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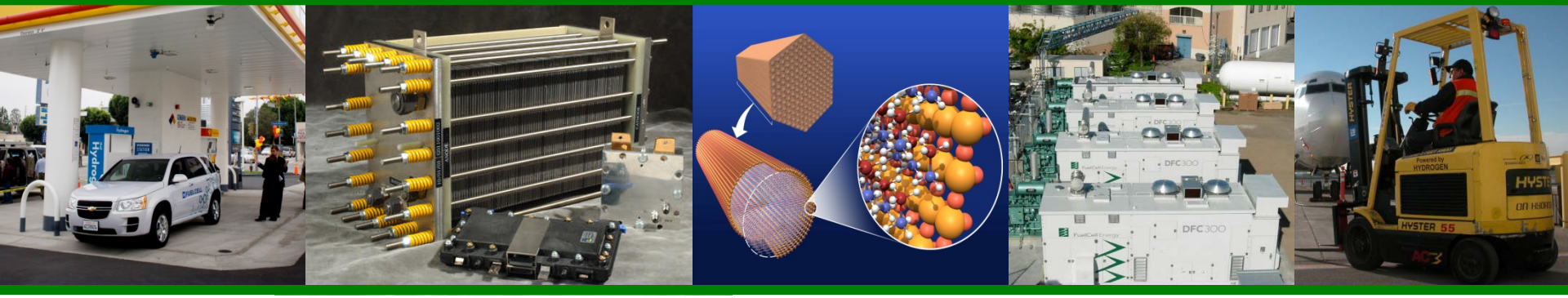

Hydrogen Delivery
- Session Introduction -

Scott Weil

2012 Annual Merit Review and Peer Evaluation Meeting

May 17, 2012

Delivery Sub-Program Goal

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- Improve fuel cell electric vehicle competitiveness by reducing the cost of producing, delivering, and dispensing H_2 to below a threshold of \$2-\$4/kg H_2 by 2020
- Delivery sub-program target: reduce the "Delivery" portion of this cost to \$1 – 2/kg by 2020

Tube trailer gas transport

Liquid transport

Pipeline transmission

Technology Targets & Status

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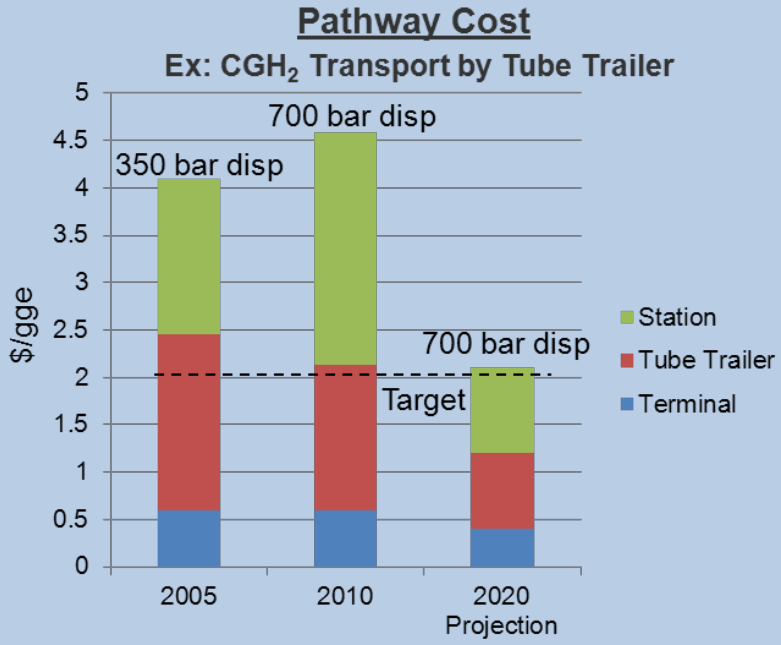
Delivery Element	2011 Status*	Goal (2015 Targets)**
Tube trailers	• Capital cost: $930/kg of H_2 transported (180 bar steel vessels) • Capacity: ~300kg (180 bar steel vessels)	• Reduce capital cost 22% to < $730/kg of H_2 transported • Increase capacity >1.3x to 700kg
Large Scale Liquefaction	• Installed capital cost: $190M • Process energy required: >8kWh/kg of H_2	• Reduce installed capital cost 21% to $150M • Reduce process energy required 12% to 7kWh/kg of H_2
Pipeline technology	• Installed steel pipeline cost: $765K/mi on average	• Reduce cost/mile (installed 8" equivalent diameter, excluding ROW) 4% to <$735K/mi
Forecourt compression (1000 kg/day station)	• Capital cost: $450K for two 860 bar compressors (each rated at 50% of peak flow)	• Reduce installed capital cost 11% to $400K for two 860 bar compressors (each rated at 50% of peak flow)
Forecourt storage (1000 kg/day station)	• Storage tank cost: $1000/kg H_2, $1100/kg H_2, and $1450/kg H_2 respectively for 160, 430, and 860 bar storage.	• Reduce tank cost/kg H_2 stored by 14-18% to $850, $900, and $1200/kg H_2 for low, moderate, and high pressure storage (160, 430, and 850 bar respectively).

