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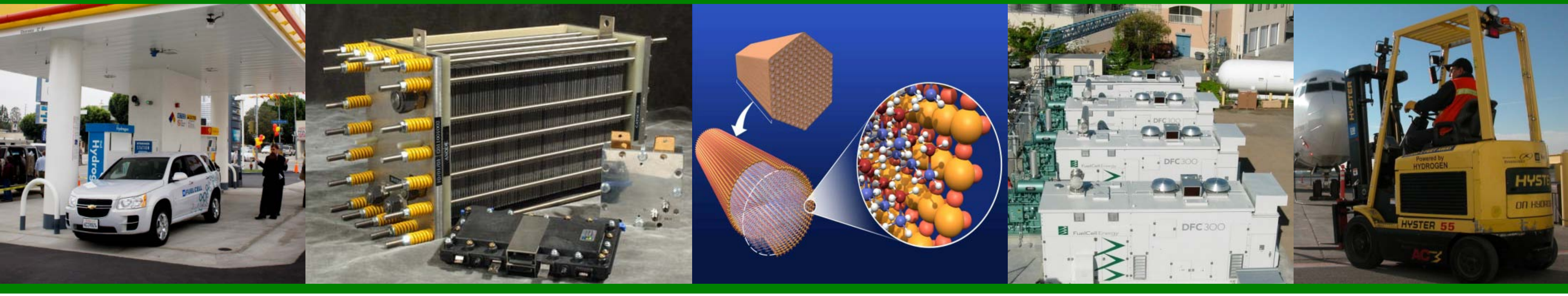

Hydrogen Delivery Sub-program - Session Introduction -

Scott Weil

2011 Annual Merit Review and Peer Evaluation Meeting

May 10, 2011

Goals and Objectives

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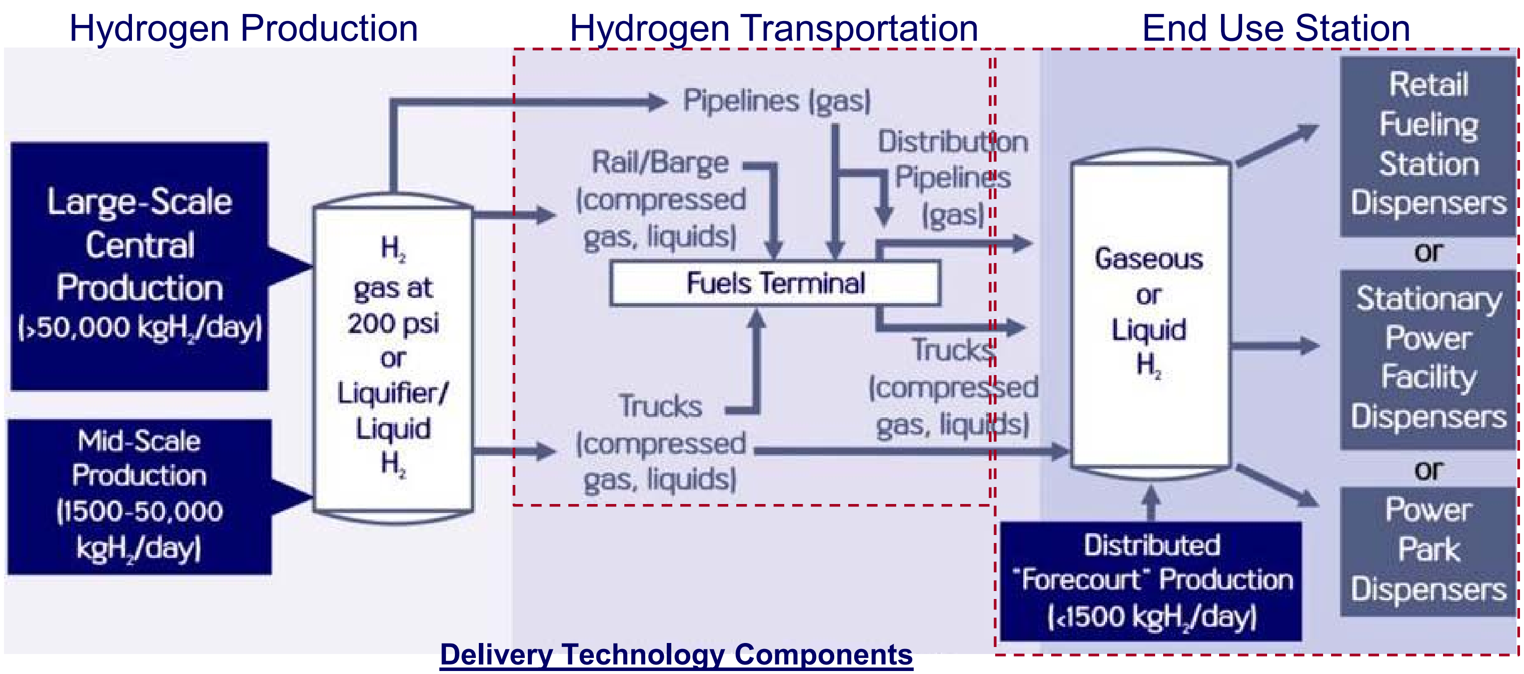
Develop technologies to reduce the cost of H_2 delivery to the point that H_2 is competitive with other energy carriers and fuels



