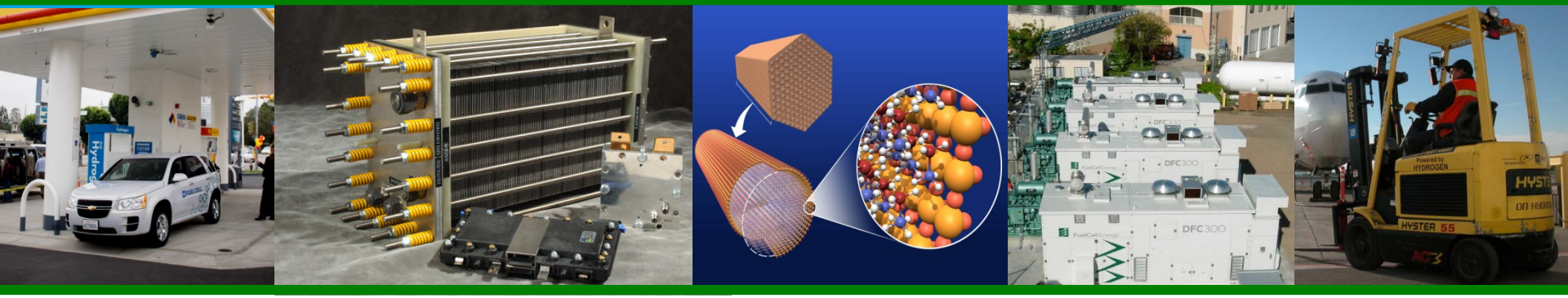
U.S. DEPARTMENT OF ENERGY



Manufacturing R&D Program Area
- Plenary Presentation -

Nancy L. Garland, Ph.D.

Fuel Cell Technologies Office

2017 Annual Merit Review and Peer Evaluation Meeting

June 6, 2017

Goals and Objectives

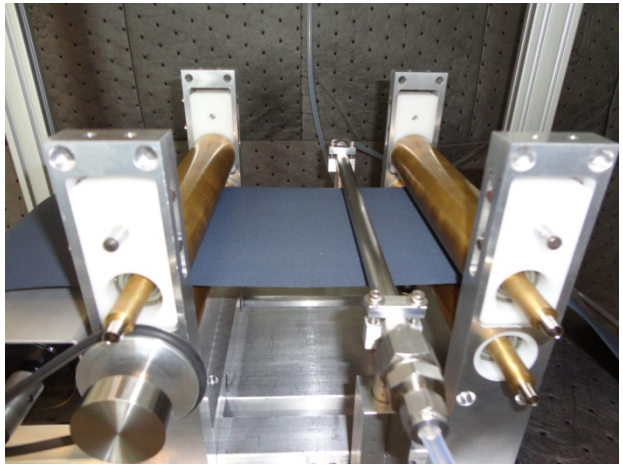
Goals:

- Reduce the cost of manufacturing hydrogen production, delivery, storage, and fuel cell component systems through research, development, and demonstration.
- Identify areas where the United States might have viable manufacturing opportunities

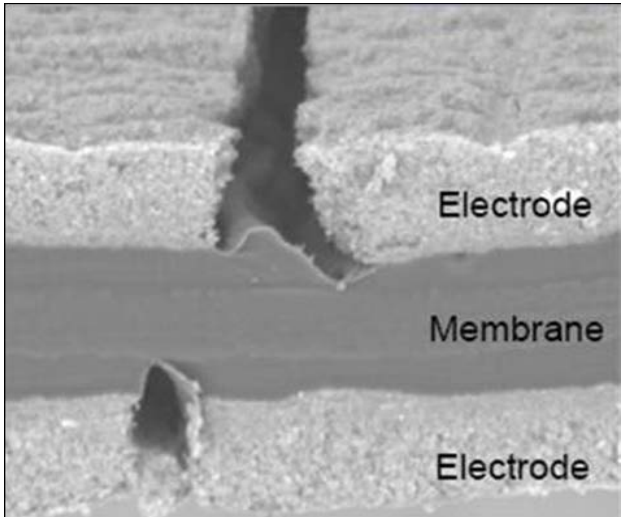
Objectives

- Develop manufacturing techniques to reduce the cost of automotive fuel cell stacks at high volume (500,000 units/year) from the 2008 value of $38/kW[1] to $20/kW by 2020.
- Develop processes to manufacture compressed hydrogen pressure vessels for onboard storage at a cost of $10/kWh by 2020, with an ultimate target of $8/kWh.
- Support efforts to reduce the cost of manufacturing components and systems to produce hydrogen at <$4/gge (2007 dollars) (untaxed, delivered, and dispensed) in 2020.

