NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Scale-up Challenges of Novel Pt Catalysts

Catalysis Working Group

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LANL

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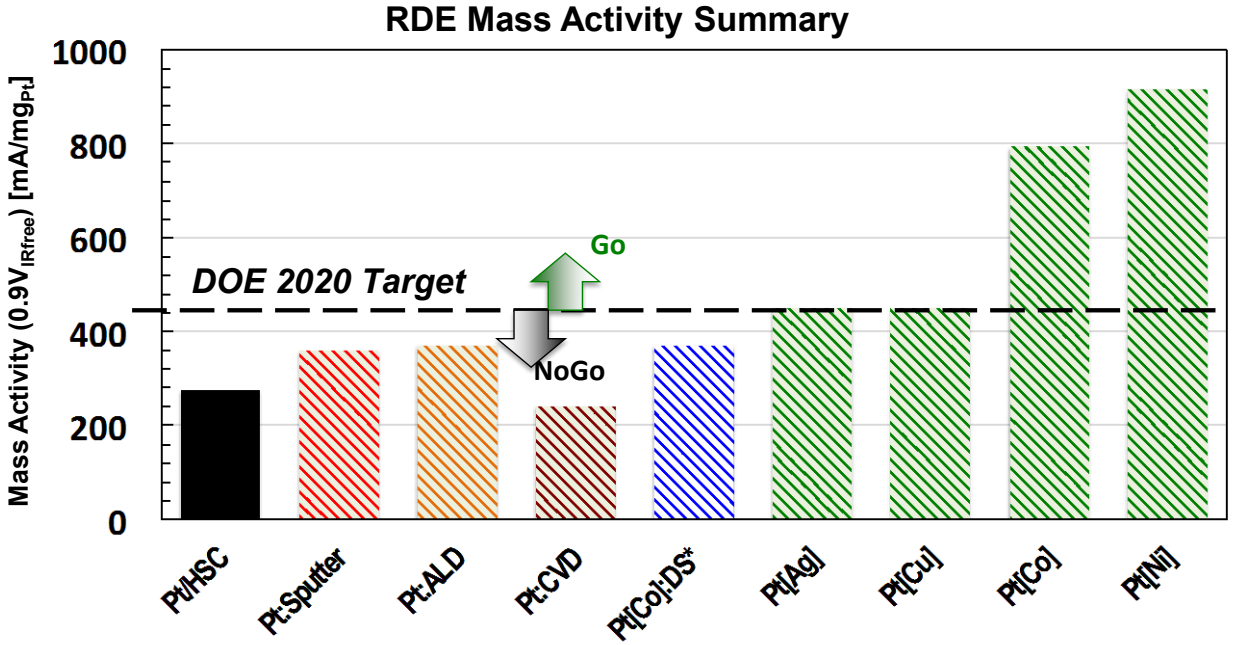
What does scale up mean?

- **First, I'm not sure – or it depends**
  - From a novel catalyst development standpoint it could be enough to do RDE(mg) or MEA.
  - For commercial production kg to tons. (Batch or Continuous)
- **For this group both could be under consideration.**
- **Scale up concerns highly dependent on specific catalyst system/synthesis route.**
- **Novel catalysts often very different from traditional catalysts.**

What background do I have to discuss?

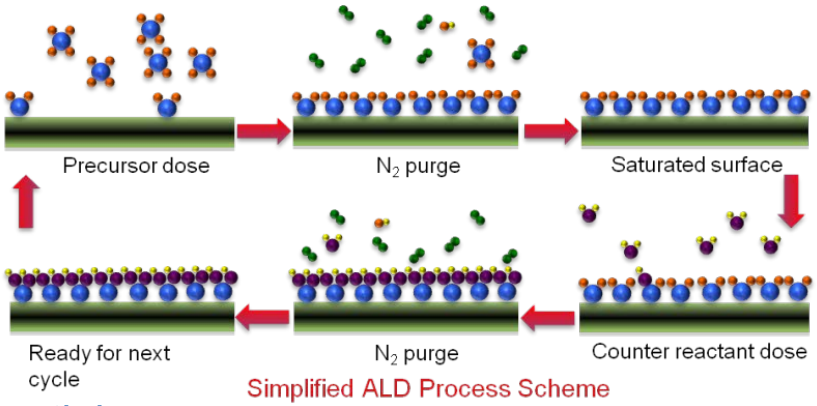
- **Major project PI investigating multiple synthesis routes.**
- **Overlap with SA Inc/NREL Analysis and Manufacturing including DFMA/TEA.**
- **Consistent eye towards manufacturability.**



