Integration of MEA Components
- Status and Technology Gaps –
A Stakeholder's Perspective

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3M Fuel Cell Components Program

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3M Fuel Cell Components

Integration of MEA Components

3M perspectives on technology development needs and gaps.

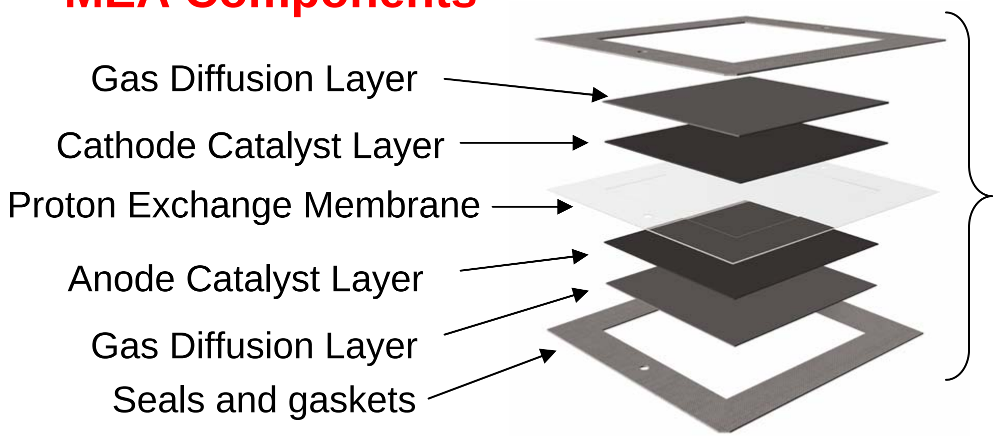
Outline:

1. What does MEA integration mean?
2. Where the technology may be going with regard to 2015
3. Status and relative gaps for 2015 at the individual component level
4. Status and relative gaps for 2015 at the MEA integration level
5. Suggestions where DOE should concentrate its efforts in the near future
6. Other general suggestions and recommendations

1. What does MEA integration mean? Depends on your location on the Fuel Cell food chain:

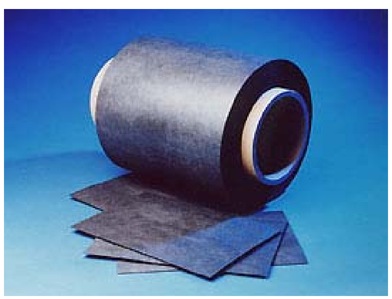
At the MEA Level

MEA Components



Component Integration

Automated MEA Manufacture



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Stack Insertion

- Component materials and properties optimized for functional performance
- Component materials manufactureable at scalable volumes with in-line process control and high quality as roll-goods.
- Roll – to – roll processing of ultimately discrete parts from roll-good inputs
- Robust manufacturing methodology (ISO 9001- 2008 requirements)

1. What does MEA integration mean?

Depends on your location on the Fuel Cell food chain

At the Stack Integration Level

- Integrated 5 or 7 layer MEA’s designed to the stack-required form factors that meet all registration and alignment specifications
- Packaging and MEA handling robustness to enable rapid MEA/plate assembly
- Documentation and traceability
- Ultimately mutually integrated MEA and Stack Plate designs for rapid (seconds per part) automated lay-up of MEA/bi-polar plates with perfect registration and alignment.

3M views the MEA as a System. Each component has many requirements to be met simultaneously.

- Understand customer required performance, durability and cost requirements
- Optimize components consistent with high volume manufacturing processes
- Integrate the components into an MEA, accounting for – and + synergistic effects.

Integrated MEA

Seals and Gasket Requirements

Gas Diffusion Media Requirements

Membrane Requirements

Fuel Cell Stack and System Derived Requirements For the MEA

Durability

Performance

Low Cost

Catalyst Requirements

- Low H_2O_2 production or high radical scavenging for membrane life
- High stability against dissolution, agglomeration under voltage cycling
- High stability against support oxidation at high potentials, temperatures
- Freeze tolerance

- High Specific Activity (A/cm^2-Pt) and Mass Activity (A/mg-Pt)
- High electrochemical surface area (cm^2-Pt/ cm^2-planar)
- High utilization in the electrode, at all current densities
- Negligible mass transfer overpotential at high current densities
- Minimal ionic and electronic losses (IR) under dry conditions
- High tolerance to impurities (internal as well as external)
- Load transient capable under cool, wet conditions

- Robust, low cost catalyst electrode fabrication process
- High performance at low precious metal (Pt) loadings
- Easy and effective precious metal reclamation

2. Where the technology may be going, re 2015 and beyond

A. Catalysts
- Pt and Pt alloys
  - Graphitized carbon blacks for dispersed nano-particles
- Extended surface area catalysts – thin film types vs dispersed Pt/C only
  - Non-carbon based supports – completely corrosion free