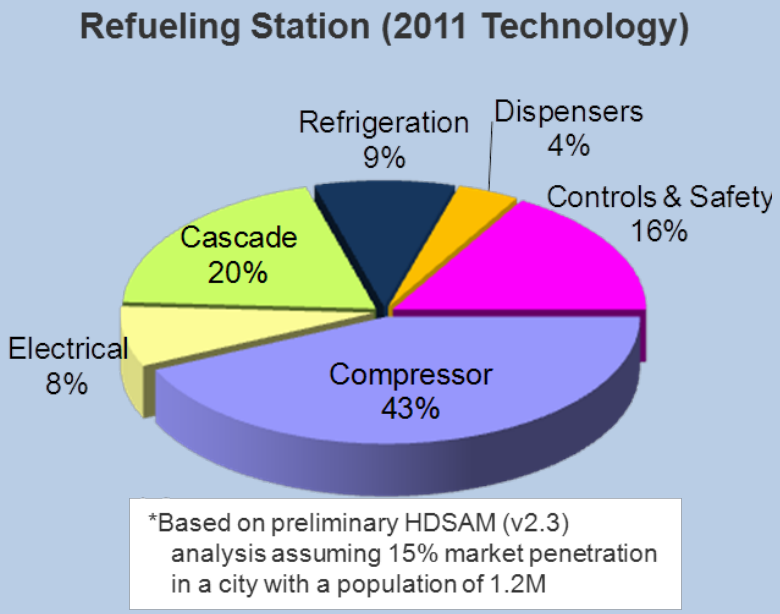
* High volume projections based on the latest data employed in HDSAM (v. 2.3) – in final review.

** Based on the new DOE-FCTP MYRD&D technical targets for Delivery – in final review.

Challenges/Barriers

- **Early market scenario: Tube trailers & Forecourt technology:**
  - Shift in emphasis to near-term H_2 infrastructure needs
  - ***Cost, reliability, and efficiency of station compressors***
  - Possible trade-offs between delivered pressure and forecourt compression (cost)
  - Tube trailer vessel capacity
  - Regulatory issues with transportation of high-pressure transport vessels





Challenges/Barriers

Early/mid-term market scenarios: Liquid H_2 delivery & Forecourt technology

- Energy efficiency of liquefaction: emissions under current US grid sources
- Transfer boil off
- Capital cost

- **Long-term market scenario: Pipelines**
  - Managing embrittlement (steel pipelines) to reduce lifetime cost
  - Capital, installation, and right-of-way costs
  - Hydrogen quality
  - Bulk storage (geologic)

- **Cross-cutting issues:**
  - Fuel cost vs. purity standards
  - Vehicle range vs. storage pressure & its impact on delivery cost
  - Production pressure vs. station compression needs
  - Impact of code requirements on transport and station costs