Approaches for Pt Deposition (novel catalyst synthesis) from NREL led project

Vapor Deposition (evaporation, sputtering)

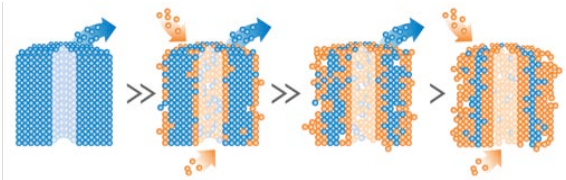
- CVD (Tennessee)
- atomic layer deposition (ALD)
  (NREL, Stanford, CNSE)



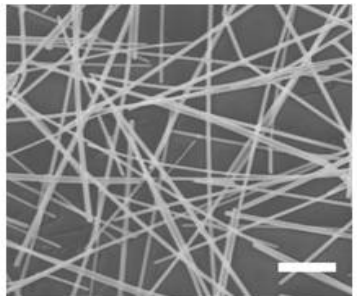
Simplified ALD Process Scheme

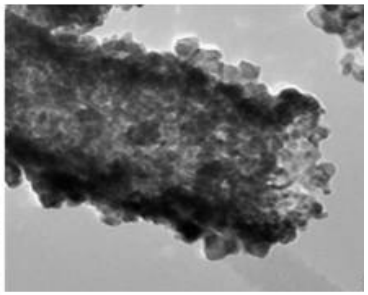
Solution Deposition (electrochemical, underpotential, microwave)

- spontaneous galvanic displacement (SGD)
  (NREL, Delaware)


Simplified SGD Process Scheme

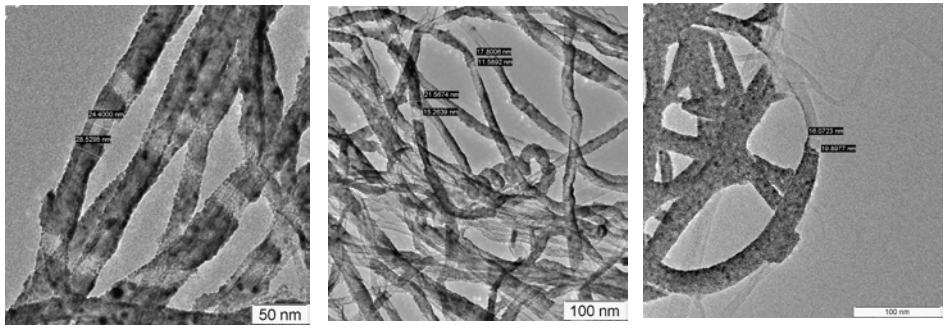
Metal	E^0	# of e^-
$Au^{3+} + 3\ e^- \leftrightarrow Au$	1.498	3
$Pt^{2+} + 2\ e^- \leftrightarrow Pt$	1.180	2
$Pd^{2+} + 2\ e^- \leftrightarrow Pd$	0.951	2
$Ag^{+} + e^- \leftrightarrow Ag$	0.800	1
$Cu^{2+} + 2\ e^- \leftrightarrow Cu$	0.340	2


Ag nanowires (NW)

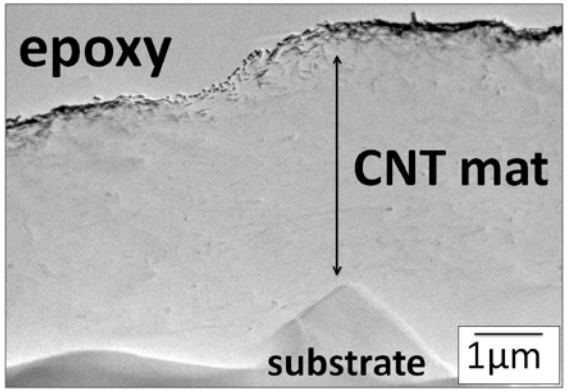

Pt nanotubes (NT)

