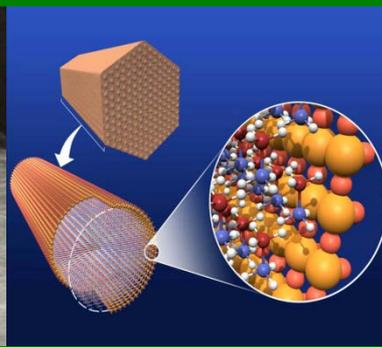




U.S. DEPARTMENT OF
ENERGY



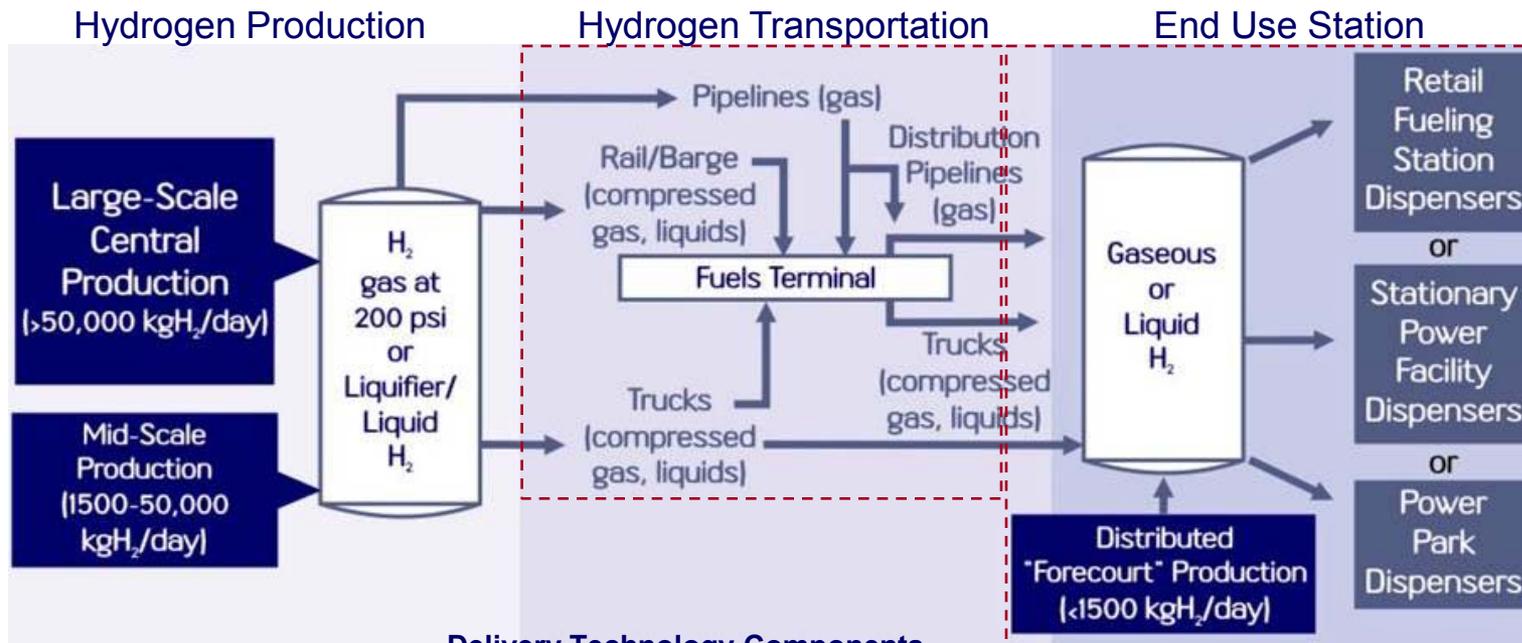
Hydrogen Delivery Sub-program - Session Introduction -

Scott Weil

*2011 Annual Merit Review and Peer Evaluation Meeting
May 10, 2011*

Goals and Objectives

Develop technologies to reduce the cost of H₂ delivery to the point that H₂ is competitive with other energy carriers and fuels



