Automotive Fuel Cell R&D Needs

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USCAR / FreedomCAR Fuel Cell Tech Team Industry Members

Craig Gittleman, David Masten and Scott Jorgensen
General Motors

James Waldecker, Shinichi Hirano and Mark Mehall
Ford Motor Company

Tarek Abdel-Baset
Chrysler LLC

Overview

- Purpose: To provide automotive OEM perspective on topics recommended for study in the DOE Fuel Cell Subprogram
- Categories described within DOE Fuel Cell Request for Information (RFI):
  - Balance of Plant Component Development
    - Transportation Systems (e.g., humidifier membranes, compressors)
    - Stationary Systems
    - Fuel processors for stationary systems (alternate fuels, durability, impurities)
  - Stack Component Integration
    - Integration of state-of-the-art components into high-performance, low-cost stacks
    - Integration of state-of-the-art components into high-performance, low-cost Membrane Electrode Assemblies (MEAs)
  - Other Innovative Concepts
    - Long-term technologies
    - Alkaline fuel cells
- Not all OEMs agree on value of Integration & BOP funding

Focus on Fundamental Research

- Some OEMs believe that further scientific breakthroughs are required to overcome barriers related to cost and durability to enable FC vehicle commercialization. <u>Increased funding on FC **fundamental research** is imperative</u>: (1) catalysts, (2) MEA components, (3) plates.
  - For all technical topic areas, activities should facilitate breakthroughs in:
    - materials development
    - acquisition of fundamental knowledge
    - development of analytical models and experimental tools
  - Optimization efforts based on state-of-the-art materials and components will not enable commercialization, & fundamental research should be prioritized in an FOA instead of cell/stack integration or BOP component development.
- Other OEMs believe, while fundamental research remains a high priority and must continue, that
  - State-of-the art materials have developed to the point where integration projects are necessary to understand the importance of component interactions and to further FC technology, and
  - Development of integrated MEAs, stacks & systems are needed to measure progress against FreedomCAR targets.

Topics Where OEMs Disagree

Cell/Stack Integration

- Some OEMs are in favor of an FOA including the following areas:
  - Integration of the advanced materials (membranes, catalysts, plates, seals) into robust, high-performance, low-cost MEAs and stacks. Novel integration methods are likely required to meet cost targets and optimize interfacial properties. Testing should be on full systems to evaluate material response to DOE targets for drive cycle durability, transient response and cold start. Integration should be done at pilot-scale to ensure manufacturability.
  - Automotive Vehicle/System Demonstration: Technology Validation funding supports development of full automotive FC power systems, stimulates the supplier base, and is the only avenue to measure against FreedomCAR and DOE targets.
- **Some OEMs oppose these efforts on the basis that state-of-the-art materials are still not sufficient to enable commercialization**. Given this perspective, investment in demonstration or system integration using the fuel cell technology available today is not a high-value investment for U.S. taxpayers, and will divert our precious resources from development of the core fuel cell technologies that should be given priority in the R&D funding portfolio.

