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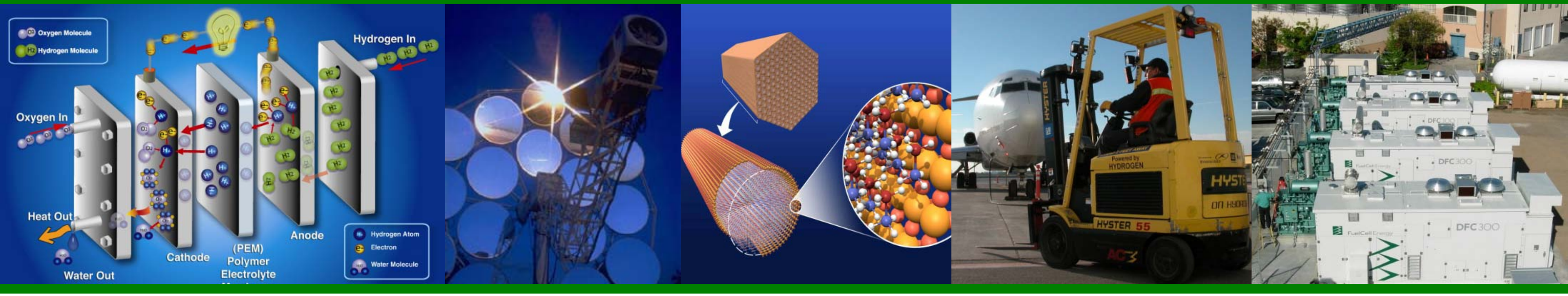


Hydrogen Production

Sara Dillich

2010 Annual Merit Review and Peer Evaluation Meeting

(8 June 2010)

Goal and Objectives

***Goal*: Develop technologies to produce Hydrogen from clean, domestic resources at reduced cost.**

Near-term: Distributed Production
(produced at station to enable low-cost delivery)

- *Natural gas reforming*
- *Renewable liquid reforming*
- *Electrolysis*

Longer-term: Centralized Production
(large investment in delivery infrastructure needed)

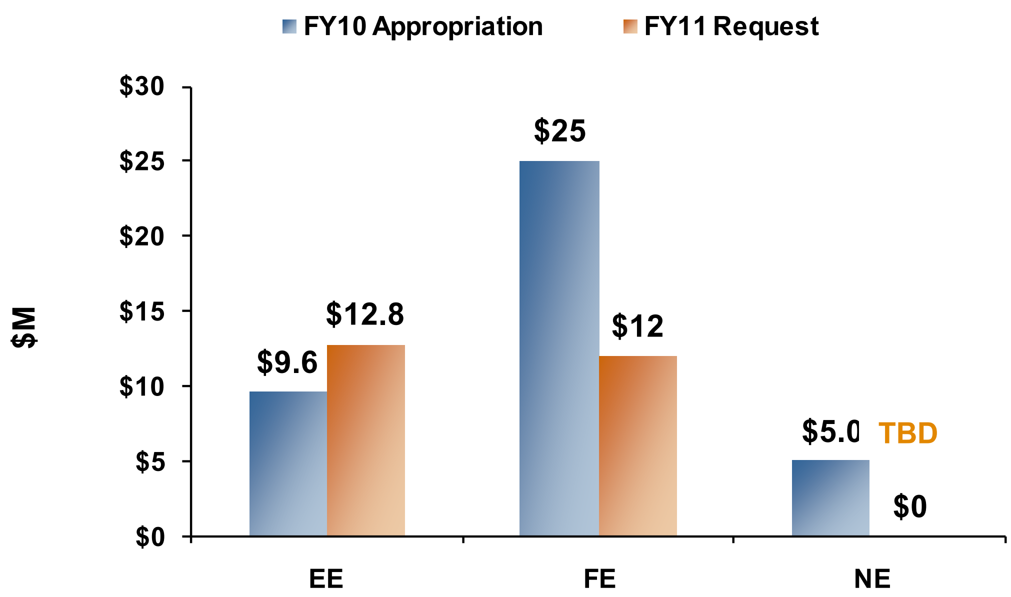
- *Biomass gasification*
- *Coal with sequestration*
- *Wind- and solar-driven electrolysis*
- *Solar high-temperature thermo-chemical water splitting*
- *Nuclear-driven steam electrolysis*
- *Photoelectrochemical, biological production*

In the United States, about 9 million tons of hydrogen are produced annually for industrial purposes, and there are about 1,200 miles of hydrogen pipelines.

