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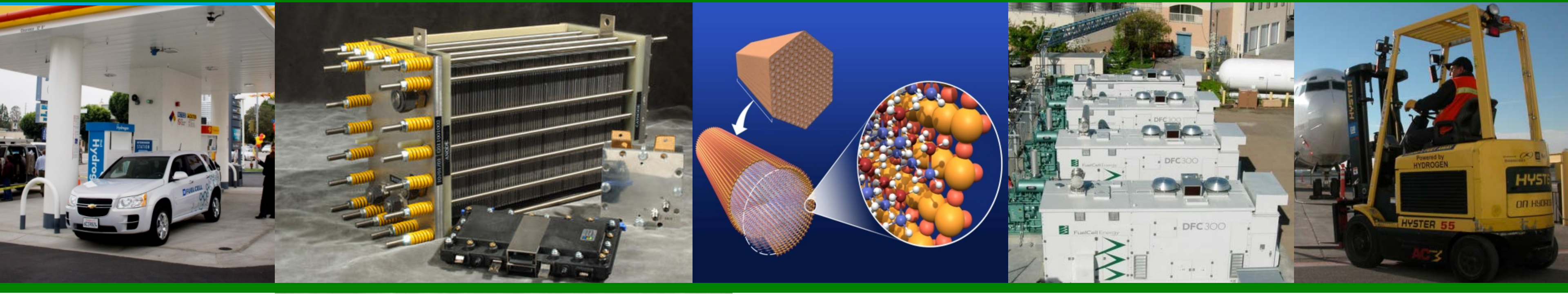


Hydrogen Delivery

- Session Introduction -

Erika Sutherland

2013 Annual Merit Review and Peer Evaluation Meeting

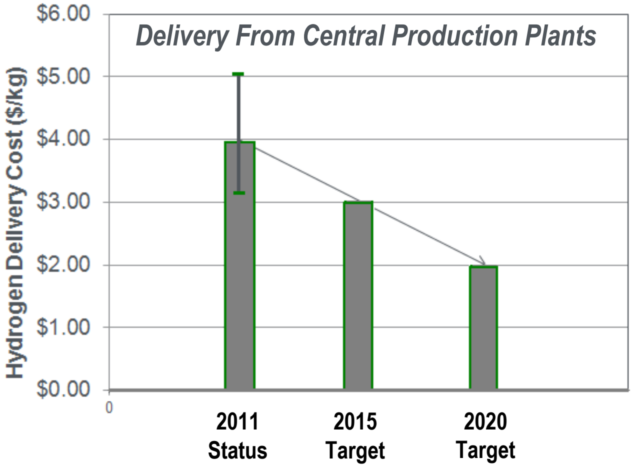
May 15, 2013

Delivery Goals and Objectives

GOAL: Improve fuel cell electric vehicle competitiveness by reducing the cost of delivering, and dispensing H_2 to below a threshold of \$1-\$2/kg H_2 by 2020.

Objectives

- ***Reduce the cost of transport and distribution of hydrogen from central production plants to <\$1.40/gge by 2015 and <\$1.30/gge by 2020.***
- ***Reduce the cost of compression, storage and dispensing (CSD) of hydrogen from central production plants at the forecourt to <\$1.60/gge by 2015 and <\$0.70/gge by 2020.***
- ***Reduce the CSD cost of hydrogen produced through distributed production to <\$2.15/gge and <\$1.70/gge by 2020.***



Technology Targets & Status

Delivery Element	2012 Status*	Goal (2015 Targets)**
Tube trailers	• Capital cost: \$740/kg of H_2 transported (250 bar composite vessels) • Capacity: 720kg (250 bar composite vessels)	• Reduce capital cost to < \$730/kg of H_2 transported ✓ Increase capacity to 700kg
Large Scale Liquefaction	• Installed capital cost: \$186M • Process energy required: >8kWh/kg of H_2	• Reduce installed capital cost 20% 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: \$675K for three 860 bar compressors (each rated at 50% of peak flow)	• Reduce installed capital cost 11% to \$400K for two 860 bar compressors and improve reliability to eliminate the back up. (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. 2.32) .

