Regenerative Fuel Cells for Energy Storage

April 2011

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Outline

1. Regenerative Fuel Cells at Giner
2. Regenerative Systems for Energy Storage
    1. Economics
    2. Electrolyzer Optimization
    3. Fuel Cell Optimization
    4. What to do with O_2?
    5. High Pressure Electrolysis vs. External Pumping
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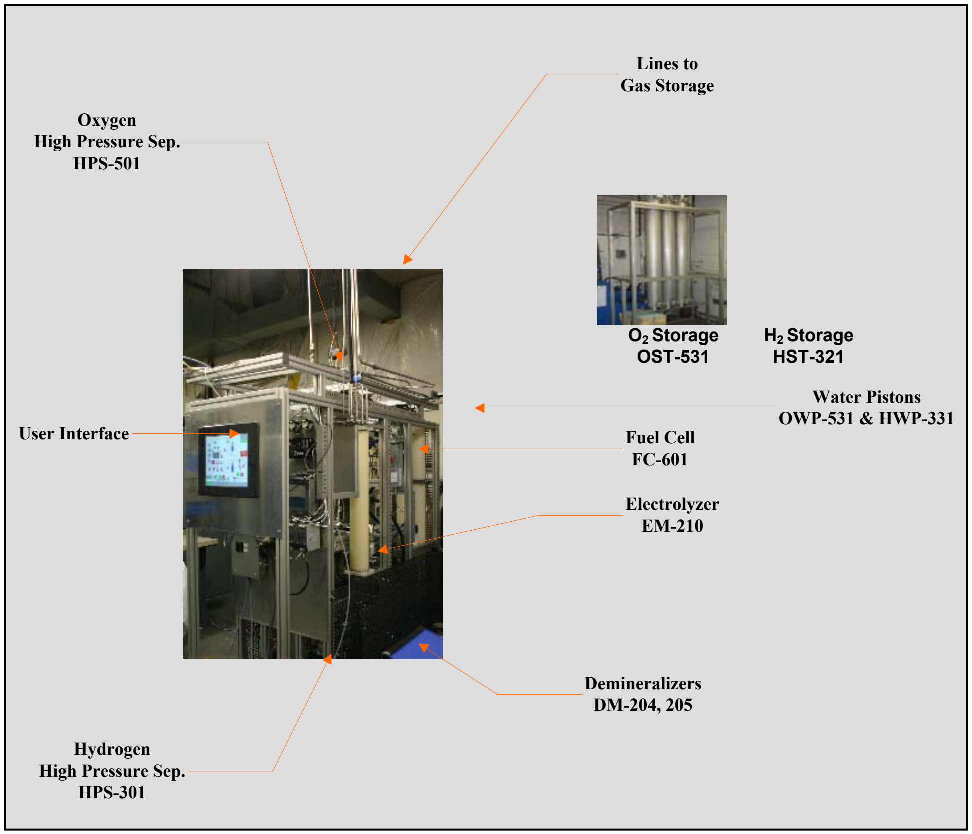
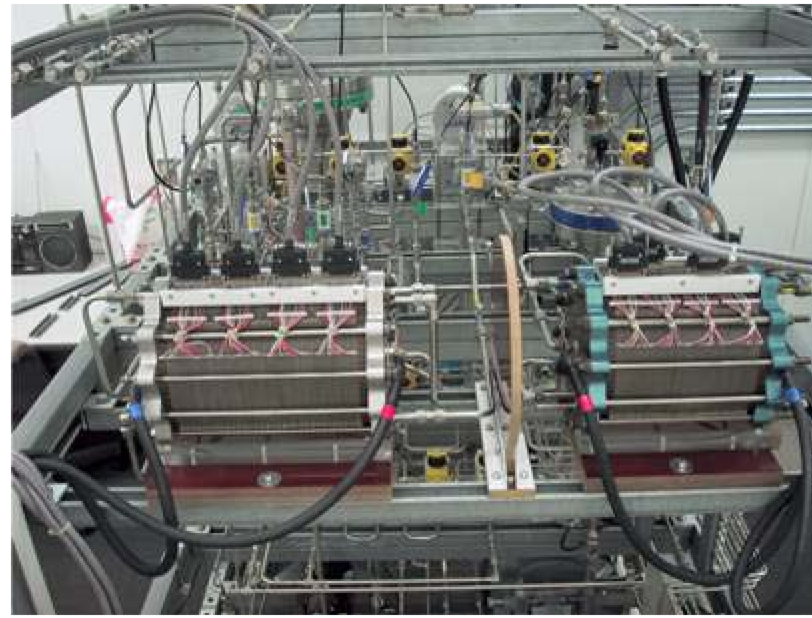
RFC System Challenges



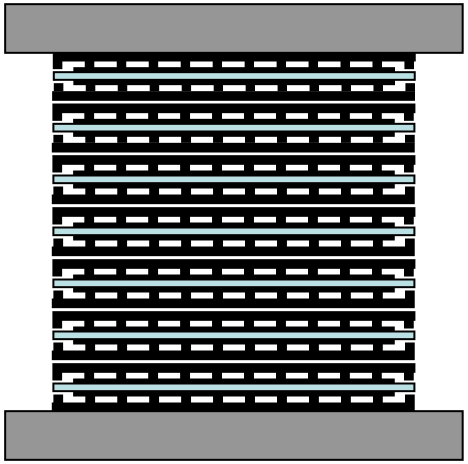


Regenerative Fuel Cell System at NASA Glenn Research Center (above)
Regenerative Fuel Cell System for High-Altitude Airships at Giner (left)

Existing state of the art regenerative fuel cell systems require two separate stacks and significant auxiliary support hardware