[1]http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mass_production_cost_estimation_report.pdf



QC Diagnostics at NREL



Defect in Membrane Electrode Assembly

FCTO Manufacturing Strategy

Two Pillars

Improved Quality and Quality Control

- Develop defect diagnostics
- Correlate defect size and shape to changes in performance
- Develop domestic capability for repair and refurbishment

→ Enhanced global manufacturing competitiveness

Process Development and Optimization

- Reduce process steps in FC manufacturing
- Improve carbon fiber winding for hydrogen storage

→ Reduced manufacturing processes & cost

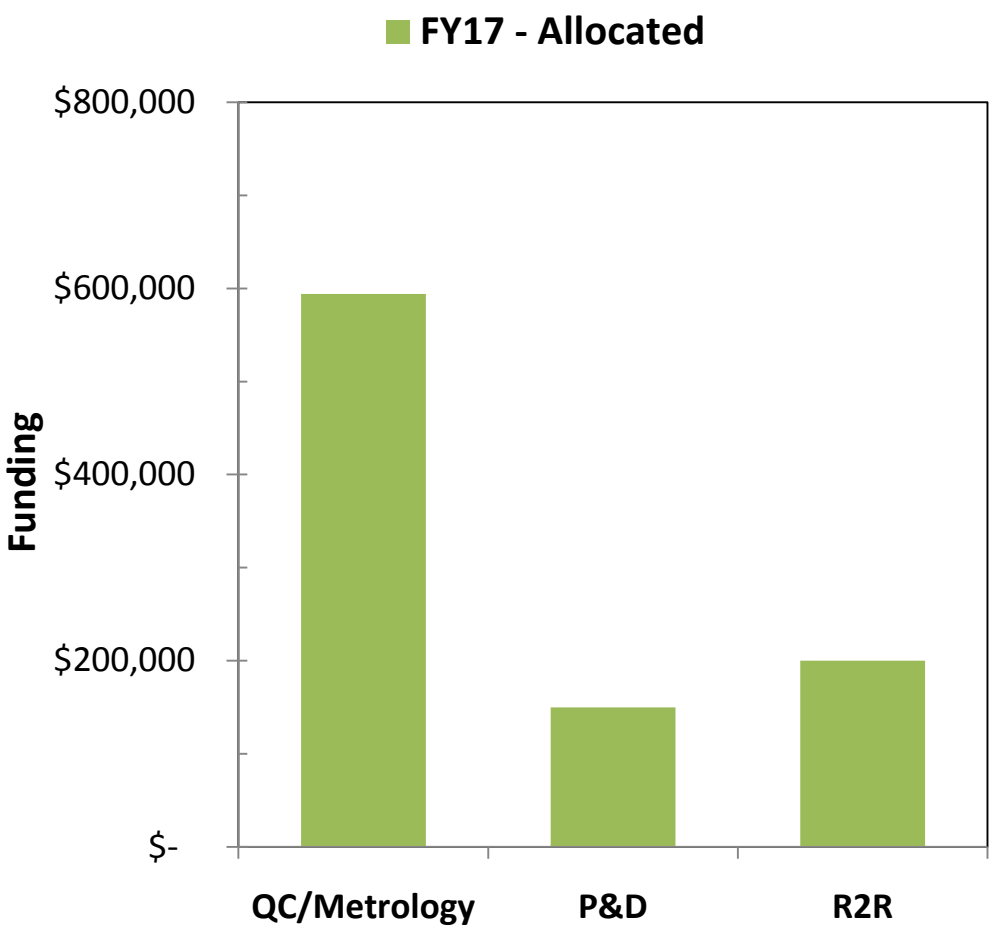
HTAC subcommittee on manufacturing

Manufacturing R&D is needed to reduce the cost of hydrogen and fuel cell components so that they will be competitive globally

Budget: Manufacturing R&D

U.S. DEPARTMENT OF ENERGY

FY 2017 Appropriation = $0M*

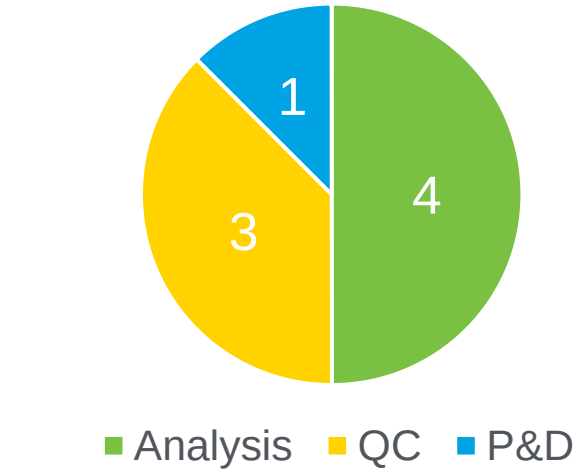


*$1 Million in CR Funds

EMPHASIS

- Quality control critical to enabling low-cost manufacturing with reduced waste; correlate defect morphology with loss in performance (NREL, LBNL)
- Fiber reinforced composite pipeline coupler (Automated Dynamics)
- SBIR Phase 2: Cross-polarized detection of membrane pinholes (Mainstream)
- Leveraging cross-cutting manufacturing opportunities across EERE (AMO, VTO)