Delivery Technology Components

- Storage at production site
- Liquefier (gas to liquid)
- Carrier production/regeneration

- Pipelines
- Trucks, rail, barges - vessels
- Pipeline compressors
- City gate storage
- Geological storage
- Terminals

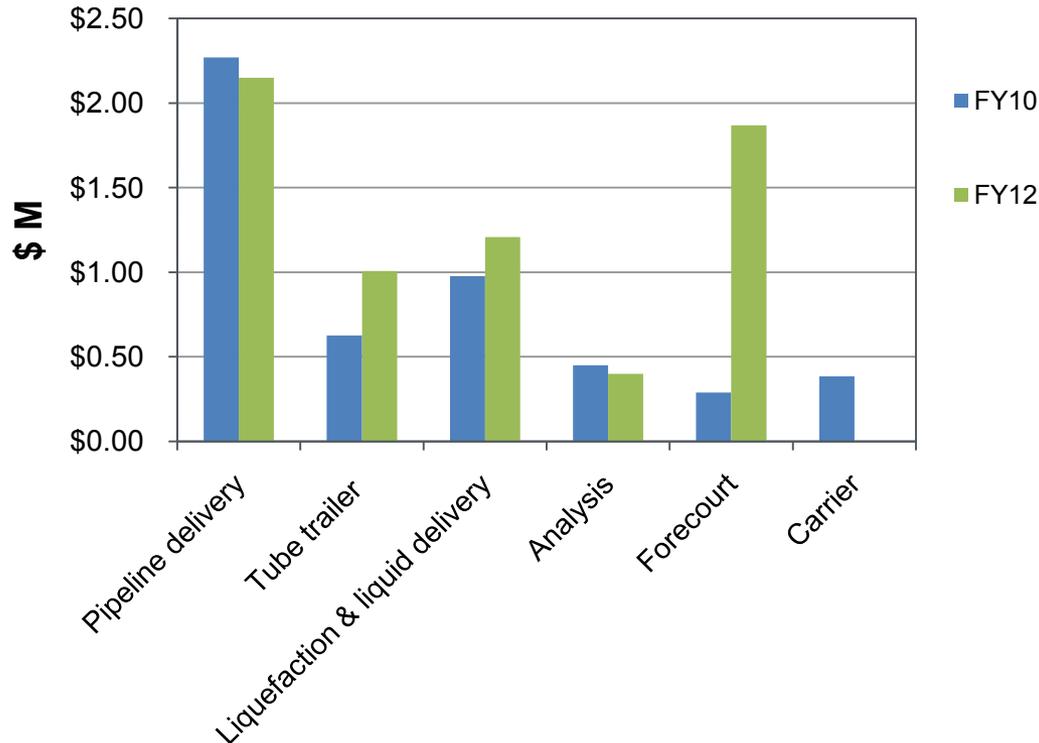
- Carrier transfiguration
- Separation/purification
- Forecourt storage
- Compression/vaporization
- Fuel dispensers

Crosscutting Delivery Technology Components

- Sensors & controls
- Health & human safety
- Codes & standards
- Rights of way/permitting

FY 2010 Appropriation = \$5.02M

FY 2012 Request = \$6.63M



EMPHASIS

- **Reduce pipeline delivery cost**
 - ▶ Centrifugal pipeline compressor design using “off-the-shelf parts”
 - ▶ High RPM pipeline compressor design to reduce size and cost while increasing efficiency
 - ▶ Fiber reinforced polymer pipeline alternative to steel pipeline
- **Increase the gas capacity of tube truck delivery**
 - ▶ Large volume /high pressure vessel
 - ▶ High pressure/low temperature glass fiber wrapped vessel
- **Increase the efficiency of H₂ liquefaction**
 - ▶ Helium cycle with a novel heat exchanger configuration
 - ▶ Magnetic cooling
- **Analysis of costs**
 - ▶ Update HDSAM to \$2007 and evaluate technology and economies of scale cost drivers
 - ▶ Evaluate delivery pathways and key cost drivers