Fuel Cell vs. Electrolyzer: Stack Comparison

Fuel Cell Stack



Membrane

Catalyst

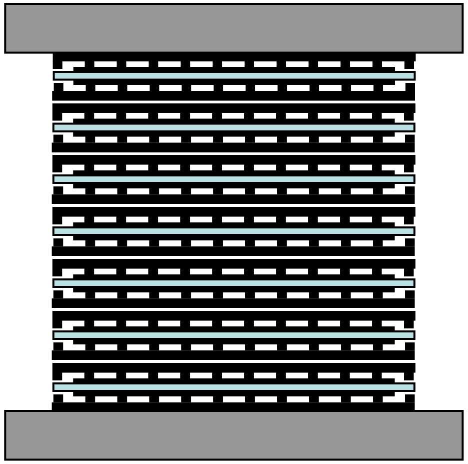
Bipolar Plates

End Plates

Never on at the Same Time

Combine Them

Electrolyzer Cell Stack



Membrane

Catalyst

Bipolar Plates

End Plates

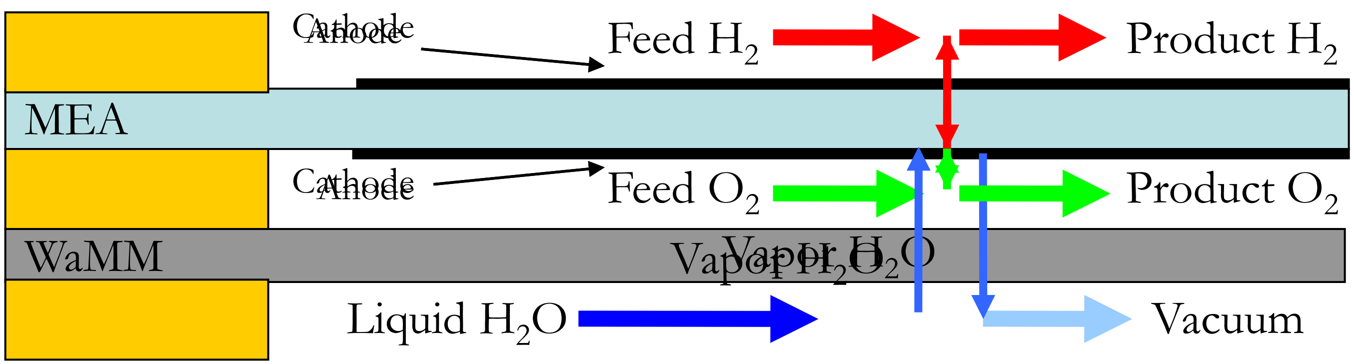
Issues Motivating WaMM Development

- Unitized Regenerative Fuel Cell:
  - Could save volume/weight of extra stack, however, water management becomes difficult.
- Fuel Cell Mode:
  - Almost impossible to avoid liquid water flooding the cathode in pressurized systems operating at low stoich.
  - Systems must operate at lower pressure/high recirculation rates to remove water.
    - Complicated in low gravity
    - Parasitic Efficiency Loss
- Electrolyzer Mode:
  - The same features required in a fuel cell to evacuate product water will also stop feed water from reaching the electrode during electrolysis
- Solution: keep water in the vapor phase

Single Cell Operation

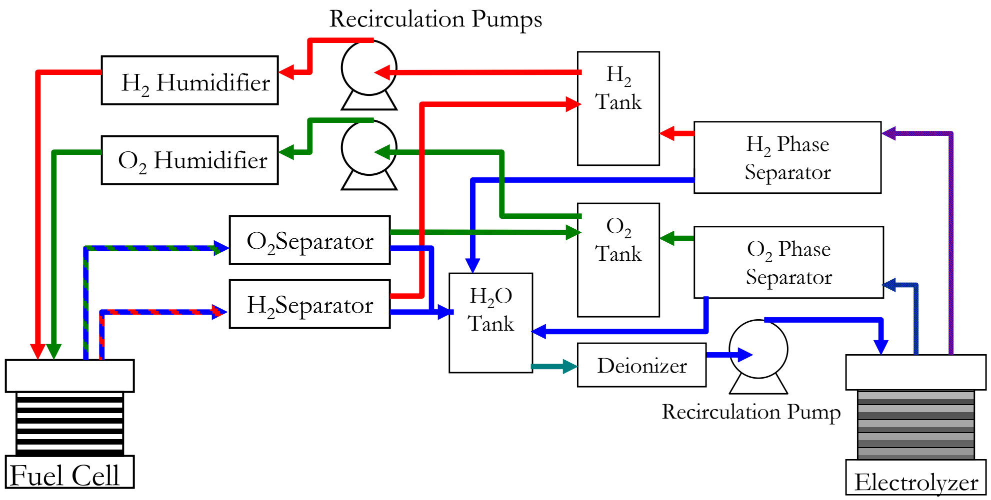
Fuel Cell:

Electrolyzer:

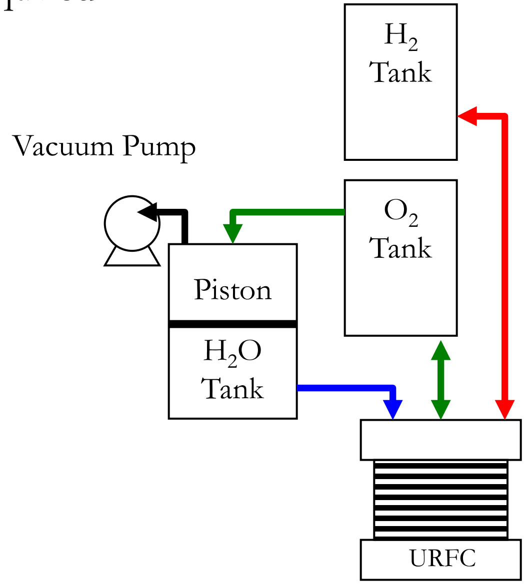


System Implications

- Vapor fed electrolyzer produces >99.9% dry product gases: no liquid gas phase separators required
- Electrolyzer feed water can be static feed for further system simplification: no liquid recirculation pumps required
- Fuel cell feed gases can be static feed: no gas recirculation pumps required
- Fuel cell is humidified *in situ* by product water: no external humidifiers required
- Because water permeable plate is relatively insusceptible to impurities in feed water, water purity constraints can be relaxed: no deionization beds required