Number of Projects by Focus Area

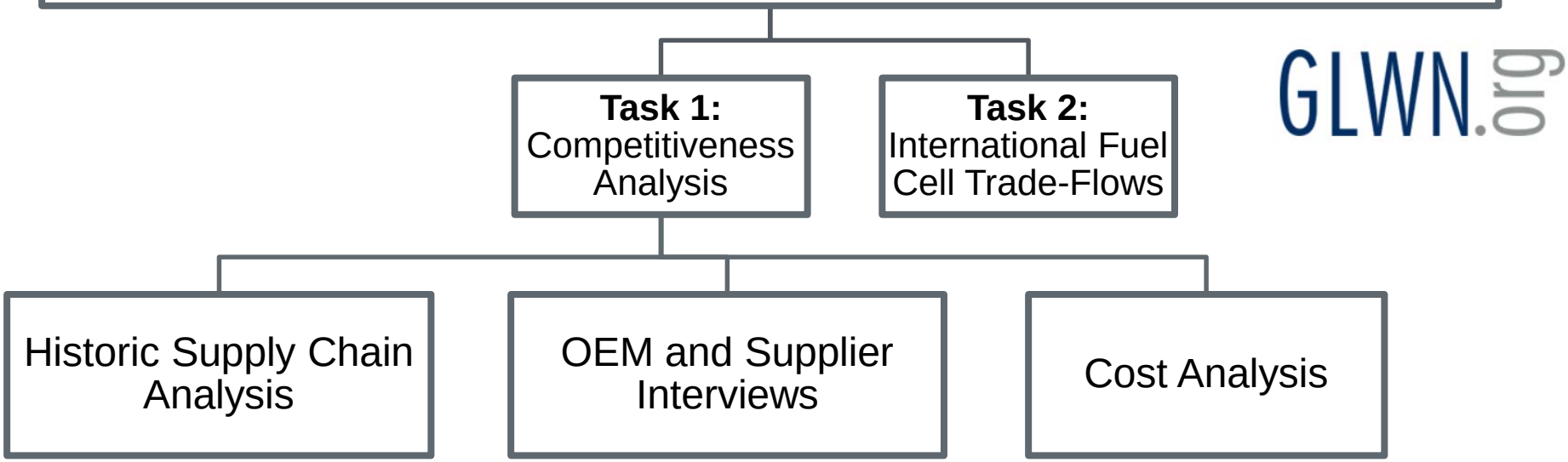


Accomplishments: Global Manufacturing Competitiveness

U.S. DEPARTMENT OF ENERGY

Clean Energy Supply Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells

U.S Department of Energy Project DE-EE-0006935



GLWN.org

Goal:

- **Determined the state of hydrogen and fuel cell manufacturing**
- **Characterized the factors that impact the global competitiveness of fuel cell- and hydrogen-related manufacturing**

#MN014
Tue. 1:45
MD C

Goal is to identify key factors determining U.S. competitiveness

Accomplishments – Questionnaire for OEMs and suppliers

U.S. DEPARTMENT OF ENERGY

Bipolar Plate - Technology and Manufacturing Readiness

GLWN.org

	BPP Technology and Manufacturing Readiness			
	OEM's		Tier 1's	
	Technology	Manufacturing	Technology	Manufacturing
1. Is current component design ready for launch at 1,000 vehicles/yr?	**YES**	**YES**	**YES**	**YES**
2. Is current technology & manufacturing development ready for production >1,000 vehicles/yr. to at least 100,000 vehicles/yr.?	**YES**	**YES** for some, others more process development for 100k vehicles/yr	**YES**	**NO** -Added presses or new roll equipment needed
3. Are components available from credible suppliers that meet OEM cost / performance targets at 100,000 vehicles/yr.?	**Yes** for most	**NO** - need investment for 100k/yr	**Yes -** Current design is credible for 100k/yr	**NO** - Will need more presses or in-line process for 100k/yr
4. What are the R&D shortfalls in technology or manufacturing for 100,000 vehicles/yr. and what timing to achieve?	Defined tolerances. Timing is 3-4 yrs	Stamping or roll-to-roll continuous production	Eliminate plate ctgs, improve electrical conductivity, sealing solutions	High volume production of plates. "In-line process"
5. How many more vehicle powertrain demonstrations will be required before OEMs are ready to commit funds to produce 100,000 vehicles /yr?	At least two sets. One at 1000 and one at 10,000, before 100k.	No project unless neutral business case with variable cost. R&D funding of supply chain	OEM call	Run @ Rate demonstrations to step volume

Current capability up to 10,000 vehicles/year, further substantial investment needed for 100,000/year

Conclusions on global competitiveness

U.S. DEPARTMENT OF ENERGY

Component	World leader (s)	U.S. prognosis
Bipolar plate	Europe and Asia	moderate
Catalyst	Europe and Asia	low to moderate
GDL	Europe, Asia, and U.S.	moderate
Membrane	U.S.	high
Pressure Vessel	Europe, Asia, and U.S.	high

GLWN.org

Additional effort is needed by the U.S. fuel cell community:

