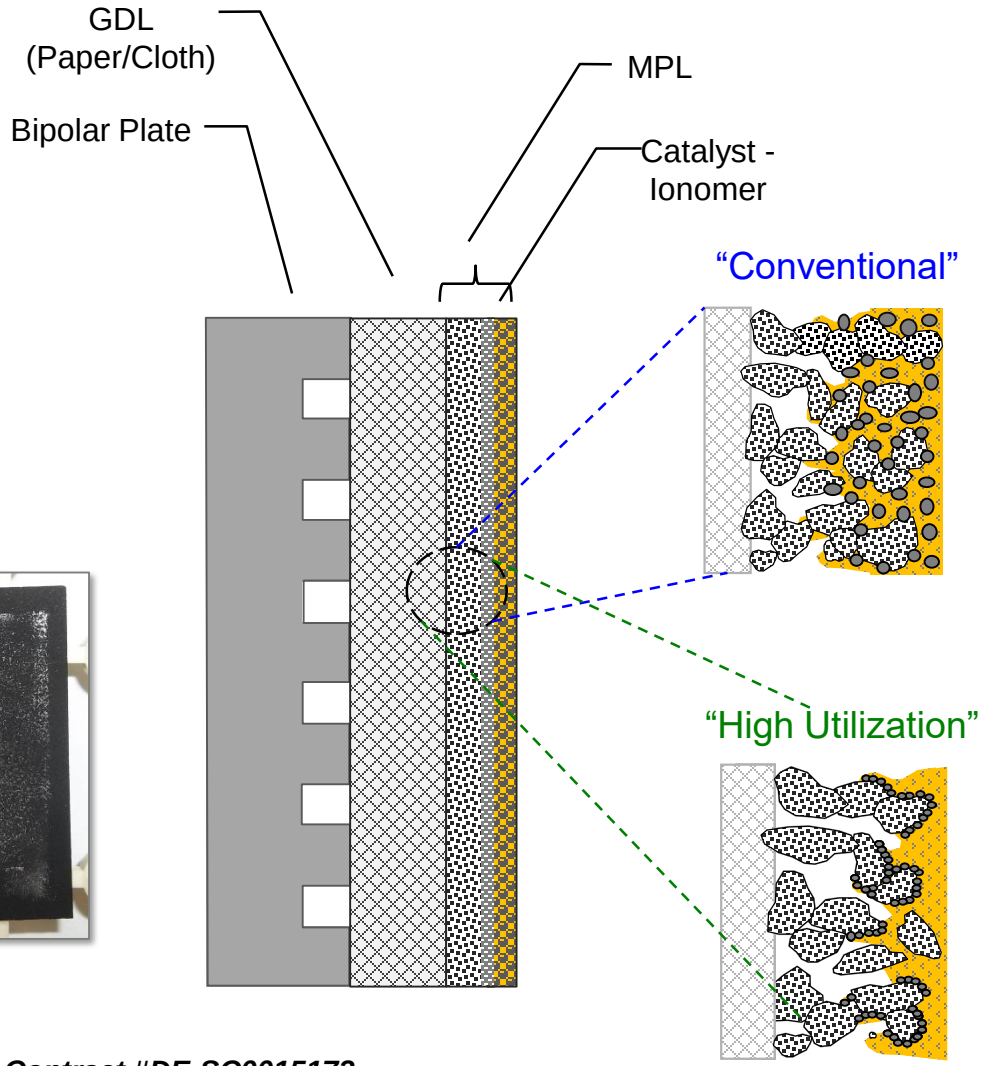
Prior Work



Prior Work: FARADAYIC® Tin Electrocatalysis

- **FARADAYIC® Sn Deposition**
- **CO_2 Conversion to Formate**
- **GDE-Based Electroreactor**



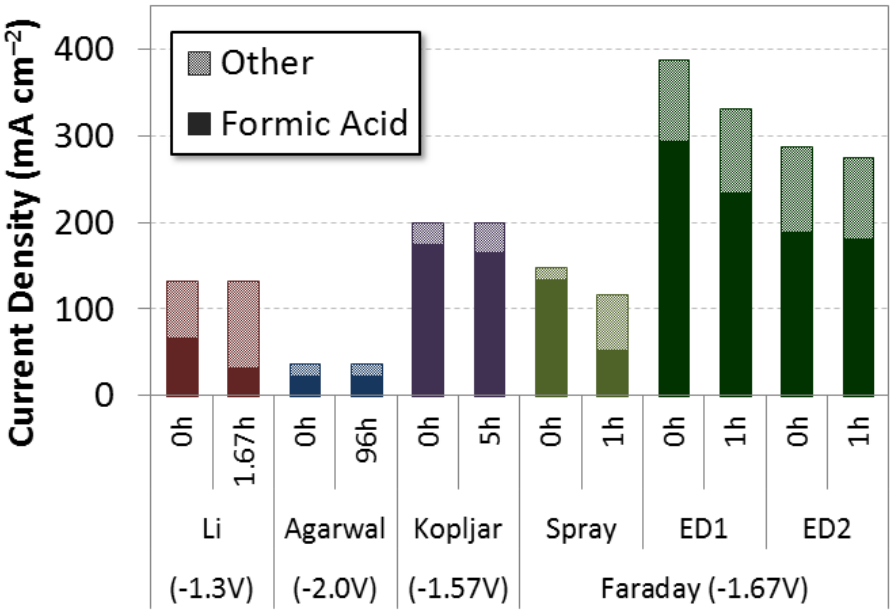


DOE STTR Contract #DE-SC0015173

FARADAY TECHNOLOGY, INC.

Preliminary Results

- Preliminary **FARADAYIC®** **ElectroDeposition (ED)** samples show significantly increased total and FA-efficient current densities relative to conventional **spray-coating method** and literature data
  - $j_{total} \geq 275$ mA cm^{-2}
  - %FA $\geq 70\%$
- Favorable short-term catalyst durability
- Significant potential for optimization
  - Ionomer loading
  - Sn electrocatalyst loading
  - Sn electrocatalyst ED parameters
  - GDE (GDL/MPL) parameters



(Half-cell potentials vs SHE)

Li and Oloman. *J Appl Electrochem* **35**: 955, 2005.