The key challenge in this sub-program is to reduce the cost of delivering H₂ (including on-site compression, storage, and dispensing) to \$1/gge.*

Delivery Element	Goal (2015/2017 Targets)*	Status**
Tube trailers	<ul style="list-style-type: none"> • Reduce capital cost to < \$200,000 • Increase capacity to 1100kg 	<ul style="list-style-type: none"> • Capital cost: \$470,000 capital cost (250 bar carbon fiber vessel, • Capacity: 550kg • Cost contribution: \$0.9/kg H₂
Liquefaction	<ul style="list-style-type: none"> • Reduce installed capital cost to \$100M • Increase energy efficiency to 87% 	<ul style="list-style-type: none"> • Installed capital cost: \$200M • System Efficiency: 76% • Cost contribution: \$1.6/kg H₂
Pipeline technology	<ul style="list-style-type: none"> • Reduce cost/mile (installed) to <\$490K 	<ul style="list-style-type: none"> • Installed steel pipeline cost: \$3M/mile • Cost contribution: \$1.7/kg H₂ • Compressor cost contribution: \$0.1/kg H₂
Forecourt compression (1000 kg/day station)	<ul style="list-style-type: none"> • Reduce installed capital cost to \$187.5K for 700 bar, 1500kg/day dispensing 	<ul style="list-style-type: none"> • Capital cost: \$1.5M for 700 bar dispensing (cost contribution of \$2/kg H₂) • Capital cost: \$0.5M for 350 bar dispensing (cost contribution of \$0.8/kg H₂)
Forecourt storage (1000 kg/day station)	<ul style="list-style-type: none"> • Reduce tank cost/kg H₂ stored to \$300 (current \$1000) 	<ul style="list-style-type: none"> • Storage tank cost: \$1000/kg H₂ stored (\$0.4/kg H₂)

*Based on FY10 MYPP targets. These are being updated this year.

** High volume projections based on HDSAM (v. 3) – will be peer reviewed and publicly vetted.

Capital costs are an issue for all pathways.



- **Tube trailers (early market scenario)**

- ▶ Capacity
- ▶ Capital cost
- ▶ Regulatory issues with transportation of high-pressure vessels



- **Liquid H₂ delivery (early and mid-term market scenarios)**

- ▶ Energy efficiency of liquefaction
- ▶ Transfer boil off
- ▶ Capital cost

- **Pipelines (long-term market scenario)**

- ▶ Managing embrittlement (steel pipelines) to reduce lifetime cost
- ▶ Capital and installation costs
- ▶ Cost & durability/reliability of pipeline compressors
- ▶ Hydrogen quality
- ▶ Bulk storage (geologic)



- **Forecourt**

- ▶ Cost/efficiency and reliability of station compressors and dispensers
- ▶ Capital cost per kg H₂ stored of station storage

Identified design parameters to increase trailer capacity to 800 kg and reduce capital cost to \$450/kg H₂ stored

Prior Accomplishments

- Met key interim program goals:
 - ▶ Successfully tested 250 bar vessel/ISO frame capable of 600 kg H₂ capacity
 - ▶ Achieved a projected reduction in tube trailer delivery cost of >33%
 - ▶ Identified a route to increase capacity to 1,100 kg H₂ and reduce trailer cost by 50% using cold compressed glass fiber vessels



Recent Accomplishments

- Completed a design trade study on carbon fiber wrapped vessels :
 - ▶ Vessel pressure can be increased an additional 100 bar (350 bar)
 - ▶ Carrying capacity can be increased an additional 33% (800 kg H₂)
 - ▶ Transport cost can be reduced another 10%
- Successfully fabricated and hydroburst tested a full-scale glass fiber wrapped vessel



Future Work

- Complete design and qualification of a 350 bar tank
- Pressure and thermal cycle test full scale glass fiber wrapped vessels



PIs: Lincoln Composites and LLNL

Increased Claude-cycle efficiency; Fabricated alternative H₂ liquefaction prototype