Delivery Sub-Program Budget

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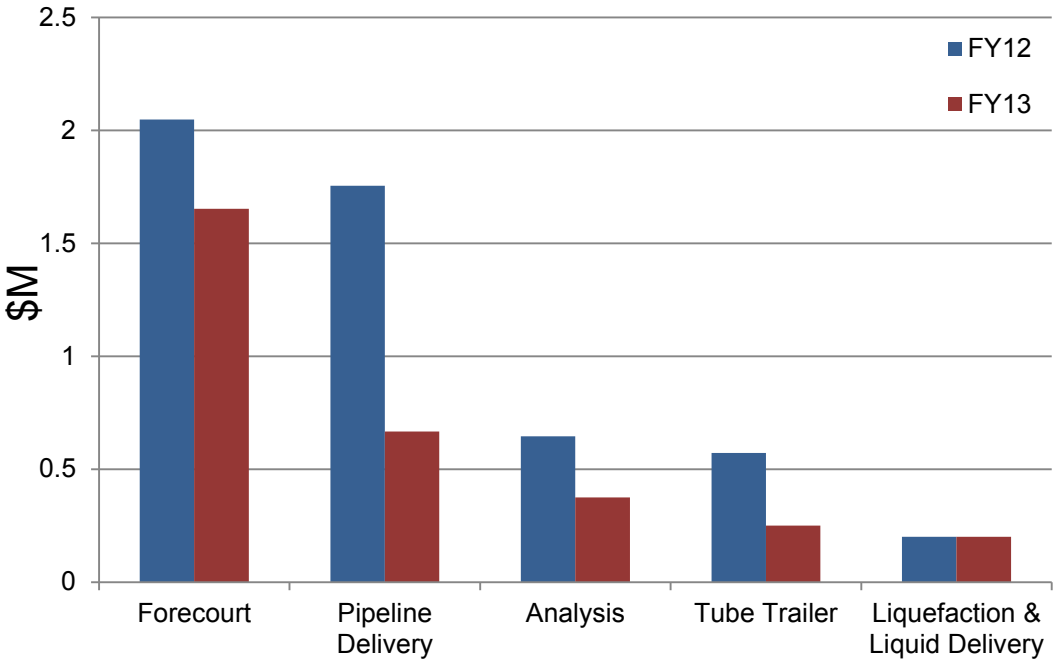
FY 2012 Appropriation = $5.2M

FY 2013 Request = $2.9M



EMPHASIS

- **Pathway cost analyses**
  - Cost reduction options for near- and mid-term infrastructure development timeframes
- **Reduce forecourt cost**
  - Improved compressor durability
  - Reduced storage cost
  - Reduction in station compression needs
- **Reduce tube trailer gas delivery cost**
  - Maximize transport capacity at constant or reduced $/kg of H_2 transported
- **Increase the efficiency of H_2 liquefaction**
  - High efficiency magnetic cooling
- **Reduce pipeline delivery cost**
  - Centrifugal pipeline compressors – reduced system cost and improved reliability
  - Fiber reinforced polymer pipeline – reduced installation cost