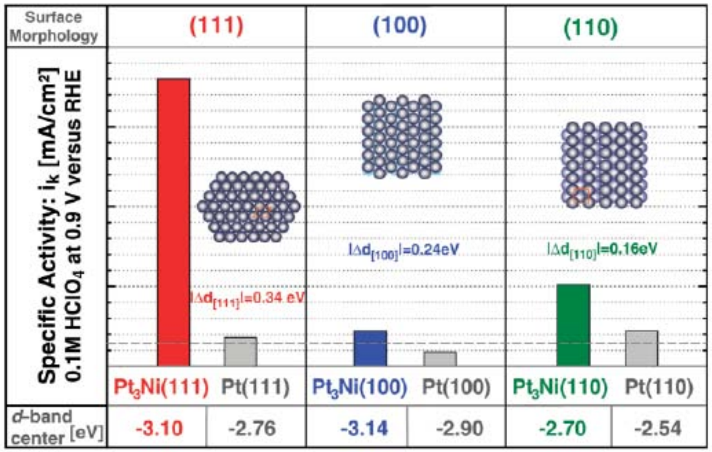
B. Membranes and Ionomers
- Materials with improved durability – mechanical and chemical stability
- Materials designed for improved proton transport and lower swelling through improved understanding of structural properties
- Ion conductors designed for interfacing the catalyst

C. Gas Diffusion Media (EBL + MPL)
- Still based on carbon fiber non-wovens and papers
- Hydrophobic and hydrophilic treatments to tailor water management for both anode and cathode
- MPL's with corrosion-less conductors
- Engineered electrode backing layers for optimized reactant transports

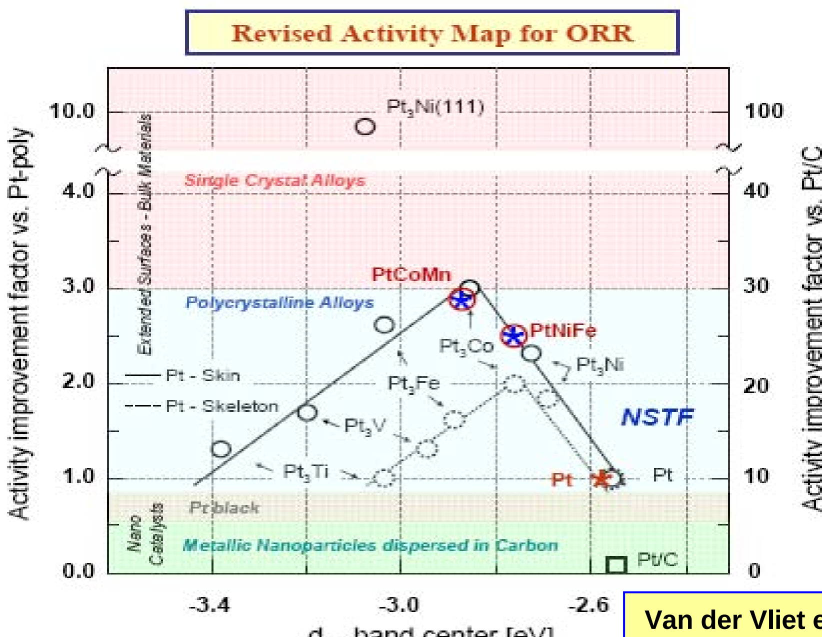
D. Gasket, seal materials
- Improved materials
- New seal concepts

2. A. Where the technology may be going, re 2015 and beyond –

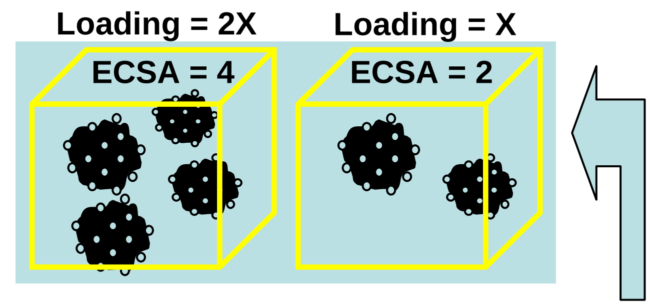
Catalysts: Extended surface area types vs self-similar geometries