Examples of Scale up Issues (Sputtering)

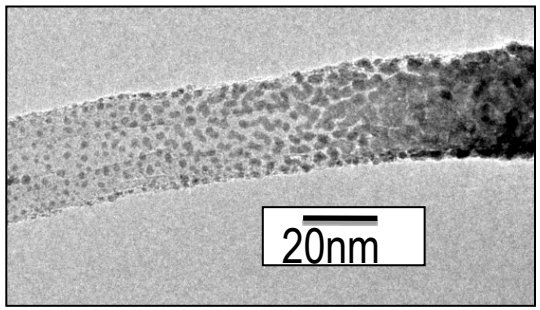
Focused on CNT mats where continuous Pt coatings have been observed

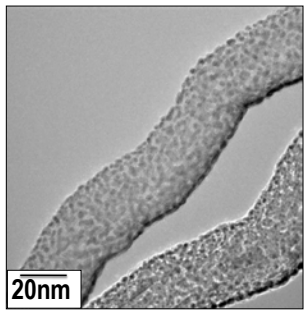


Target coating only occurs at top edge of mat as would be expected by (line of sight) sputtering. Yield is a major problem.



Microscopy shows transition between particles and continuous film. Particle size suggests continuous films ~2nm thickness.

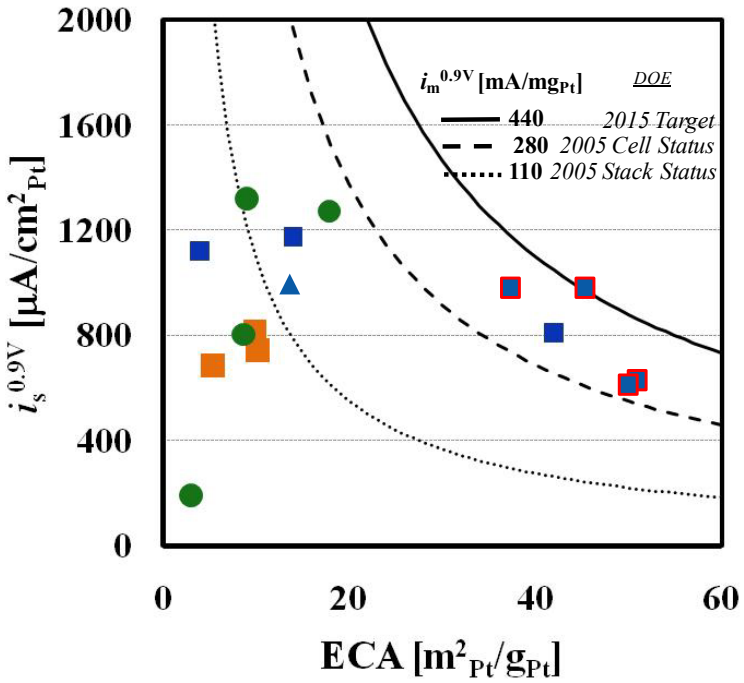




Sputtering works great for large scale process (NSTF), more complicated without vacuum roll to roll systems.

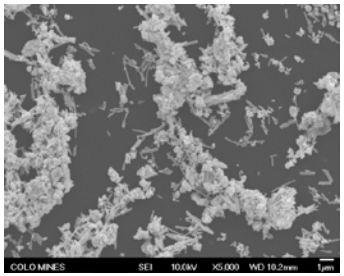
Accomplishments and Progress

Pt SGD: Scale Up (2012, AMR)

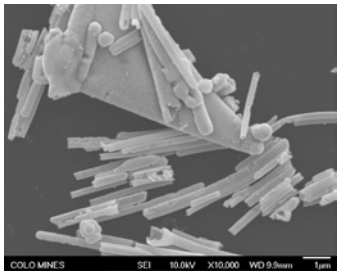


- Scale up of high performing SGD sample was performed to create increased catalyst quantities for characterization and electrochemical testing.
- High ECA and mass activity achieved, significant variability between batches.