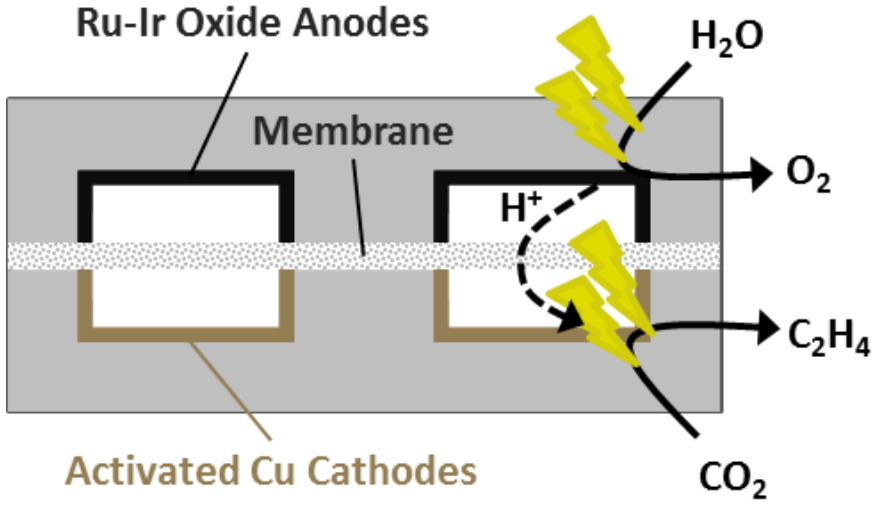
Agarwal et al. *ChemSusChem* **4**: 1301, 2011.

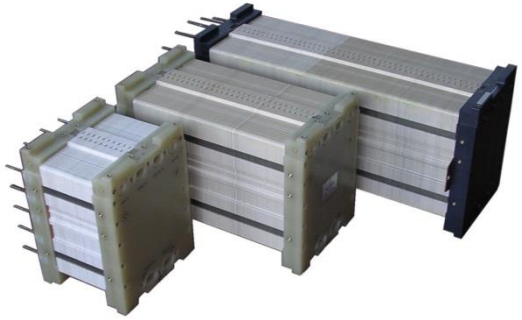
Kopljgar et al. *J Appl Electrochem* **44**: 1107, 2014.

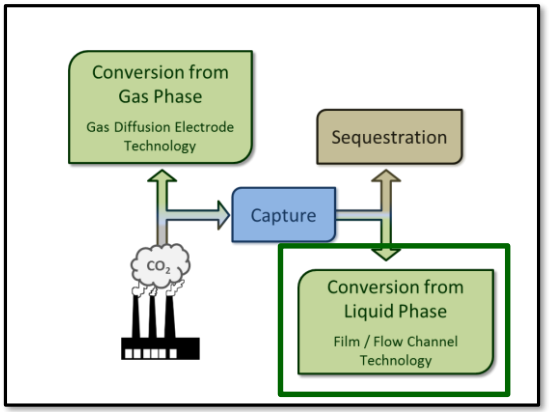
DOE STTR Contract #DE-SC0015173

FARADAYIC® Cu Film Electrocatalysts

- Flow channels for electrolytes
- CO_2 reduction on Cu catalyst
- O_2 evolution on commercial mixed oxide anode
- Anticipate direct use of CO_2-laden capture media
  - Amines, etc.





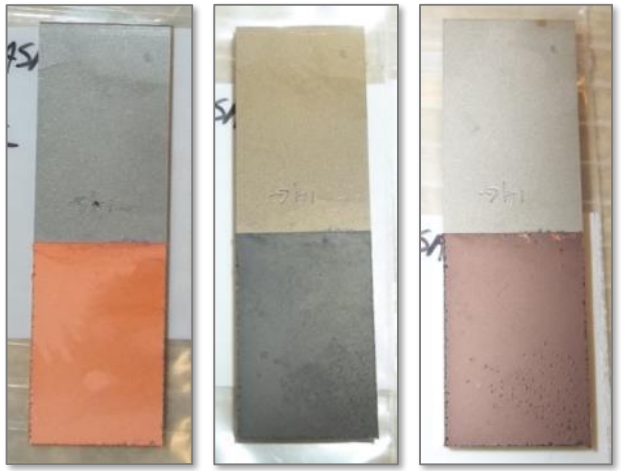


NASA SBIR Contract #NNX14CC53P
DOE STTR Contract #DE-SC0015812

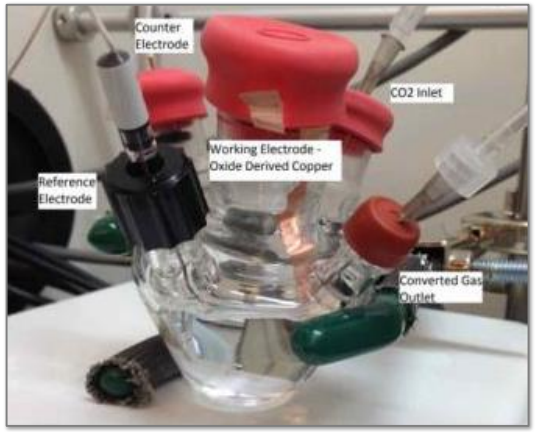
FARADAY TECHNOLOGY, INC.