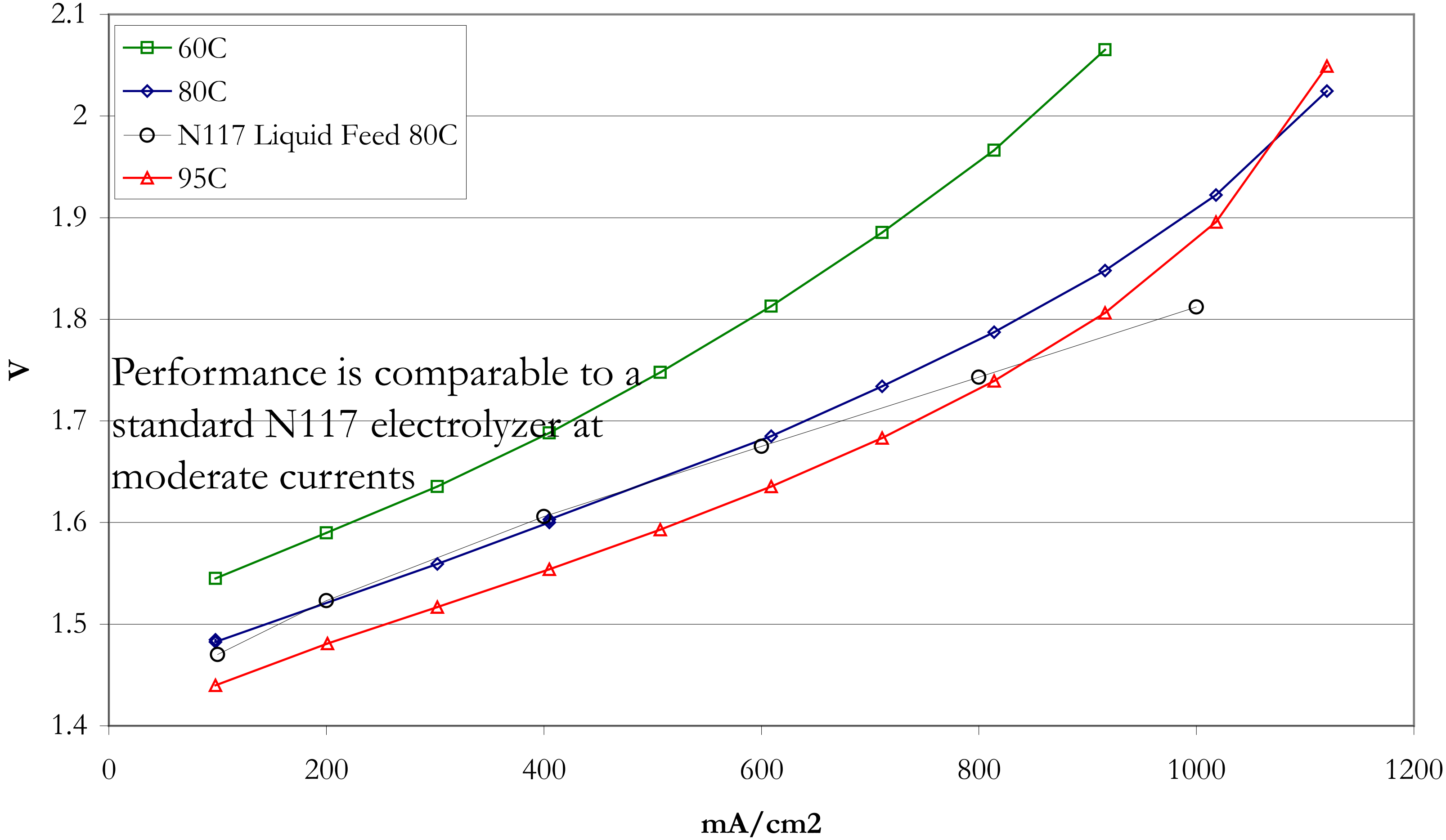


Traditional RFC System

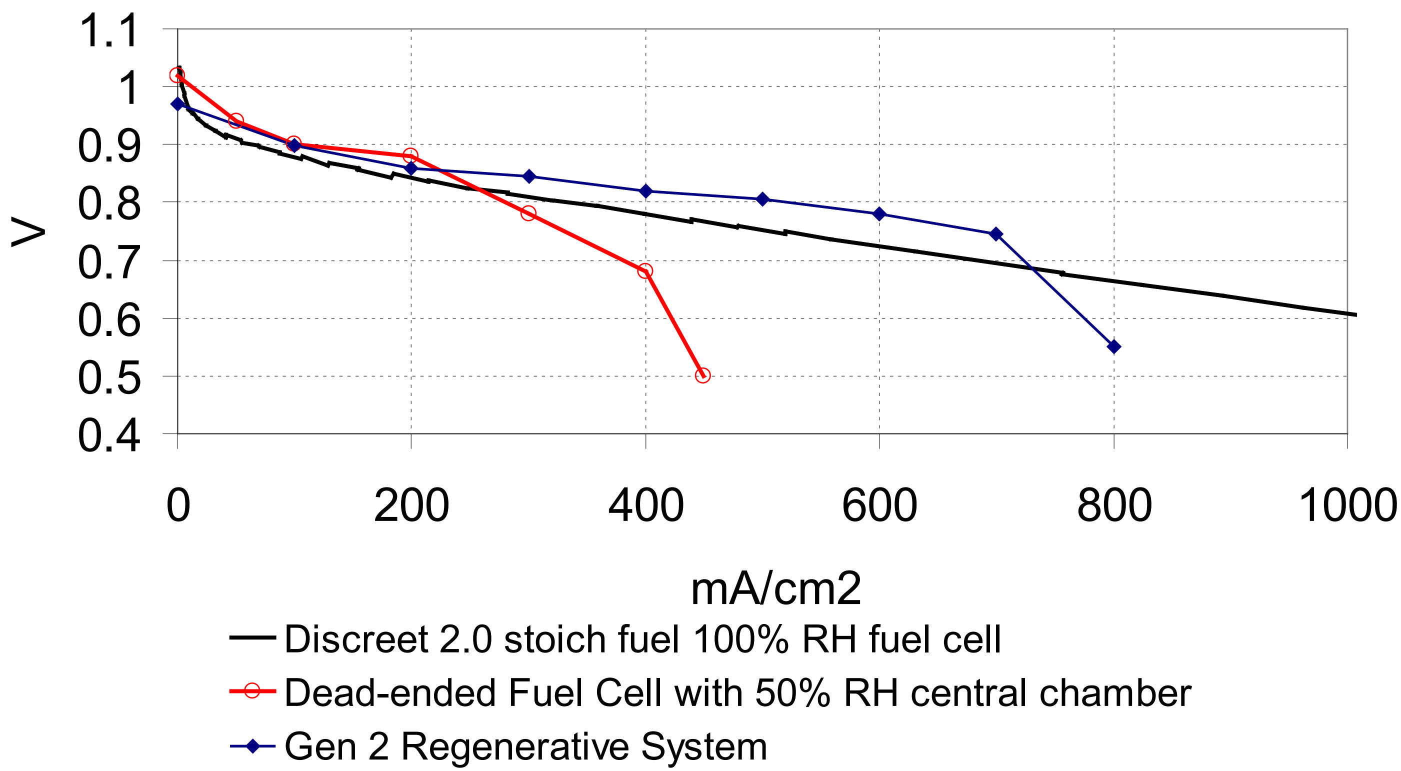


WaMM-Based URFC System

URFC: Electrolyzer Performance

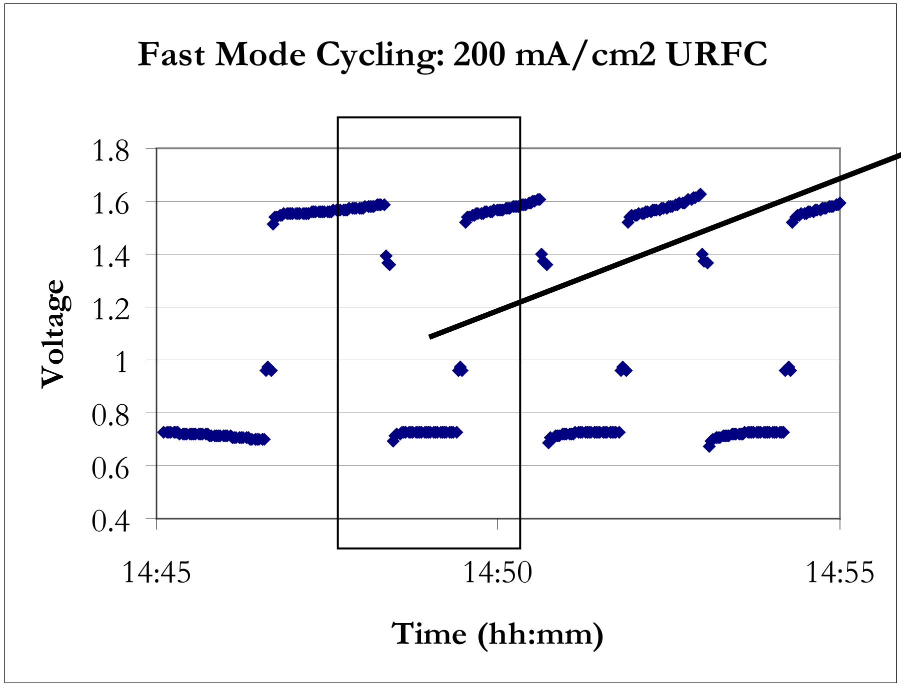


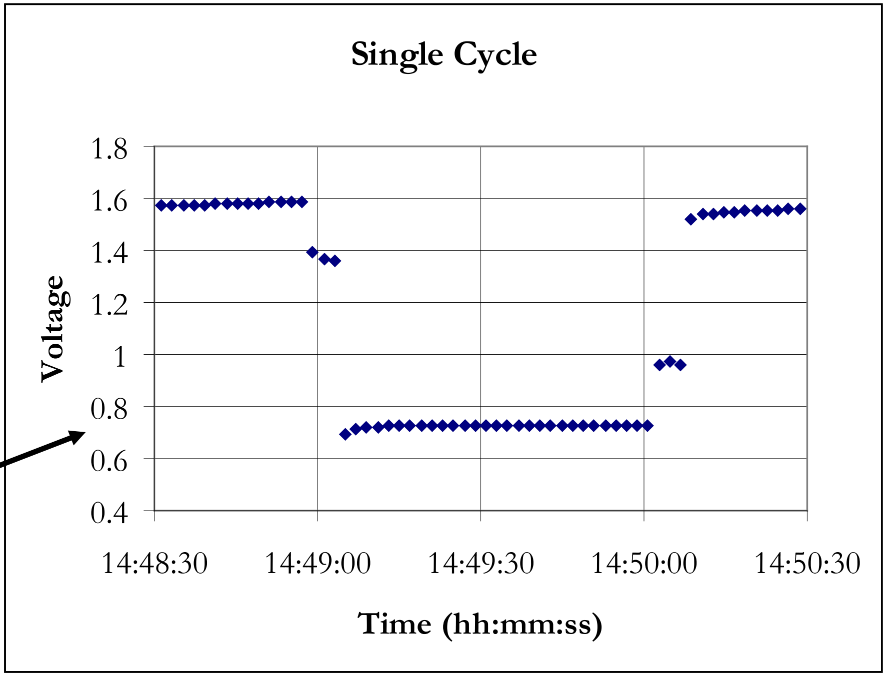
URFC: Fuel Cell Testing



URFC: Mode Cycling

•Because system is vapor based, it can change modes very quickly
•Turn around time around 5 seconds





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Cost of Electrolysis is Becoming Competitive

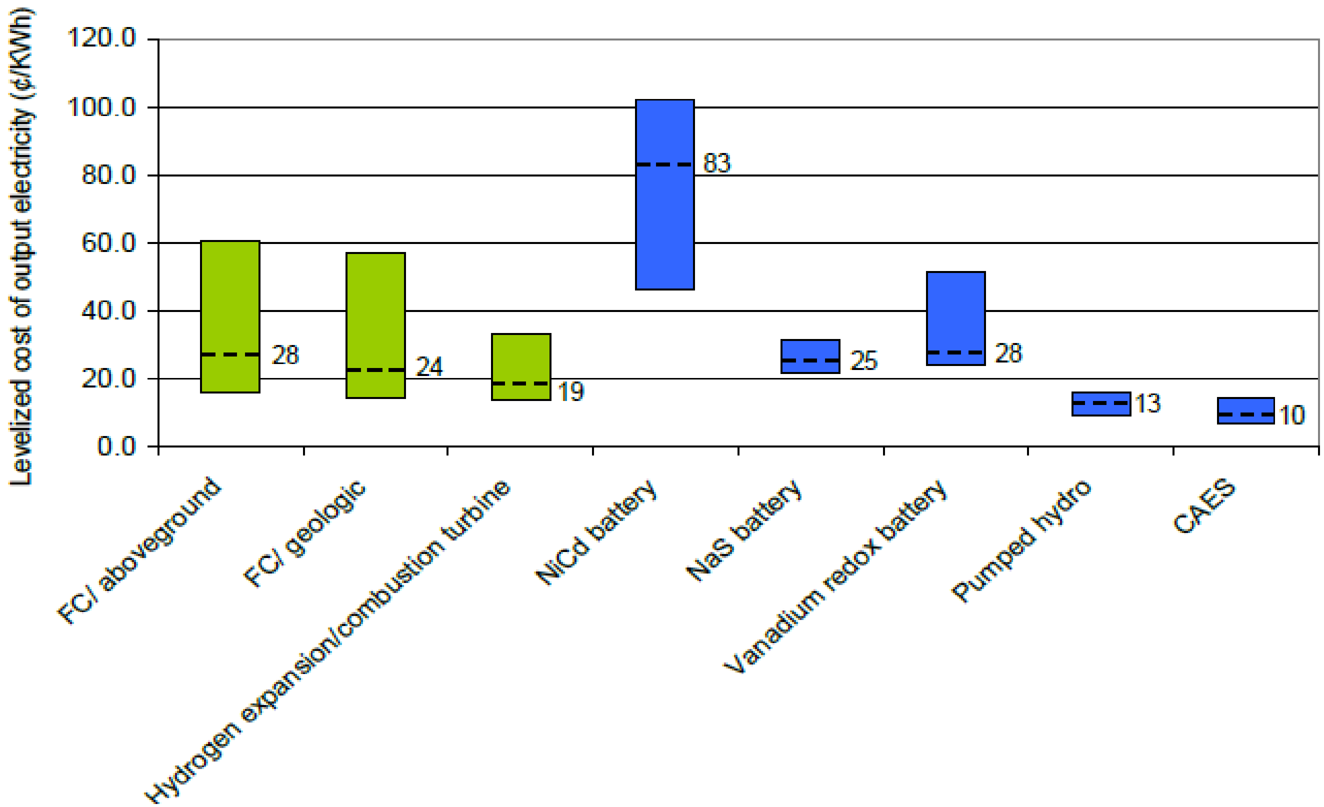
Table 1 COSTS OF HYDROGEN FROM PEM ELECTROLYSIS *Based on US Department of Energy's H2A Model*	
Item	Cost $/kg
Capital Cost	$0.79
Fixed O&M	$0.49
Power Cost ($0.039/kWh)	$1.95
Other Variable Costs (utilities etc.)	$0.01
High Pressure Storage (pumps and tanks)	$1.80
Total Cost	**$5.04**
Miles travelled kg H_2/gallon of gasoline	50/30
Total Cost in gallons of gasoline equivalent	**$3.02**