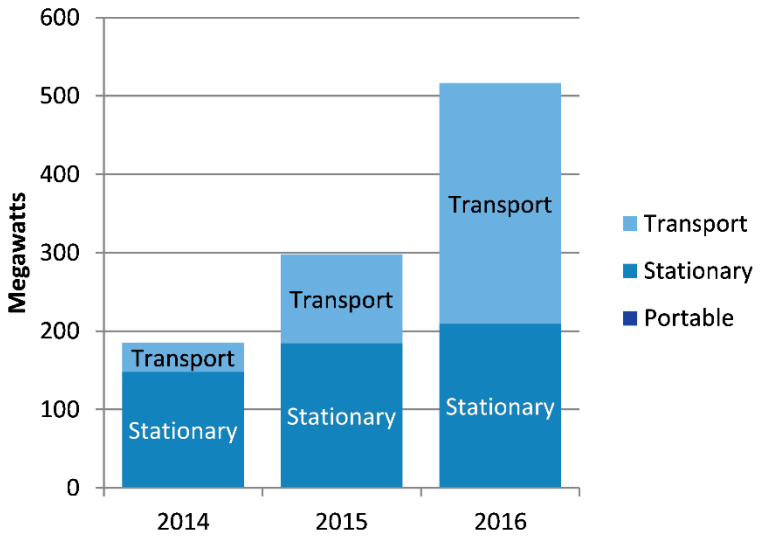
- **to maintain its current competitive position in GDL and membrane manufacturing**
- **to increase its capabilities in bipolar plate and catalyst production.**

Accomplishments – Global shipment data

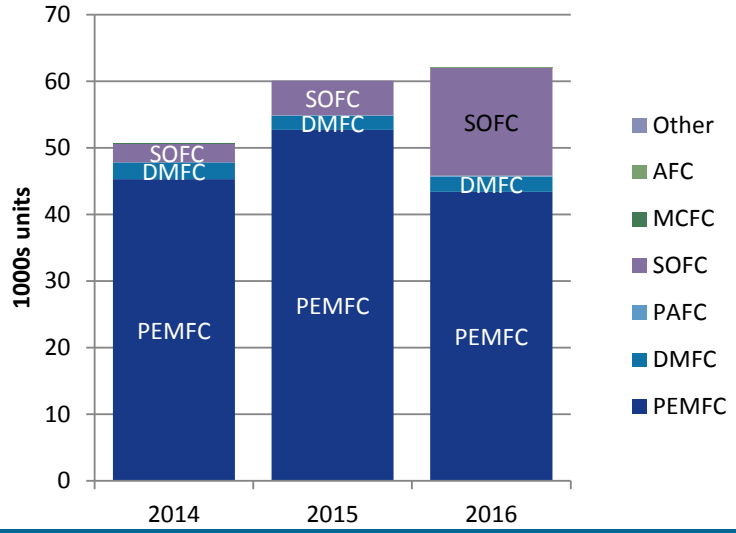
U.S. DEPARTMENT OF ENERGY

- Strong growth in transport sector is dominated by Toyota's Mirai, and, increasingly, by range extenders and FC buses in China
- Strong stationary unit sales - due to domestic ene-farm fuel cell program in Japan
- Large stationary systems (100kW+ scale) - only moderate growth
- Portable units decrease further as consumer chargers are discontinued
- The global revenues for 2016 are $1.6B.

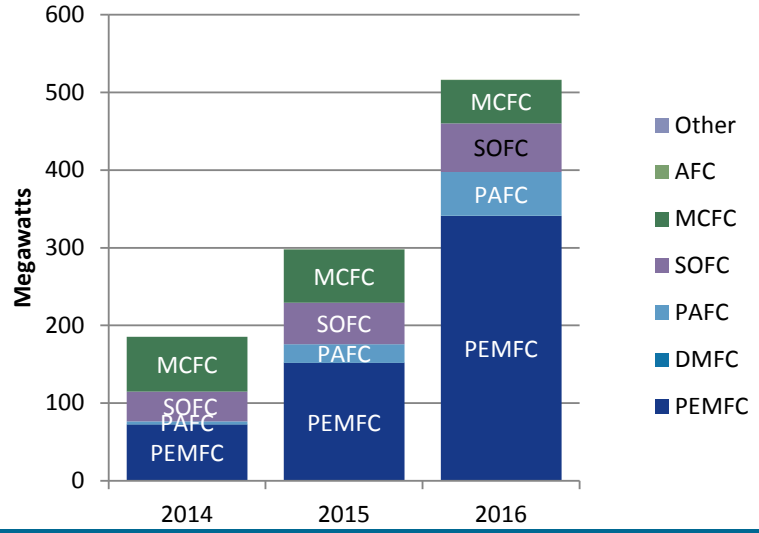
Total power as f(application) shipped by year



Total # of shipments as f(fuel cell chemistry) shipped by year



Total power as f(fuel cell chemistry) shipped by year



E4tech GLWN.org

Strong growth in number of megawatts shipped in the transport sector

Accomplishments - Supply Chain

U.S. DEPARTMENT OF ENERGY

OFCC Project Objectives

1. Increase **communication** between OEMs and hydrogen and fuel cell component suppliers.
2. Support establishment of a **web-accessible database** with Virginia Clean Cities.
3. **Standardize** component and subsystem component specifications.
4. Develop strategies to lower cost, increase performance, and increase durability of components.