Testing of FARADAYIC® Cu Film Electrocatalysts

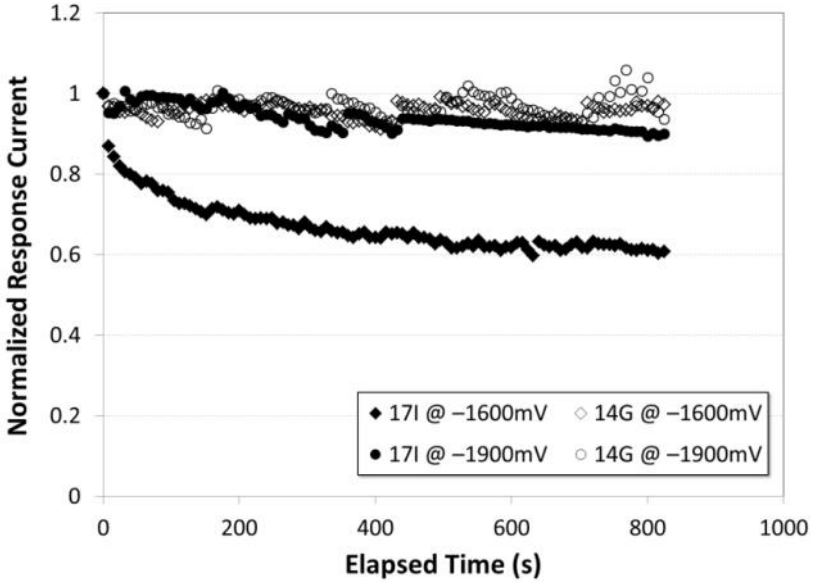
Deposit Oxidize Reduce

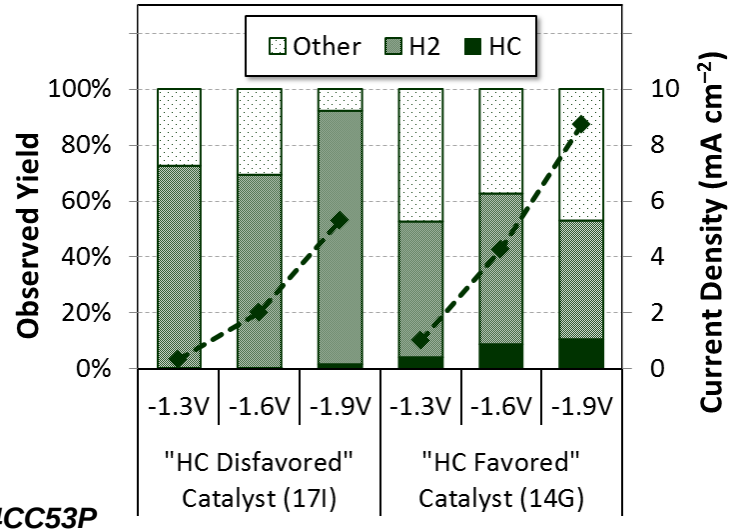


Li & Kanan, J Am Chem Soc 134: 7231 (2012)



Chronoamperometry
&
GC Product Analysis



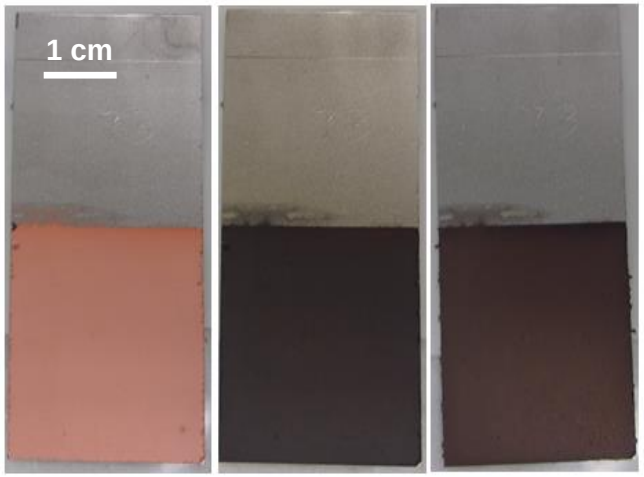


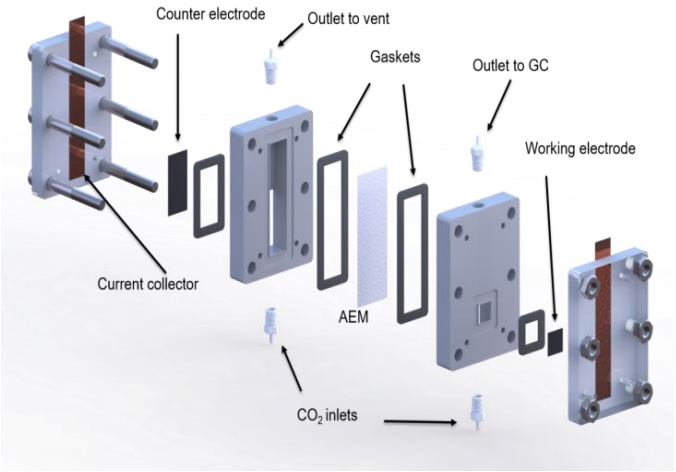
NASA SBIR Contract #NNX14CC53P

FARADAY TECHNOLOGY, INC.

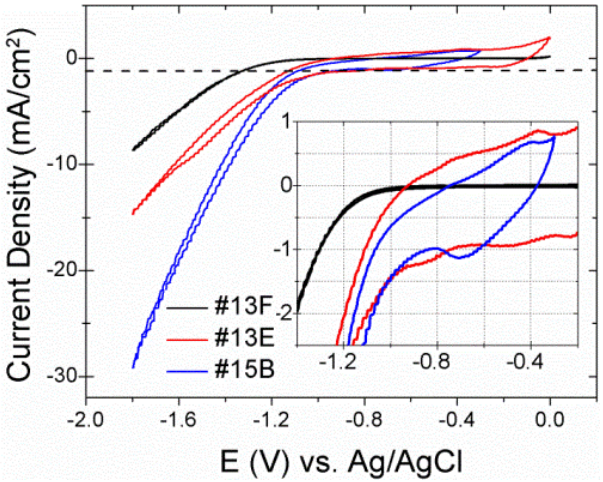
Testing of FARADAYIC® Cu Film Electrocatalysts