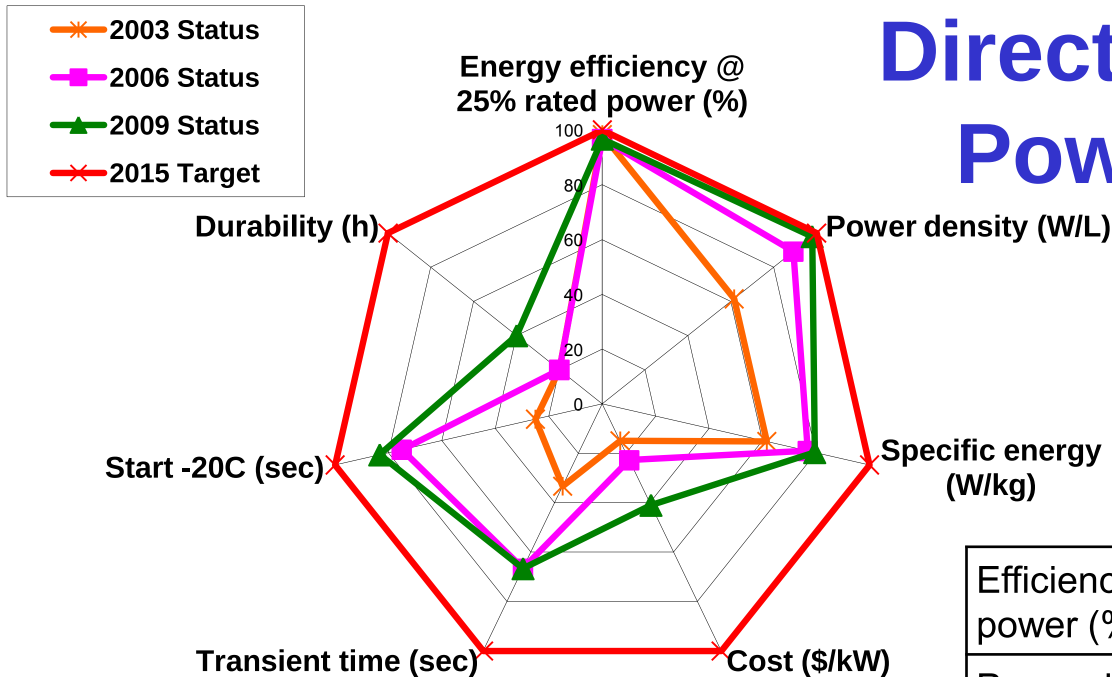
Topics Where OEMs Disagree

Balance of Plant Technology Development

- OEMs agree than BOP cost can be reduced by system simplification enabled by development of more robust stack & MEA components, with focus on fundamental research to deliver enablers.
- Component Development
  - Some OEMs believe that development of BOP components should not be included in FOA because they are not pre-competitive.
  - Other OEMs believe that some BOP components (i.e., humidifiers, compressors, RH sensors) should be included in FOA provided appropriate targets are defined for these components by DOE.
- System Models
  - Some OEMs believe that development of analytical system & BOP models that calculate stack inlet and outlet stress factors as a function of vehicle operating conditions should be included in FOA.
  - Some OEMs believe that it is OEM responsibility to develop such models on their specific systems.

Where We Stand

Direct H_2 Fuel Cell Power System



= from Technology Validation

= from DTI calculations
= from 2007 Honda status
= from Nuvera
= from GM

	2003 Status	2006 Status	2009 Status	**2015 Target**
Efficiency @ 25% power (%)	59	58	58	**60**
Power density (W/L)	400	580	637	**650**
Spec. energy (W/kg)	400	500	517	**650**
Cost ($/kW)	167	110	61	**25**
Trans. time (sec)	3	1.5	1.5	**1**
Start from -20C (sec)	60	20	18	**15**
Durability (h)	1000	1000	2000	**5000**

While Cost & Durability have improved steadily over the past three years, they remain our greatest challenge

Top Challenges to Automotive Fuel Cell Commercialization

- Cost
  - Less expensive base materials
  - Less material (driven by higher performance/power density)
  - Less expensive integration (MEA & Stack) processes
  - Less expensive BOP components
  - Fewer BOP components (simpler systems)
- Durability
  - Robust materials
  - Robust interfaces
  - Robust operation (operating conditions, load leveling, start-stop, freeze)
  - Durable BOP components
- High Temperature Operation (not captured with current targets)
  - Driven by ability to reject heat from system (radiator size)
  - OEMs near term goal is 95°C w/ stretch goal of 120°C
  - Needs:
    - Materials (stack and BOP) that enable higher temperature operation
    - Materials (stack and BOP) that are robust to higher temperatures