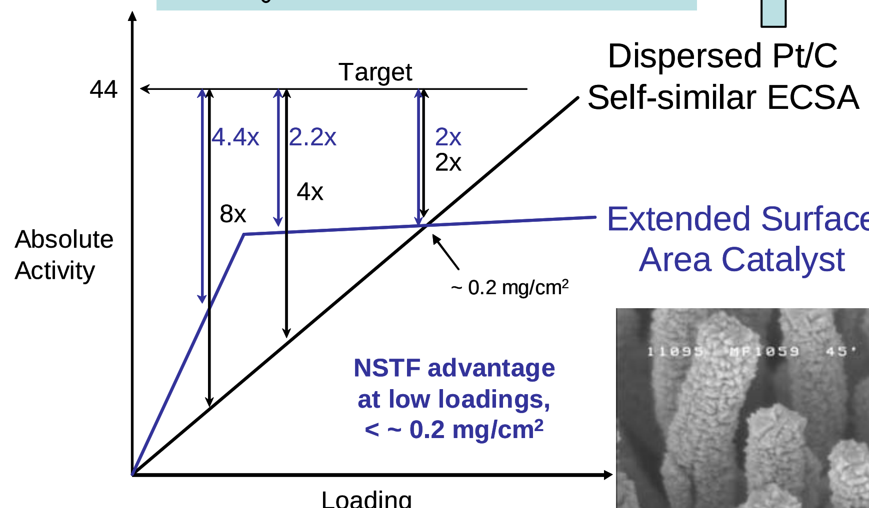


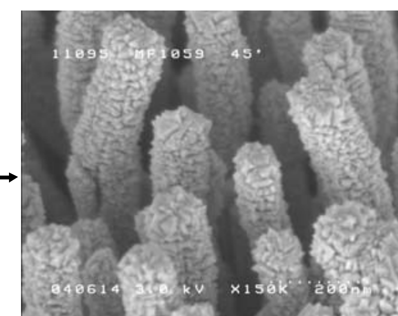
Stamenkovic et al., Science 315(2007) 493



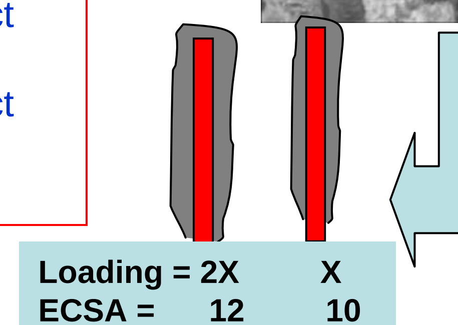
Van der Vliet et al., 216th ECS Meeting, Vienna, Oct. 2009







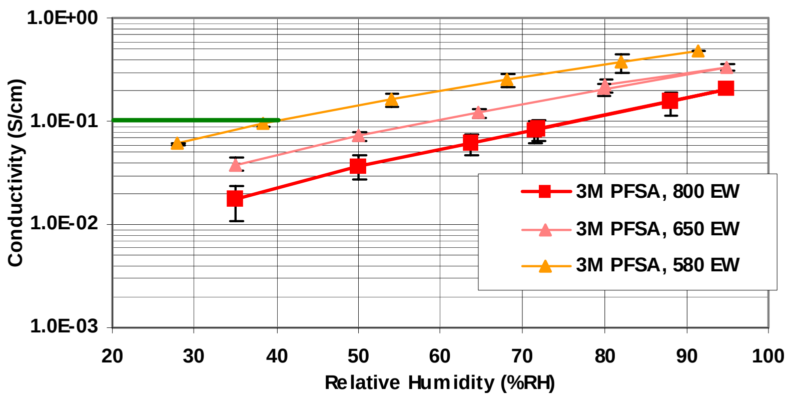
- Specific activity-particle size effect
- Pt dissolution-particle size effect
- Carbon support corrosion

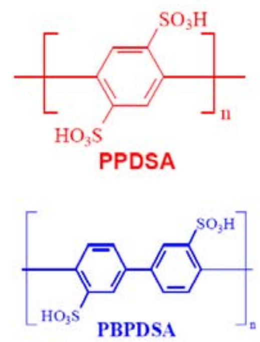


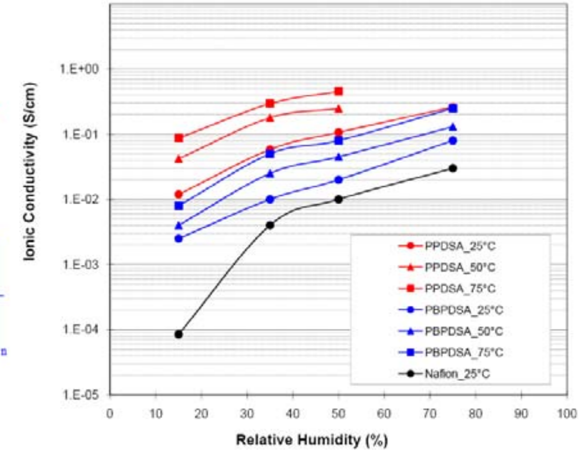
2. B. Where the technology may be going, re 2015 and beyond -