Prior Accomplishments

- Developed software that accounts for ortho-para LH₂ effects and helps identify efficiency improvements
- Completed design of a continuous catalytic heat exchanger (CHEX) – projected to improve HX performance
- Designed and fabricated 5 of 8 sub-systems for active magnetic regenerative refrigerator (AMRR)



Recent Accomplishments

- Improved ortho-para conversion performance with a catalyst – reduces total power required for liquefaction by 2.4%
- Fabricated the CHEX for testing
- Fabricated and integrated all sub-systems into a prototype AMRR device – in testing

Future Work

- Complete testing of the CHEX device
- Incorporate lessons learned from AMRR prototype testing into the design of a final phase rotary device
- Fabricate and test a demonstration-scale rotary AMRR device

PIs: Praxair, GEECO, and Heracles Energy Corp.

Projected reduction in installed pipeline costs of 15%

Prior Accomplishments

- Identified steel microstructures responsible for H₂ embrittlement resistance
- Determined that the level of H₂ permeation through fiber reinforced polymer (FRP) pipeline materials will meet DOE targets and FRP burst strength
- Demonstrated no degradation in FRP after 8mo of accelerated aging (equivalent to 5yrs at room temperature)

Recent Accomplishments

- Developed models to simulate the effects of H₂ on the mechanical properties of pipeline steels
- Demonstrated a 3x design margin for FRP through flaw tolerance testing
- Projected reduction in installed pipeline cost of 15%

Future Work

- Establish protocols with codes committees to develop performance qualification test methodology for FRP
- Initiate FRP performance testing

PIs: U. Illinois, SECAT, SNL, ORNL, SRNL



Projected reduction in pipeline compressor capital cost of 20% and O/M costs of 30% based on new designs

Prior Accomplishments

- Completed an initial design study of a pipeline compressor (Concepts NREC) concept that utilizes off-the-shelf technology and is projected to meet the DOE FY2017 targets
- Completed an initial design of a high speed pipeline compressor (MITI) that also is projected to meet the DOE FY 2017 targets



Recent Accomplishments

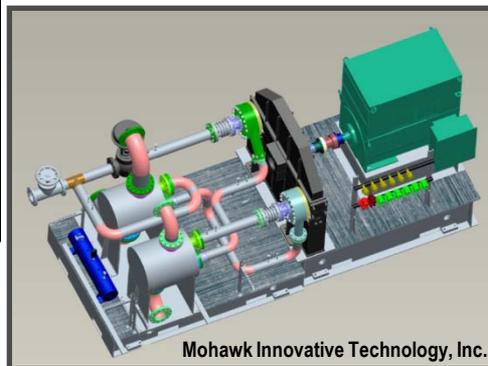
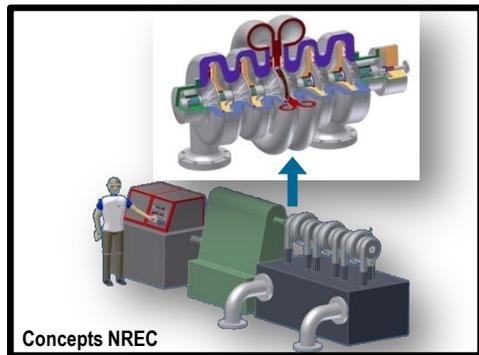
- Completed detailed design and thermomechanical analyses of the Concepts NREC compressor concept
- Completed detailed design and thermomechanical analyses of a single-stage MITI prototype compressor
- Fabricated key components (e.g. rotor) for prototypes of each compressor technology