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

Delivery Budget

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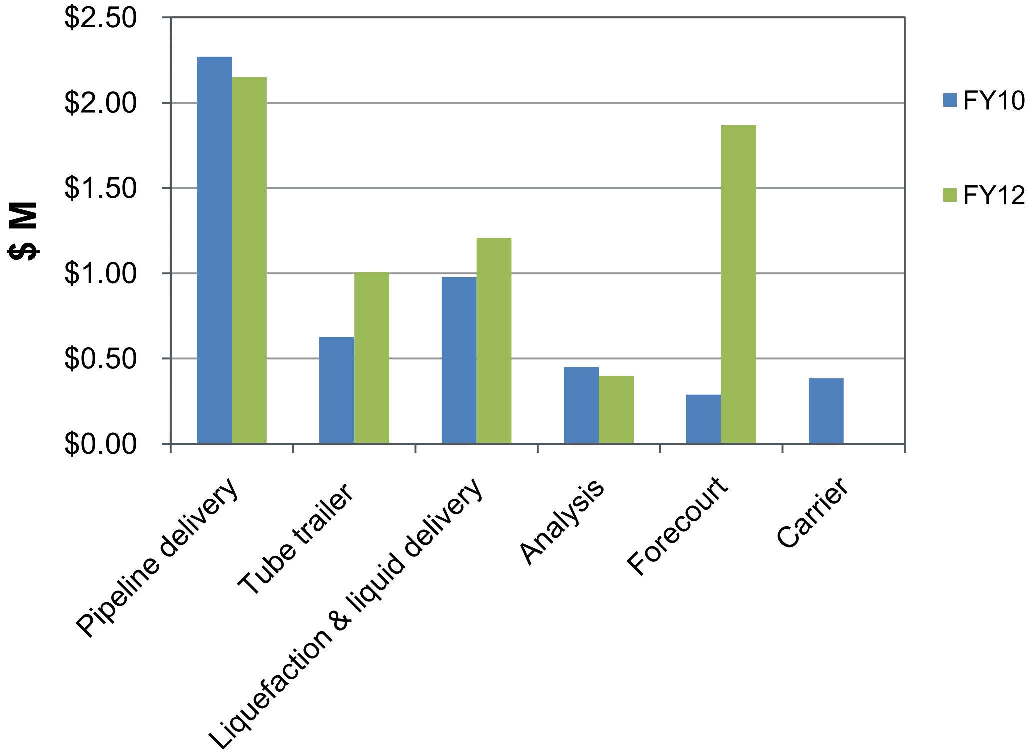
FY 2010 Appropriation = $5.02M

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 H_2 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

Challenges

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The key challenge in this sub-program is to reduce the cost of delivering H_2 (including on-site compression, storage, and dispensing) to $1/gge*.

Delivery Element	Goal (2015/2017 Targets)*	Status**
Tube trailers	• Reduce capital cost to < $200,000 • Increase capacity to 1100kg	• Capital cost: $470,000 capital cost (250 bar carbon fiber vessel, • Capacity: 550kg • Cost contribution: $0.9/kg H_2
Liquefaction	• Reduce installed capital cost to $100M • Increase energy efficiency to 87%	• Installed capital cost: $200M • System Efficiency: 76% • Cost contribution: $1.6/kg H_2
Pipeline technology	• Reduce cost/mile (installed) to <$490K	• Installed steel pipeline cost: $3M/mile • Cost contribution: $1.7/kg H_2 • Compressor cost contribution: $0.1/kg H_2
Forecourt compression (1000 kg/day station)	• Reduce installed capital cost to $187.5K for 700 bar, 1500kg/day dispensing	• Capital cost: $1.5M for 700 bar dispensing (cost contribution of $2/kg H_2) • Capital cost: $0.5M for 350 bar dispensing (cost contribution of $0.8/kg H_2)
Forecourt storage (1000 kg/day station)	• Reduce tank cost/kg H_2 stored to $300 (current $1000)	• Storage tank cost: $1000/kg H_2 stored ($0.4/kg H_2)

*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.