Regenerative Systems Can Make Renewables More Competitive …But Efficiency is Extremely Important

100 MW Installed Wind, 33 MW Electrolyzer, 22,500 kg Storage, 25 MW Fuel Cell	Windmill Only	Windmill with 50% Efficient Regenerative System	Windmill with 40% Efficient Regenerative System
Windmill Cost ($1000/kW 20 Year Amortization at 5%)	$ 8,024	$ 8,024	$ 8,024
Annual Storage H2 Cost (20 Year Amortization)	$ -	$ 181	$ 181
Annual Electrolyzer and Fuel Cell System Cost ($500 kW electrolyzer, $500/kW fuel cell) (20 Year Amortization)	$ -	$ 2,648	$ 2,648
Annual Operating, Maintenance, Refurbishment $1.5 MM	$ 2,000	$ 2,705	$ 2,705
Annual Off-Peak Power Yield (GW) -	307	205	205
Annual On-Demand Power Yield (50% Efficiency) -	0	50.6	40.5
Annual Value of “Off-Peak” Power @ 3.0¢/kWh	$ 10,731	$ 7,190	$ 7,190
Annual Value of “Peak” Power @ 15¢/kWh	$ -	$ 7,588	$ 6,071
Annual Profit	**$ 707**	**$ 1,220**	**$ (297)**