OFCC
OHIO FUEL CELL COALITION

Accomplishments:

- **An integrated network** of regional Technical Exchange Centers:
  - East Coast (CCAT)
  - Midwest (OFCC)
  - Central States at NREL's National Fuel Cell Technology Evaluation Center
  - West Coast (UC Irvine)
- **The Technical Exchange Centers**:
  - Collect and catalog non-proprietary product information from regional suppliers and OEMs
  - Maintain a supplier contact list to introduce OEMs to suppliers
  - Hold annual supply chain exchanges

Held 2 supply chain exchanges this FY
Provided product information and contact list to VCC

#MN012
Tue. 11:30
MD C

Accomplishments – Supply Chain

U.S. DEPARTMENT OF ENERGY

Virginia Clean Cities Project Objectives:

1. Expand the domestic supply chain of fuel cell & hydrogen components and systems.
2. Build and populate a comprehensive communications database.
3. Drive U.S. companies to the website via an aggressive outreach campaign.

www.hfcnexus.com

Virginia Clean Cities

Progress

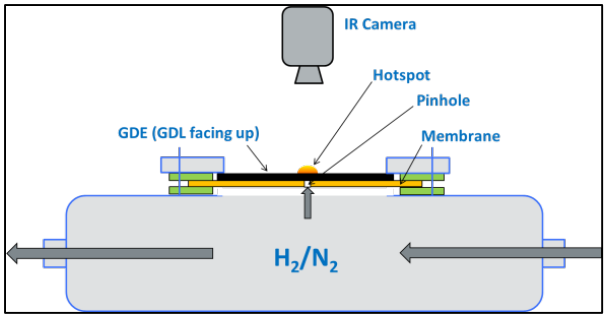
- Launched July 2016
- Developing the Matchmaker Interface
- Enabling in-line website advertising for fuel cell companies
- Mobile-friendly interface
- Instructional videos
- 337 companies and organizations (220 at launch)

#MN013 Tue. 12:00 PM MD C

Quality Control Diagnostics for Fuel Cells

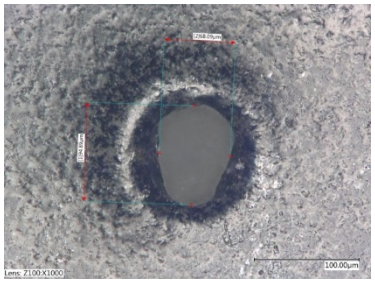
U.S. DEPARTMENT OF ENERGY

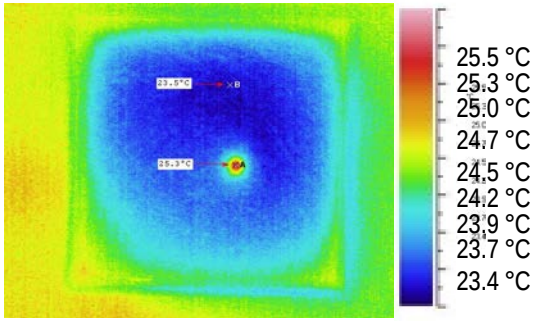
2016



Through-plane reactive excitation used to detect:

- Failure of membrane integrity in CCMs, half-cells, or full MEAs
- Location & severity of failure





90 µm diameter pinhole in 18 µm thick membrane

$\Delta T = 1^0C$

2017

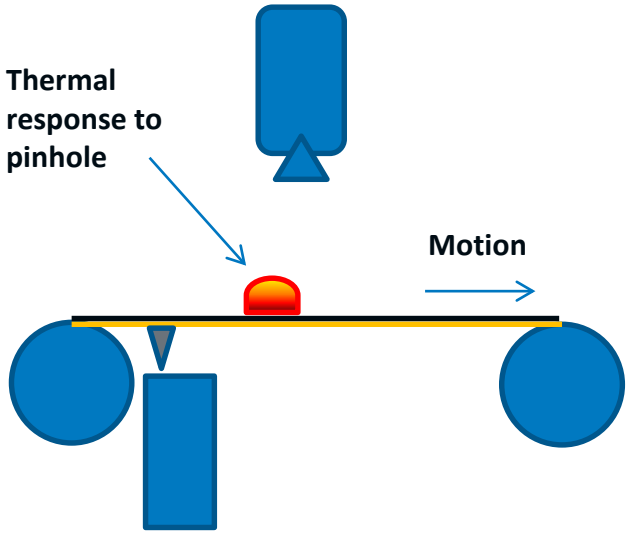


Diagram of in-line TPRE concept configuration

#MN001 Tue. 11:00 AM MD C

NREL NATIONAL RENEWABLE ENERGY LABORATORY

NREL is developing advanced diagnostics for in-line detection of micro-size manufacturing defects in fuel cell materials.

