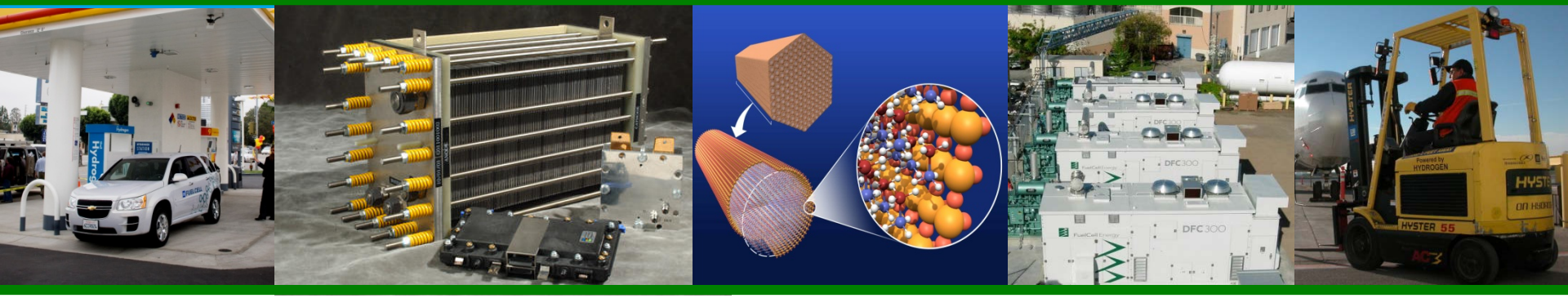
U.S. DEPARTMENT OF ENERGY



Manufacturing R&D Program Area
- Plenary Presentation -

Nancy L. Garland

Fuel Cell Technologies Office

2015 Annual Merit Review and Peer Evaluation Meeting

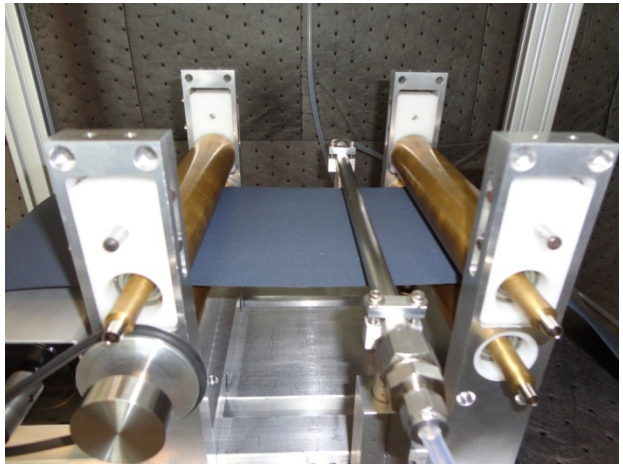
June 8 - 12, 2015

Goal and Objectives

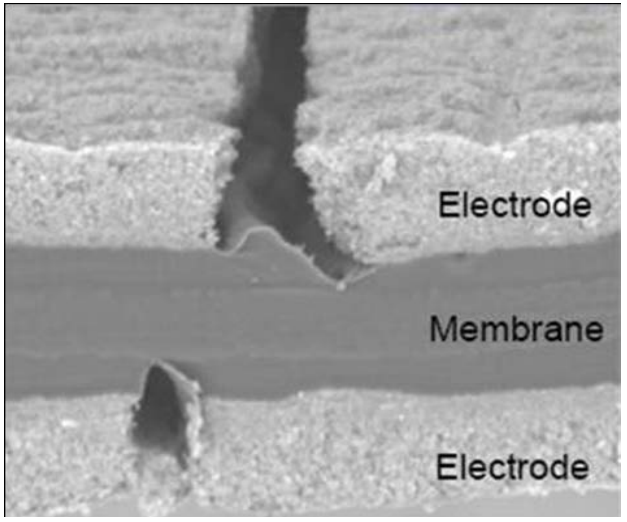
Goal: Reduce the cost of manufacturing hydrogen production, delivery, storage, and fuel cell systems

Objectives

- Reduce the cost of manufacturing components and systems that produce and deliver hydrogen at <$4/gge (2007 dollars) (untaxed, delivered, and dispensed) by 2020.
- Develop processes to fabricate compressed hydrogen pressure vessels leading to a total onboard storage system cost of $10/kWh by 2020, with an ultimate target of $8/kWh.
- 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 to $20/kW by 2020.
- Analyze and identify areas where the United States might have specific, viable manufacturing opportunities.
- Other specific objectives are in the FCTO MYRD&D Plan.



QC Diagnostics at NREL



Defect in Membrane Electrode Assembly

Manufacturing Challenges & Strategy

Barriers

- Lack of High-Volume Membrane Electrode Assembly (MEA) Manufacturing Processes
- Low Levels of Quality Control (QC)
- Lack of Standardized Balance-of-Plant Components
- High-cost Carbon Fiber for Hydrogen Storage Tanks
- Lack of Reliable Hydrogen Compressors

Strategy

- Identify cost drivers of manufacturing processes
- Modify processes to eliminate process steps
- Increase automation
- Improve yields and reduce scrap
- Scale-up laboratory fabrication methods to low-cost, high-volume production

R&D Focus

- In-line defect diagnostics for QC of MEAs and MEA components
- Global manufacturing competitiveness of hydrogen and fuel cell technologies
- Expand domestic supply chain for manufacturing hydrogen and fuel cell systems

Key Areas

Hydrogen Delivery

- Develop innovative, low-cost processes for manufacturing fiber-reinforced composite pipe (FRP)