Future Work

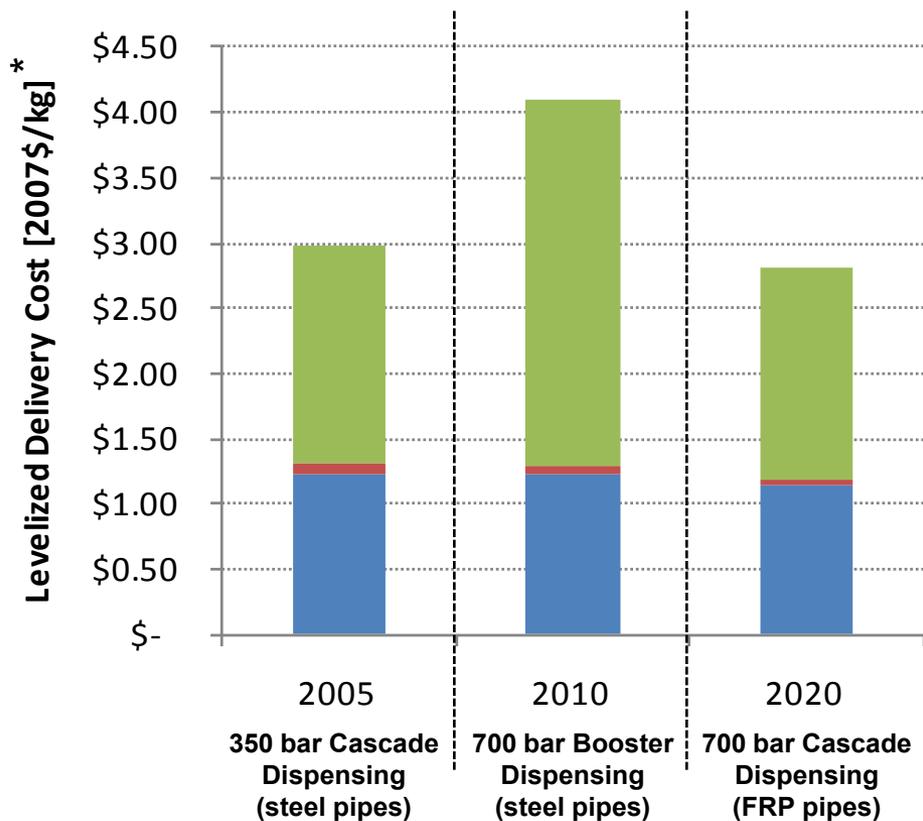
- Conduct component testing and post-test analysis
- Fabricate compressor prototypes for performance testing

PIs: MITI, Concepts NREC, ANL

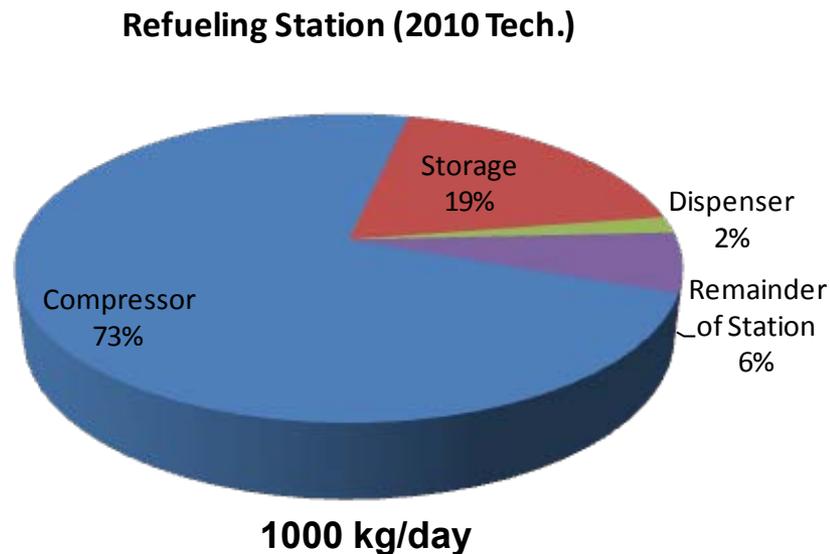


Station costs now dominate pathway delivery costs.