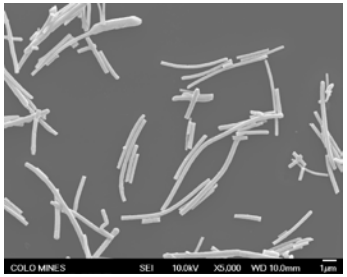
Batch 1



Batch 2



Batch 4



				Pt Wt %			
	ECA (m^2/g_{Pt})	$i_s^{0.9V}$ ($\mu A/cm^2_{Pt}$)	$i_m^{0.9V}$ (mA/mg_{Pt})	XRF (NREL)	XRF (LANL)	EDS (NREL)	EDS (ORNL)
Batch 1	38.6	1050	400	82	77.5	80-86	87-91
Batch 2	53.0	630	340	95	95	96-99	98-100
Batch 3	45.6	980	450	94	90	94-96	94-97
Batch 4	51.0	640	330	96	92	95-97	93-95
Average	47.0	820	390				

Batch 3

Reproducibility/ Quality Control Batch vs. Continuous

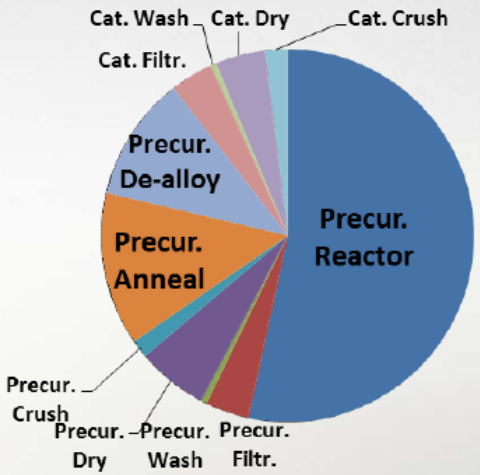
- Current commercial suppliers track batch numbers, catalysts are supplied with associated specifications
- Batch processes don't have the same QA/QC tools that can be applied to continuous processes.
- Assuming 10g/vehicle. A 2 kg batch supplies 200 vehicles. 1 ton supplies 100,000 vehicles

http://www.hydrogen.energy.gov/pdfs/review14/fc018_james_2014_o.pdf

De-alloyed PtNiC Catalyst Cost Summary: 500ksys/year

Breakdown of Entire Catalyst Synthesis

Breakdown of Manufacturing Step Costs



- 86 grams catalyst per system
- Pt cost dominates
- Precursor Reactor step is 53% of manufacturing cost
- Precursor Reactor, Annealing, and De-alloy combine to almost 80%

At 1k Systems/Year
(excluding Pt)