Cost

- Less expensive base materials
  - Catalysts, appropriately, get most attention (low PGM, non-PGM)
  - Other materials still too expensive
    - Plates (i.e. high Ni/Cr content stainless) & coatings (i.e. Au)
    - GDL
    - Membranes
    - Seals
- Less materials (driven by high power density, smaller stack)
  - Low resistance membranes
  - Minimal gas transport losses
  - Lower interfacial contact resistances
  - Lower voltage decay rates
- Less expensive integration (MEA & Stack) processes
  - Combining discretely manufactured components may be too expensive
- Less expensive BOP components (i.e., humidifier, compressors)
- Fewer BOP components (i.e., valves, sensors, diagnostics)
  - Enabled by advances in stack materials (i.e., catalysts, membranes)

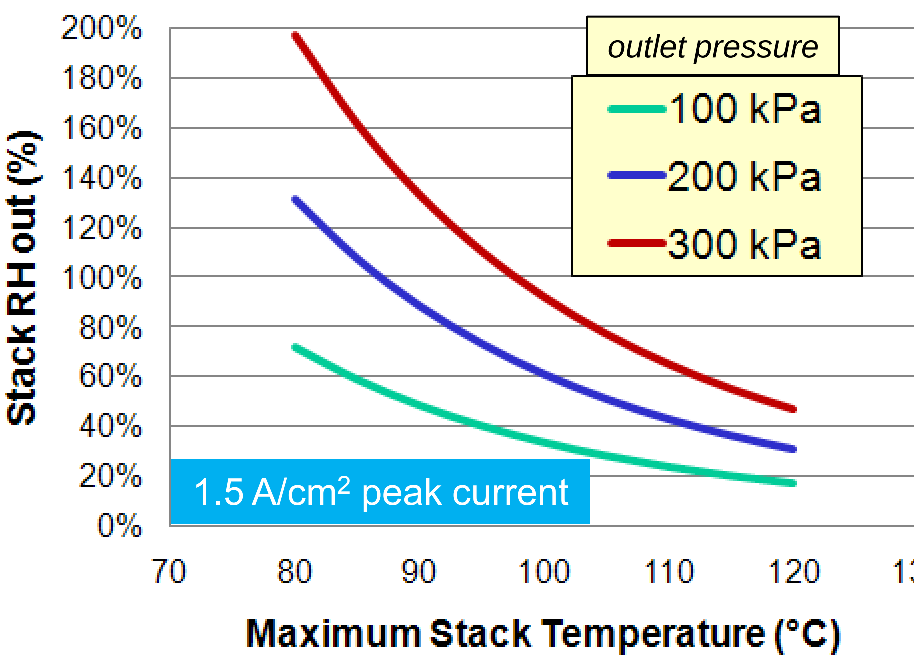
Durability

- **Durability** and **Cost** are integrally related
  - Low PGM loading electrodes more sensitive to Pt dissolution & contamination
  - Non-PGM catalysts have not proven stable to high potentials
  - Low EW membranes exhibit high swelling and poor mechanical durability
  - Thin membranes more susceptible to shorting and pinholes
  - Hydrocarbon membranes tend to be brittle
- Robust Materials
  - **Cathode Catalysts** & **Membranes** are proven to limit stack life
  - Other materials must be robust to FC operation & durability must not be sacrificed to reduce cost
- Robust Interfaces
  - Maintaining low resistances and strong bonding at component interfaces (plate/GDL, GDL/electrode, electrode/membrane) critical for FC durability
- Robust Operation (operating conditions, load leveling, start-stop, freeze)
  - Extremely sensitive to material set & system design
  - Any valuable work in this area should be fundamental in nature

High Temperature Operation

Automotive FC systems must be designed for their peak power operating point

- The hottest (& driest) conditions will exist at peak power
  - >90% of the time system will run colder &, thus, wetter
- Stack humidity will depend on system temperature & pressure
  - While there is no universal agreement among OEM's on automotive FC system pressure, systems are not expected to operate above 300 kPa-abs.