Example: Pipeline delivery pathway



- Refueling Station
- Compressor
- Pipeline



* Cost projections based on 15% market penetration

Identified key barriers to delivery and forecourt cost reductions

Prior Accomplishments

- Completed fuel station footprint and wind-to-LH₂ analyses and added 700 bar gas and cryo-compressed delivery options to models
- Demonstrated electrochemical hydrogen compressor (EHC)
 - ▶ Achieved a 300:1 compression ratio in a single stage design
 - ▶ Passed 500 hr testing at that time
 - ▶ Project a 5x reduction in energy consumption and improved device reliability relative to current technology

PIs: FuelCell Energy, ORNL, LLNL, ANL, NREL, PNNL

Recent Accomplishments

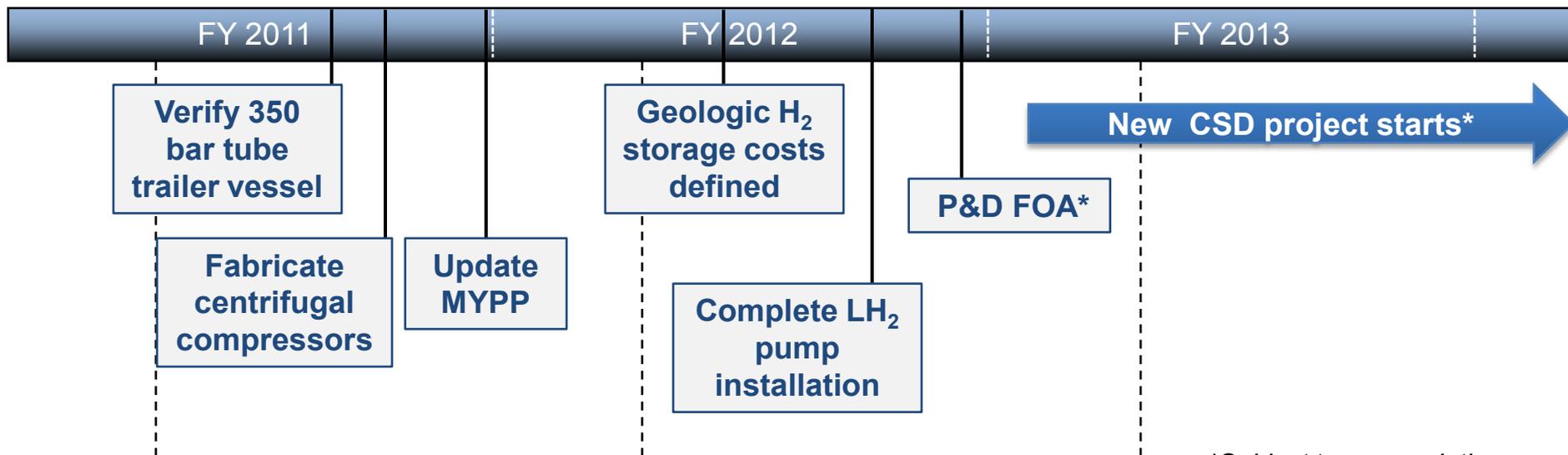
- Published pipeline cost analysis study
- Updated HDSAM/H2A, including \$2007
- Identified a key cost barrier: compression, storage, and dispensing (CSD) at the forecourt
- Achieved 420 bar in a 2-stage EHC design, with the potential to reach 840 bar. Doubled the rate of compression

Future Work

- Identify technology and pathway options to reduce refueling station costs
- Design test facility to test 2-stage, 840 bar EHC
- Detailed design of reinforced concrete steel lined storage vessel

Key Milestones & Future Plans

- Update HDSAM (to 2007 dollars) – publication in progress
- Verify tube trailer vessel capacity to 350 bar
- Complete prototype centrifugal compressor systems in preparation for testing
- Pipeline working group meeting (9/11)
- Update Delivery technology/cost targets and Multi-Year Plan – in progress
- Establish the feasibility and define the cost for geologic hydrogen storage
- Complete LH₂ pump installation at LLNL in preparation for refueling and cryo-compressed vessel tests