** Based on the new DOE-FCTP 2012 MYRD&D technical targets for Delivery

Delivery Challenges

Compressor reliability and high capacity delivery methods are key challenges in both the near and longer term.

Near-term

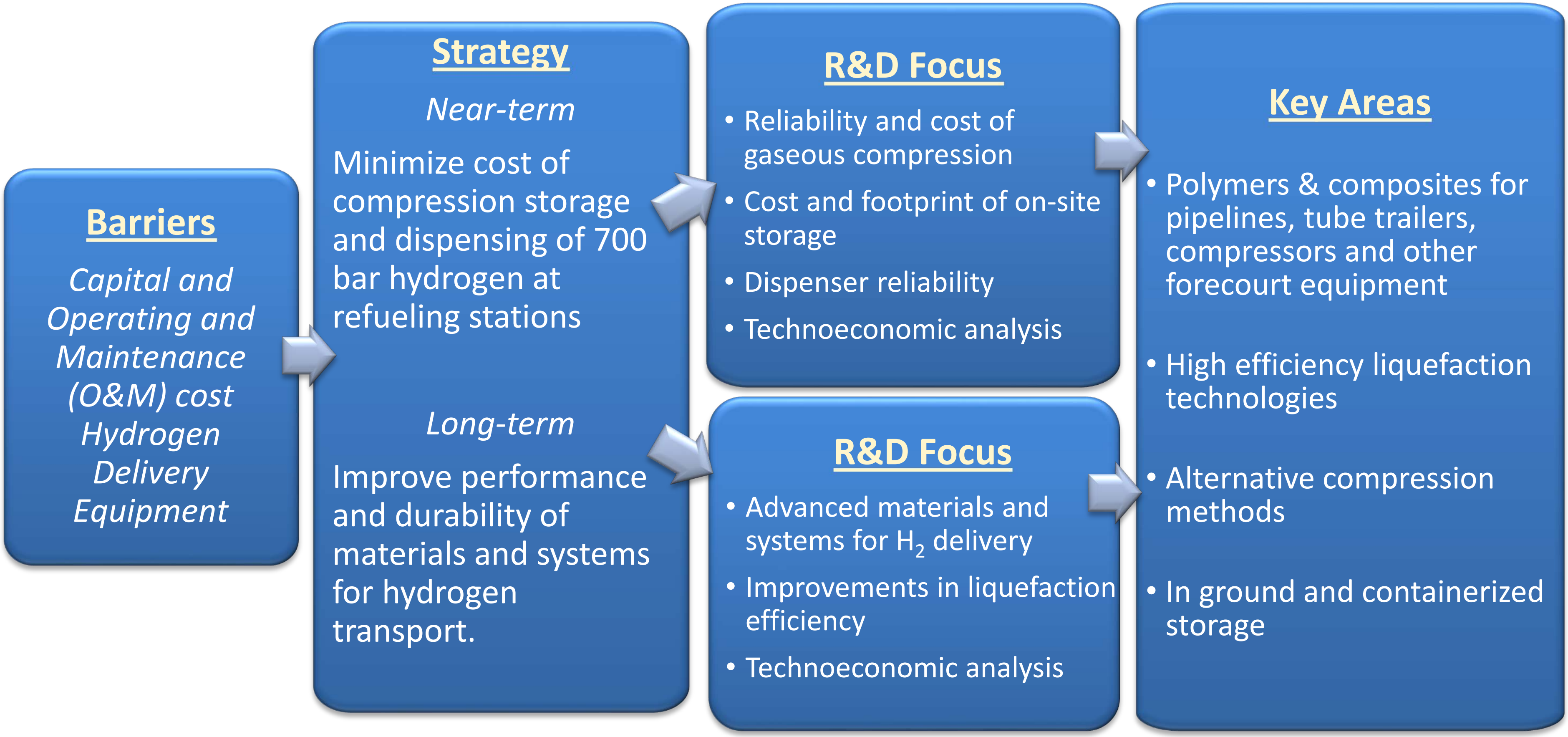
- *Forecourt compressor cost, reliability & efficiency*
- *Dispenser cost and reliability*
- *Tube trailer delivery capacity and cost*
- *Forecourt storage footprint and cost*
- *Liquefaction cost and efficiency*