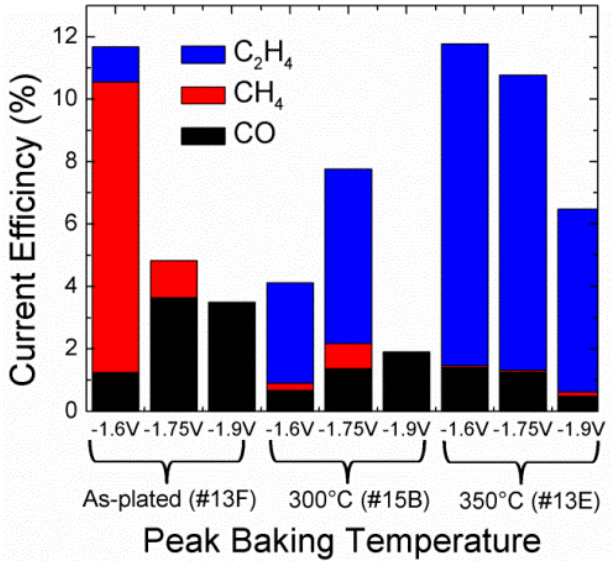
Deposit Oxidize Reduce





Cyclic Voltammetry
&
GC Product Analysis





DOE STTR Contract #DE-SC0015812

FARADAY TECHNOLOGY, INC.

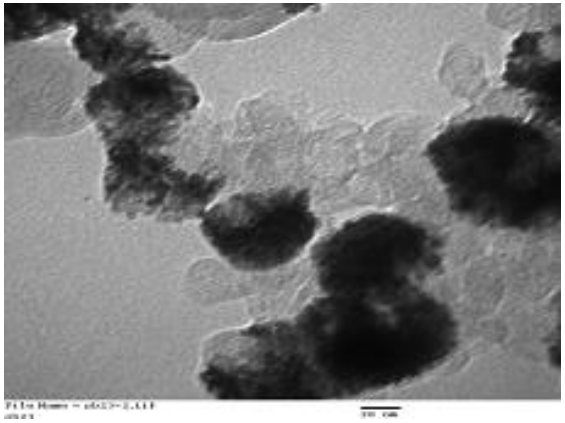
Prior Work: FARADAYIC® ElectroCatalyzation

- Low-loading deposition of Pt fuel cell catalyst
- Beta-scale batch system (NSF)
- Pilot-scale reel-to-reel system (OH)

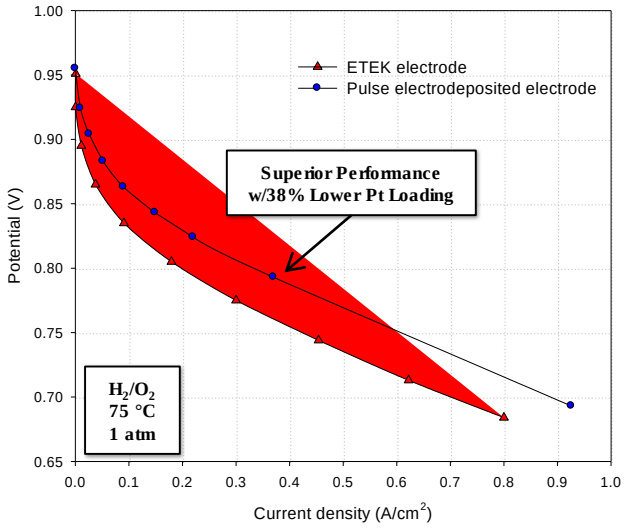
Batch System **Continuous Reel-to-Reel**