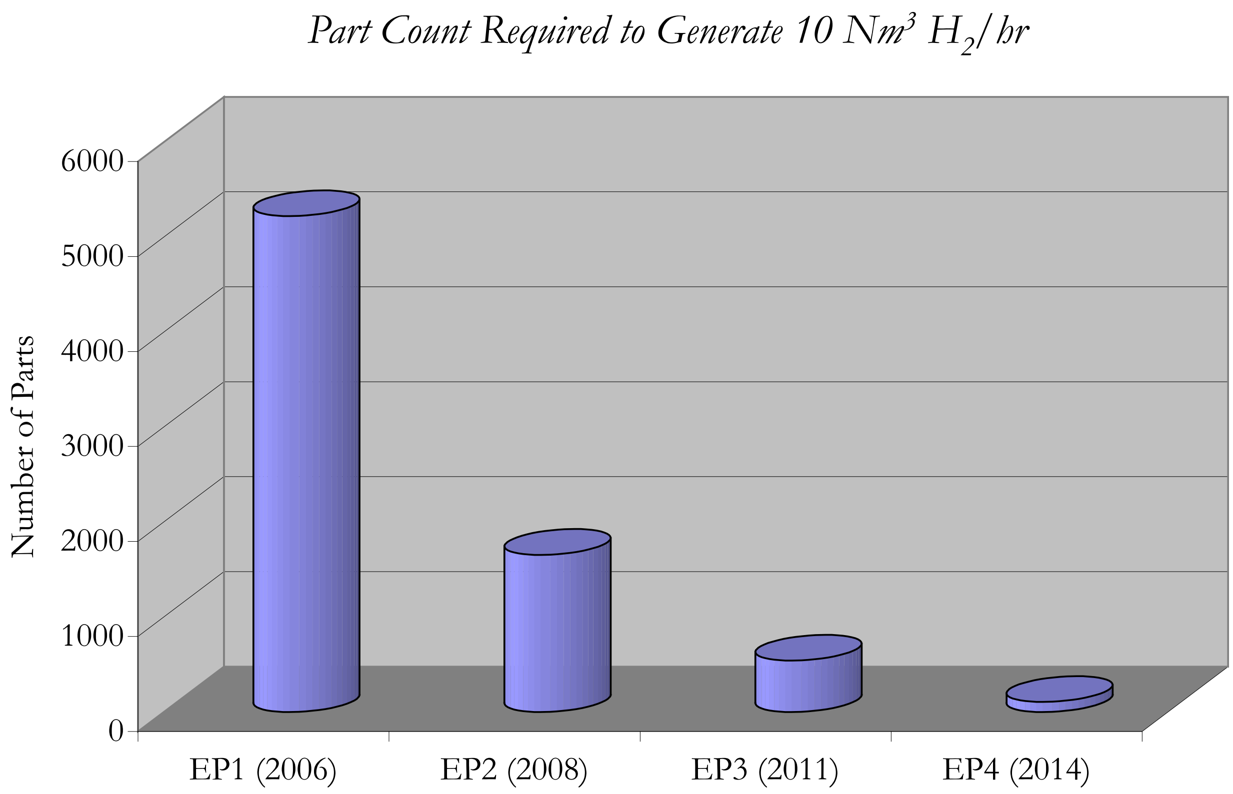
Follows analysis by Dunn and Shimko 2010 DOE Merit Review

…Don't Just Take our Word for it…



Kevin Harrison 2010 DOE Merit Review,
http://www.hydrogen.energy.gov/pdfs/review10/pd031_harrison_2010_o_web.pdf

By Increasing Efficiency and Lowering Part Counts Electrolysis Cost has Been Dramatically Lowered



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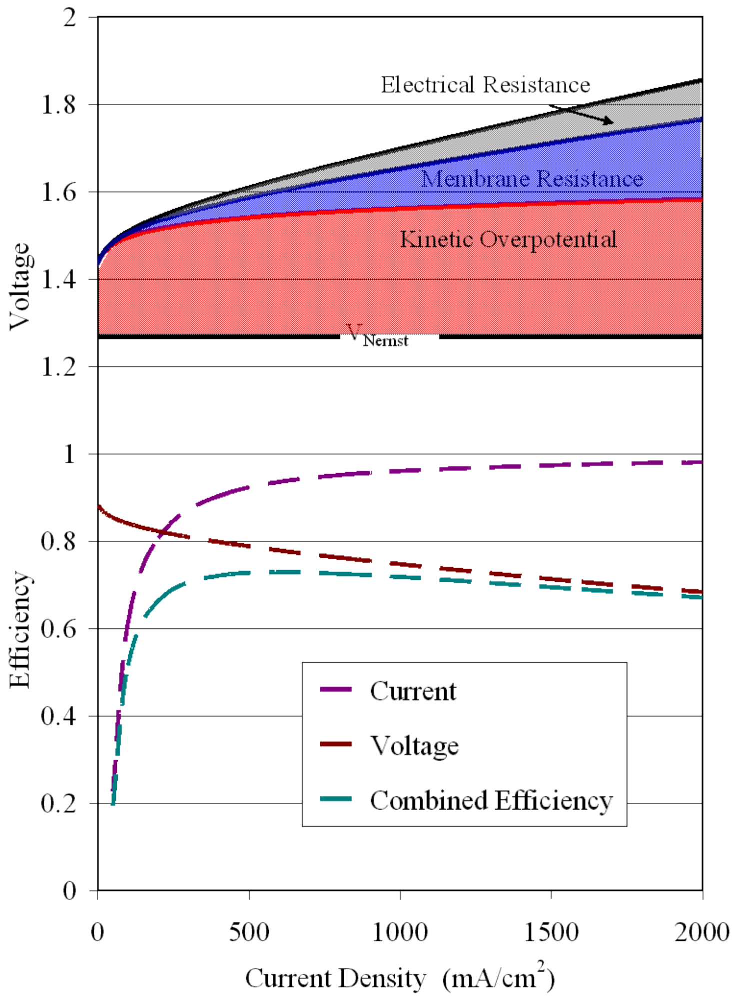
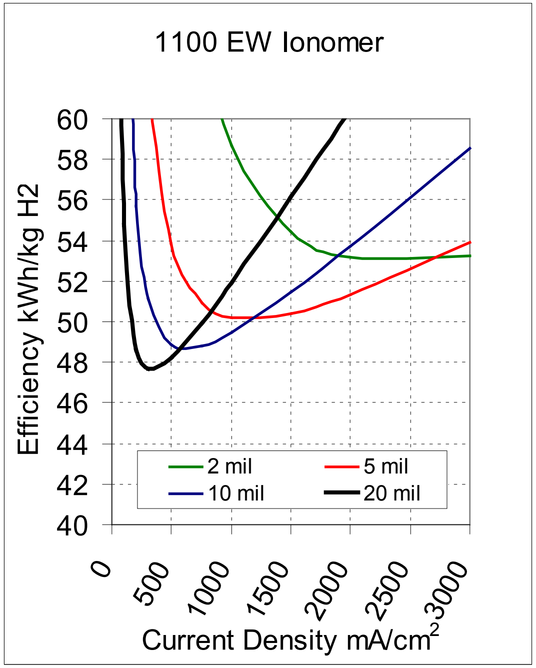
Optimizing Performance For Electrolyzers