Membranes

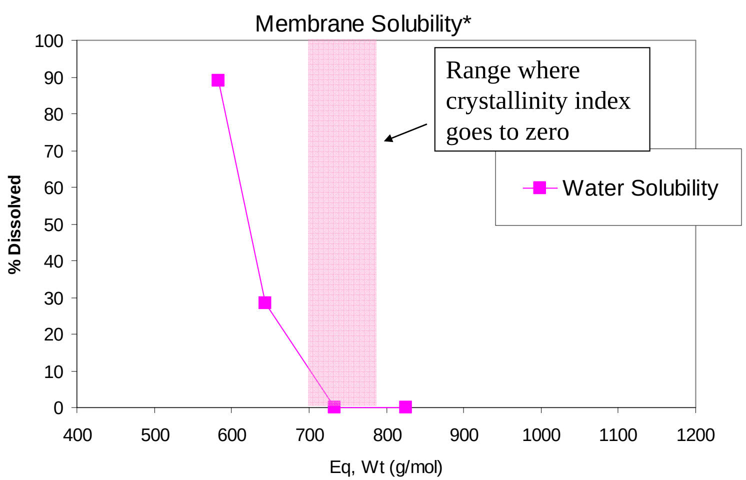
Materials exist that meet any one of the requirements. The real target for membranes is to provide **a single membrane material that can meet all conductivity and durability requirements**.



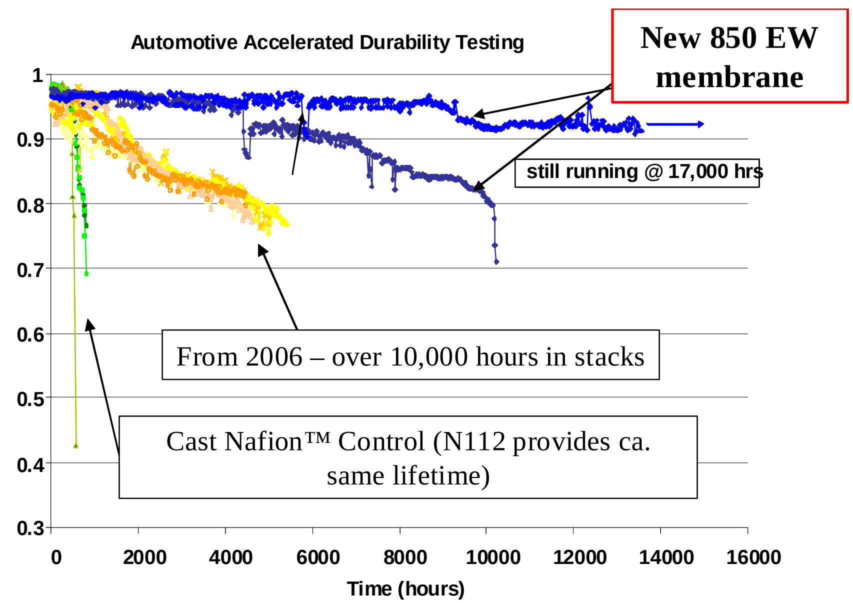




Morton Litt, AMR, June 2009



* Can vary with process conditions



Steve Hamrock, AMR, June 2009

3. Status and relative gaps for 2015 at the individual component level

A. Catalysts
- Status against targets in MYRDD plan table 3.4.12
- and other critical requirements

B. Membranes
- Status against targets in MYRDD plan table 3.4.11
- and other critical requirements

C. Gas Diffusion Layers
- Material Properties and
- other needs and issues

D. Gaskets and Seals
- Materials Properties and
- other needs and issues

3. A. i. Catalysts – status relative to 2015

Table 3.4.12 Technical Targets: Electrocatalysts for Transportation Applications							3/10 Status	
Characteristic	Units	2005 Status [a]		Stack Targets			3M NSTF-MEA (50 cm^2 or as noted)	Dispersed Pt alloy/C (short stack) (1)
		Cell	Stack	2010	2015			
Platinum group metal total content (both electrodes)	g / kW (rated)	0.6	1.1	0.3	0.2		$0.19 g_{Pt}/kW$, 400 cm^2 short stack	0.22
Platinum group metal (pgm) total loading [b]	mg PGM / cm^2 electrode area	0.45	0.8	0.3	0.2		0.15 – 0.2	0.225
Cost	$ / kW	9	55 [c]	5 [d]	3 [d]			
Durability with cycling							• 50-cm^2: 7000 • Stack: 2000 (2)	50-cm^2: 5500 Stack: 2000 + (test still running – expect 5500 hrs) (3)
Operating temp ≤80°C	hours	>2,000	~2,000 [e]	5,000 [f]	5,000 [f]			
Operating temp >80°C	hours	N/A [g]	N/A [g]	2,000	5,000 [f]			
Electrochemical area loss [h]	%	90	90	<40	<40		17	45 (4)
Electrocatalyst support loss [h]	mV after 100 hours @ 1.2V	>30 [i]	N/A	<30	<30		0	>> 100 (5)
Mass activity [j]	A / mg Pt @ 900 $mV_{iR-free}$	0.28	0.11	0.44	0.44		0.18 - PtCoMn 0.40 -New alloy	0.4
Specific activity [j]	µA / cm^2 @ 900 $mV_{iR-free}$	550	180	720	720		2100 – PtCoMn 2500 – New alloy	730

(1) Customer input based on stack data (unless otherwise mentioned).
(2) GM short-stack testing. Protocol includes automotive system-relevant voltage- and RH-cycles.
(3) 5500 hrs demonstrated for dispersed Pt/C (0.4 mg_{Pt}/cm^2 loading) at the stack and module level.
(4) Target may be irrelevant. Suggest changing/adding mass-activity target for end-of-life.
(5) Target may be irrelevant. Start-stop (C-corrosion) related voltage loss is highly dependent on system mitigation strategy. Recommend including appropriate start-stop testing to demonstrate overall durability (e.g. 5000 hrs) target.