U.S. Patent 6,080,504 Granted

TEM of Pt on Carbon



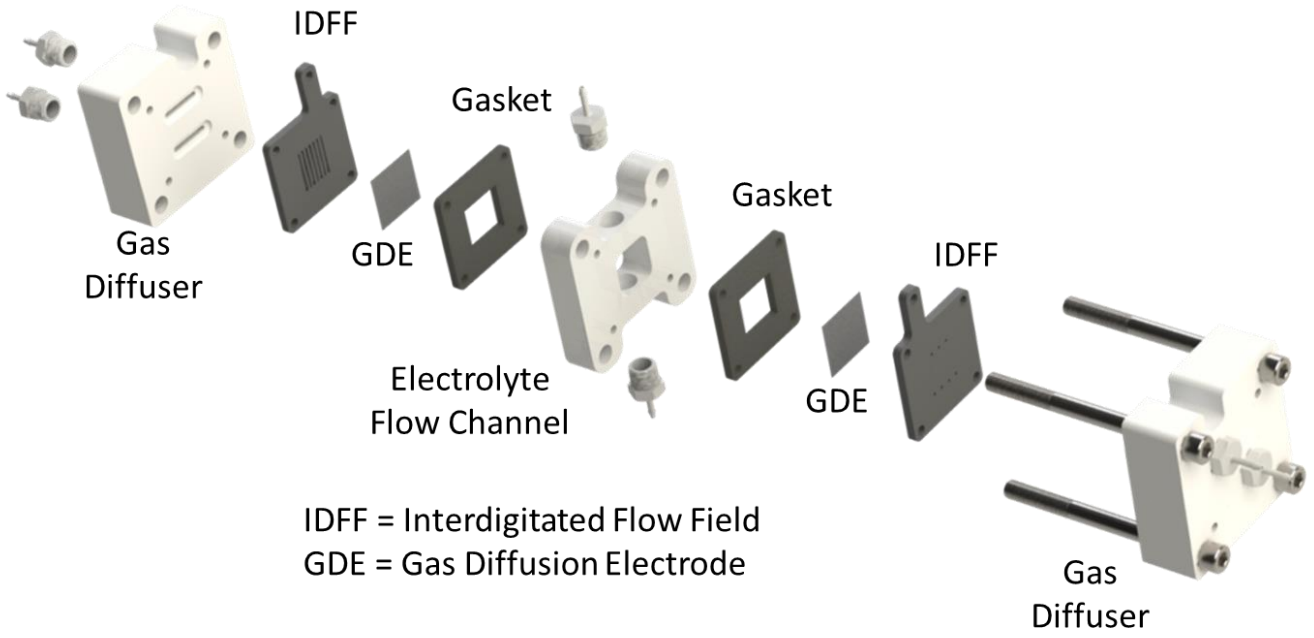
Performance Comparison



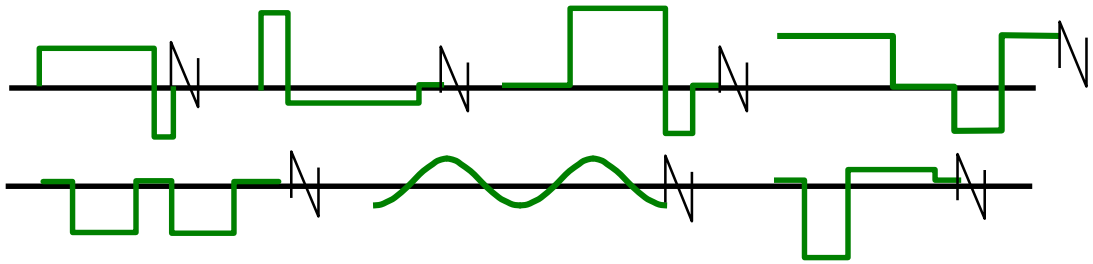
FARADAY TECHNOLOGY, INC.

Prior Work: MIT Electroreactor Design

- Brushett Group – Electroreactor fabrication expertise
- Available tools include: CNC mill, laser cutter, 3-D printer
- Direct fabrication of SolidEdge/SolidWorks 3-D models
- COMSOL Multiphysics simulation of 3-D models



Program Description



Objective of Phase I Base

The Phase I objective is to demonstrate the potential for economical, scalable pulsed FARADAYIC® ElectroDeposition of Cu GDE electrocatalysts for carbon dioxide reduction to ethylene.

The questions to be answered in the Phase I program are:

1. Can the potential be shown to ***fabricate by FARADAYIC® Electrodeposition techniques micro-structured copper electrocatalysts*** suitable for use in GDE electrocatalytic systems?
2. Can the potential be shown for the catalysts of Objective 1 to afford ***high activity and selectivity*** for the reductive conversion of CO_2 to hydrocarbons?
3. Can the potential be demonstrated for these electrocatalysts and reactors to afford ***competitive process economics as compared to currently available carbon sequestration/conversion technologies***?

Program Tasks

Task "0": Kickoff Meetings (**Faraday**)

Task 1: Benchtop ElectroDeposition Cell (**Faraday**)

Task 2: FARADAYIC® Copper ElectroDeposition Tests (**Faraday**)

Task 3: Cu GDE Catalyst Characterization / Evaluation (**MIT**)

Task 4: Laboratory-Scale Electroreactor (**MIT**)

Task 5: Economic / Scale-Up Analysis (**Faraday**)

Task 6: Reporting and Program Management (**Faraday**)

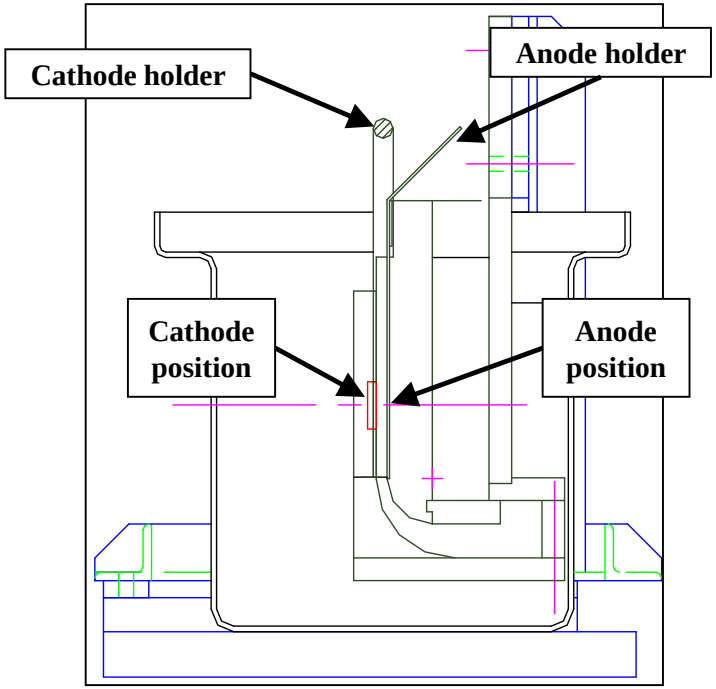
Task: Kickoff Meeting(s)

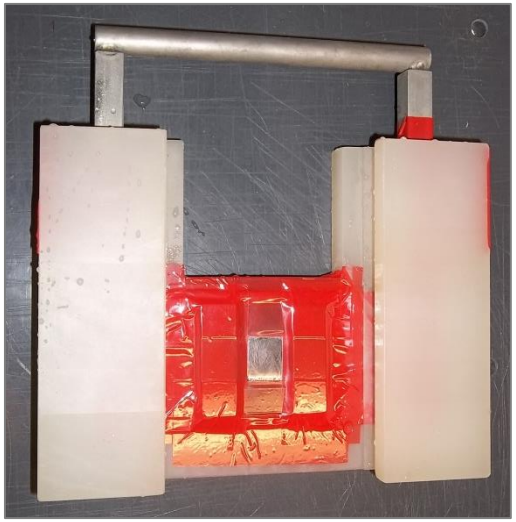
- **Faraday & DOE TPOC**
  - Engage TPOC
  - Identify DOE priorities

- **Faraday & MIT**
  - Review program goals
  - Identify / discuss milestones and completion targets
  - Synchronize work plans