Longer-term

- *Pipeline compressor cost, reliability & efficiency*
- *Pipeline cost and reliability*
- *Forecourt compressor throughput*
- *Low-cost high-capacity delivery methods*
- *High volume liquefaction cost and efficiency*

Delivery Strategy

Maximize pathway cost impact by focusing R&D efforts on lowering the cost of compression, storage and dispensing (CSD) at the forecourt



Barriers

Capital and Operating and Maintenance (O&M) cost Hydrogen Delivery Equipment

Strategy

Near-term

Minimize cost of compression storage and dispensing of 700 bar hydrogen at refueling stations

Long-term

Improve performance and durability of materials and systems for hydrogen transport.

R&D Focus

- Reliability and cost of gaseous compression
- Cost and footprint of on-site storage
- Dispenser reliability
- Technoeconomic analysis

R&D Focus

- Advanced materials and systems for H_2 delivery
- Improvements in liquefaction efficiency
- Technoeconomic analysis

Key Areas

- Polymers & composites for pipelines, tube trailers, compressors and other forecourt equipment
- High efficiency liquefaction technologies
- Alternative compression methods
- In ground and containerized storage

H_2 Delivery MYRD&D chapters available at: *http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html*

Delivery Strategy

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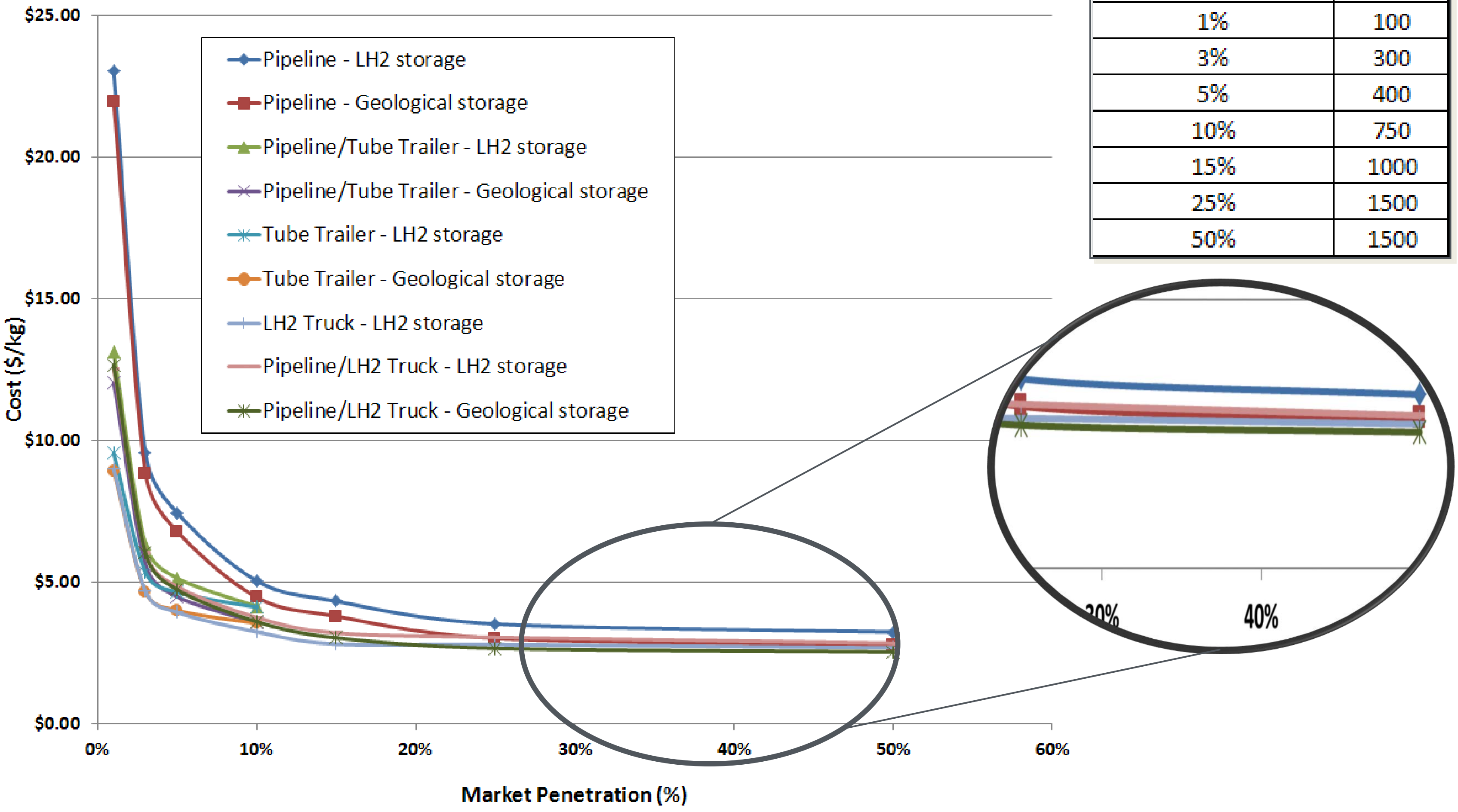
Pipeline delivery pathways become economically viable at high market penetrations