MEAs

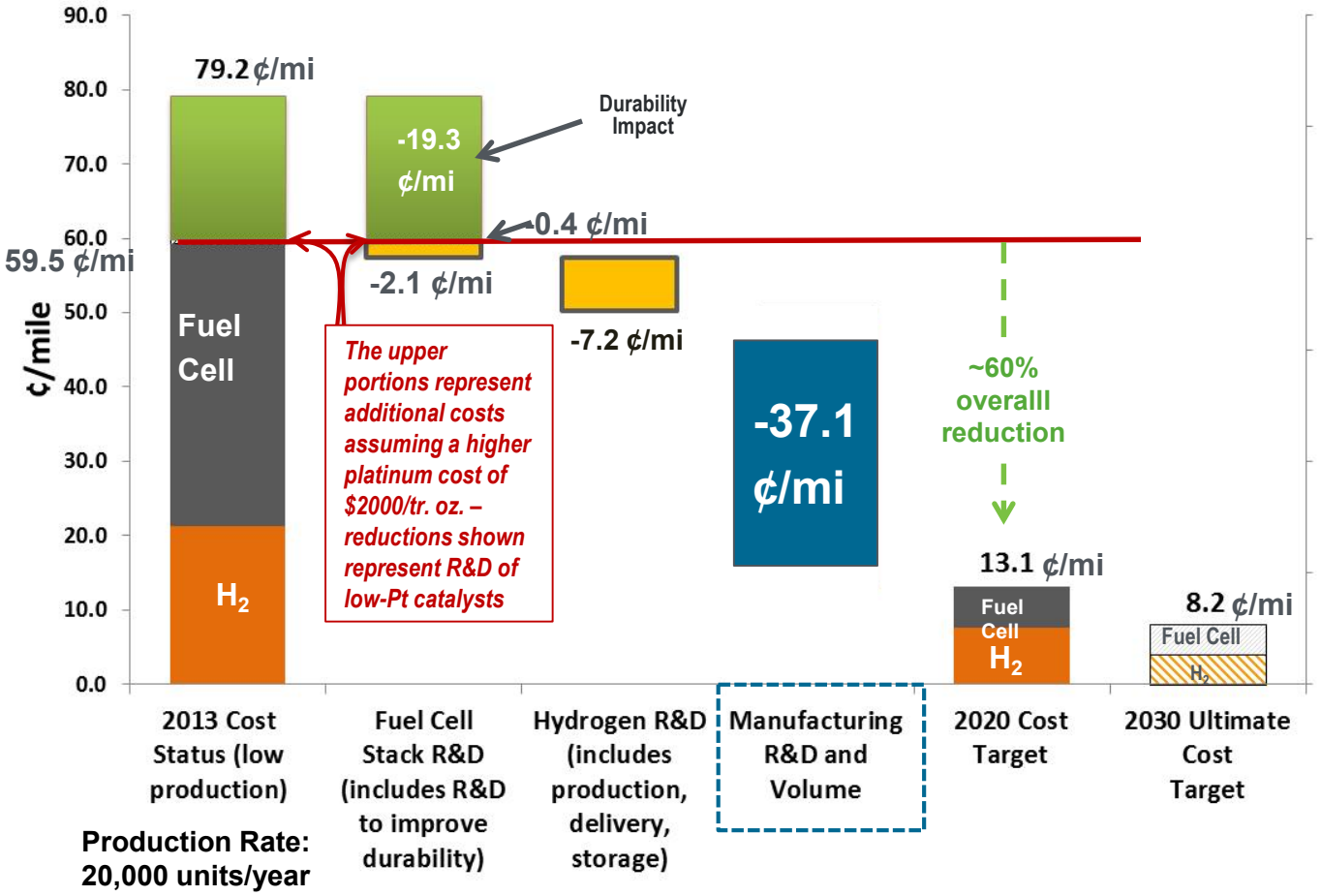
- Develop diagnostics for in-line QC of MEAs and components
- Quantify the effect of defects on performance and durability

Manufacturing MYRD&D available at:
http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

FCEV Cost Reduction Pathways

U.S. DEPARTMENT OF ENERGY

Opportunities for cost reduction



Manufacturing R&D Assumptions

- Fuel Cell Cost: $280/kW (@ 20,000 units/yr)→ $55/kW
- H_2 Production: $8.00 → $6.00/gge
- H_2 Storage: $29/kWh (@20,000 units/yr)→ $17/kWh

Technology Assumptions @ Target

- **Fuel Cell Cost:** $55/kW → $40/kW
- **Fuel Cell Durability:** 150,000 miles
- **Hydrogen Production Cost:** $6.00/gge → $4.00/gge
- **H_2 Storage Cost:** $3,170 ($17/kWh)→ $1,700 ($10/kWh)
- **FCEV fuel economy :** 53 mpgge → 76 mpgge → 112 mpgge
- **Annual miles driven:** 14,500 mi
- **Platinum cost:** $1,500/tr. oz.