- Current DOE target of 120°C requires >300 kPa-abs system to achieve 50% RH
- US OEMs currently focusing on 95°C peak power system, where RH could range from 40 - >100% RH depending on pressure
  - PEM conductivity too low at lower RH
- Other stack/system materials (seals, humidifier materials) must be compatible with high temperatures

HTWMG 6-18-09 (Gittleman)

Peak Power Targets Reconsidered

- Vehicle FC **Peak Power** requirements are governed by cost, system size (power density) and thermal constraints (heat rejection)
- Current FreedomCAR targets at peak (rated) power include
  - Specific MEA power density: 1000 mW/cm^2
  - Stack efficiency: 55%
- OEM concerns
  - Rated power efficiency is not critical because a very small percentage of drive cycle occurs at full power
  - Heat rejection is not considered
- Proposal
  - Eliminate **Stack Efficiency** target at rated power
  - Add Q/ITD target for baseline system (80kW)
    - Q/ITD is proportional to radiator size
    - Could enable elimination of stack temperature target because Stack T is rolled into Q/ITD target

$$Q/ITD = \frac{\text{heat rejected}}{\text{Initial Temperature Difference}} = \frac{Q\ (kW)}{T_{system} - T_{ambient}\ (°C)}$$

Example Heat Rejection Analysis

FreedomCAR & Fuel Partnership

Assumptions: 80 kW stack, 40°C max ambient temperature

Example system	Temp	Current Density	Voltage	Power density	Q/ITD
	°C	*A/cm2*	*V*	*W/cm2*	*W/K*
3M (2009 AMR data)	80	1.7	0.6	1.0	2.10
3M (assumed 95°C)	95	1.7	0.6	1.0	1.53
3M (assumed 120°C)	120	1.7	0.6	1.0	1.05
Nuvera (New Project Plan)	80	3	0.5	1.5	2.92
Nuvera (to match 3M @80°C)	96	3	0.5	1.5	2.10
Nuvera (to match 3M @95°C)	117	3	0.5	1.5	1.53
Nuvera (to match 3M @120°C)	151	3	0.5	1.5	1.05

Nuvera stack at $3 A/cm^2$ would need to run at close to 120°C target to match 3M system running at 95°C, and over 150°C to match 3M system running at 120°C

3M data from 2009 AMR (Debe). Nuvera plan from 2009 Kickoff Meeting (Cross)

Peak Power Targets

OEM Proposal

- Keep 2015 specific power density target: >1000 mW/cm^2.
- Eliminate stack efficiency at rated power target.
- Efficiency should be governed by low power (drive cycle average). Current ¼ power efficiency target is 60%.
- Add Q/ITD target at rated power for 80kW stack & 40°C ambient temperature: < 1.35 - 1.5 kW/K.
- Eliminate stack maximum outlet temperature at rated power target.
- Keep membrane maximum temperature target at 120°C as stretch goal, with 95°C as interim target.
  - Membranes with high low RH, 120°C conductivity can enable BOP cost reductions
    - Smaller radiators
    - Less expensive air handling equipment
    - Smaller (or no) humidifier

FOA Technical Topics Areas

- MEA component level studies
  - Robust, low-cost material development
  - Fundamental studies of component performance and degradation mechanisms.
- MEA Integration
- Cell/Stack Integration
- Balance of Plant & Systems

Catalyst/Electrode Development

Some OEMs assert that catalyst funding is not adequate to fill the gaps for fuel cell cost and durability, and that increased funding is necessary. Others believe that the already high proportion of funding for catalyst projects is appropriate.