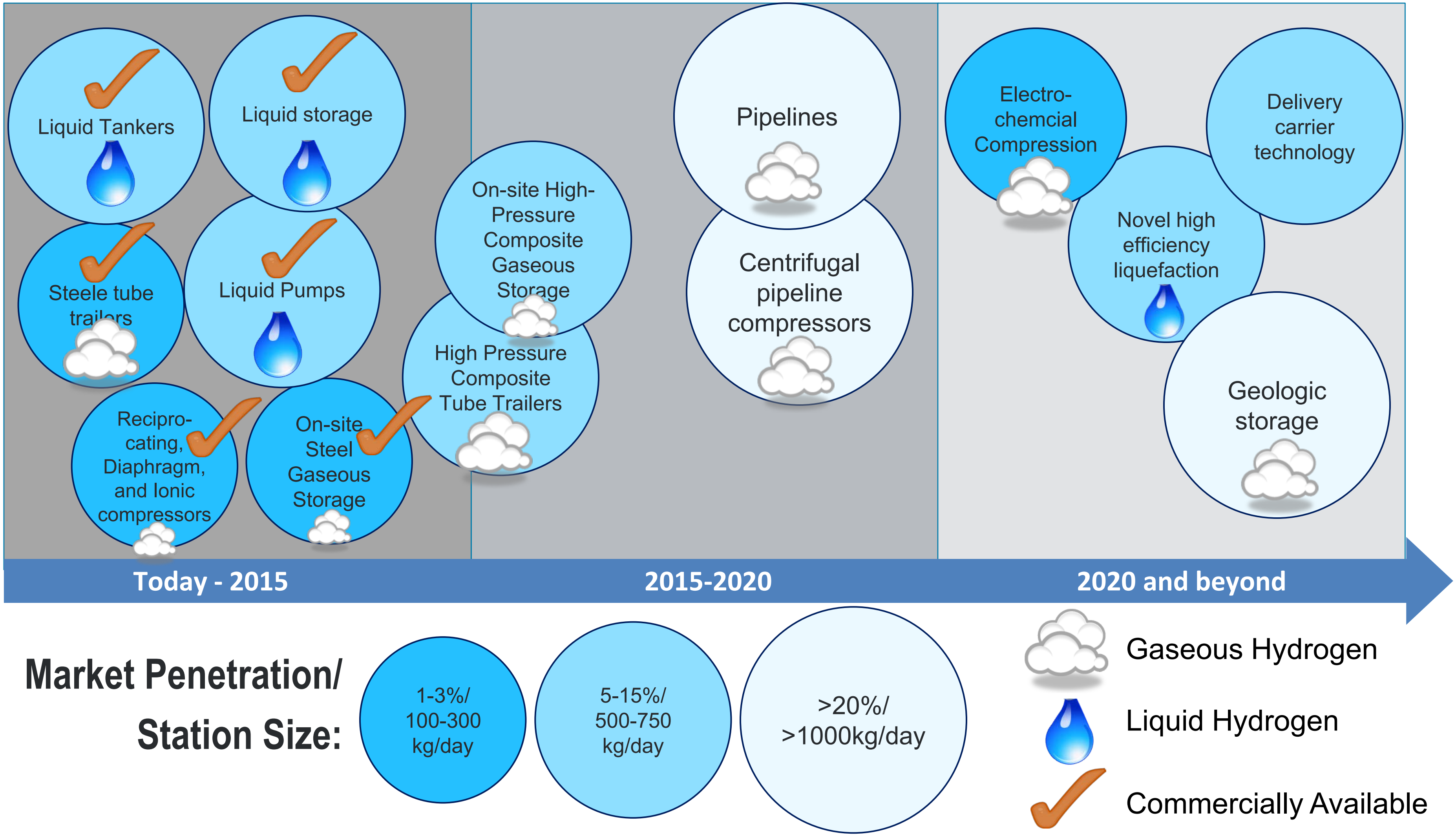
HDSAM V.2.32 (2007$ update):