Budget

FY 2011 Request = $24.8 M

FY 2010 Appropriation = $39.6 M



EMPHASIS

- Focus biomass based processes to achieve $3.00/gge delivered hydrogen cost in 2020.
- Reduce hydrogen cost from distributed water electrolysis to achieve $3.70/gge in 2015.
- Continue research on longer-term renewable technologies.
- Continue steam electrolysis R&D funded by Next Generation Nuclear Plant Project
- Complete laboratory-scale development of first generation separation and purification technologies for coal-derived syngas; initiating engineering-scale development of separation and purification technologies.

Challenges

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The *key objective* is to reduce cost of H_2 (delivered, dispensed & untaxed)

Pathway	Report	Status
Steam Methane Reforming	*Distributed Hydrogen Production from Natural Gas*, NREL, October, 2006	\$2.75-\$3.05/gge
Electrolysis - Distributed - Central (Wind)	*Current (2009) State -of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis*, NREL, September, 2009.	\$4.90-\$5.70/gge ~ 75% membrane efficiency(PEM) \$2 .70-\$3.50/gge ~75% membrane efficiency (PEM)
Photoelectro-chemical (PEC)	*Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production,* Directed Technologies Inc., December, 2009.	\$4-\$10/gge (projected cost assuming technology reaches technology readiness). Promising PEC materials identified, but durability issues remain.
Biological	*Technoeconomic Boundary Analysis of Biological Pathways to Hydrogen Production*, Directed Technologies Inc., September, 2009.	\$3-\$12/gge (projected cost assuming technology reaches technology readiness). 15% solar-to-chemical energy efficiency by microalgae

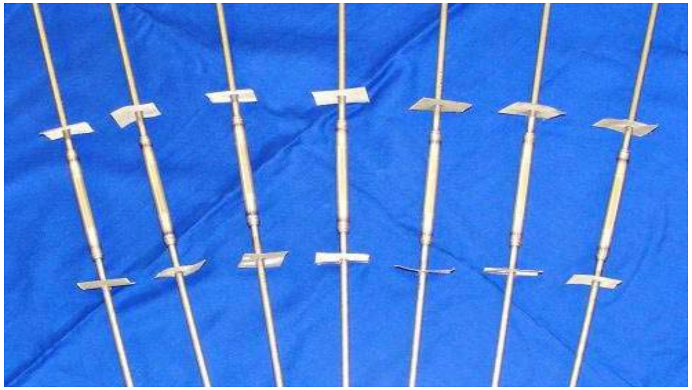
Target and Status costs are 2009 projected high volume costs (Centralized pathway costs do not include dispensing costs, cost targets for STCH, PEC and Biological are technology readiness using H2A assumptions)