Catalyst Concept	**Higher mass activity**			**Higher stability**
	Higher specific activity	Sufficient ECSA	Less sub-surface PGM	
Alloy nanoparticles				
Core/shell nanoparticles				
Thin, continuous PGM layers				
Facet oriented controlled catalysts				
Non-carbon supports				

Present funding adequate, no further funding needed

Present funding insufficient, **further funding needed.**

No present DOE funding, **funding needed**

- Activity & stability of all concepts may be improved by a better understanding catalyst-support interactions
- Improved understanding of performance and durability of all high activity catalysts at higher current density is needed

Other MEA Subcomponents

- Membrane Development
  - Development of guidelines for tailoring microstructure
    - optimizing proton conductivity
    - minimizing swelling
    - increasing mechanical strength
  - Tracking microstructural changes during operation and how changes impact performance & durability
- GDL Development
  - Development of low-cost GDLs with tailored properties to enable robustness towards both dry and wet conditions.
    - Base Paper
    - Microporous Layer
- Seal Materials Development
  - low-cost & processable
  - chemically, thermally & mechanically stable
  - very low electrical conductivity & gas permeation

Fundamental MEA Level Studies

- Understanding of catalyst layer flooding associated with ultrathin electrodes, particularly at low temperature.
  - Same amount of water is generated in less volume… where does the water go
  - GDL/electrode & electrode membrane water transport resistances must be understood
  - Issue compounded at low temperatures (start-up) conditions
- Studying the impact of catalyst layer & GDL properties and structure on water vapor transport and O_2 transport resistance.
  - Measurements of H_2O & O_2 transport
  - Porosity distribution
    - Void space fraction, shape, size, connectivity
    - Porosity over range of humidity
  - H_2O & O_2 transport models
- Proton transport in electrode layers
  - Fundamental studies of ionomer structure
  - Electrode proton transport models and f(T, RH)
  - Mechanisms for electrode proton transport loss
  - Proton transport mechanisms in ionomer-free electrodes

MEA Integration

Challenges

- Not all components are compatible with each other
  - Thin, low PGM electrodes can be sensitive to membrane type. Incompatible materials lead to poor performance and rapid voltage decay.
  - GDL properties can have an impact on membrane and electrode life (membrane cracking & shorting, electrode cracking).
- Interface optimization is important
  - Plate/GDL: electrical contact resistance, water management
  - GDL/electrode: water management, electrical contact resistance, mechanical bonding
  - Electrode/membrane: water management, proton transport resistance, mechanical bonding
- Interfaces must be robust to
  - Increasing contact resistances
  - Loss of adhesion

MEA Integration

Recommended areas for inclusion in FOA

- Fundamental studies of component interactions
  - Impact on FC performance
    - Wet & dry conditions
  - Impact on voltage decay rate
    - Diagnosing sources of losses (kinetic, ohmic, transport)
      - i.e., do interfacial resistance increase with FC operation?
      - i.e., does water transport across component interfaces change with time?
      - i.e., do membrane degradation byproducts adsorb on catalyst sites?
  - Impact on membrane life
    - Mechanical Degradation
      - i.e., do cracked electrodes accelerate mechanical membrane failure?
    - Chemical Degradation
      - i.e., do leached metals from alloy catalysts promote formation of radicals that attack the ionomer?
    - Shorting Failure
      - i.e., do GDL & electrode properties impact membrane shorting?

MEA Integration - continued

- Development of techniques for measurement of interfacial parameters (*ex-situ & in-situ*)
  - GDL/electrode & electrode/membrane contact resistances
    - Thermal
    - Electrical
    - Protonic
  - Adhesion
- Interaction studies should be done on of state-of-art materials
  - Low PGM loading catalysts
  - Robust, low resistance, low cost membranes
  - Roll-processed non-woven GDLs
- Novel, low-cost integration methods
  - Generate strong, controlled interfaces
  - Eliminate integration steps (full unitized assembly)
  - Must be continuous (i.e., roll processable) and scalable