Market Penetration (%)	kg/day
1%	100
3%	300
5%	400
10%	750
15%	1000
25%	1500
50%	1500



Delivery Technologies

Timeframes and Market Size Served



Today - 2015

- Liquid Tankers ✓ 💧
- Liquid storage ✓ 💧
- Steele tube trailers ✓ ☁
- Liquid Pumps ✓ 💧
- Recipro-cating, Diaphragm, and Ionic compressors ✓ ☁
- On-site Steel Gaseous Storage ✓ ☁

2015-2020

- On-site High-Pressure Composite Gaseous Storage ☁
- High Pressure Composite Tube Trailers ☁
- Pipelines ☁
- Centrifugal pipeline compressors ☁

2020 and beyond

- Electro-chemcial Compression ☁
- Delivery carrier technology
- Novel high efficiency liquefaction 💧
- Geologic storage ☁

Market Penetration/ Station Size:

- 1-3%/ 100-300 kg/day
- 5-15%/ 500-750 kg/day
- >20%/ >1000kg/day

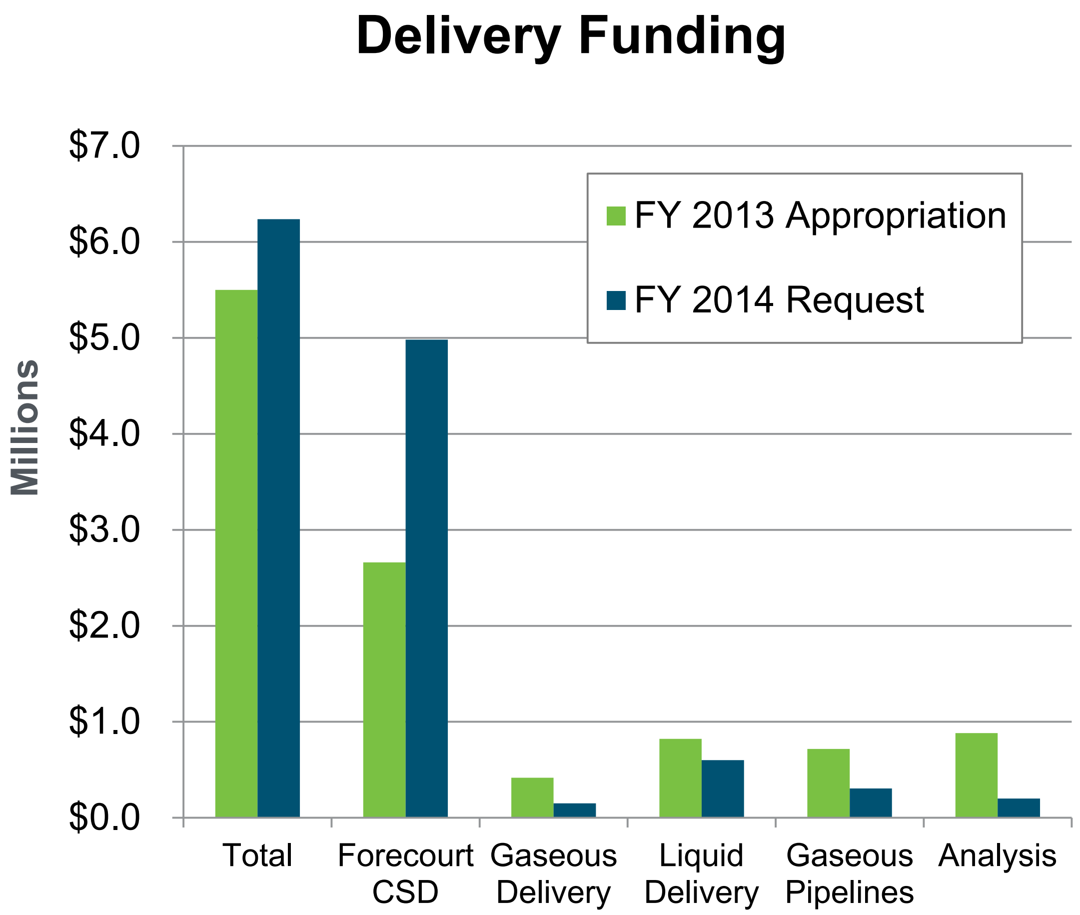
☁ Gaseous Hydrogen

💧 Liquid Hydrogen

✓ Commercially Available

Budget

FY 2013 Appropriation: $5.5M ***FY 2014 Request: $6.2M***



Funding based on anticipated new starts

2013/14 Emphasis

- Station Optimization Analysis

Distribution

- Continue to work on lowering the cost of near and long term distribution analysis.

Forecourt CSD

- Lower Cost by addressing compression cost and reliability