Major Challenge: Capital Equipment Costs

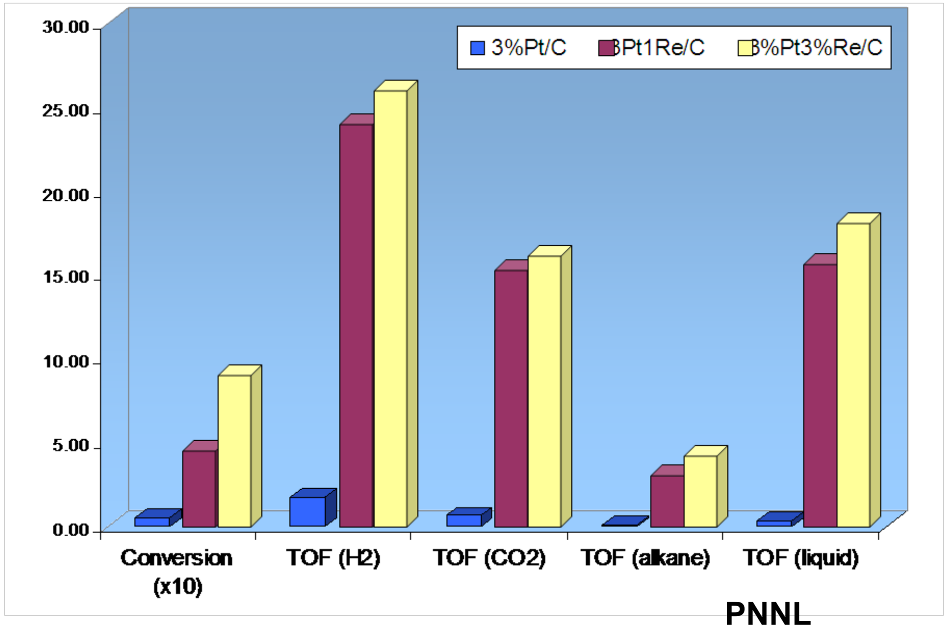
- Biomass Based Processes
  - Catalyst efficiency and durability
  - Capital equipment cost
  - Feedstock cost and handling
- Electrolysis
  - Capital equipment cost
  - Integration with renewable electricity generation
- Biological, Photoelectrochemical, Solar Thermochemical
  - H_2 production rate
  - Materials efficiency
  - Reactors and process development
- Nuclear Driven Processes
  - Durability of high temperature electrolysis cells
- Coal-based Processes
  - Capital equipment cost
  - Capture and sequester carbon

Reforming and Separations Processes

- **Demonstrated long-term (500 hr) stable H_2 flux performance for a Pd-Au alloy membrane in a syngas/ WGS environment. (Pall)**
- **Minimized the acid sites for undesired reaction pathways for aqueous phase reforming of BDL using Pt-Re/C catalysts, resulting in H_2 yields well above 60%. (PNNL)**
- **Showed steady performance of a 1%Rh- 1%Ce on Al_2O_3 catalyst during 60 hours of bench-scale reactor system tests of catalytic partial oxidation and autothermal reforming of bio-oil. 7.3 g hydrogen were produced per 100 g bio-oil. This yield could increase to 9.6 g after completing water-gas shift. (NREL)**



Pall Pd-Au alloy membranes



PNNL

2010 Progress & Accomplishments

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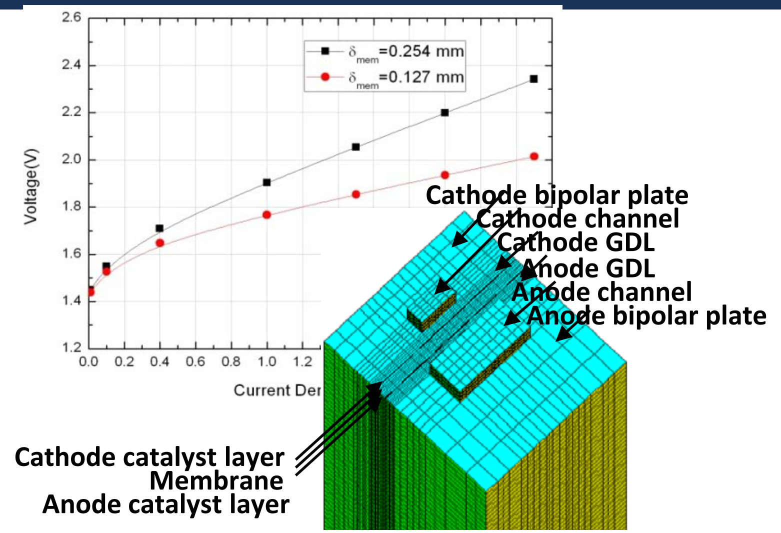
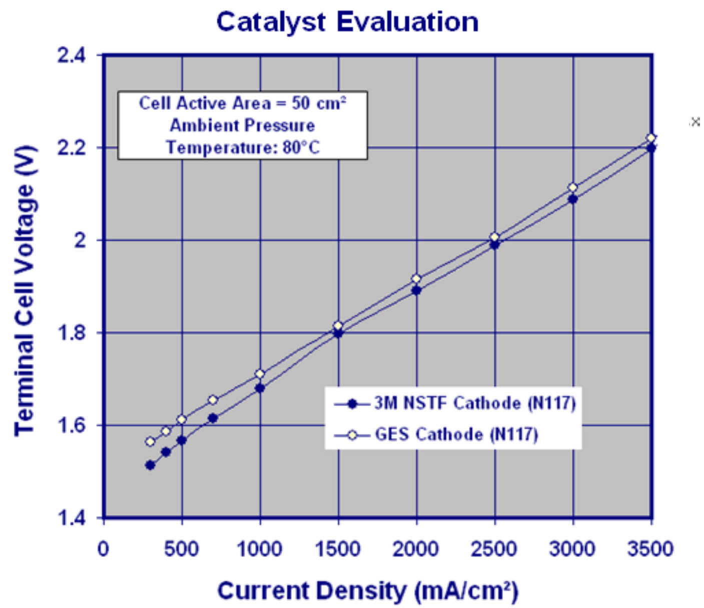
Electrolysis