Technology Assumptions @ Ultimate Target

- **Fuel Cell Cost:** $30/kW
- **H_2 Production Cost:** $2.00/gge
- **H_2 Storage Cost:** $1,350 ($8/kWh)

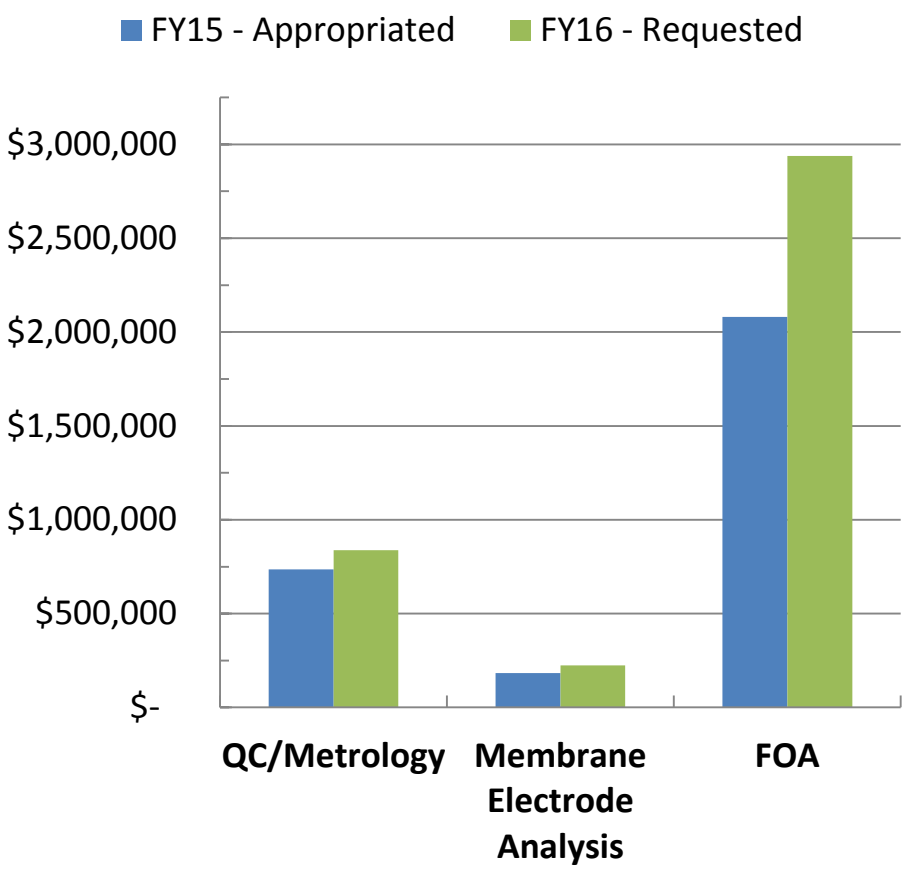
Manufacturing R&D and volume are key to achieve cost reduction

Budget: Manufacturing R&D

U.S. DEPARTMENT OF ENERGY

FY 2016 Request = $4M

FY 2015 Appropriation = $3M



EMPHASIS

- Quality control critical to enabling low-cost manufacturing with reduced waste; correlate defect morphology with loss in performance (NREL, LBNL)
- New analysis projects: global manufacturing competitiveness with CEMI and enhancing the supply chain (GLWN, OFCC, JMU)
- 2015 FOA topic: fiber reinforced pipeline manufacturing
- Future focus could include improved manufacturing processes to reduce cost and increase reliability & efficiency of:
  - Compressors
  - Hoses
  - Seals
  - Station storage
- Leveraging efforts across EERE where cross-cutting manufacturing challenges exist

Technical Accomplishments: QC

U.S. DEPARTMENT OF ENERGY

Laser-drilled knife holes to improve flow uniformity

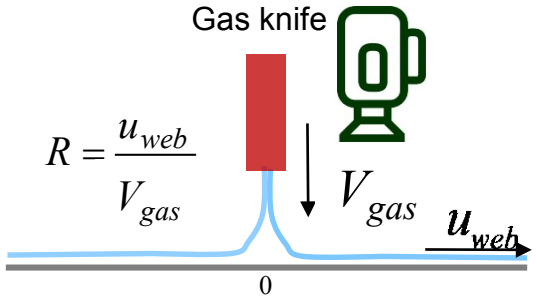
Large-plenum gas knife to improve pressure uniformity of reactive impinging flow (RIF)

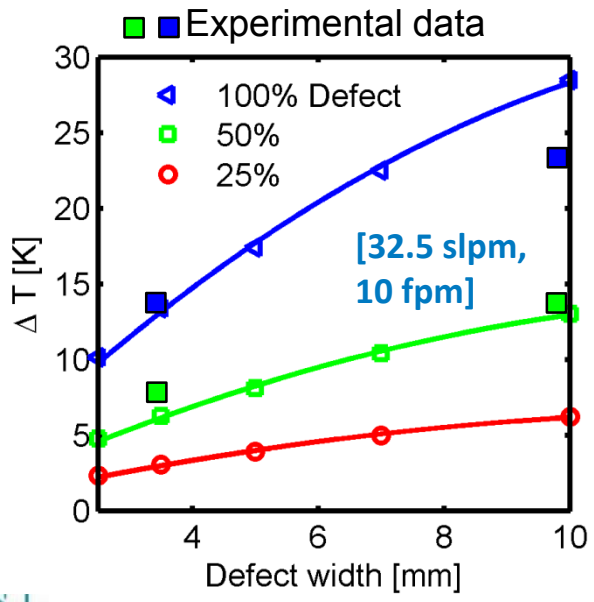
Micrometer tools to set height location

Demonstrated IR/RIF on NREL research web-line

Technical Accomplishments: QC

- **Impinging flow model from LBNL:**
  - **Predicts operating conditions required for defect detection**
  - **Predicts achievable thermal response given defect size, i.e., detection limits**
  - **Good quantitative agreement with experiment**