Cell/Stack Integration

Recommended areas for inclusion in FOA

- Fundamental studies of (a) impact of stack materials on MEA durability and (b) impact of MEA materials on stack durability
  - Seals
    - i.e., do materials leach from seals that lead to voltage decay or membrane degradation?
  - Plates
    - i.e., do membrane degradation products accelerate plate corrosion?
    - i.e., do plate corrosion products lead to membrane degradation?
- Fundamental studies of metal plate / GDL interfaces to obtain understanding and predictive models for electron transfer and water management. Parameters should include
  - GDL Properties
  - Compression pressure
  - Plate coating material/thickness
  - Plate surface roughness

Cell/Stack Integration

OEMs feel than any stack integration projects should meet the following criteria

- Stack Integration projects should use state-of-art or more advanced components
  - Low PGM loading electrodes
  - Robust, low resistance, low cost membranes
  - Low cost, robust seal materials
  - Low cost, robust non-woven GDL
  - Low cost, robust plate materials
- Stack Integration projects should include testing within realistic automotive systems to enable measurement of DOE targets
  - Transient Response
  - Cold Start Time
  - Drive Cycle Durability
- Stack Integration projects should be conducted on pilot scale equipment that can be readily scaled up to a full manufacturing process

Balance of Plant

Needs

- The balance of plant constitutes a significant portion of the FC system cost

			2008 Status	2009 Status	2008 Status	2009 Status	2008 Status	2009 Status
			Current (2008, 2009)		2010		2015	
DOE Target:	Stack Cost	$\$/kW_{e\ (net)}$	-	-	$25	$25	$15	$15
Study Estimate:	Stack Cost	$\$/kW_{e\ (net)}$	$38	$27	$29	$24	$25	$20
DOE Target:	System Cost	$\$/kW_{e\ (net)}$	-	-	$45	$45	$30	$30
Study Estimate:	System Cost	$\$/kW_{e\ (net)}$	$75	$62	$62	$54	$51	$46

  - DTI projects 2015 FC system cost of ($46/kW based on existing DOE projects).
  - More than half the projected 2015 cost is from BOP ($26 of $46). Less than 5% of the 2010 budget is allocated for BOP & automotive System projects

- Durability (failure or performance degradation) of BOP components can be a life limiting factor in FC systems

Balance of Plant

Challenges

- There have been several BOP component projects over the years. In general, they have not provided much value to the OEMs.
- No targets exist for any BOP components except compressors (which may be outdated)
- Before engaging projects on BOP technology, pre-work must be done to define targets for
  - Performance (i.e., water transfer rate for humidifies, efficiency for compressors)
  - Operating Window (temperature, pressures, gas flows & compositions)
  - Cost
  - Volume & weight
  - Durability
- Primary Issues
  - Performance requirements & operating window are strongly dependent on system design, for which there is no industry consensus
  - Without integrated systems, it is very difficult to monitor progress towards DOE FC system level targets

Balance of Plant

Recommended areas for inclusion in FOA

- Humidifier Technology
  - development of materials for low cost, compact, high performance water vapor transport exchangers that allow better management of humidification in a more efficient package. Research should focus on durable, lightweight, low cost materials that would enable compact humidifiers. Focus should include durability and understanding the root causes of membrane water transfer rate degradation.
- No other BOP topics of consensus among OEMs
- Rather, OEMs recommend focus on developing stack materials that enable system simplification
  - Cathode catalysts w/ high H_2/Air performance at high current densities that enable low pressure air handling equipment
  - High temperature, low RH membranes that enable smaller radiators and less expensive humidifier and air handling equipment
  - Robust materials that reduce the need for complex control systems and stack health monitoring

Summary

- Cost and durability are the greatest technical barriers to the development of fuel cell vehicles. Wider temperature range operation with practical heat rejection is also important.
- While OEMs disagree regarding the value of integration efforts and BOP component development, they do agree that fundamental research is necessary in these areas.
- OEMs agree that the following areas deserve increased or continued funding:
  - MEA components (e.g. catalysts, membranes) and their interactions
  - Fundamental aspects of unit cell design
  - BOP technology (e.g. humidifier materials)