- $802/system
- $9,322/kg catalyst
- $10/$kW_{net}$

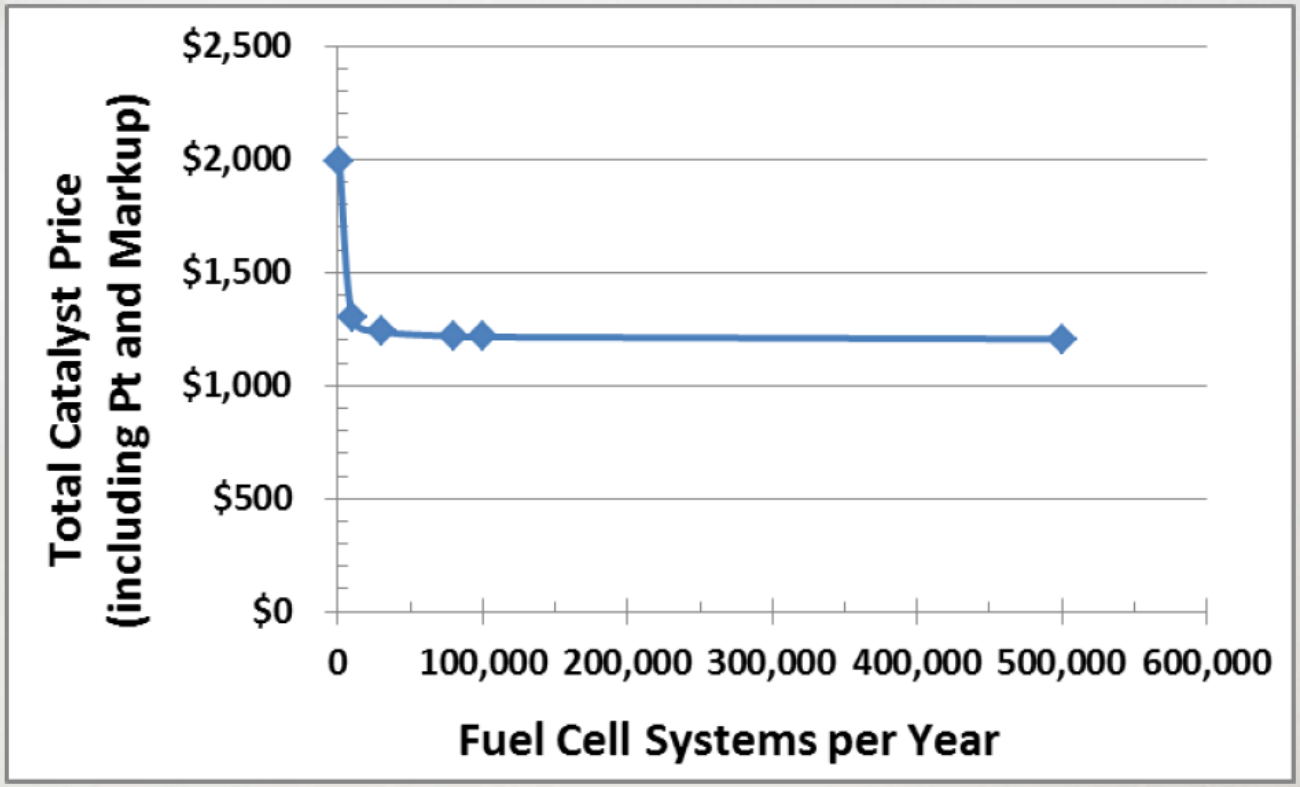
At 500k Systems/Year
(excluding Pt)

- $14/system
- $169/kg catalyst
- $0.18/$kW_{net}$

http://www.hydrogen.energy.gov/pdfs/review14/fc018_james_2014_o.pdf

Expected Catalyst Price to Fuel Cell Fabricator

$1,190/system Pt price at all production rates.



- Knee in curve is at ~20k systems/year.
- Price drops steeply due to initially very small processing batch sizes.