Analysis

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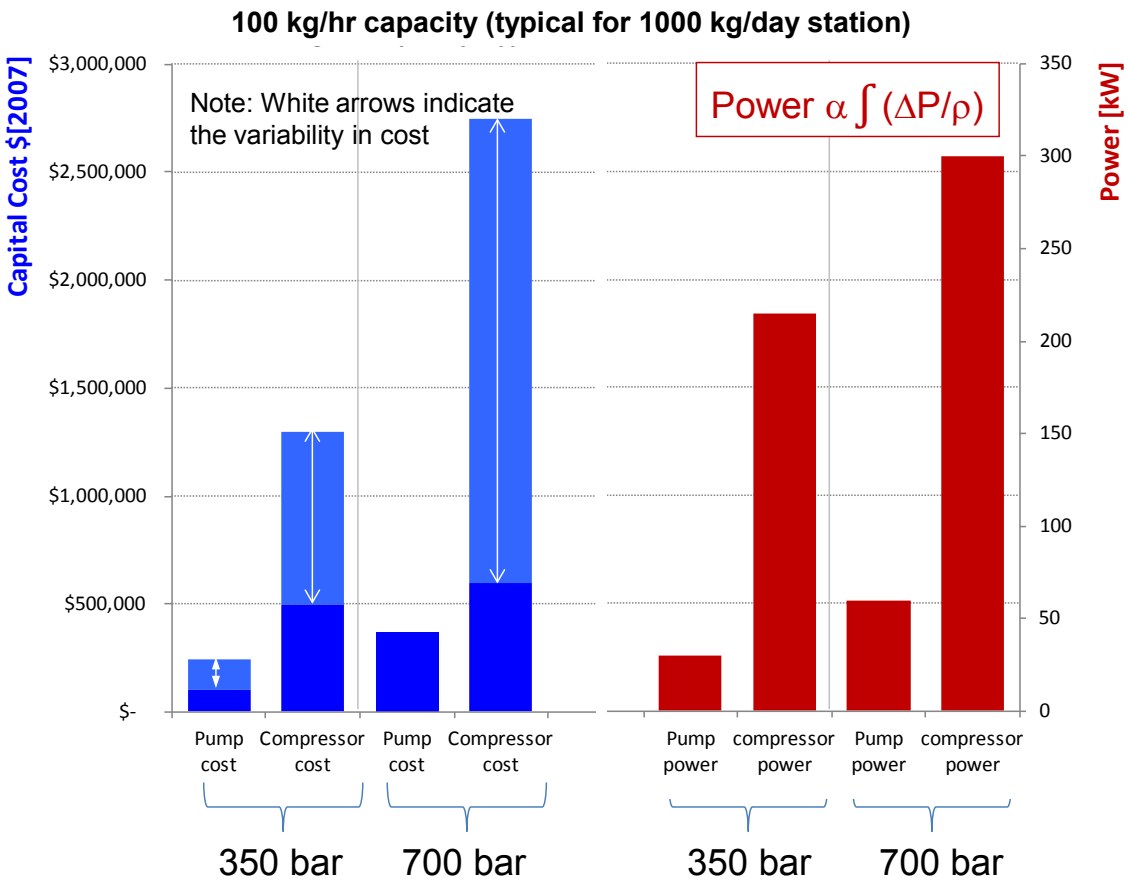
Challenge: *Identify key cost factors in various Delivery pathways & evaluate options to reduce cost over various market scenarios*

Progress: *(1) New HDSAM version (v2.3) is complete & on-line and (2) evaluating potential benefits of moving compression upstream*



PIs: ANL, PNNL, NREL, consultant

- **Issues with compressors:**
  - High capital cost per unit of throughput
  - Underutilization of capital in early markets
  - High power demand (electrical upgrades)
  - Limited fill rate without significant cooling
- **Potential solution: Move capital upstream of the refueling station:**
  - Better utilization (multiple markets)
  - Economies of scale
  - Risk is distributed between different market segments/applications

Forecourt Technology

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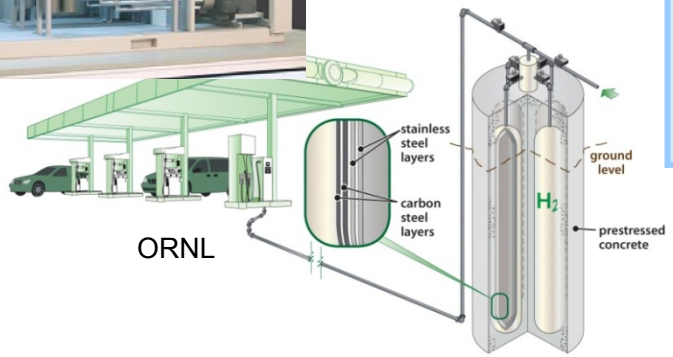
Challenge: *High refueling station costs may impede commercial investment in early motive markets (MHE and FCVs)*

Progress: *(1) Projected reduction in station storage costs of 11% (61% to 2015 targets) and (2) evaluating more durable approaches to compression*

Past Year's Accomplishments

- ORNL initiated a series of design trade studies and preliminary cost estimates of their steel-lined reinforced concrete station vessel concept
- FuelCell Energy (FCE) validated 2-stage electrochemical compressor (EHC) hardware feasibility at 7,000 psi level and increased H_2 flux 40% above their Gen 1 design

Linde



ORNL

Recent Accomplishments

- ORNL – completed engineering calculations, manufacturing process flow, and cost assessment for composite vessel design options
- NREL developed a test protocol for real-time monitoring of power use (on-going) in Linde's new ionic compressor at AC Transit Emeryville station
- FCE achieved 12,000 psi (820 bar) in a single stage EHC unit (800:1 compression ratio)