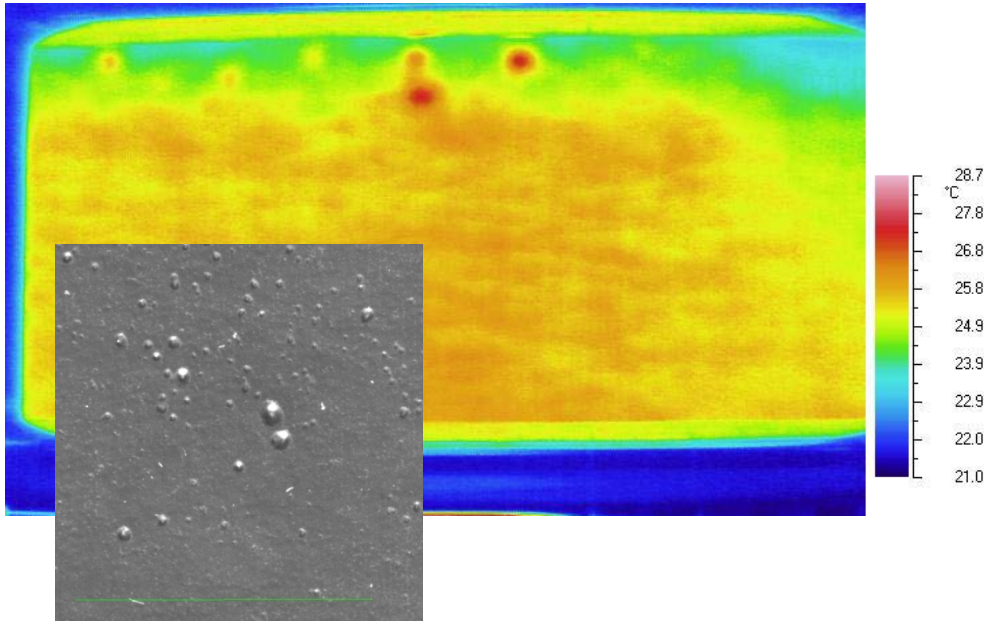
Defect	Minimum detectable defect at ΔT_d=1°C	Minimum detectable defect at ΔT_d=2°C
100% reduction	0.24 mm	0.5 mm
50% reduction	0.51 mm	1.05 mm
25% reduction	1.07 mm	2.3 mm

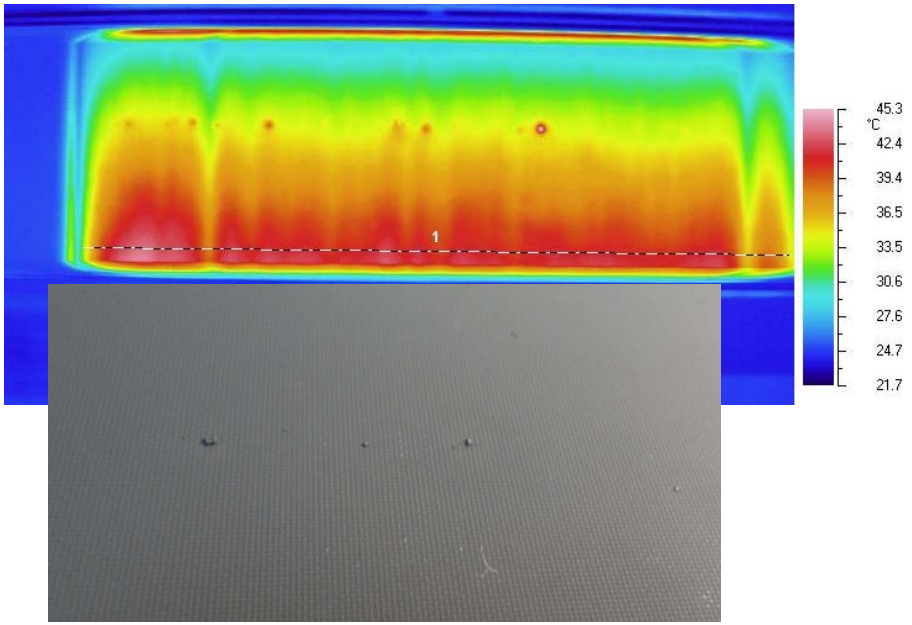
Enhanced impinging flow model with web motion for RIF

Technical Accomplishments: QC

U.S. DEPARTMENT OF ENERGY

- In-plane IR/DC
  - Detected carbon debris applied to GDE, under a laminated membrane
  - 10 fpm on bench-top roller
  - Detected electrode coating lumps on decal
  - 10 fpm on research web-line





Applied IR/DC techniques on GM and Ion Power electrodes

U.S. DEPARTMENT OF ENERGY

Topic 1

Facilitate the Development and Expansion of a Robust Supply Chain for Hydrogen and Fuel Cell Systems and Components

FOA Requirements and Project Deliverables

The outcome and deliverables from this topic area must address both:

(1) Outreach activities that facilitate the development of a robust domestic hydrogen and fuel cell supply chain

(2) Reports that identify supply chain gaps and strategies to overcome these gaps and reduce supply chain costs

New Analysis projects - selections

U.S. DEPARTMENT OF ENERGY

Topic 1 Facilitate the Development and Expansion of a Robust Supply Chain for Hydrogen and Fuel Cell Systems and Components

The Ohio Fuel Cell Coalition

Integrated Regional Technical Exchange Centers

Objective: Develop a national technical exchange network that will expand the hydrogen and fuel cell supply chain and promote the standardization of components to lower the system costs

Virginia Clean Cities
James Madison University

Fuel Cell Hydrogen Opportunity Center

Objective: Expand the domestic supply chain of components and systems necessary for the manufacture and scale-up of the fuel cell and hydrogen supply chain.