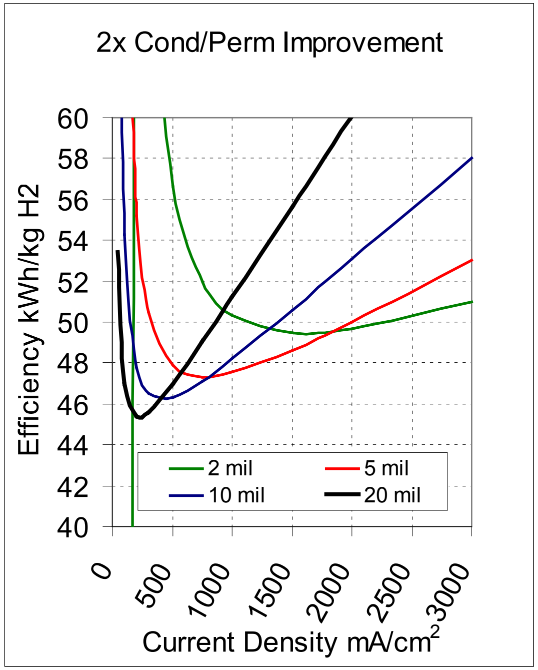


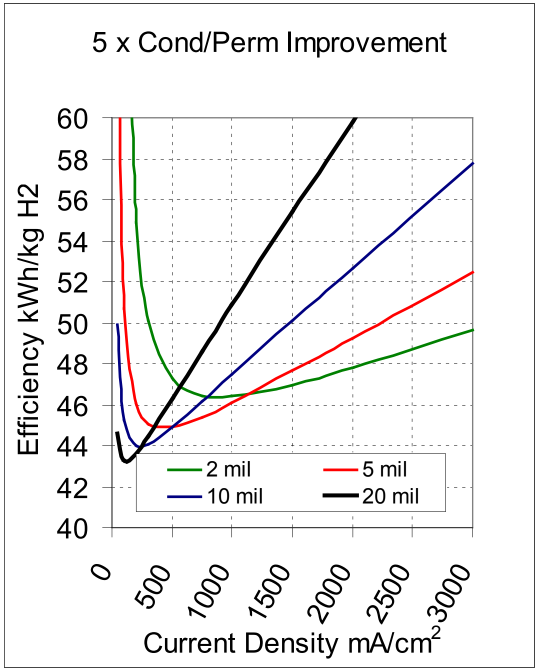
Similar to fuel cells, the majority of efficiency losses are due to slow oxygen kinetics and membrane resistance

For cell operating at 1000 psi and 80°C with Nafion 117

Improvements in Lowering Permeability can Greatly Improve Operating Efficiency



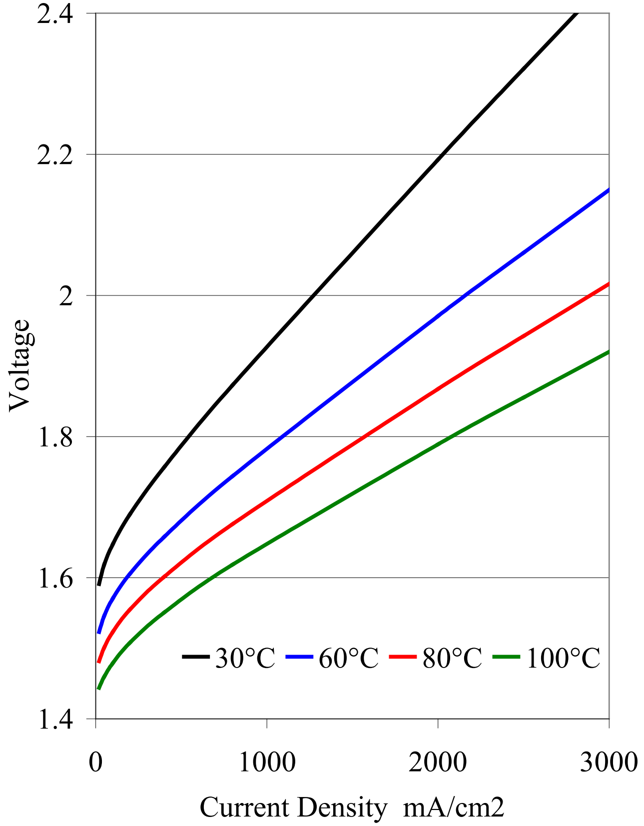


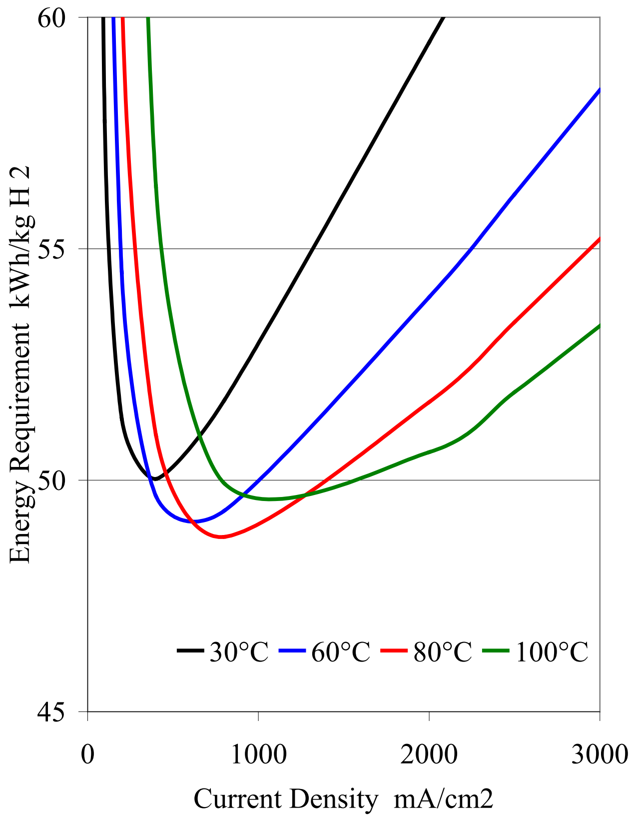


Operation at 80°C and 1000 psi

Using Current PFSA's Thick Membranes is Required for High Pressure Operation

Membranes and Catalysts that can Tolerate High Temperatures Can Greatly Improve Efficiency