Accomplishments - Breadth of capabilities for QC

U.S. DEPARTMENT OF ENERGY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Summary of electrode irregularity studies to date

Parametric Study (Impact of XX on…)	Initial Performance: Total Cell	Initial Performance: Local	Prolonged Performance: Total Cell	Lifetime: Total Cell
Irregularity Size (0.125, 0.25, 0.5, 1 cm^2)				
Membrane Thickness (25, 50 µm)				
Irregularity Location (Inlet, Center, Outlet)				
MEA Configuration (GDE, CCM)				
Catalyst Loading (0.15/0.15, 0.2/0.2 mg Pt/cm^2)				
Irregularity Shape (Square, Rectangle, Circle)				
Catalyst Layer Thickness Variations (Thin, Bare Spots)				
Irregularity Aspect Ratio				
Slot Die Coating/Manufacturing Defects (Droplet, Scratch, Cut)				
Ionomer Coating Thickness Variations				

Little/No Impacts Moderate Impacts Significant Impacts Ongoing Work

Local defects may have minimal impact on fuel cell performance initially, but may have a huge impact later

National Lab Tech Transfer

U.S. DEPARTMENT OF ENERGY

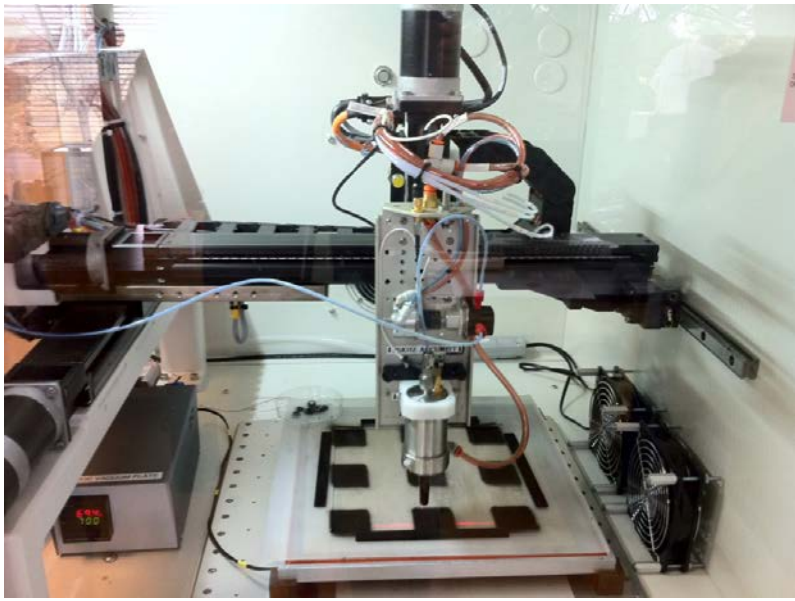
SBIR Phase II collaboration with Mainstream Engineering (prior year funding)

- Advance QC prototype device to more commercializable configuration; project based on NREL's optical inspection patents
- NREL role
  - Technical assistance, In situ testing of membrane defects
- Georgia Tech role
  - Provide membranes for in situ testing and optical scanning

#MN015 Tues. 2:45 PM MD C

DOE is enabling prototype scale-up of optical inspection device in the near future

Material-process-performance relationships for GDEs



Lab Scale – Ultrasonic Spray
Used to demonstrate new materials and for fundamental studies

#MN019 Mon. 7:00 PM Exhibit Halls – Lower Level

4-lab Consortium to improve R2R processes

U.S. DEPARTMENT OF ENERGY

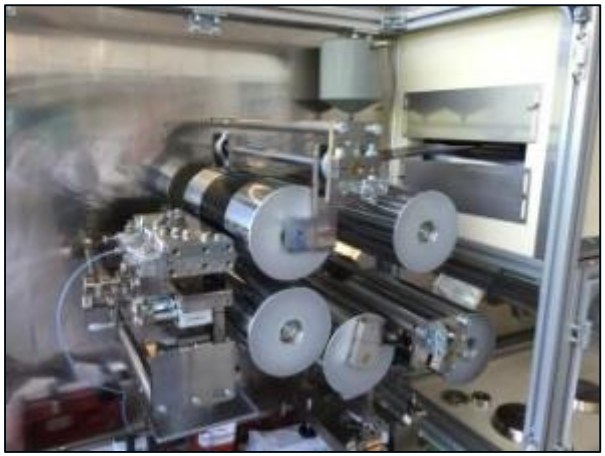
Why R2R for manufacturing?

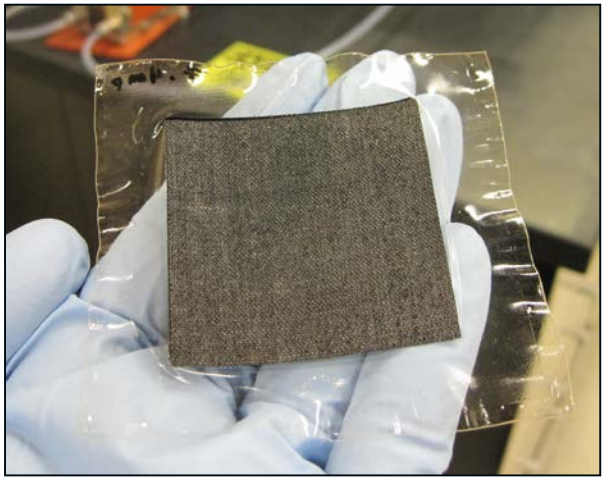
- Roll-to-roll (R2R) is the only manufacturing process platform that will meet cost and volume targets of fuel cell components
- R2R enables conversion of multiple dissimilar materials into a multi-layer cell
- R2R processing assumed in most cost analyses for high volume production of MEAs/cells

- **AMO, FCTO, and VTO funded a 4-lab consortium to develop manufacturing processes using R2R for lithium ion batteries, fuel cells, water purification ($1M from FCTO)**
- **Pre-negotiated CRADA**
- **FedBizOps solicitation (www.fbo.gov)**
- **Solicitation Number: ORNL-R2RAMM-2017-02-02**

#MN018 Tues. 4:15 PM MD C

Novel R2R manufacturing technologies enable cost reduction while investments in new materials and electrodes increase energy density, power density, and reliability.