Integrated Regional Technical Exchange Centers
Ohio Fuel Cell Coalition

U.S. DEPARTMENT OF ENERGY

Proposed work:

- **Create an integrated network** of regional Technical Exchange Centers:
  - East Coast (CCAT)
  - Midwest (OFCC)
  - Central States (NREL's National Fuel Cell Technology Evaluation Center)
  - West Coast (UC Irvine)

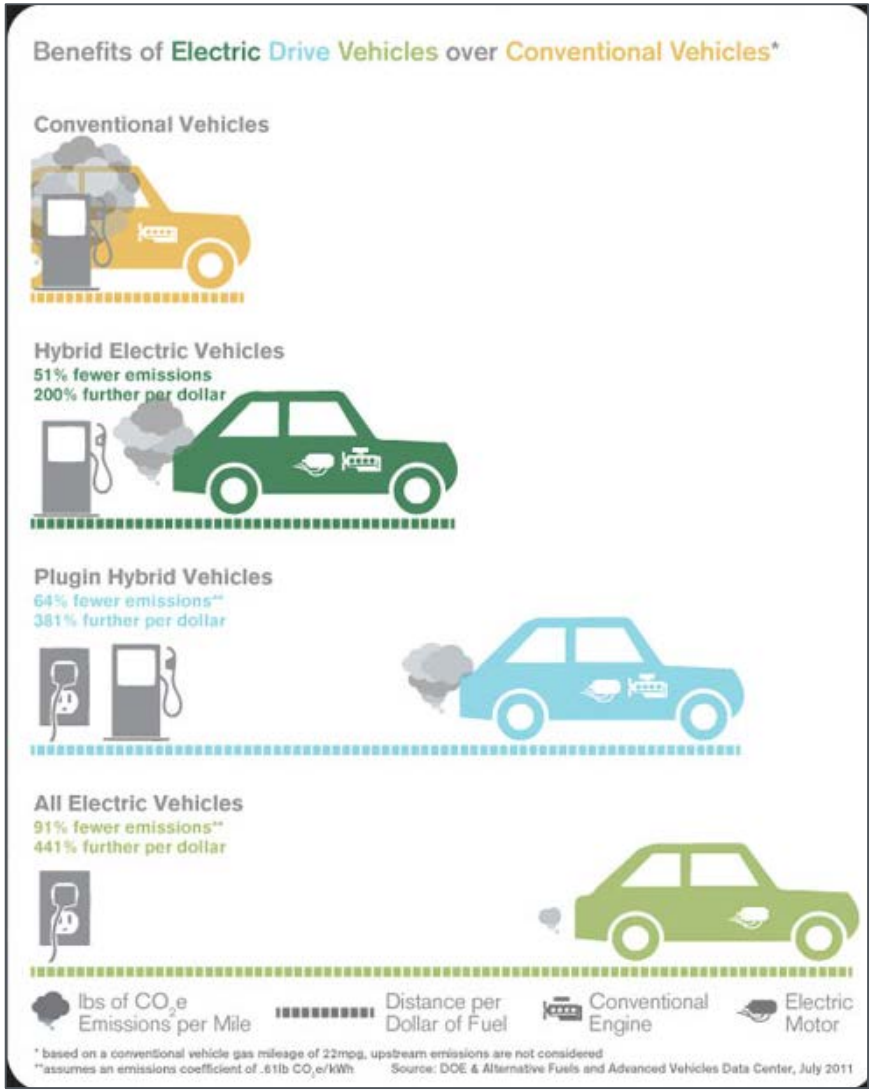
- **The Technical Exchange Centers** will:
  - Collect and catalog non-proprietary product information from regional suppliers and OEMs
  - Maintain a supplier contact list to introduce OEMs to suppliers
  - Hold annual supply chain exchanges
- **Working Groups** will:
  - Comprise members from the OEMs and hydrogen and fuel cell suppliers
  - Analyze the specific needs of the OEMs with the multiple suppliers
  - Promote cooperation between suppliers and the **standardization** of component specs

Supply chain (a) the initial supplier (vendor or plant), (b) a supplier, (c) a manufacturer (production), (d) a customer, and (e) the final customer.

OFCC OHIO FUEL CELL COALITION

Workplan

- Build and populate comprehensive database on Internet
  - Encourage supplier engagement
  - Release and maintain a public directory
- Attract U.S. companies to website with outreach campaign using trade associations, webinars, social media, personal contacts



Source: http://www.birchstudio.com/data-vis.php

JAMES MADISON UNIVERSITY

U.S. DEPARTMENT OF ENERGY

Topic 2

Analysis of U.S. Hydrogen and Fuel Cell Manufacturing Global Competitiveness (with NREL)

FOA Requirements and Project Deliverables

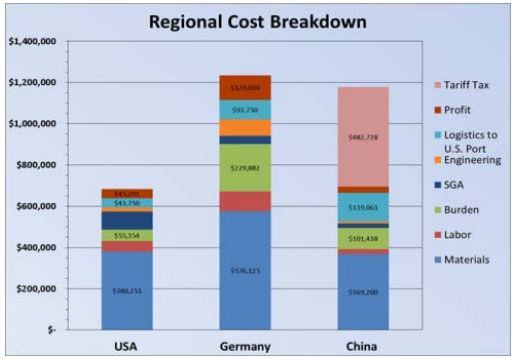
The outcome and deliverables from this topic area must address both:

(1) Global Competitiveness Analysis of hydrogen and fuel cell technologies manufacturing