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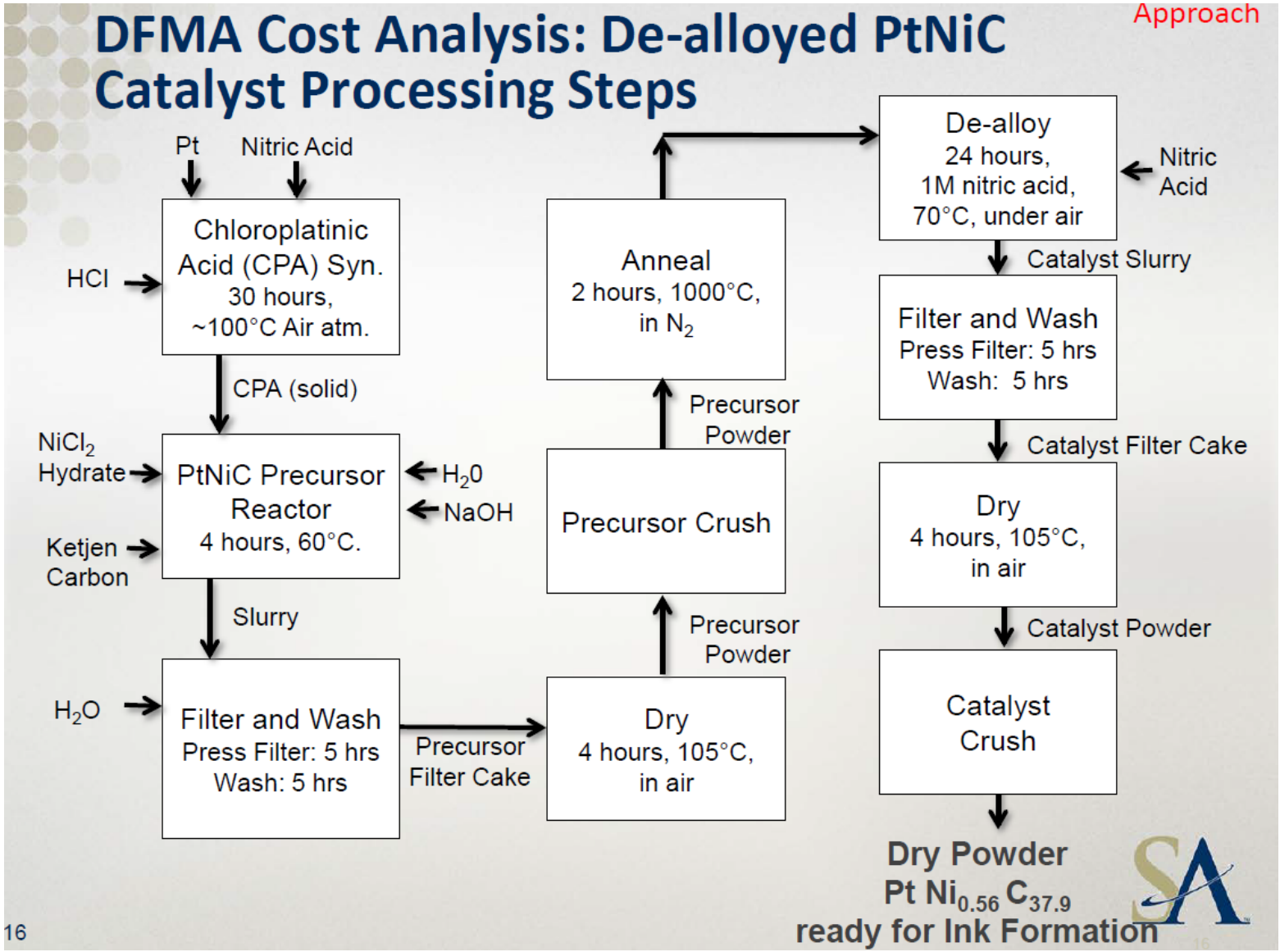
http://www.hydrogen.energy.gov/pdfs/review14/fc018_james_2014_o.pdf



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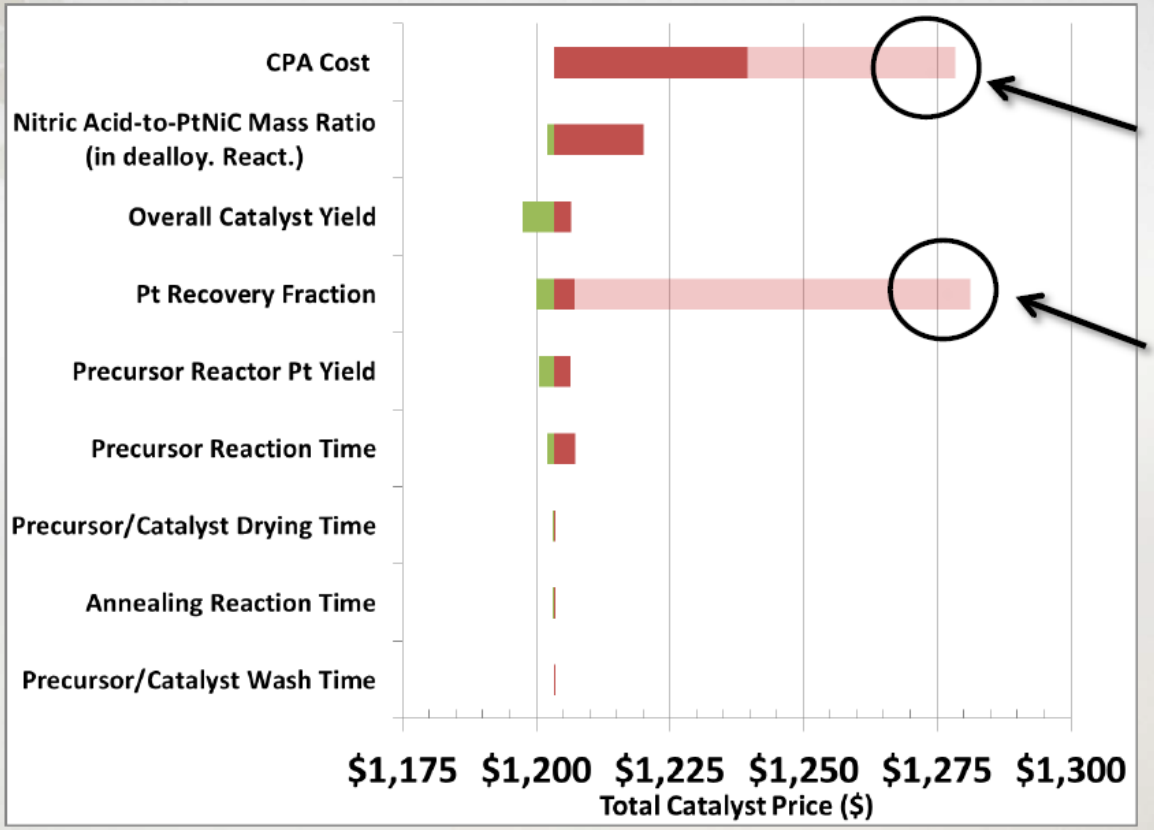
Tornado Chart (at 500k systems/year)