- **Proton Energy**
  - **–55% Reduction in catalyst loading by using new formulations and deposition techniques**
  - **–Electrochemical model used to optimize flow field improving performance and reduce cost by 30%**
  - **–Combined result in >20% cost reduction in cell cost**
- **Giner Electrochemical Systems**
  - **–Pt loading reduced by >10x using 3M's low Pt catalysts**
  - **–>60k hrs cell separator life with new carbon coating (12x improvement!)**
  - **–Improved dryer decreasing H_2 loss to <3%**
- **National Renewable Energy Laboratory**
  - **–Energy storage analysis completed- projected hydrogen based storage would be cost competitive on a lifecycle basis with NaS and flow battery technology should the FCT program meet their cost and efficiency goals.**



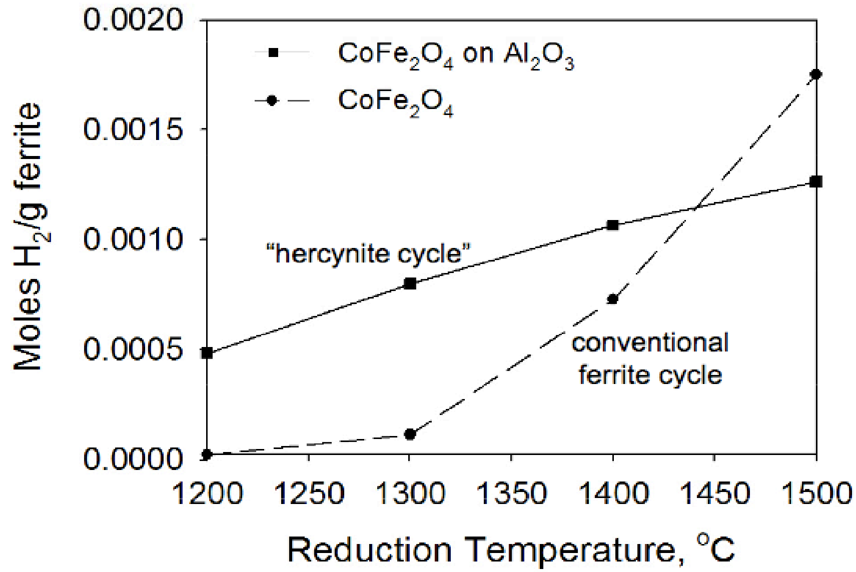


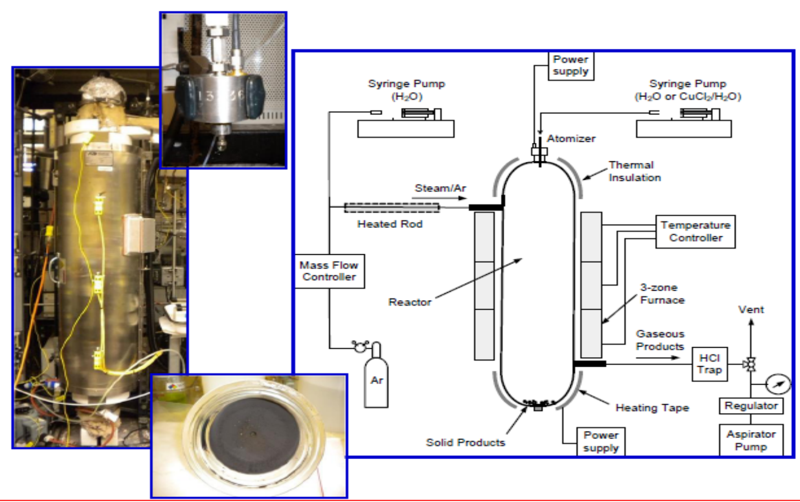
Solar Driven HT Thermochemical

- Hercynite is stable and generates hydrogen at lower temperature than ferrites. Ceria shows stability and higher kinetics. Focus is on ceria-doped hercynite formulations. (U. of Colorado)