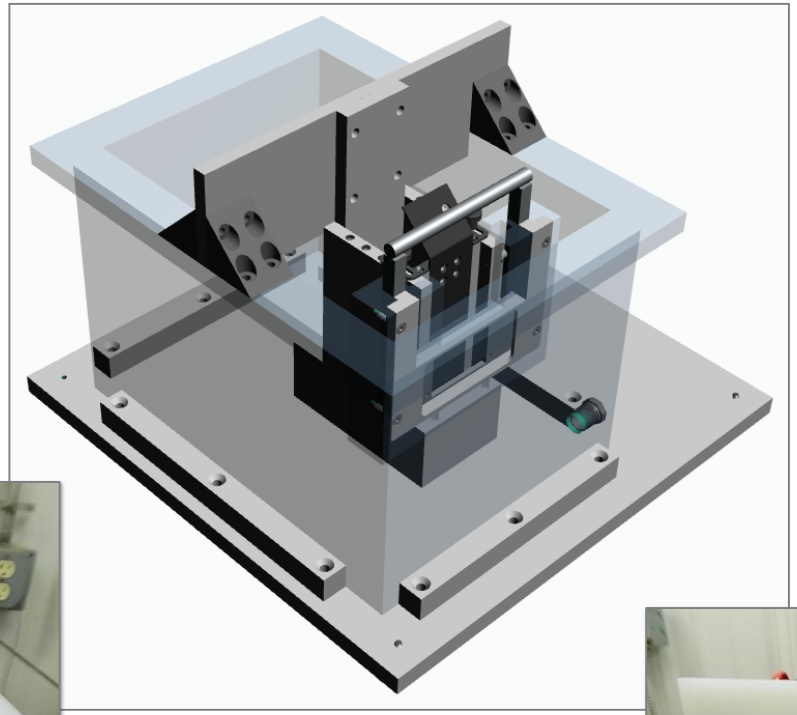
Task 1: Construction of Cu Deposition Apparatus

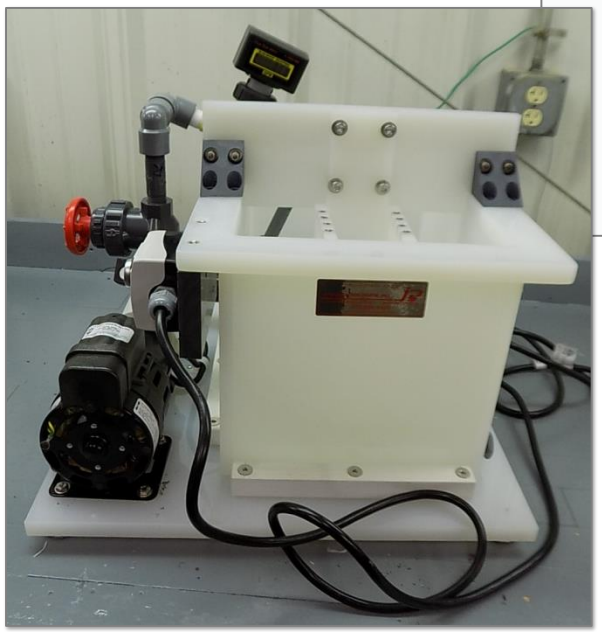
- Patented FARADAYIC® ElectroCell
  - *U.S. 8,329,006 – 8,226,804*
    7,947,161 – 7,553,401

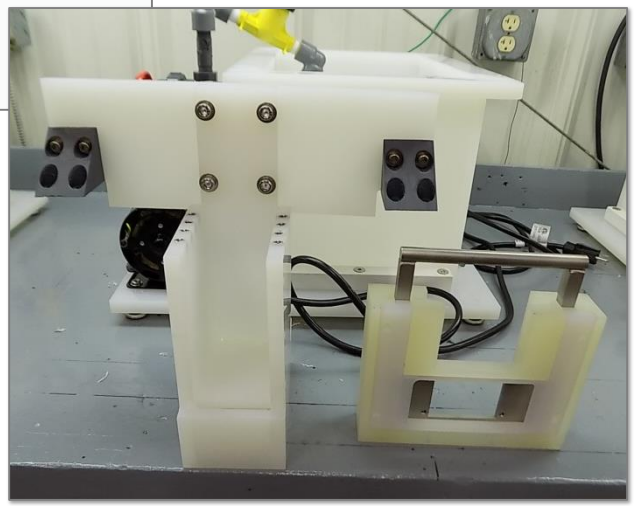




Task 1: Construction of Cu Deposition Apparatus







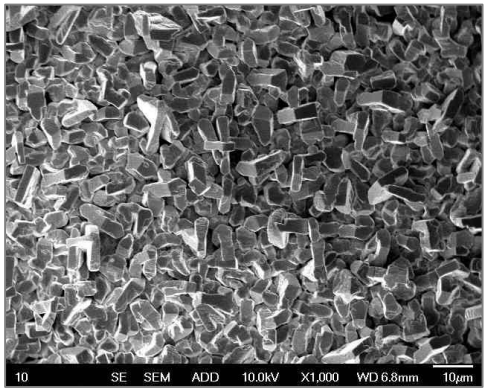
FARADAY TECHNOLOGY, INC.

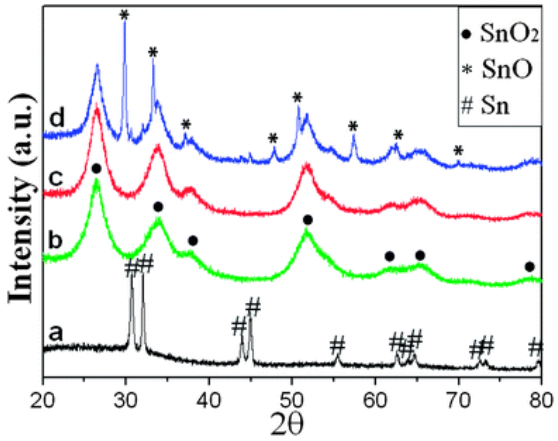
Task 2: FARADAYIC® Copper ElectroDeposition