Challenges: Techno-economic

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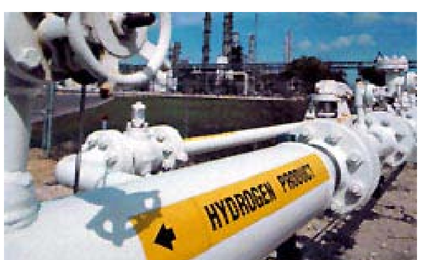
Capital costs are an issue for all pathways.



- **Tube trailers (early market scenario)**
  - Capacity
  - Capital cost
  - Regulatory issues with transportation of high-pressure vessels
- **Liquid H_2 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 H_2 stored of station storage

Progress: Tube Trailer Delivery

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Identified design parameters to increase trailer capacity to 800 kg and reduce capital cost to \$450/kg H_2 stored

Prior Accomplishments

- Met key interim program goals:
  - Successfully tested 250 bar vessel/ISO frame capable of 600 kg H_2 capacity
  - Achieved a projected reduction in tube trailer delivery cost of >33%
  - Identified a route to increase capacity to 1,100 kg H_2 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 H_2)
  - Transport cost can be reduced another 10%
- Successfully fabricated and hydroburst tested a full-scale glass fiber wrapped vessel

Lincoln Composites

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

Progress: H_2 Liquefaction

Increased Claude-cycle efficiency; Fabricated alternative H_2 liquefaction prototype

Prior Accomplishments

- Developed software that accounts for ortho-para LH_2 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.

Progress: Pipeline Materials

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Projected reduction in installed pipeline costs of 15%

Prior Accomplishments

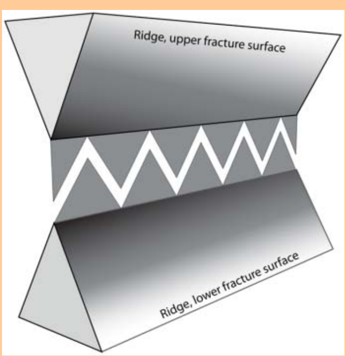
- Identified steel microstructures responsible for H_2 embrittlement resistance
- Determined that the level of H_2 permeation through fiber reinforced polymer (FRP) pipeline materials will meet DOE targets and FRP burst strength
- Demonstrated no degradation in FRP after 8mo of accelerated aging (equivalent to 5yrs at room temperature)

Recent Accomplishments

- Developed models to simulate the effects of H_2 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

Progress: Pipeline Compression

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

Prior Accomplishments

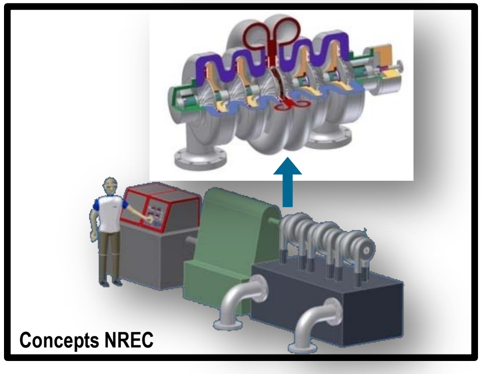
- Completed an initial design study of a pipeline compressor (Concepts NREC) concept that utilizes off-the-shelf technology and is projected to meet the DOE FY2017 targets
- Completed an initial design of a high speed pipeline compressor (MITI) that also is projected to meet the DOE FY 2017 targets