Future Work

- Optimize vessel designs for cost reduction and verify code compliance via structural analysis
- Reduce EHC stack part count by 30% and validate baseline stack performance (5 cells)

PIs: ORNL, FuelCell Energy, NREL

Tube Trailer Delivery

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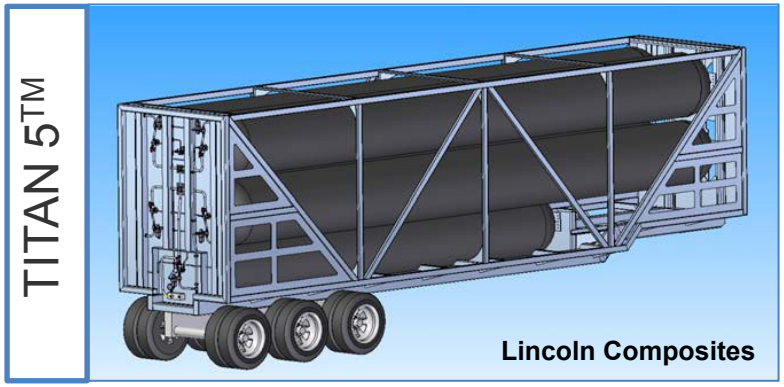
Challenges: *Reduce tube trailer delivery cost by 13 and 32% respectively to meet the 2015 and 2020 cost targets for tube trailer delivery*

Progress: *New design meets 2015 capacity target at a projected cost of $750/kg of H_2 transported (80% to 2015 target)*

Past Year's 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



Recent Accomplishments

- Received DOT special permit approval for Titan™
- Designed and delivered a trailer capable of holding 5 large cylinders
  - 18% increase in volume capacity compared to 4 cylinder module
- Developed a fault tree map for fiber composite pressure vessels

Future Work

- Qualify TITAN 5™ system components for CHG:
  - Fire protection components
  - Valves and manifolds
- Draft a detailed report on the status and future viability of the cold gas transport option

PIs: Lincoln Composites and LLNL

H_2 Liquefaction

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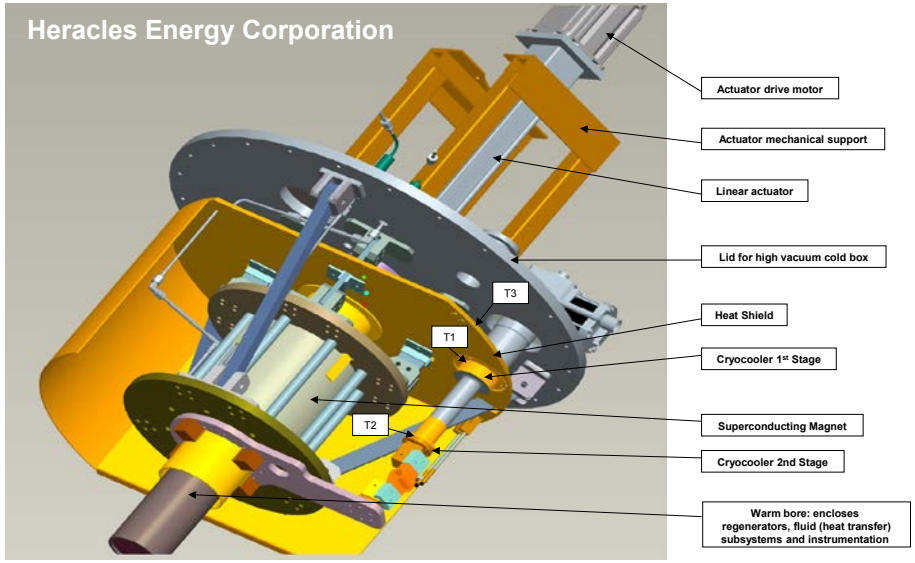
Challenges: *Increased liquefaction efficiency*

Progress: *Phase 1 demonstration of a system with the potential to reduce energy consumption by 32% (meets 2020 target)*