- Voltage of an electrolytic cell for the Sulfur-Ammonia cycle has been reduced from 1.2V to less than 1.0V by increasing temperature/pressure, controlling pH, and improving cell design. Quantitative hydrogen production has been measured. (SAIC)

- An hydrolysis reactor was built with an aspirator to allow reduced pressure operation (0.4 bar vs. 1 bar), resulting in yields up to 98% of the desired products (with less side product CuCl) while reducing steam demand by 35%, thereby improving efficiency. (ANL)

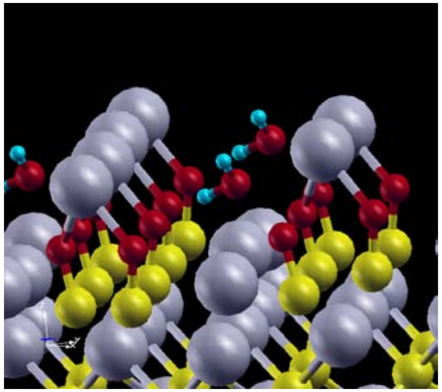




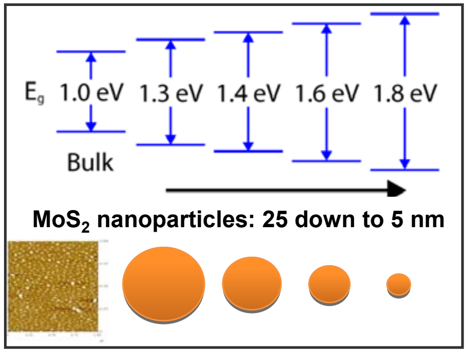
Photoelectrochemical

- New Additions to the PEC Materials Theory "Tool Chest" to Facilitate Technical Breakthroughs
  - Constructed first principle models of the PEC interface based on III-V semiconductor systems (NREL/LLNL)
  - Observed effects of O, H and OH termination (LLNL)
  - Established important correlations between surface morphology and interaction with interfacial water molecules (LLNL)

- Significant Progress in the Development of PEC Materials, Interfaces and Water-Splitting Devices
  - Successfully demonstrated bandgap tailoring in photoactive MoS_2 nanoparticles (Stanford University)
  - Identified crystalline semiconductor device configurations based on current III-V materials with >15% STH conversion efficiency (NREL)
  - Identified thin-film device configurations based on current chalcopyrite and silicon compound materials with >5% STH conversion efficiency (UH/MVS)



PEC Interface Theory



PEC Materials R&D

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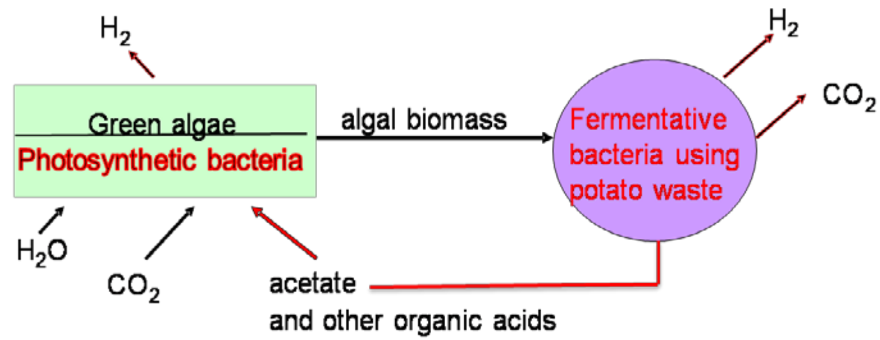
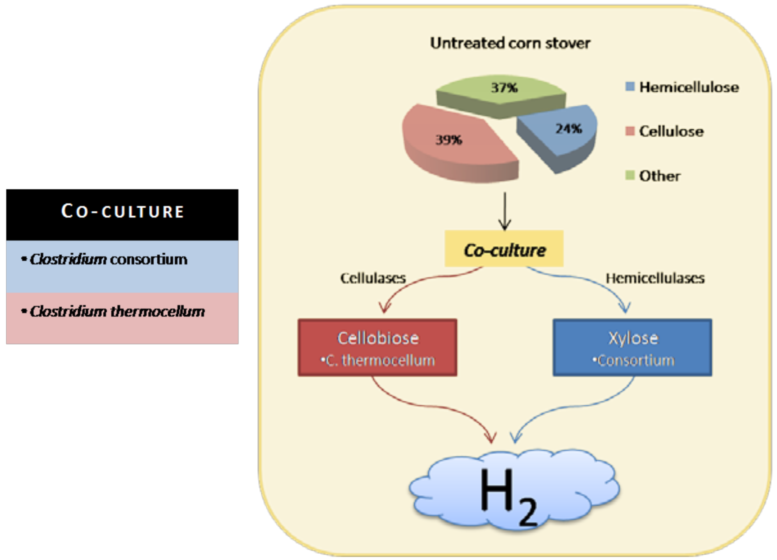
Biological