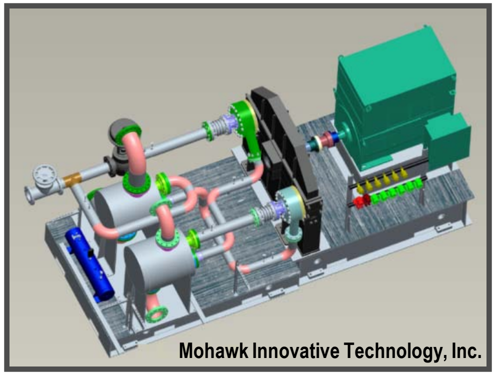
Recent Accomplishments

- 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

Progress: Analysis/Forecourt CSD

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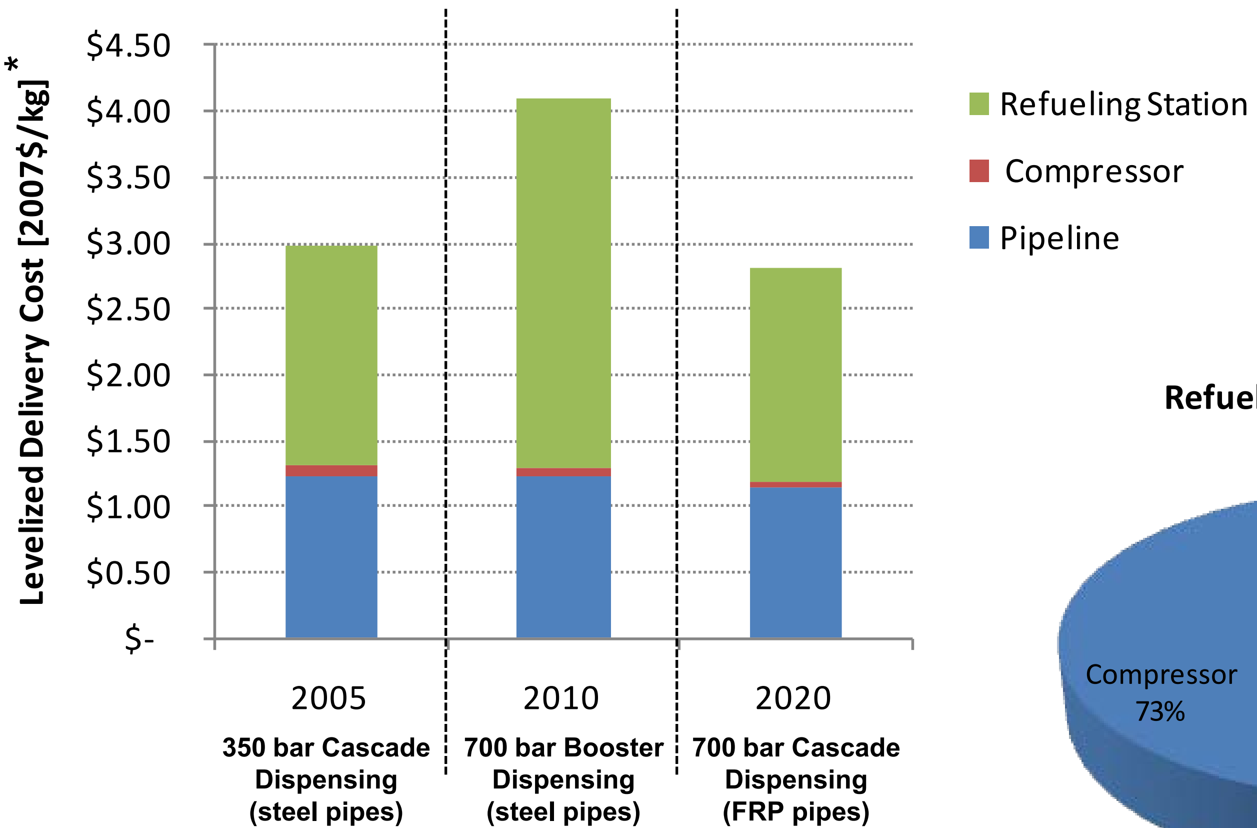
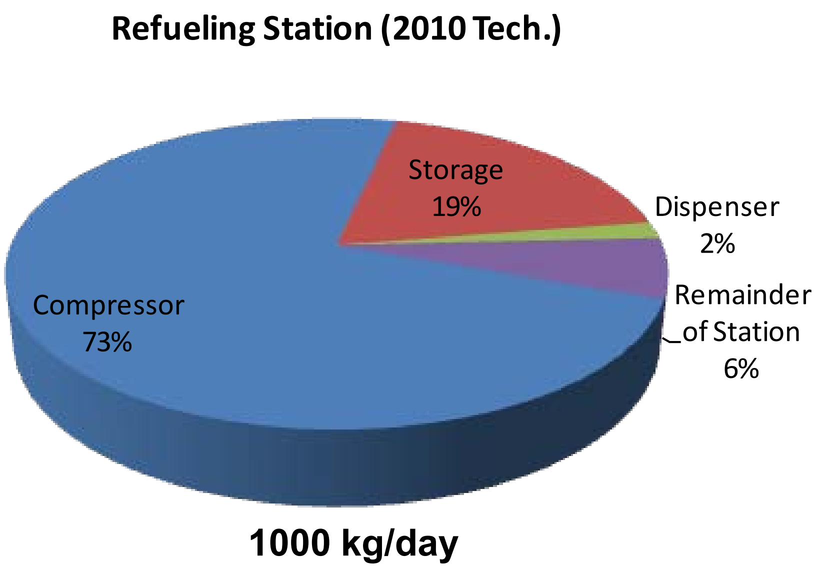
Station costs now dominate pathway delivery costs.