Past Year's Accomplishments

- Improved ortho-para conversion performance with a catalyst – reduces total power required for liquefaction by 2.4%
- Fabricated a continuous catalytic heat exchanger for testing – projected to improve performance
- Fabricated all sub-systems for a prototype active magnetic regenerative refrigerator (AMRR)



Recent Accomplishments

- Passed Phase 1 objectives for magnetic liquefaction prototype
  - Integrated all sub-systems into a working prototype AMRR device
  - Achieved <240K with the prototype AMRR

Future Work

- Phase 2 – demonstrate cooling down to 120K, incorporating a bypass flow modification to the system

PI: Heracles Energy Corp.

Pipeline Delivery – Challenges/Progress

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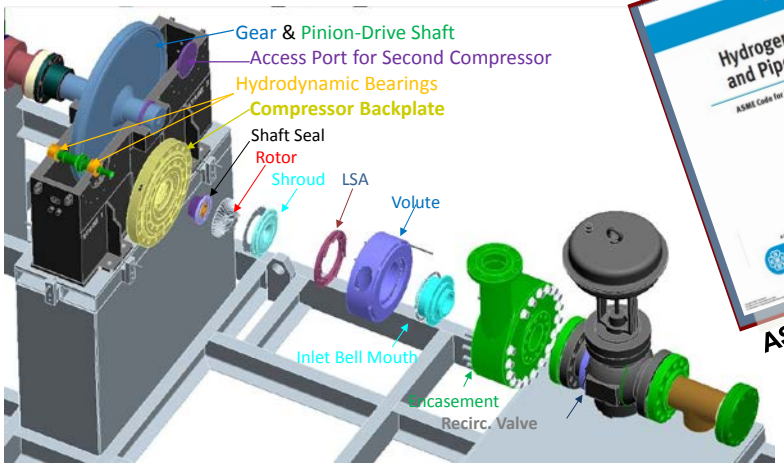
Challenges: *H_2 embrittlement of pipeline steel & the cost of pipeline infrastructure and large-scale gas compression are significant economic barriers*

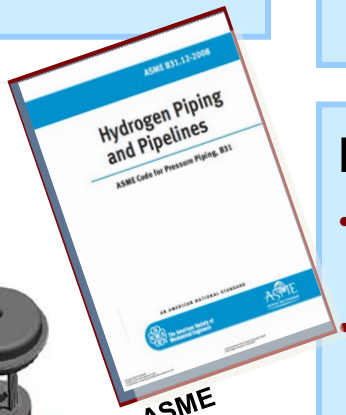
Progress: *FRP pipeline codification process started (FRP meets 2015 cost target) and compressor CapEx reduction of 20% (67% to 2020 target)*

Past Year's 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
- Completed detailed design and thermomechanical analyses of two prototype centrifugal compressor concepts



Concepts NREC



ASME

Recent Accomplishments

- Established protocols with codes committees to develop performance qualification test methodology for FRP pipeline
- Observed that >10ppm O_2 retards fatigue crack growth in pipeline steel exposed to H_2
- Fabricated key components for two single-stage centrifugal compressors units that will undergo operational testing

Future Work

- Perform full life fatigue and stress rupture testing for FRP piping.
- Expand pipeline steel testing beyond X52 to higher-strength steels, such as X70 and X80
- Finish compressor prototype builds and carry out system shakedown tests