Start-stop cycling
Load transient response
Cell reversal tolerance
Impurity sensitivity
Break-in conditioning

3. B. i. Membranes – status relative to 2015

Table 3.4.11 Technical Targets: Membranes for Transportation Applications

Characteristic	Units	2005 Status [a]	2010	2015	3/10 Status: 3M PEM-50cm[2]	3/10 Status: Other's
Inlet water vapor partial pressure	kPa	50	<1.5	<1.5		
Oxygen cross-over [b]	mA / cm^2	5	2	2	< 0.5, 20 µm	
Hydrogen cross-over [b]	mA / cm^2	5	2	2	< 2 , 20 µm	
Membrane conductivity at inlet water vapor partial pressure and:						
Operating temperature	Siemens / cm	0.10	0.10	0.10	0.12 @ 120°C, 40% RH	
20°C	Siemens / cm	0.07	0.07	0.07	0.10 @ 30°C	
-20°C	Siemens / cm	0.01	0.01	0.01	0.014	
Operating temperature	°C	<80	≤120	≤120	≤ 120°C	
Area specific resistance	Ohm - cm^2	0.03	0.02	0.02		
Cost [c]	$ / m^2	25 [d]	20	20		
Durability with cycling					▪ 17,000 in 50 cm^2 cell ▪ Stack TBD	
At operating temperature of ≤80°C	hours	~2,000 [e]	5,000 [f]	5,000 [f]		
At operating temperature of >80°C	hours	N/A [g]	2,000	5,000 [f]		
Unassisted start from low temperature	°C	-20	-40	-40	- 20	
Thermal cyclability in presence of condensed water		Yes	Yes	Yes	Yes	

- **Impact on low ECSA catalysts**
- **Mechanical durability under RH cycling**
- **Chemical stability (oxidative, hydrolytic)**

3. C. Gas Diffusion Media – status relative to 2015

Gas Diffusion Media: EBL (electrode backing layer) + MPL

Gas Diffusion Media: Material Properties

- Roll-good processable (flexibility)
- Cost
- Area specific resistance
- Gas and liquid permeability
- Mechanical properties (tenting, stress-strain)
- Coatability
- Durability, stability, corrosion resistance
- Uniformity of caliper
- Surface smoothness

Gas Diffusion Media: Other needs and issues

- The fundamental state of understanding of current state-of-the-art carbon fiber based gas diffusion layers and their dispersed carbon micro-porous layers is generally thought to be well behind that of current FC membranes and catalysts.
- Furthermore the production costs of these GDM materials do not offer much opportunity for reduction to the levels believed to be required for large scale MEA commercialization in fuel cell vehicles.
- Improved durability
- A break-through technology may be required for the final GDM component solution.

3. D. Gaskets and Seals – status relative to 2015

Gaskets and Seals: Materials Properties

- Roll-good processable
- Mechanical properties (compression set resistance, …)
- Chemical resistance
- Robustness and performance over – 40 to 120 ^{o}C range, dry to wet
- H_2 and O_2 permeability, leak rates
- Durability
- Cost

Gaskets and Seals: Other needs and issues

- Alternative materials and manufacturing methods to develop seals and gaskets
- The mating surfaces where the seals/gaskets have to be applied becomes challenging in a manufacturing environment
- Costs to produce are measured in pennies but costs to the integrator to install and use are in dollars.
- Material quality becoming more important. The best, most durable MEA will be of no use if the seals and gaskets fail.
- Another issue is deciding where to put the seals and gaskets – with the MEA or on the plate, or split between them? e.g. seal vs sub-gasket + adhesive. This helps MEA manufacturing, but impacts the stack design and cost of assembly.
- There is an opportunity to optimize the synergy between the seals, MEA's and system designs to lower the stack costs.

4. Status and relative gaps for 2015 at the MEA integration level

A. Status and relative gaps vs DOE MYRDD Table 3.4.13.

B. Other relative gaps for 2015 at the MEA integration level

4. A. Status and relative gaps for 2015 at the MEA integration level

Table 3.4.13 Technical Targets: MEAs				
Characteristic	**Units**	**2005 Status [a]**	**2010**	**2015**
Operating temperature	°C	<80	<120	<120
Inlet water vapor partial pressure	kPa	50	<1.5	<1.5
Cost [b]	$ / kW	60 [c]	10	5
Durability with cycling At operating temp of ≤80°C At operating temp of >80°C	 hours hours	 ~2,000 [d] N/A [f]	 5,000 [e] 2,000	 5,000 [e] 5,000 [e]
Unassisted start from low temperature	°C	-20	-40	-40
Performance @ ¼ power (0.8V)	mA / cm^2 mW / cm^2	200 160	300 250	300 250
Performance @ rated power	mW / cm^2	600	1,000	1,000
Extent of performance (power density) degradation over lifetime [g]	%	5 [h]	10	5
Thermal cyclability in presence of condensed water		Yes	Yes	Yes