- National Renewable Energy Laboratory
  - Demonstrated continuous fermentative/photobiological H_2 production process using potato waste as the feedstock achieving a maximum molar yield of 5.6 H_2/glucose
  - Established a microbial co-culture system that can synergistically utilize both the cellulose and hemicellulose components of untreated corn stover biomass - elimination of the pretreatment step lowers the feedstock cost and improves the overall technoeconomic outlook of fermentative hydrogen production





2010 Progress & Accomplishments

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Hydrogen from Coal

- Tests under water-gas shift feed streams initiated; best alloy membrane has demonstrated a H_2 flux rate of 411 scfh/ft^2 (Eltron)
  - Lifetime testing reactor operated several tests to 600 hours; initial baseline membrane testing in H_2/N_2 feed streams show stable performance at 200 scfh/ft^2.
  - Down-selected catalyst tested in streams with 20 ppm H_2S. Stable H_2 flux observed for 160 hrs.
- 359 scfh/ft^2 H_2 flux achieved with 3-5 μm Pd/Inconel membrane at 442^{o}C and 100 psi ΔP. (WPI)
  - Built engineering-scale prototype membrane (2”OD, 6”length, 8.8 μm). Total test 63 days at 450^{o}C, 15 psi ΔP, 80 scfh/ft^2 H_2 flux, 99.99% purity (calculates to 340 scfh/ft^2 H_2 flux)
- Tested five separators using PdCuTM alloy which showed increased surface stability in bench-scale tests. (UTRC)
  - Colloidal Pd/Nano Oxide membrane to show H_2 flux 400 scfh/ft^2

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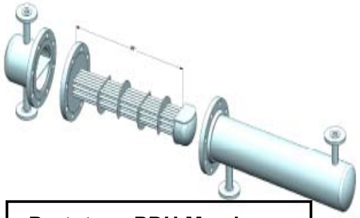
WPI Pd/Inconel H_2 Separation Membranes