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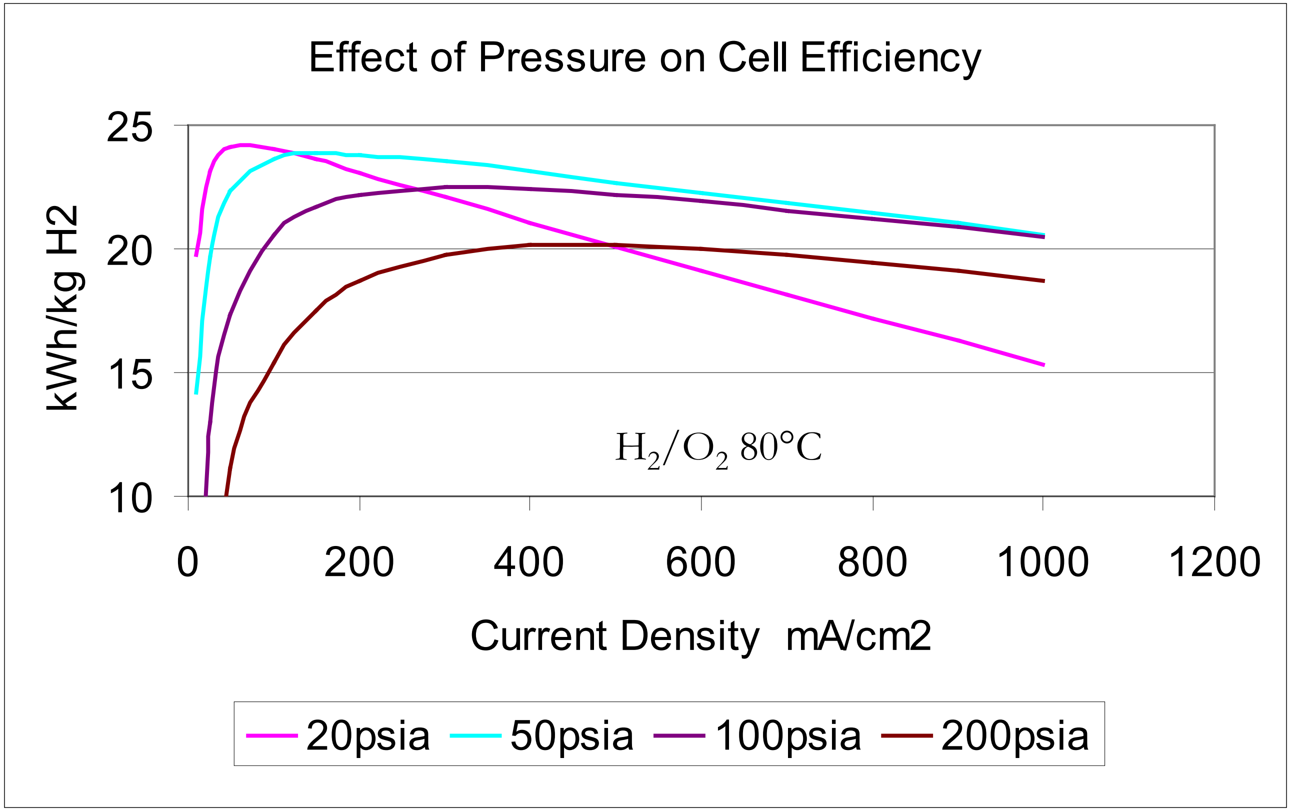
Due to Crossover, Fuel Cells Generally do not Benefit From "Nerstian Boost" of High Pressure



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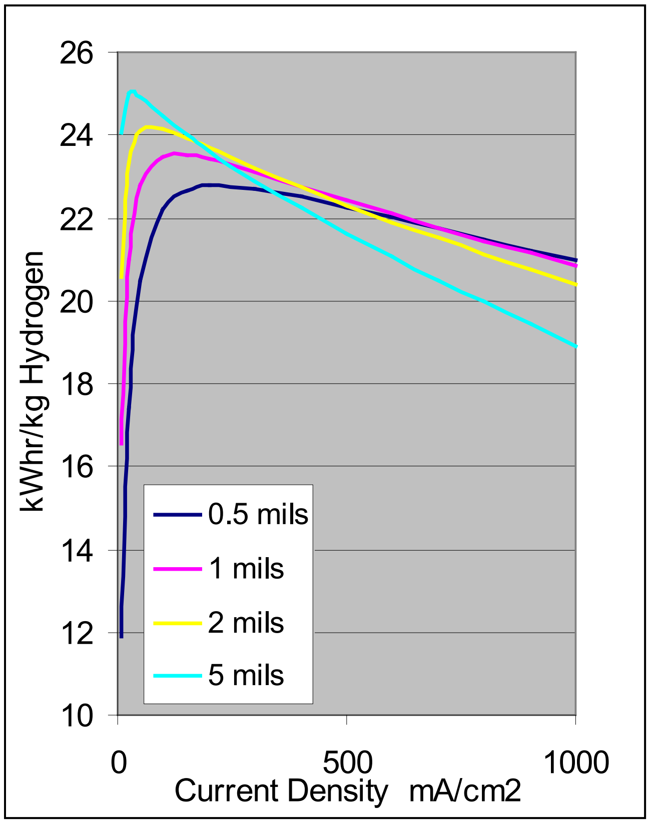
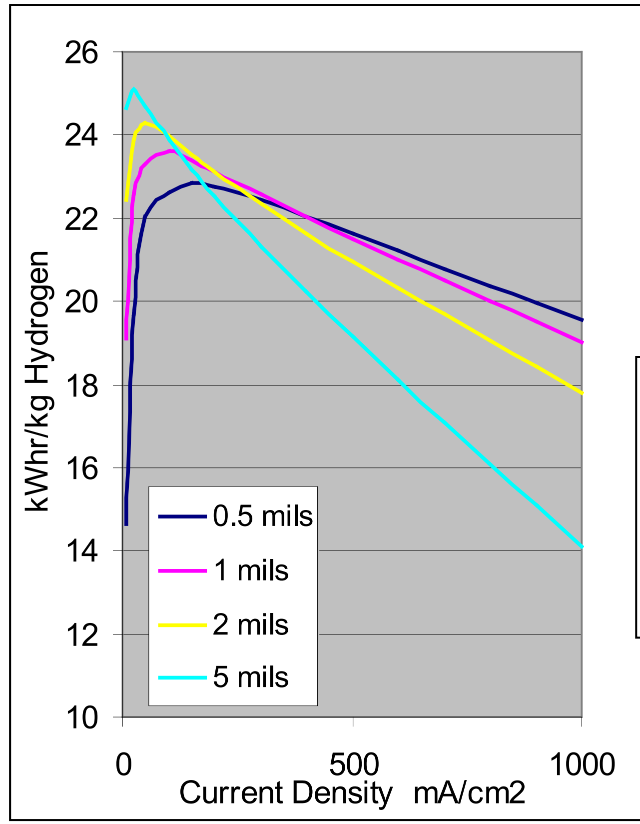
If Operating on Air, Fuel Cells Need a Thin Membrane