3M 50 cm^2 MEAs: (Pt/C or NSTF with 3M PEM)	**Other's**
≤ 120	
Targets under revision	
17,000 (80 ºC) 1,500 (120ºC, Pt/C, 825 EW PFSA, 24% RH), 2,200 (30-120ºC, NSTF, 850 EW, No Stabilizer)	
-20	
Dependent on loading	
> 1,000mW at 620mV	
Stack tests TBD	
Yes	

- **Cool/wet transient power-up**
- **Freeze start**

4. B. Other relative gaps for 2015 at the MEA integration level

Natural conflicts between MEAs and the rest of the stack/system forced by low system cost:

- No standardization (low volumes, different seal designs, compression levels, operating conditions, and MEA form factors for each OEM stack) that would enable lower cost MEA's

- Discontinuity between requirements for lowest cost, high volume compatible stack and plate designs and materials which conflicts with optimum flow field design for best MEA performance.

- Possible impact of low cost stack and BoP hardware and materials on MEA durability:
    - Impurity effects of leachants from balance of plant and stack components on MEAs with very low loaded catalysts (10 g/vehicle) having lower surface areas due to requirements for more corrosion resistant support materials and larger Pt grain sizes, and thinner, lower EW membranes
    - Mechanical effects and changes over time from thinner, less robust stack plates
    - Driver for lower cost stack and BoP materials leading to worsening of these effects

Outline for Slides 18 - 26

- Fundamental science of fuel cell materials and mechanisms
- Improved Component Properties
- MEA Integration
- Innovative Concepts

5. Suggestions where DOE should concentrate its efforts (continued)

A. Fundamental science of fuel cell materials and mechanisms:

   i. Understanding basic mechanisms of:
      a) proton transport – the relationship of polymer morphology and protogenic groups to proton transport, “the holy grails.”
      b) fundamentals of PEM degradations mechanisms
      c) oxygen reduction reaction (ORR) on extended metallic surfaces – dependence on crystalline facets, surface structures, and how they change during the electrochemical reactions or with ageing
      d) ORR on Pt or Pt alloys under very dry conditions
      e) surface area and specific activity loss mechanisms from high voltage cycling of extended-surface catalysts
      f) loss mechanisms of extended-surface catalysts

   ii. Encourage development of standardized methods for measuring the key functional performance and durability factors of the MEA components.

   iii. Encourage research and development of *in-situ* characterization concepts and methodologies that might be deployed in vehicle stacks for real-time on-board diagnostics.

   iv. Encourage modeling at the right level. Model simpler, more fundamental mechanisms that have a better chance of being right. Use to feed into more complex MEA system models that often do not embody all the right physics, or have adequate calibrated parameters to be reliable.

5. Suggestions where DOE should concentrate its efforts (continued)

B. Improved Component Properties

i. Catalysts

a) Development of low-loaded PGM electrodes that will enable less than 10 g of PGM per vehicle:

- improved performance at high current densities as well as improved mass activity at high potentials. Mass activity does not directly correlate with cell voltage at 1.5 to 2 A/cm^2 where anode drying and cathode flooding can determine the mass transport over-potential.
- fundamental understanding and remediation of voltage decay due to multiple mechanisms of oxidation, impurity adsorption, surface reconstruction, loss of surface area, for extended surface catalysts as well as nanoparticles.
- Improved ORR activity under dry conditions.
- Emphasize the need for new materials and approaches to address all the performance, durability and cost requirements as soon as possible up-front, not just one or two main ones that look promising (like high surface area or mass activity).
  - Assess first the worst performance factors and any potential fundamental barriers that might not ultimately be able to be overcome in order to displace existing approaches, such as realistic estimates of the cost and speed of manufacturing to make high volumes.
  - Judge its performance and durability gaps at the catalyst loadings required for the ultimate high volume production rates (10 g/vehicle) as an indicator of the magnitude of or time to overcome all the gaps. (How far is it from 0.6 V at 2 A/cm^2 (to meet future stack costs) when the catalyst cost is equivalent to 10 g of Pt/vehicle?)