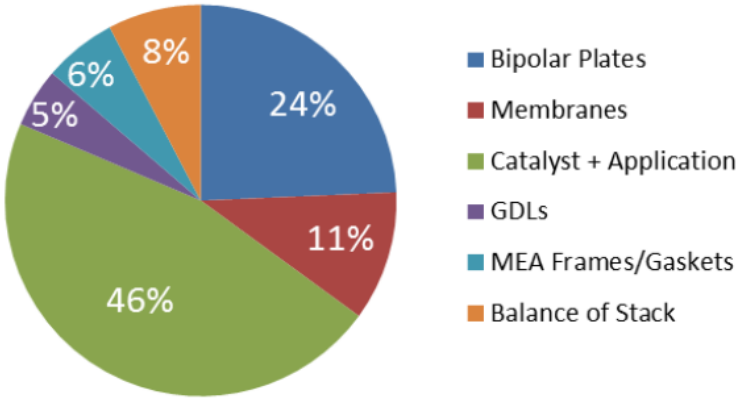
(2) Assessment of the state of global fuel cell markets

Workplan:

- Identify the 5 high value components, generate generic drawings, and conduct detailed cost analysis (CBA, DFMA®, VSM) in 3 global regions
- The results will include: global cost leaders, best global manufacturing processes, key factors determining competitiveness, and opportunities for cost reduction.



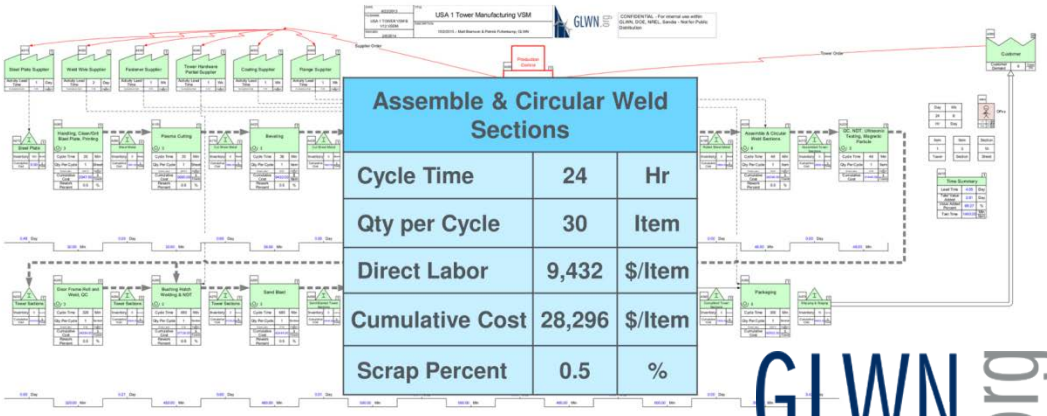
Stack Cost Breakdown (500,000 Units/year)



Cost Analysis Methodologies

- Global Cost Breakdown Analysis (CBA, top)
- Design for Manufacturing & Assembly (DFMA®, left)
- Value Stream Mapping (VSM, bottom)

USA 1 Tower – 17 Process Steps



Sources: (left) fuel cell stack cost breakdown; (right top and bottom) offshore wind turbine Tower Cost Breakdown Analysis and Value Stream Mapping of 5 MW Tower (Ref. MN-014 FCTO 2015 Annual Merit Review and Peer Evaluation)

GLWN.org

Outcomes:

o Identify areas where the **U.S.** might have **viable manufacturing opportunities** or vulnerabilities

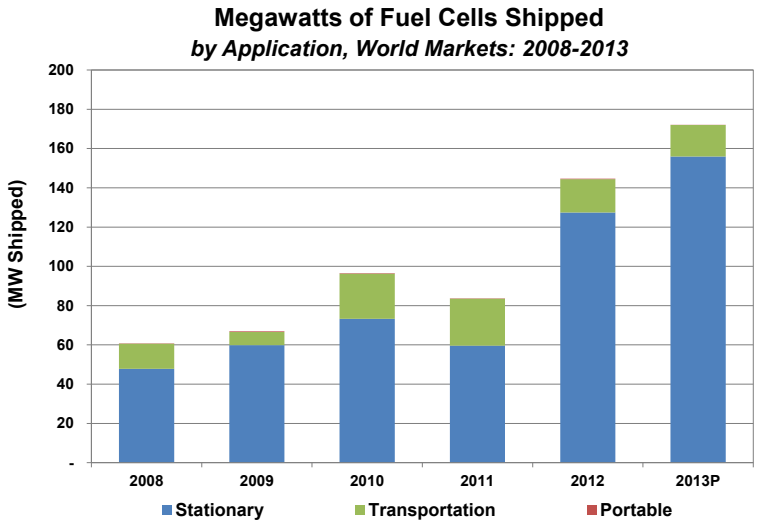
o Identify potential "**tipping points"** where the U.S. could **lose or gain leadership** within segments of the supply chain

o Identify **high value-added segments** of the supply chain that dictate other upstream/downstream products

o Show which **segments** are particularly well-suited to **U.S. strengths** (e.g., requiring a highly skilled, innovative workforce)

Analysis to assess the status of global fuel cell markets

- Report out of H&FC units, size (MW), country, and application



GLWN.org

Accomplishments: Manufacturing

U.S. DEPARTMENT OF ENERGY

HTAC Manufacturing Subcommittee Report

With NREL, the Subcommittee implemented a questionnaire and obtained industry feedback on manufacturing technologies in use and under consideration

Executive Summary

- Significant progress has been made in commercialization of fuel cells and hydrogen production
- Adoption is at a "tipping point" and requires further cost reductions to be self-sustaining
- Suppliers and OEMs are reluctant to invest in areas that could reduce cost, due to uncertain demand
- Initiatives in a few key areas could have significant impact and move industry into the next phase of growth

Recommendations:

1) Targeted demand stimulation programs (such as Market Transformation), including deployments in/outside the U.S.
2) Selected key component cost reduction and standardization
3) Greater access to additive & other advanced manufacturing techniques