Extremely high CPA cost ($1/g) adds ~0.93/kW to baseline cost

No Pt Recovery (0%) adds ~$0.97/kW to baseline

- Many parameters have only small impact.
- Recovery of Pt is vital. Needs to be 80%+.
- Important to assess the cost of CPA at high production rates.
  (Current (low vol.) vendor quotes ($1/g) are much higher than DFMA projections.)

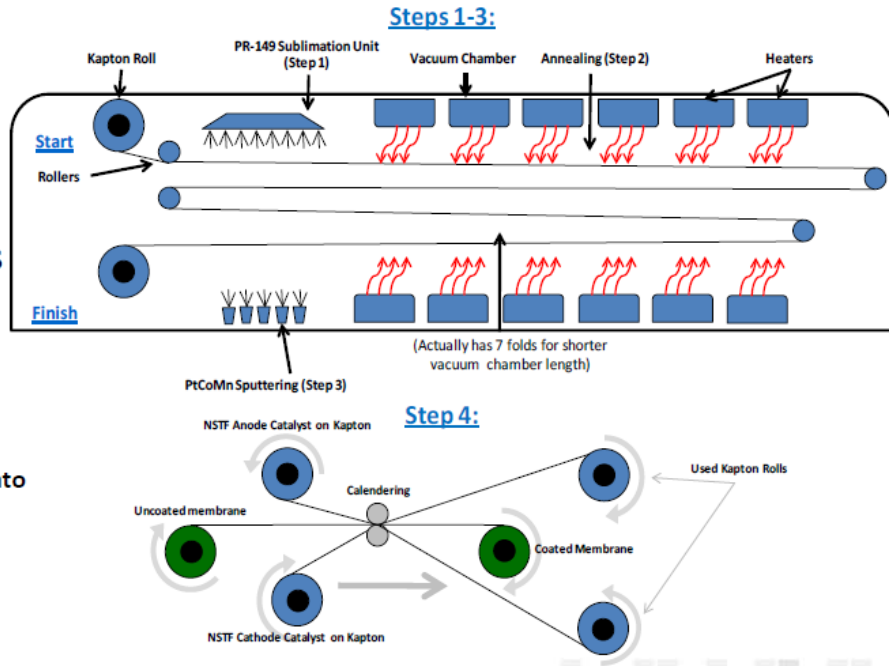
http://www.hydrogen.energy.gov/pdfs/review10/fc018_james_2010_o_web.pdf

NanoStructured Thin Film (NSTF) Catalysts

New for 2009

- DFMA® analysis conducted
- Process based on open-literature description of 3M process
- Assumptions discussed/vetted with 3M
- Cost results are consistent with 3M proprietary price projections
- 4-step roll-to-roll process:
  1) Sublimation of PR-149 (Perylene Red pigment 149) onto DuPont Kapton® polyimide web
  2) Vacuum annealing
  3) Platinum or metallic alloy is vapor deposited onto the crystalline nanostructures
  4) Roll-to-roll transfer of catalyst from Kapton® to membrane