5. Suggestions where DOE should concentrate its efforts (continued)

B. Improved Component Properties

i. Electrode Structures and Materials

   a. Electrode structures designed for high performance at a range of operating conditions and humidification levels.
   b. Ionomers optimized for electrodes and/or catalyst interface
   c. Non-carbon based supports – completely corrosion free
   d. Better understanding of relationship between electrode material sets/structures and performance/durability under a wide range of operating conditions.

ii. Membranes

   a) Development of low cost membrane materials that will enable achievement of cost, durability, efficiency and peak power performance requirements **with a single membrane.**
   b) Materials with improved durability – mechanical and chemical stability
   c) Materials designed for improved proton transport and lower swelling through improved structure property understanding
   d) Increased focus on operation up to 95 – 100 ^{o}C, and less on materials for 120 ^{o}C, dry performance

5. Suggestions where DOE should concentrate its efforts (continued)

B. Improved Component Properties (continued)

iii. Gas Diffusion Media: electrode backing layer (EBL) + microporous layer (MPL)

a. Cost is a big issue with current high temperature processing required for EBL’s
b. Current gas diffusion media (GDM) are designed primarily for use with high surface area, low specific activity Pt/C nanoparticle catalysts, for which single phase water removal is generally adequate. Usually, the same GDM are used on the anode and cathode. Higher activity thin film (extended-surface) catalysts will rely on both vapor and liquid water transport mechanisms to operate robustly at all temperatures. Opportunities exist for better EBL’s to be designed for enhanced liquid water transport as well as vapor transport
c. This is an opportunity for non-woven carbon paper technology for EBL’s to be engineered for ideal structure-function properties: area specific resistance, pore structure, water transport properties, freeze-thaw tolerance, roll-to-roll manufacturing and processing.
d. Is there the possibility to eliminate the GDL entirely – incorporate the properties into the bi-polar plate?

iv. Gaskets and Seals

a. Continued improved materials
b. New simplified stack sealing and assembly concepts
c. Mechanical seals, etc.?

5. Suggestions where DOE should concentrate its efforts (continued)

v. New component materials in general:

(anything that can change the basis of competition)

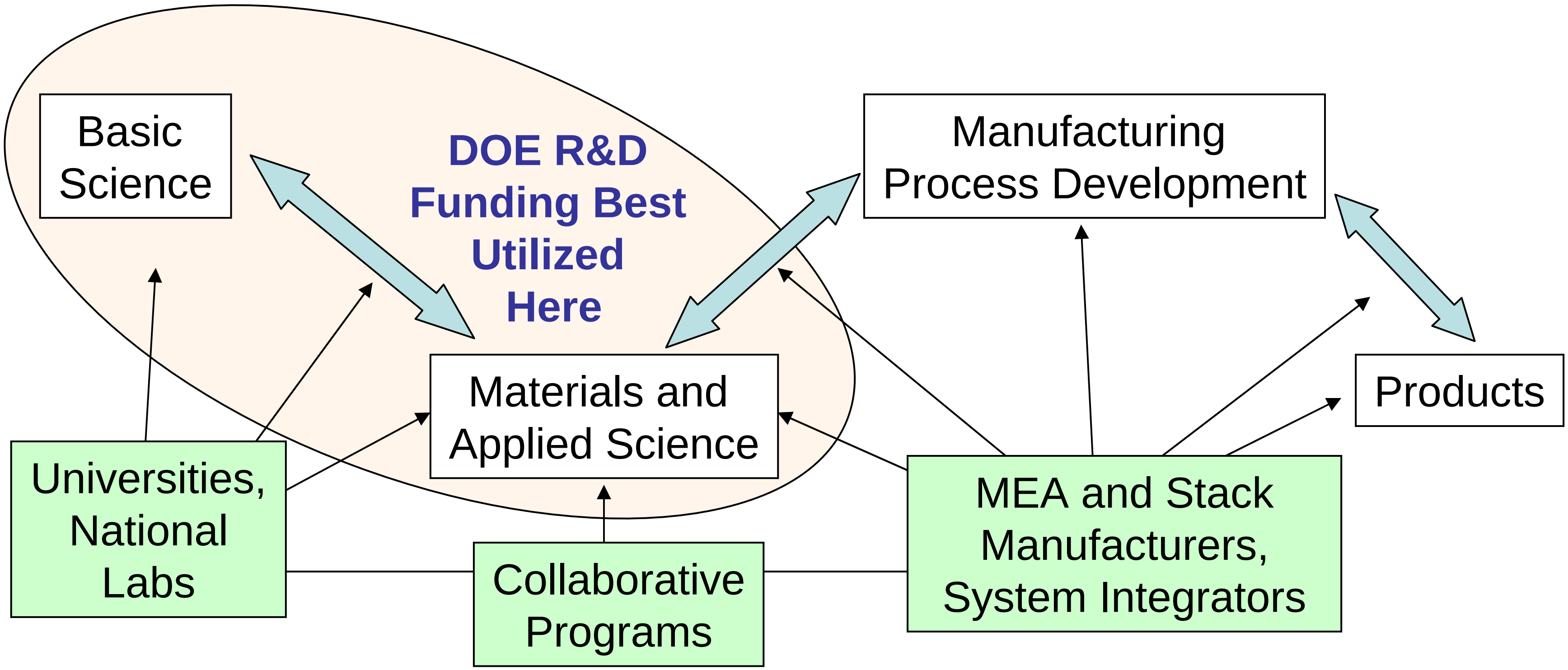
a) Development of new materials, fundamental understanding and the things connecting them (see next slide)

b) Game changers vs more mature technology paths:
- use fundamental understanding to estimate ultimate entitlement potential
- judge all component property requirements, not just one or two primary ones.