PIs: SNL, ORNL, SRNL, Concepts NREC, MITI

Summary

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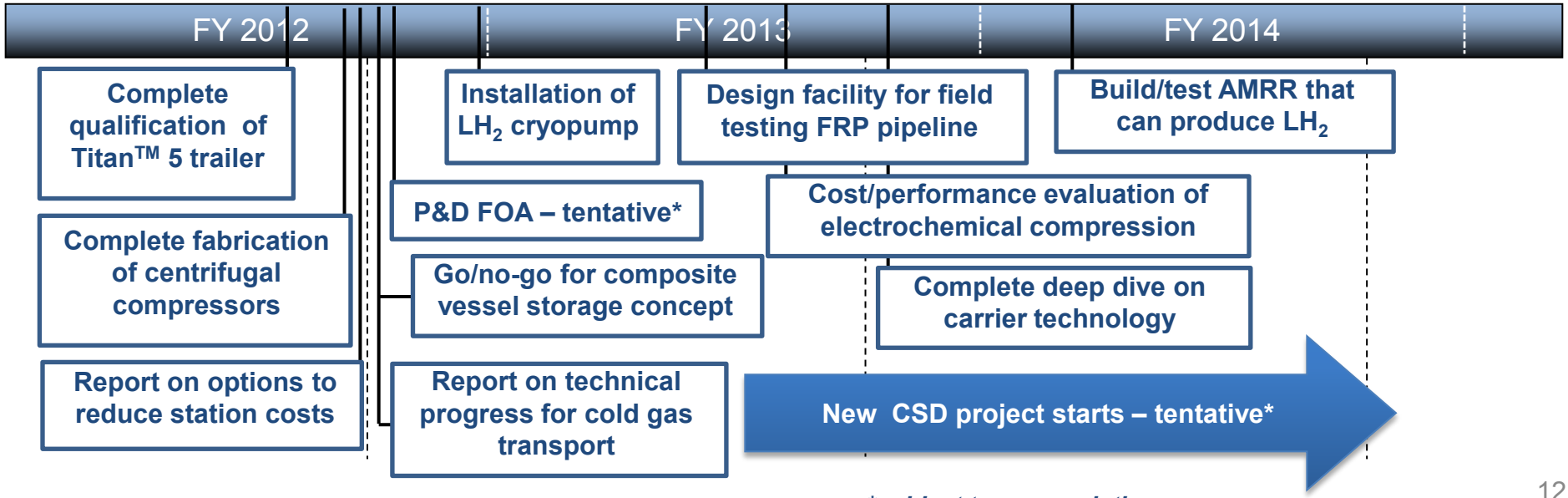
Major milestones & Future Solicitations

- Published update version of HDSAM (v 2.3), completed new sub-program targets, and initiated early market optimization analysis
- Met 2015 target for tube trailer vessel capacity
- Single stage prototype centrifugal compressor systems being fabricated for testing
- Passed phase 1 objectives for magnetic liquefaction prototype
- Established protocols with codes committees to develop performance qualification test methodology for FRP pipeline
- *Identify technologies and optimized delivery pathway options that meet an as-dispensed H_2 cost of <$4/gge*
- *Complete technical and economic characterization and analysis of novel compression options that have the potential to reduce current refueling station costs by a minimum of 15%.*



**subject to appropriations*

Session Instructions

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- This is a review, not a conference.
- Presentations will begin precisely at 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 and other portable devices.
- Photography and audio and video recording are not permitted.

Reviewer Reminders

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- Deadline to submit your reviews is **May 25th at 5:00 pm EDT.**
- ORISE personnel are available on-site for assistance.
  - **Reviewer Lab Hours:** Tuesday – Thursday, 7:30 am – 8:30 pm; Friday 7:30 am – 1:00 pm.
  - **Reviewer Lab Locations:**
    - Crystal Gateway Hotel—*Rosslyn Room* (downstairs, on Lobby level)
    - Crystal City Hotel—*Roosevelt Boardroom* (next to Salon A)
- Reviewers are invited to a brief feedback session – at 5:15 pm today, in this room.

For More Information

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H_2 Delivery Sub-Program

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Participating Organizations/Collaborators

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- **Analysis**
  - ANL
  - NREL
  - PNNL
  - Consultants
- **Forecourt Compression/Storage**
  - NREL/Linde/AC Transit
  - Fuel Cell Energy
  - ORNL
- **H_2 Liquefaction & Liquid Delivery**
  - Linde Corporation
  - LLNL
  - Prometheus Energy
- **Tube Trailer Delivery**
  - Lincoln Composites
  - LLNL
- **Pipelines & Pipeline Compression**
  - Concepts NREC
  - U.S. Department of Transportation
  - I^2CNER
  - MITI
  - NASA
  - NIST
  - ORNL
  - SNL
  - SRNL
- **Sub-program Review**
  - BP
  - Chevron
  - ConocoPhillips
  - U.S. Department of Transportation
  - ExxonMobil
  - Praxair
  - Shell