Example: Pipeline delivery pathway





* Cost projections based on 15% market penetration

Progress: Analysis/Forecourt CSD

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Identified key barriers to delivery and forecourt cost reductions

Prior Accomplishments

- Completed fuel station footprint and wind-to-LH_2 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

Summary

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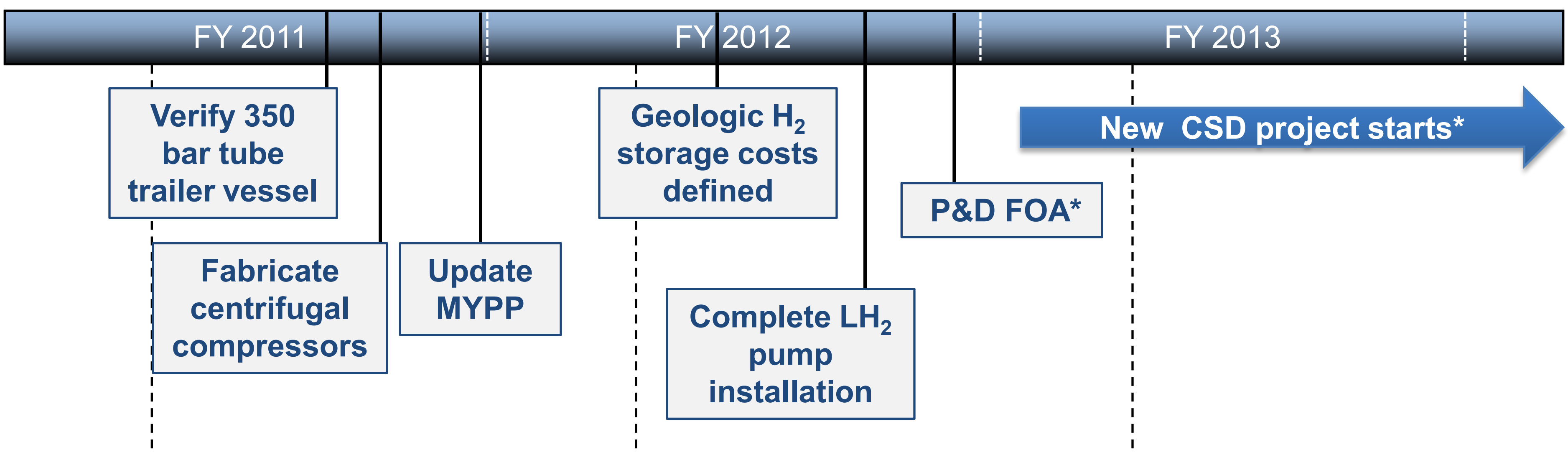
Key Milestones & Future Plans

- 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 LH_2 pump installation at LLNL in preparation for refueling and cryo-compressed vessel tests



*Subject to appropriations

For More Information

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Session Instructions

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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.

Reviewer Reminders

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- 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.

EERE Fellowship Program

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- 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/

Participating Organizations/Collaborators

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- **Analysis**
  - ANL
  - NREL
  - PNNL
- **Forecourt Compression/Storage**
  - AC Transit
  - Fuel Cell Energy
  - NASA
  - ORNL
- **H_2 Liquefaction & Delivery**
  - Gas Equipment Engineering Corporation
  - Linde Corporation
  - LLNL
  - Praxair
  - Promethius Energy
- **Pipeline & Pipeline Compression**
  - ANL
  - Concepts NREC
  - DOT
  - I^2CNER
  - MITI
  - NASA
  - NIST
  - ORNL
  - Secat
  - SNL
  - SRNL
  - University of Illinois
- **Carriers**
  - Air Products
  - PNNL
- **Sub-program Review**
  - BP
  - Chevron
  - Exxon-Mobil