- Capital cost is surprisingly low even for high capacity system



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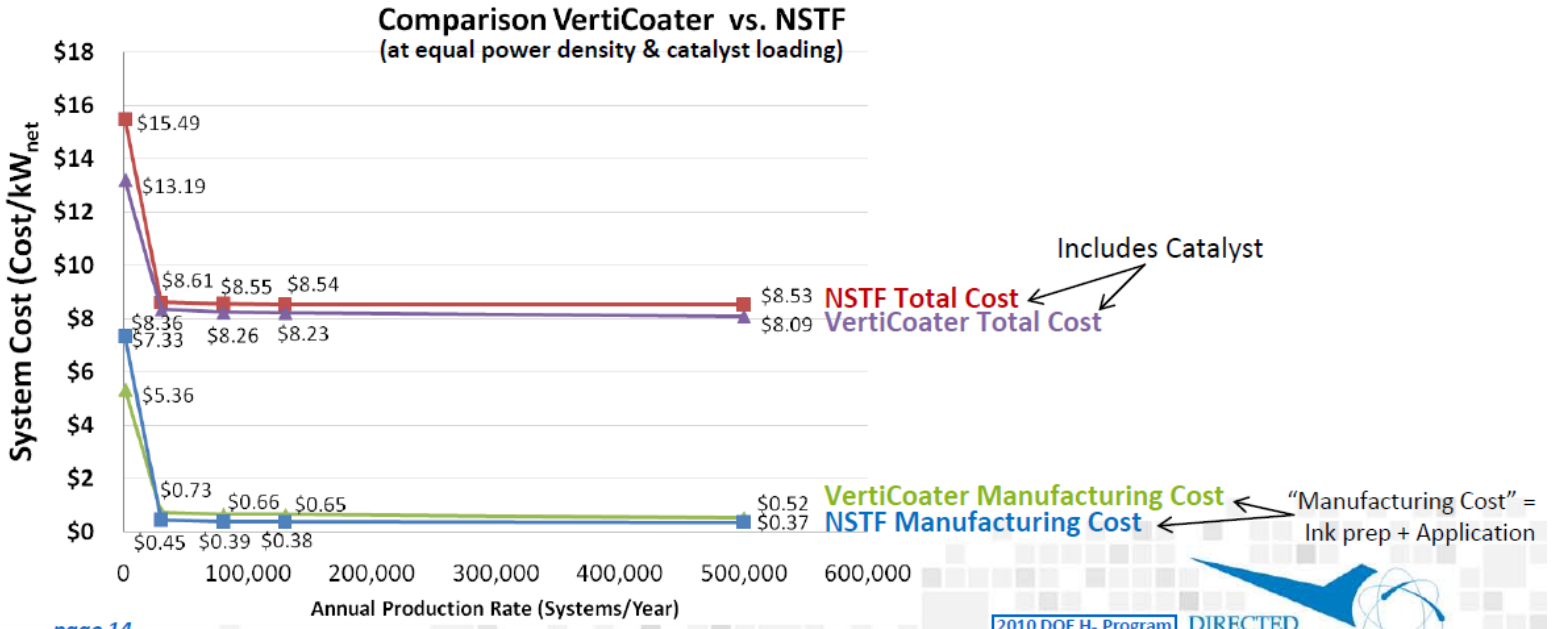
NanoStructured Thin Film (NSTF) Catalysts
New for 2009

Compared to VertiCoater method (roller application method used in 2008 analysis):

- The NSTF method assumes a PtCoMn ternary catalyst
- For a given power density & catalyst loading, the NSTF application method **($8.53/kW$_{net}$)** is slightly **more expensive** than previous **($8.09/kW$_{net}$)**
- However, NSTF catalyst *enables* the improved power density & catalyst loading used for 2009 & 2010 systems; yields a net **$10.28/kW$_{net}$** savings



Non-PGM disclaimer

- May have similar scale up concerns, wasn't my focus
- Processing costs may be high, need to make sure process is potentially scalable and cheap
- Can have similar concerns as PGM catalysts when considering quantities that are needed for different characterization needs and reproducibility (added challenges for continuous processing routes)

Discussion

- **Your thoughts???**