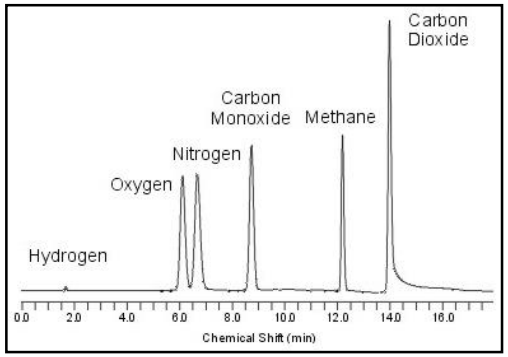
- Modified FARADAYIC® Copper ElectroDeposition Bath
  - $CuSO_4$
  - H_2SO_4
  - HCl
  - PEG
- Exploration of deposition parameter space
  - DC vs PC vs PRC
  - Peak currents
  - Frequency & duty cycle
  - $CuSO_4$, PEG concentrations
- Deposits analyzed for, e.g.:
  - Microstructure (SEM)
  - Electrocatalytic properties (CV, CA)

Task 3: Catalyst Characterization / Evaluation

- Instrumental Analysis
  - SEM
  - XRD
- Products Analysis
  - GC
- Electrocatalytic Performance
  - Polarization curves
  - Chronoamperometry

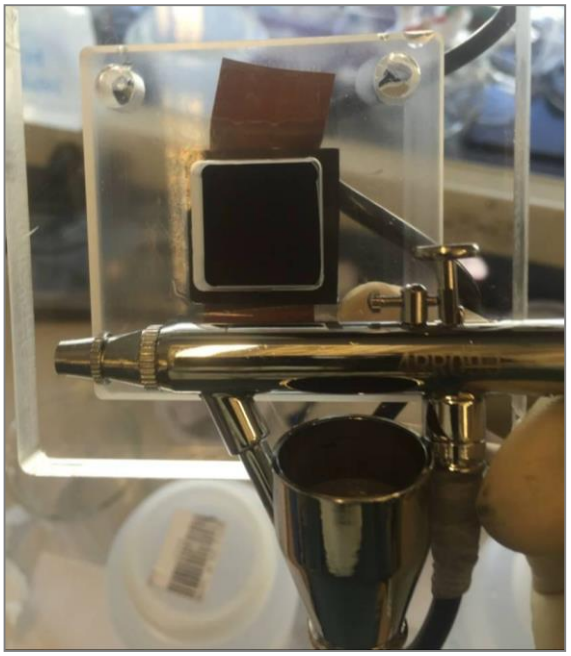




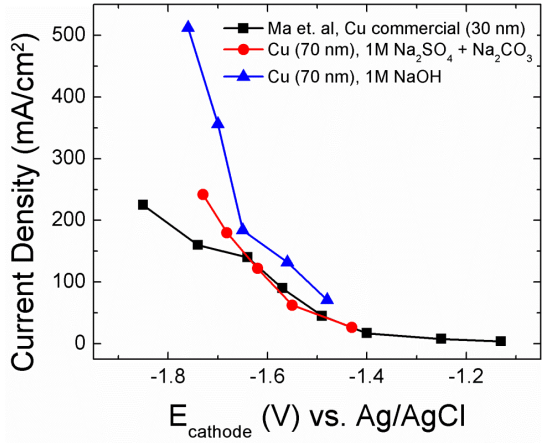


Task 3: Catalyst Characterization / Evaluation

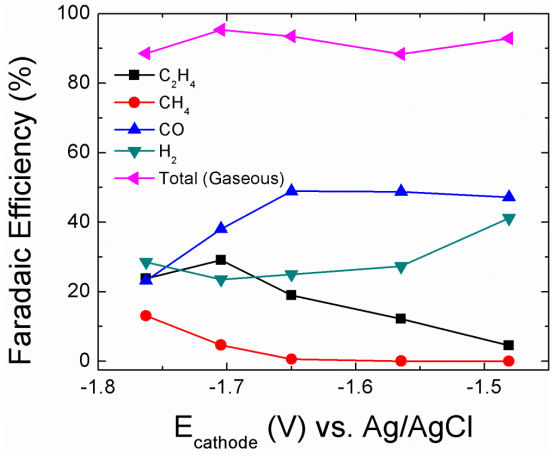
- Baseline GDE Catalyst
  - Disperse 70 nm Cu in ionomer/alcohol
  - Spray paint onto GDL