H₂ Delivery Sub-Program

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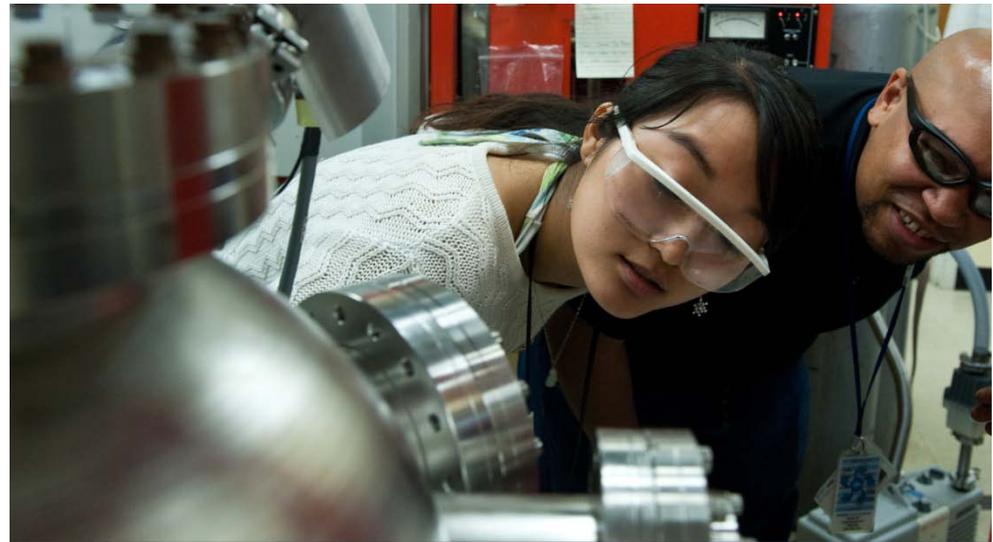
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- This is a review, not a conference.
- Presentations will begin precisely at the scheduled times.
- Talks will be 20 minutes and Q&A 10 minutes.
- Reviewers have priority for questions over the general audience.
- Reviewers should be seated in front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

- Deadline for final review form submittal is **May 20th at 5:00 pm.**
- ORISE personnel are available on-site for assistance. A reviewer-ready room is set-up in *The Rosslyn Room* (on the lobby level) and will be open Tuesday –Thursday from 7:30 am to 6:00 pm and Friday from 7:30 am to 2:00 pm.
- Reviewers are invited to a brief feedback session – at 3:45pm on Thursday, in this room.

- Fuel Cell Technologies Program Opportunities Available
 - Conduct applied research at universities, national laboratories, and other research facilities
 - Up to five positions are available in the areas of hydrogen production, hydrogen delivery, hydrogen storage, and fuel cells
 - Applications are due June 30, 2011
 - Winners will be announced mid-August
 - Fellowships will begin in mid-November 2011

www.eere.energy.gov/education/postdoctoral_fellowships/



Postdoctoral fellowships in hydrogen and fuel cell research ▶

- **Analysis**

- ▶ ANL
- ▶ NREL
- ▶ PNNL

- **Forecourt Compression/Storage**

- ▶ AC Transit
- ▶ Fuel Cell Energy
- ▶ NASA
- ▶ ORNL

- **H₂ Liquefaction & Delivery**

- ▶ Gas Equipment Engineering Corporation
- ▶ Linde Corporation
- ▶ LLNL
- ▶ Praxair
- ▶ Prometheus Energy

- **Pipeline & Pipeline Compression**

- ▶ ANL
- ▶ Concepts NREC
- ▶ DOT
- ▶ I²CNER
- ▶ MITI
- ▶ NASA
- ▶ NIST
- ▶ ORNL
- ▶ Secat
- ▶ SNL
- ▶ SRNL
- ▶ University of Illinois

- **Carriers**

- ▶ Air Products
- ▶ PNNL

- **Sub-program Review**

- ▶ BP
- ▶ Chevron
- ▶ Exxon-Mobil