WPI

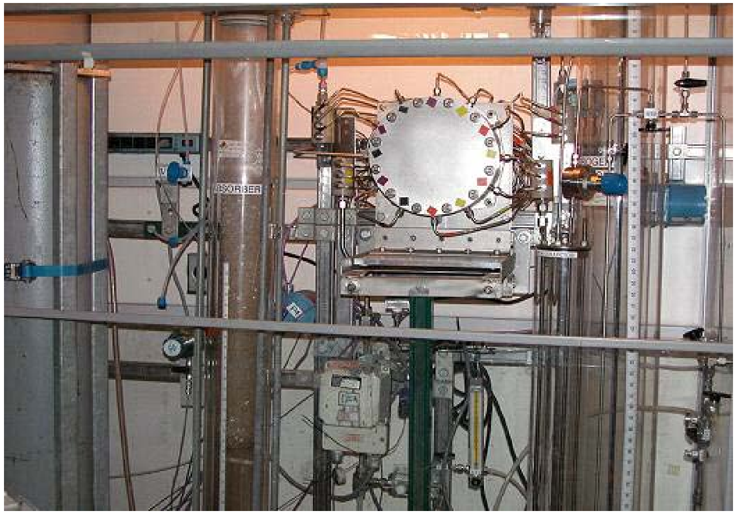


Prototype PDU Membrane Module Configuration

United Technologies Research Center

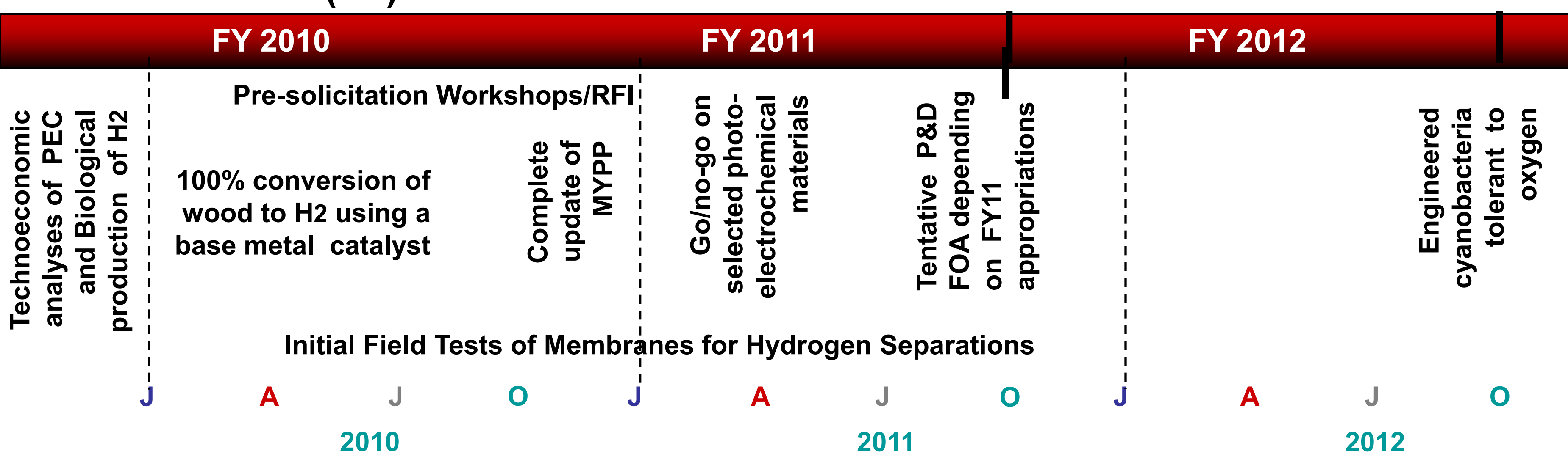
Nuclear Hydrogen Initiative

- Nuclear Hydrogen Initiative was discontinued at end of FY 2009 as a separate program, after selection of steam electrolysis as most compatible with Next Generation Nuclear Plant (NGNP)
- Development of high temperature electrolysis continuing under the NGNP project, which is also looking at other end-use applications and energy transport systems



Major Milestones & Future Solicitations

- Completed update of cost status for Hydrogen Production Pathways. Significant progress in cost reduction for all pathways since 2005.
- Initiated update of Production cost targets and Multi-Year Plan.
- Initiated a market analysis and an independent review of costs for hydrogen from Biomass Gasification. Initiated a DFMA cost analysis of an OTM reactor.
- Initiated scale-up of first generation membrane separation technologies and lab-scale development of second generation technologies with potential for significant cost reductions. (FE)



Session Instructions

- This is a review, not a conference.
- Presentations will begin precisely at the scheduled times.
- Talks will be **20 minutes** and **Q&A 10 minutes**.
- Reviewers have priority for questions over the general audience.
- Reviewers should be seated in front of the room for convenient access by the microphone attendants during the Q&A.
- Please mute all cell phones, BlackBerries, etc.

Reviewer Reminders

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- Deadline for final review form submittal is **June 18th**.
- ORISE personnel are available on-site for assistance. A reviewer lab is set-up in room 8216 and will be open Tuesday –Thursday from 7:30 AM to 6:00 PM and Friday 7:30 AM to 3:00 PM.
- Reviewer feedback session – **Thursday, at 5:45pm (after last Hydrogen Production and Delivery session), in this room.**

For More Information

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