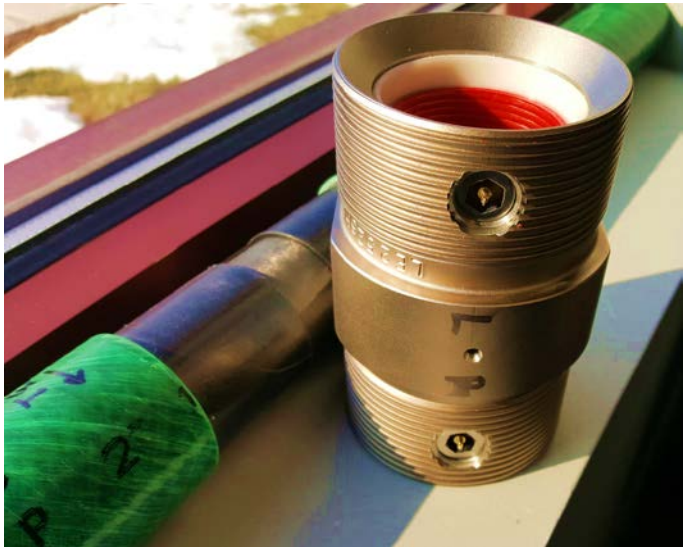


Hydrogen delivery – Pipeline coupler that does not leak

U.S. DEPARTMENT OF ENERGY

Objectives:

1. Design and test a composite-based coupler to be used in the field during pipeline installation
2. 100 bar, <0.5% flow leak rate, 50 year life



AUTOMATED DYNAMICS®
Performance in Composites

Approach:

- Metal Components are not in contact with H_2; use existing technology
- Composite Components include:
  - Electrofusion of thermoplastic components (thermoplastic coated wire, neat polyethylene (PE), fiberglass reinforced PE)
  - In contact with H_2, and internal to metal components

Go/No-Go Criteria 2016	Result 2016
Tensile Load >10,000 lb	PASSED: 11,000 lb
Burst Pressure >100 bar	PASSED: 369 bar (5,356 psi)
Leak Rate <$10x10^{-4}$ cm^3 He/s	PASSED: 10^{-6} cm^3 He/s

#MN015
Tue.
2:15 PM
MD C

The approach for the coupler is now Multi-Material rather than All Non-Metal

Cross-cutting and International Manufacturing Activities

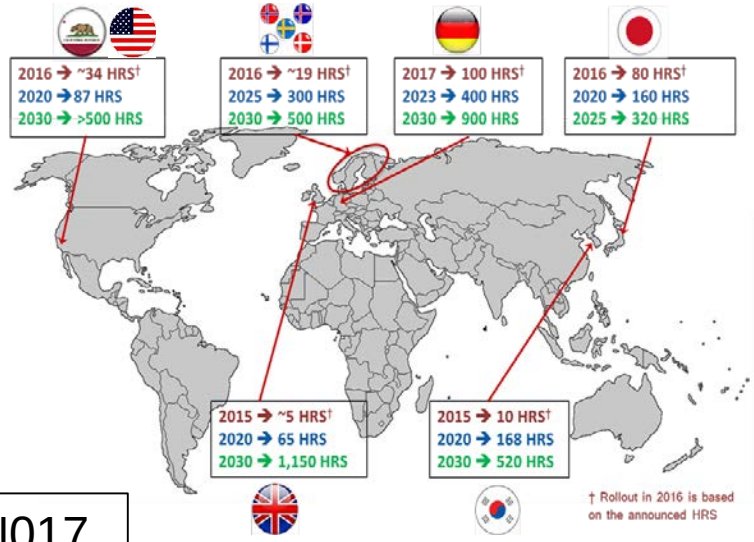
U.S. DEPARTMENT OF ENERGY

Small Business Vouchers Pilot
U.S. DEPARTMENT OF ENERGY

DOE made 3 rounds of SBV awards and the projects have started

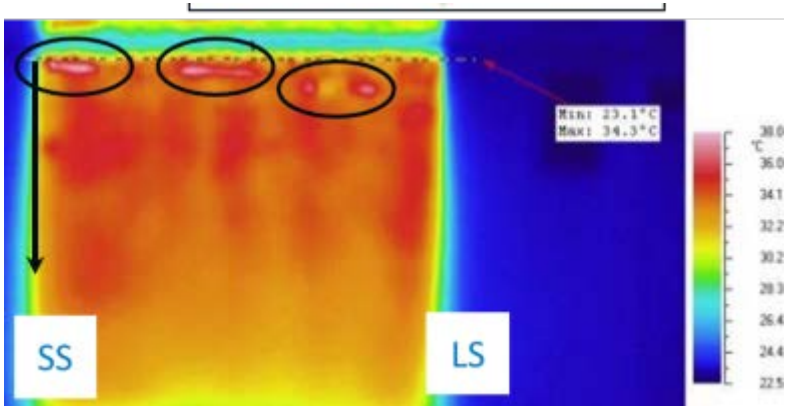
CEMAC Clean Energy Manufacturing Analysis Center