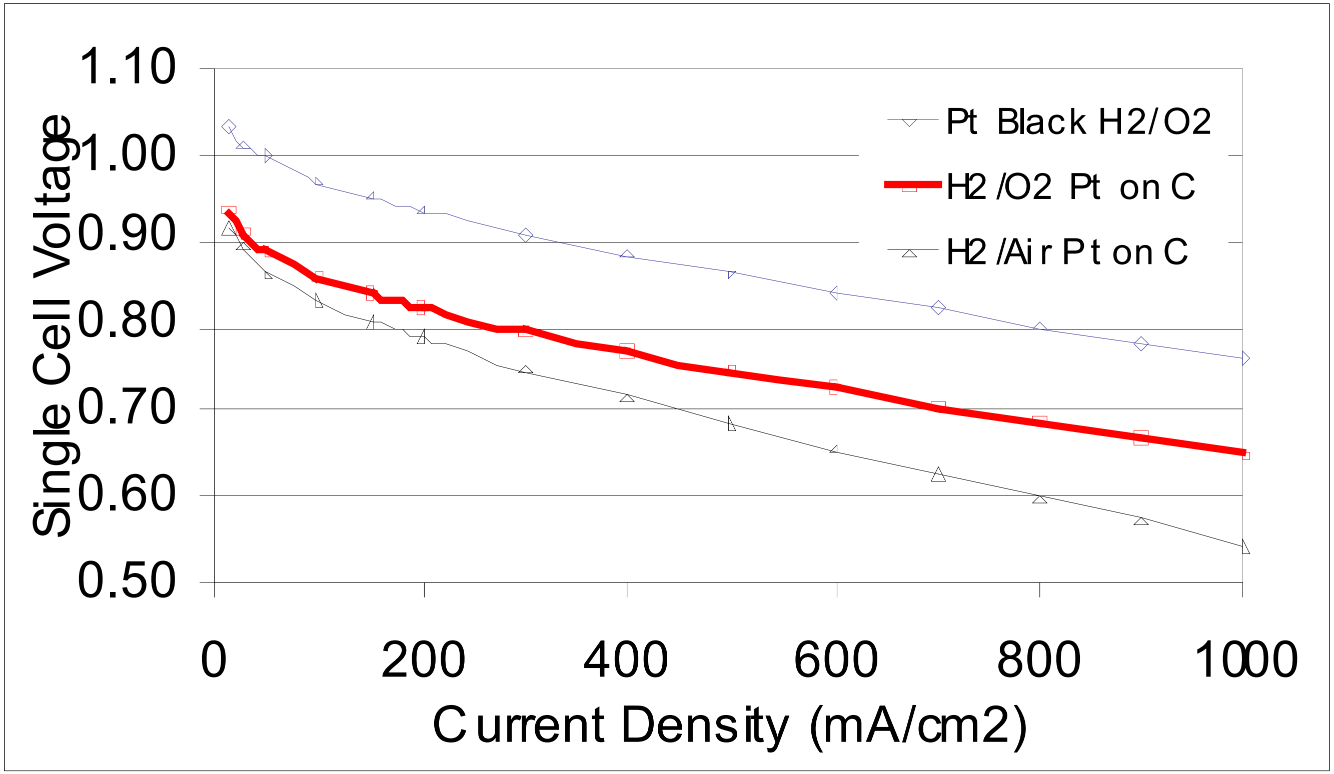




90°C
Anode/Cathode:
20/20 psia
1.1/2.0 Stoich
100/20% Inlet RH

With current PFSA membranes it is not possible to operate high pressure electrolysis with a thin membrane

With Focus on Efficiency it is Difficult to Operate with Air



Further improvements in catalysts still needed. 3M and Argonne catalysts look promising.

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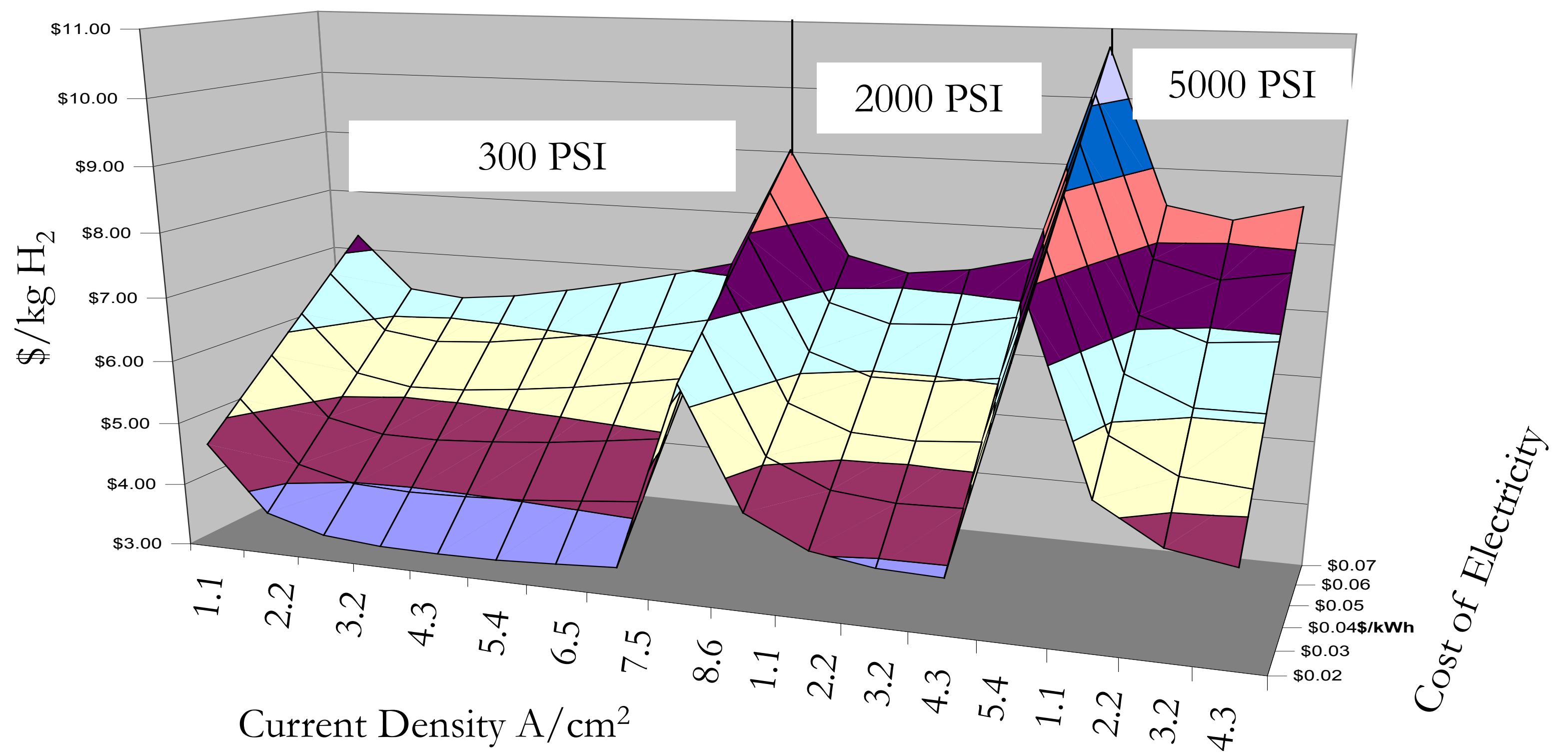
Increasing Electrolyzer Pressure Leads to System Simplification but not Necessarily Lower Cost

Complete Cost of Generating H_2 for Storage at 5000 psi as a Function of Electrolyzer Operating Parameters



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1. *Is this technology feasible for cost effective storage of renewable electricity?*
   - *Dependent on scale and duty cycle.*
     - *Fuel cell and electrolyzer duty cycle need to be closely matched*
     - *For air operating it is difficult to match fuel cell and electrolyzer membranes*
2. *What are the materials and systems barriers to developing this technology?*
   - *Membranes with lower gas permeability*
   - *Lower Cost Catalysts*
3. *What are the manufacturing issues that need to be addressed to be cost effective?*
   - *Continuing to lower part count and component cost*

Efficiency is still key for cost competitiveness.