c) Catalysts with high specificity for ORR and high tolerance to impurities generated internally or externally in the environment. (The next "addition to the periodic table" that will remove more of basic the 300mV ORR loss that Pt still succumbs to.)

d) New technologies all together for the longer term (AFC, NPMC)

DOE support for MEA and MEA component development



- DOE should focus on development of materials and MEAs which are amenable to cost effective manufacturing but not fund the manufacturing process development itself.
- Quality parameters would be determined between the customer and the manufacturer, with a focus on high volumes, lower cost with quality levels that are consistently at customer expectation levels,

5. Suggestions where DOE should concentrate its efforts (continued)

C. MEA Integration

i. Address the barriers of large area stack testing of new, promising MEA approaches to more quickly determine the real gaps and opportunities:

Barriers include things such as:

a. Issue of trying to introduce a new technology into an existing stack and system framework that is designed for a more conventional technology, i.e. anything not a "drop-in replacement" is difficult to introduce into stacks already designed for conventional approaches.
b. Correlations developed by system integrators of small-scale single cell testing with large active area short stack testing may not translate to a new non-conventional MEA approach.
c. The large expense of stack building and testing is a barrier to seriously evaluating a non-conventional MEA approach to discover its real gaps and opportunities.
d. Address the general issue of R&D – that the more established a technology, the more difficult to change its course or insert new technology in a time effective manner.

ii. Encourage understanding the non-specific synergistic effects (how one component affects another) in the MEA. The holistic view of the MEA.

iii. Investigating if and when anything in stack design can be standardized. Low volumes, different seal designs, compression levels, operating conditions, all make MEA's one of a kind. Some standardization, like form factor, could help MEA integration development greatly.

iv. Novel FC "stack" system architectures

a. ????

5. Suggestions where DOE should concentrate its efforts (continued)

D. Innovative Concepts

i. Materials synergy between PEM FC's and PEM Electrolyzers:

Due to significant developments made in PEMFC components over the last 10 years, there may now be the prospect for a strong synergy between FC and Electrolyzer MEA's that could rapidly bridge the gap between the current cost of high purity H_2 production by PEM electrolysis and the DOE targets of ~ \$2/kg-H_2.

a) catalyst supports with total corrosion resistance on both PEM cathodes and electrolyzer anodes (NSTF fuel cell cathode catalyst w/ 0.15 mg_{Pt}/cm^2 working on OER anode at 2.3 volts for 1500 hrs)
b) durable, low loading OER catalysts for electrolyzers with similar composition and structure as being developed for cell reversal tolerant PEM fuel cell anodes
c) interchangeable MEA's suitable for high performance PEM FC or PEM Electrolyzer to make a truly low cost regenerative FC system.
d) thinner, more mechanically durable fuel cell membranes to reduce impedance in water electrolyzer
e) lower cost electrolyzer cathode gas diffusion media

These examples of component synergy point to the opportunity for a highly efficient regenerative fuel cell system that utilizes the same optimized MEA components for both the electrolysis and fuel cell functions. This could introduce a new paradigm for low cost ultra-pure high pressure distributed H_2 production utilizing material MEA sets common to both fuel cells and electrolyzers and a potentially much simplified balance of plant.

6. Other General Suggestions and Recommendations

- Encourage individual component developers, when evaluating the prospects of any new approach, to consider as many of the critical functional metrics as possible that are known to be important, not just one or two properties at the top of the list. E.g. for a catalyst, just developing towards high surface area, or just high pgm mass activity is not sufficient.

- Encourage the establishment of fundamentally based criteria for assessing entitlement potential of new or current technology approaches for catalyst and membranes, to better assess whether it would ever be possible to meet or exceed the targets now or those needed long after 2015? Besides the fundamental metrics,
  a. Does it have the potential for high volume manufacturability with a path to 99% yields and 6-sigma quality?
  b. Does it lend itself to green manufacturing?
  c. Is it easily recyclable – now or in the future? Eventually all used components may have to be recaptured, returned to manufacturer for disposal.
  d. Again, bite the bullet, i.e. test a new technology approach at the believed component cost level it must meet (e.g. cost equivalent to 10g Pt/vehicle), and see what the performance and durability gap-magnitudes are for that new approach. Answer the questions, "how bad is it," and will the fundamental entitlement limits mean it will "hit the wall" short.

- Should the targets be much higher? Are they really robust enough to make it in the real world environment if they just squeak past or barely meet those targets in 2015? Is there enough fundamental bandwidth in the current technological approaches of a given component to meet the six to nine-sigma quality levels required for production of enough MEAs for 500,000 vehicles with recall rates low enough to not kill the customer's interest?