- Preliminary Results
  - Polarization curves



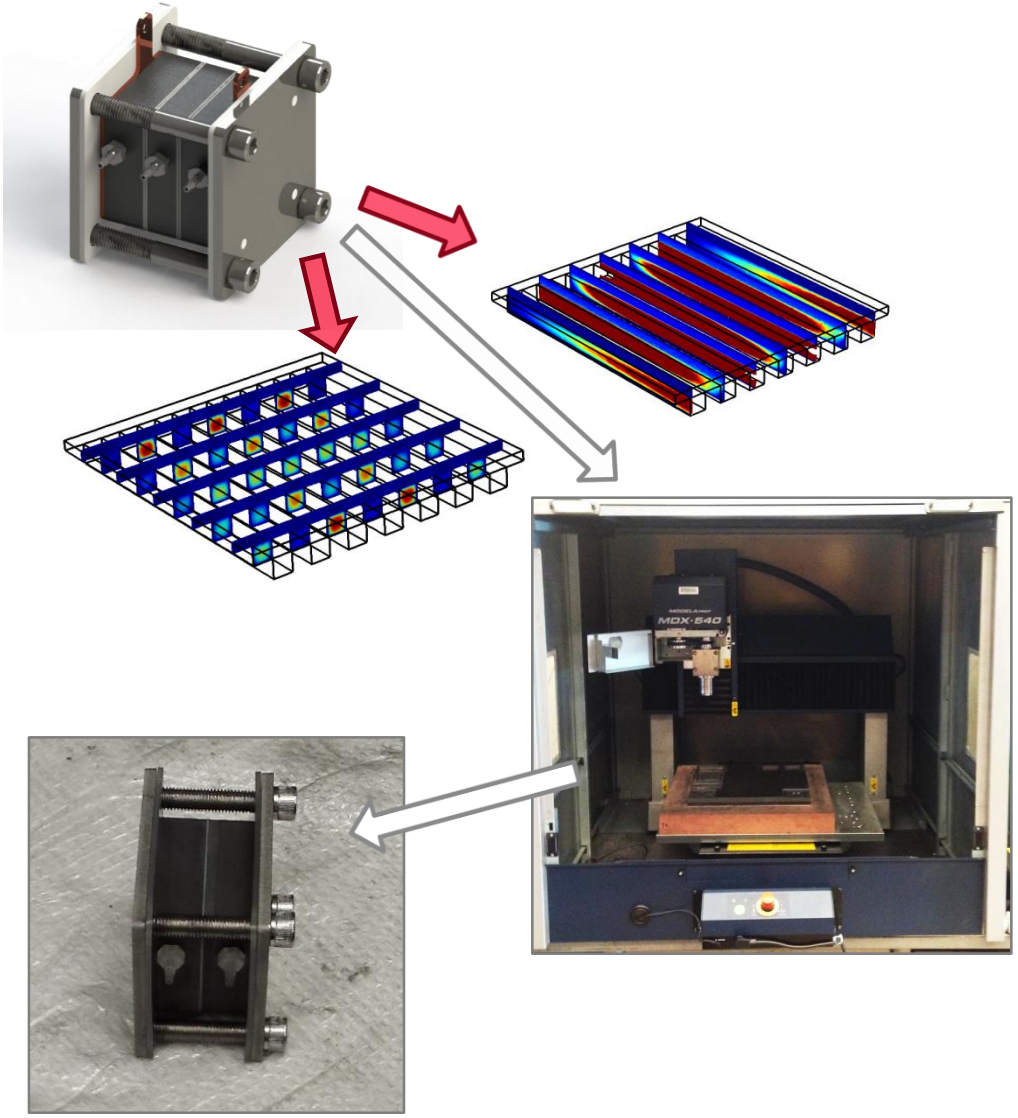
  - Electrocatalytic activity



FARADAY TECHNOLOGY, INC.

Task 4: Laboratory-Scale Reactor

- SolidWorks 3-D CAD
- COMSOL Multiphysics Modeling
- Benchtop CNC
- Electroreactor Prototype



Task 4: Laboratory-Scale Reactor

- SolidWorks 3-D CAD
- COMSOL Modeli
- Bencht
- Electro

Task 5: Economic / Scale-Up Analysis

5.1. Techno-Economic Analysis

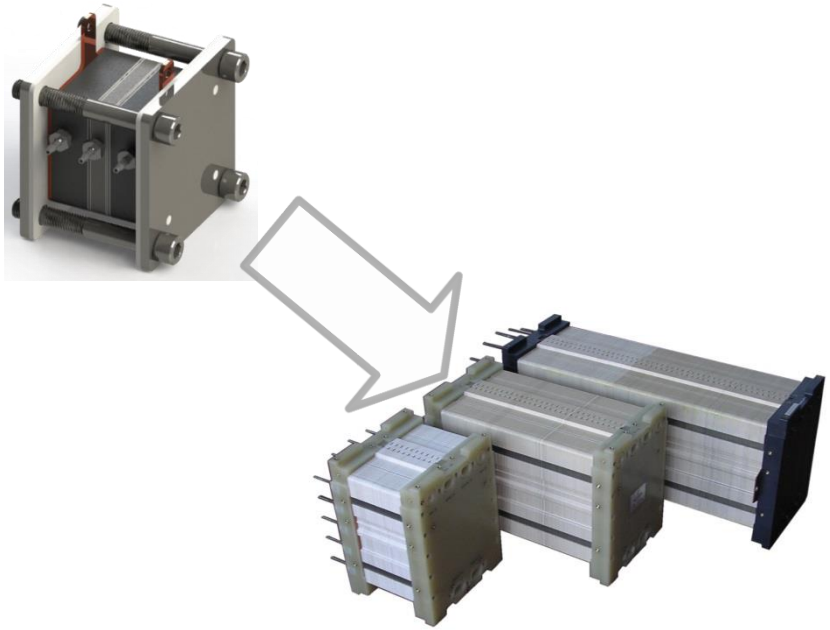
- Standard methodologies
  - EPA, DOE/NETL, etc.
- Evaluate cost/benefit of novel technology relative to existing processes

$$\mathbf{COE} = \frac{\mathbf{CCF \cdot TOC + OC_{FIX} + CF \cdot OC_{VAR}}}{\mathbf{CF \cdot MWh}}$$

$$Cost\ of\ CO_2\ Captured = \frac{(COE_{With\ CC} - COE_{Without\ CC})}{CO_2\ Captured}$$

5.2. Scale-Up Analysis

- Technology evaluation
- Market-entry / pre-commercial analysis



Task 6: Reporting and Program Management

- Centered on the management of the project to ensure milestones and reporting requirements are met
- Contractual reporting requirements
  - Final report due 4 Dec 2017
- Faraday will convene periodic internal review meetings to assess program progress toward milestones/objectives
- Faraday will continue telephone/WebEx briefings with MIT partners and/or DOE program/technical staff.

Program Tasks Status

Task "0": Kickoff Meetings (**Faraday**)
Completed by this webinar

Task 1: Benchtop ElectroDeposition Cell (**Faraday**)
Cell in final stage of build

Task 2: FARADAYIC® Copper ElectroDeposition Tests (**Faraday**)
Pending ElectroDeposition Cell

Task 3: Cu GDE Catalyst Characterization / Evaluation (**MIT**)
Apparatus & assay methods ready
First baseline GDE catalysts prepared; testing initiated

Task 4: Laboratory-Scale Electroreactor (**MIT**)
First-model reactor fabricated; future enhancements pending

Task 5: Economic / Scale-Up Analysis (**Faraday**)
Pending GDE performance results

Task 6: Reporting and Program Management (**Faraday**)
Ongoing

Action Items

1. Commission plating cell
2. Procure Cu plating bath components
3. Develop initial experimental matrix
4. Initiate copper plating tests

FARADAY TECHNOLOGY, INC.

Contact Information

Brian T. Skinn
937.836.7749
BrianSkinn@FaradayTechnology.com

Thank You!