CEMAC analyzes global clean energy manufacturing. With GLWN, CEMAC is carrying out Manufacturing Competitiveness Analysis of Hydrogen Refueling Stations and On-site Hydrogen Production



International HRS Rollouts

NREL demonstrated RIF on CEA-Liten R2R screen-printed GDEs



#MN017
Tue.
3:15 PM
MD. C

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Collaboration

U.S. DEPARTMENT OF ENERGY

REGIONAL ACTIVITIES

- Connecticut Center for Advanced Technology
- Northeast Electrochemical Energy Storage Cluster
- Ohio Fuel Cell Coalition
- UCI
- Colorado Hydrogen Coalition

DOE – EERE

- Manufacturing R&D
- Advanced Manufacturing Office
- AMO, FCTO, and VTO support 4-lab R2R consortium

INDUSTRY

- Mainstream
- Automated Dynamics

INTERNATIONAL

- Defects in GDEs detected in material supplied by CEA

National Collaborations (inter- and intra-agency efforts)

NIST Advanced Manufacturing National Program Office (AMNPO)

17

Recent and upcoming activities

U.S. DEPARTMENT OF ENERGY

- **OFCC, workshops in September 2016 and March 2017**
  - September 27, 2016 – North Canton, OH - Supply Chain Exchange and U.S. Dept. of Energy Hydrogen & Fuel Cell Supply Chain Development Stakeholder Session
    - OFCC with Stark Area Regional Transit Authority, Stark State College, and LG Fuel Cell Systems
  - March 31, 2017 – Elyria, OH - Supply Chain Exchange and Balance-of-Plant Workshop
    - Attendance: 128; S.C. Exchange participants 6 integrators, 17 Suppliers (50% new)
    - Connections: 90 meetings between integrators and suppliers
    - https://energy.gov/eere/fuelcells/downloads/2017-ohio-fuel-cell-symposium-and-balance-plant-workshop
- **Hartford, Connecticut workshop, November 2016**
  - November 17-18, 2016 – Hartford, CT - H2FC Forum w/Technology Showcase and RFI
  - Participants expressed interest in standardizing connections and fittings, air compressors, blowers, and hydrogen dispensing equipment
- **Parker, Colorado, upcoming Cleantech Manufacturing Forum, August, 2017**
  - August 17, 2017, Ride & Drive, Keynote Speaker Slade Gardner from Lockheed Martin: 3D Printing for Manufacturing, Grid Panel: Clean Energy & The Electric Grid, B2B Network/Reception

Contacts

U.S. DEPARTMENT OF ENERGY

For more information, contact:

Nancy Garland –Team Lead **202-586-5673** **nancy.garland@ee.doe.gov**
Jesse Adams 720-356-1421 jesse.adams@ee.doe.gov
Gregory Kleen 240-562-1672 gregory.kleen@ee.doe.gov
Eric Parker 202-586-5681 eric.parker@ee.doe.gov

Differentiation by types of applications and regions

U.S. DEPARTMENT OF ENERGY

Application type	Portable	Stationary	Transport
Definition	Units that are built into, or charge up, products that are designed to be moved, including auxiliary power units (APU)	Units that provide electricity (and sometimes heat) but are not designed to be moved	Units that provide propulsive power or range extension to a vehicle
Typical power range	3 W to 20 kW	0.5 kW to 400 kW	1 kW to 100 kW
Typical technology	PEMFC DMFC	PEMFC SOFC MCFC PAFC AFC	PEMFC DMFC
Examples	• Non-motive APU (campervans, boats, lighting) • Military applications (portable soldier-borne power, skid mounted generators) • Portable products (torches, battery chargers), small personal electronics (mp3 player, cameras)	• Large stationary combined heat and power (CHP) • Small stationary micro-CHP • Uninterruptible power supplies (UPS)	• Materials handling vehicles • Fuel cell electric vehicles (FCEV) • Trucks and buses

Adapted to correspond to data definitions used by Department of Energy in previous years as follows:

- Minimum fuel cell size: 3 Watt
- Regional split by region of fuel cell manufacturing (not by region of adoption)
- Educational fuel cells and toys not included

Important note by E4tech: Based on the discussions between E4tech and DoE, we believe the 2014 to 2016 data shown below is compatible with the 2008-2013P shipment data published in Nov2014 by DoE in the "2013 Fuel Cell Technologies Market Report" (p11f). However, we have no access to the Navigant datasets behind the DOE publication and therefore can not guarantee that our 2014 to 2016 data are built on the exact same methodology.