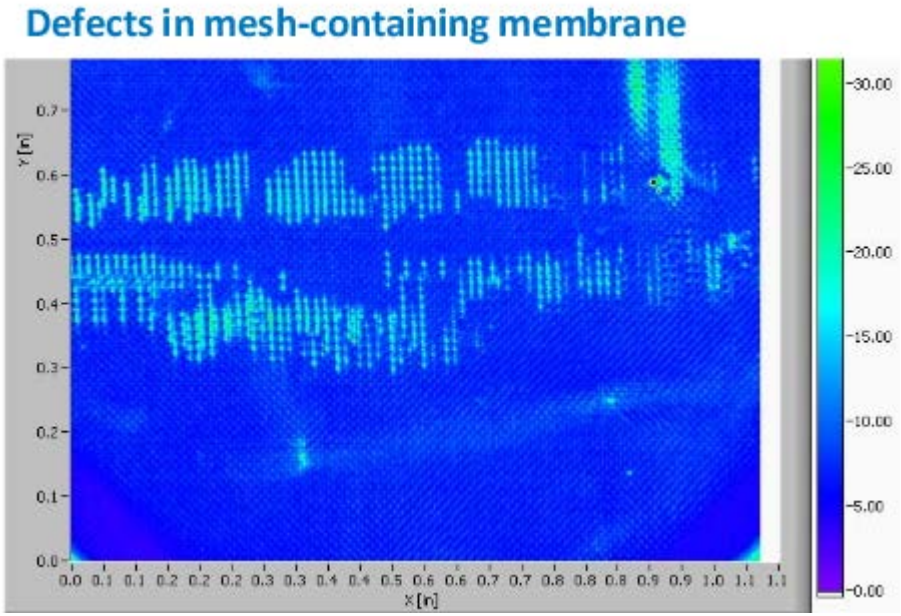
NREL NATIONAL RENEWABLE ENERGY LABORATORY

U.S. DEPARTMENT OF ENERGY

U.S. Department of Energy
Small Business Innovation Research (SBIR) and
Small Business Technology Transfer (STTR) Program
FY2015 Phase I Release 2

TTO Topic Description:

- NREL measured thickness/defects in membrane material used optical reflectance on a moving manufacturing web-line.
- The reflectance signal from the fuel cell material is captured by an array detector.
- DOE asked small businesses to design and develop quality control devices for fuel cell and fuel cell component manufacturers.



Selection: Mainstream Engineering is developing a real-time, in-line optical detector to measure membrane thickness and detect defects. The detector will lower the costs of fuel cells by reducing waste and increasing the efficiency of manufacturing.

NREL NATIONAL RENEWABLE ENERGY LABORATORY

NREL: Tech-to-Market Activities

U.S. DEPARTMENT OF ENERGY

Description	Metric	Due Date	Status
Expose Auto OEMs to NREL's manufacturing QC techniques and discuss pathways for qualification and tech transfer. NREL will identify companies with highest impact potential and interest in implementing QC methods, then do a selective 'road show' to demonstrate QC.	3 Auto OEMs/teams visited	9/30/2015	Leveraging relationships with OEMs in existing CRADAs. Continuing communications with a key FC supplier and an OEM. Despite strong interest, both entities indicate that they do not have research budget to collaborate with NREL. Planned discussion with another OEM during their visit to NREL in May.
	2 new industrial partnerships developed	9/30/2015	Existing OEM partnerships (2) ongoing.
SBIR/FOA for QC system development: Seek 3rd party vendors to work with NREL to manufacture inspection systems that could be marketed to fuel cell/MEA manufacturers. NREL will develop a target list of companies with input from AMO, NIST, etc.	Identify at least 5 potential candidates	9/30/2015	Appropriate 3rd parties were selected via a competitive FOA process. NREL provided technical input to DOE for the SBIR TTO topic The project is pending award.
	Inspection system designed, built and marketed	9/30/2015	Pending awards.

NREL NATIONAL RENEWABLE ENERGY LABORATORY

DOE's Clean Energy Manufacturing Initiative

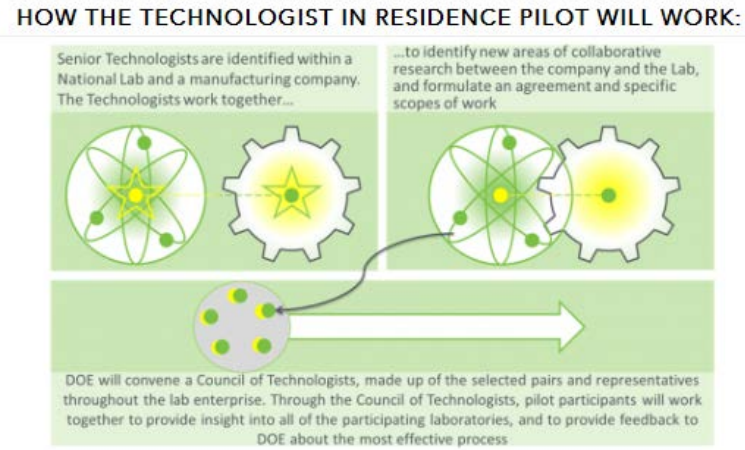
U.S. DEPARTMENT OF ENERGY

Goals of CEMI:

1. Increase U.S. competiveness in the production of clean energy products
2. Increase U.S. manufacturing competitiveness across the board by increasing energy productivity

FY15 Activities:

- Joint AMO-BTO-FCTO meeting on Additive Manufacturing (Oak Ridge, TN) March 2015
- Regional Summit (Atlanta, GA) July 2015
- Annual Summit with the Council on Competitiveness (Washington, D.C.) September 2015
- Technologist-in-Residence Pilot



Key Dates:

Solicitation launched: April 21, 2015
Submission deadline: June 21, 2015

Technologist in Residence Vision:

Catalyze strong national laboratory-industry relationships that result in significant growth in high-impact collaborative research and development

Technologist in Residence Goals:

Increase collaborative research and development between national laboratories and private sector companies
Develop a streamlined method for companies to establish long-term relationships with national laboratories that result in collaborative research and development

Cross-cutting Manufacturing Activities

U.S. DEPARTMENT OF ENERGY

NNMI Institutes
America Makes - 3D/Additive
DMDII - Digital Mfg. & Design
LIFT - Lightweight Metal Mfg.
Power America - Wide Bandgap Semiconductors
IACMI
Flexible Hybrid Electronics
Integrated Photonics
Clean Energy
Revolutionary Fibers and Textiles

Manufacturing Demonstration Facility (Oak Ridge, TN)

3D-Printed Shelby Cobra

Collaboration

U.S. DEPARTMENT OF ENERGY

REGIONAL ACTIVITIES

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

DOE – EERE

Manufacturing R&D

- EERE Additive Manufacturing Meeting
- CEMI
  - Regional and Annual Summits
- Advanced Manufacturing Office
- NREL-LBNL-ORNL collaboration on QC across several technologies (fuel cells, batteries, solar)

INDUSTRY

- GLWN
- Council on Competitiveness
- HTAC Manufacturing Subcommittee

National Collaborations (inter- and intra-agency efforts)

NIST Advanced Manufacturing National Program Office (AMNPO)

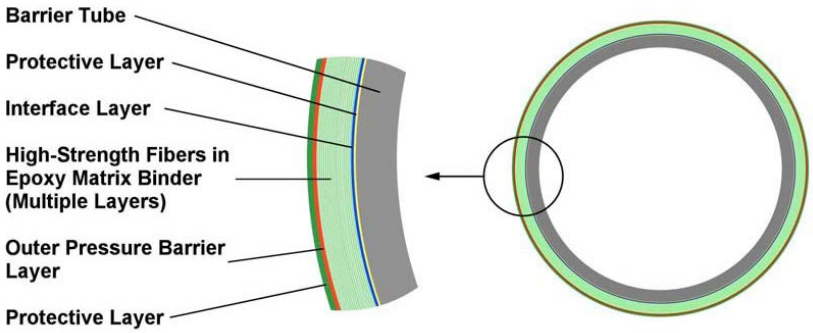
21

Funding Opportunity Announcements

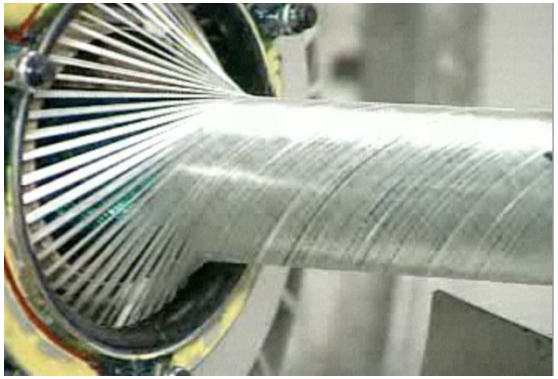
U.S. DEPARTMENT OF ENERGY

FOA Title & Link	Release Date	Topics Included	Due Date
Hydrogen and Fuel Cell Technologies Research, Development, and Demonstrations	March 3, 2015	Innovative H_2 Delivery Pipeline Manufacturing	June 4, 2015

- FCTO seeked applications to develop innovative, low-cost processes for manufacturing Fiber Reinforced Composite Pipe that:
  - Eliminate O-ring failure
  - Are capable of carrying hydrogen at 100 bar
  - Are durable for 50 years
  - Have a reasonably low leak rate



- The project should lead to:
  - Installed FRP costs that are equivalent to or lower than the cost of installing a natural gas pipeline of the same size
  - Processes that are scalable to high volume manufacturing



Recent and upcoming activities

U.S. DEPARTMENT OF ENERGY

Quality Control

- Projects underway to demonstrate in-line QC for MEAs and components

Manufacturing Competitiveness

- New projects:
  - Global competitiveness analysis - GLWN
  - Domestic supply chain development - VCU, OFCC

Fiber-Reinforced Composite Pipeline

- Funding opportunity for:
  Innovative H_2 Delivery Pipeline Manufacturing

Proton OnSite received the 2015 Presidential "E- Award" for significant contributions to increasing U.S. exports

FY 2015	FY 2016	FY 2017
2Q FY15: Manufacturing FOA for new R&D projects on hydrogen production and delivery, hydrogen storage, and fuel cells	1Q FY16: Manufacturing FOA for new R&D projects on hydrogen production and delivery, hydrogen storage, and fuel cells	1Q FY17: Manufacturing FOA for new R&D projects on hydrogen production and delivery, hydrogen storage, and fuel cells
4Q FY15: Demonstrate continuous in-line measurement for MEA fabrication from 1-60 ft/min	3Q FY16: Demonstrate processes for direct coating of electrodes on membranes or gas diffusion media	4Q, FY17 Develop processes and methods to decrease the amount of time and equipment intensity currently required for stack testing

Contacts

U.S. DEPARTMENT OF ENERGY

For more information, contact:

Nancy Garland – Acting Team Lead **202-586-5673** **nancy.garland@ee.doe.gov**
Jesse Adams 720-356-1421 jesse.adams@ee.doe.gov