- Decrease station cost and footprint through low-cost high-pressure storage
- Use recommendations from the HTAC Hydrogen Production Expert Panel and CSD workshop outcomes in portfolio planning for future new starts.

2013 Progress

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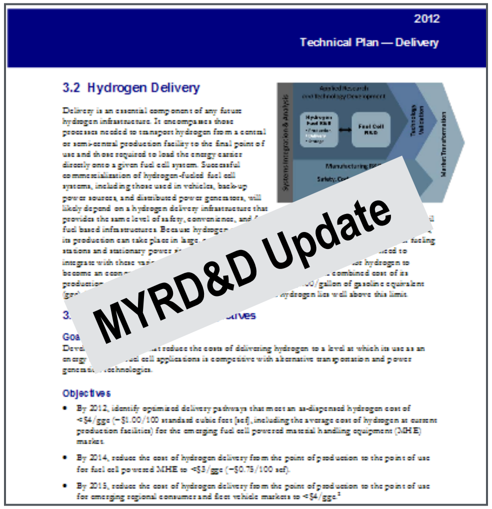

2012

Technical Plan — Delivery

3.2 Hydrogen Delivery

Objectives

MYRD&D Update

- Updated Delivery Multi-Year Research, Development and Demonstration Plan (MYRD&D) Updated Cost Reduction Waterfall Charts for all Pathways
- Successful workshop to summarize and report the key R&D needs to reduce the cost of forecourt CSD
- New SBIR project on 700 bar hydrogen dispenser hoses
- Strengthened international collaborations through joint planning of workshops, FOA plans, and IEA HIA Task 28 participation
- Independent Panel Review of Compression, Storage, and Dispensing (CSD) Costs
- Successful analysis, storage, and compression work to optimize design and lower the cost of CSD at the forecourt in both the near and longer term

2013 Progress: Analysis

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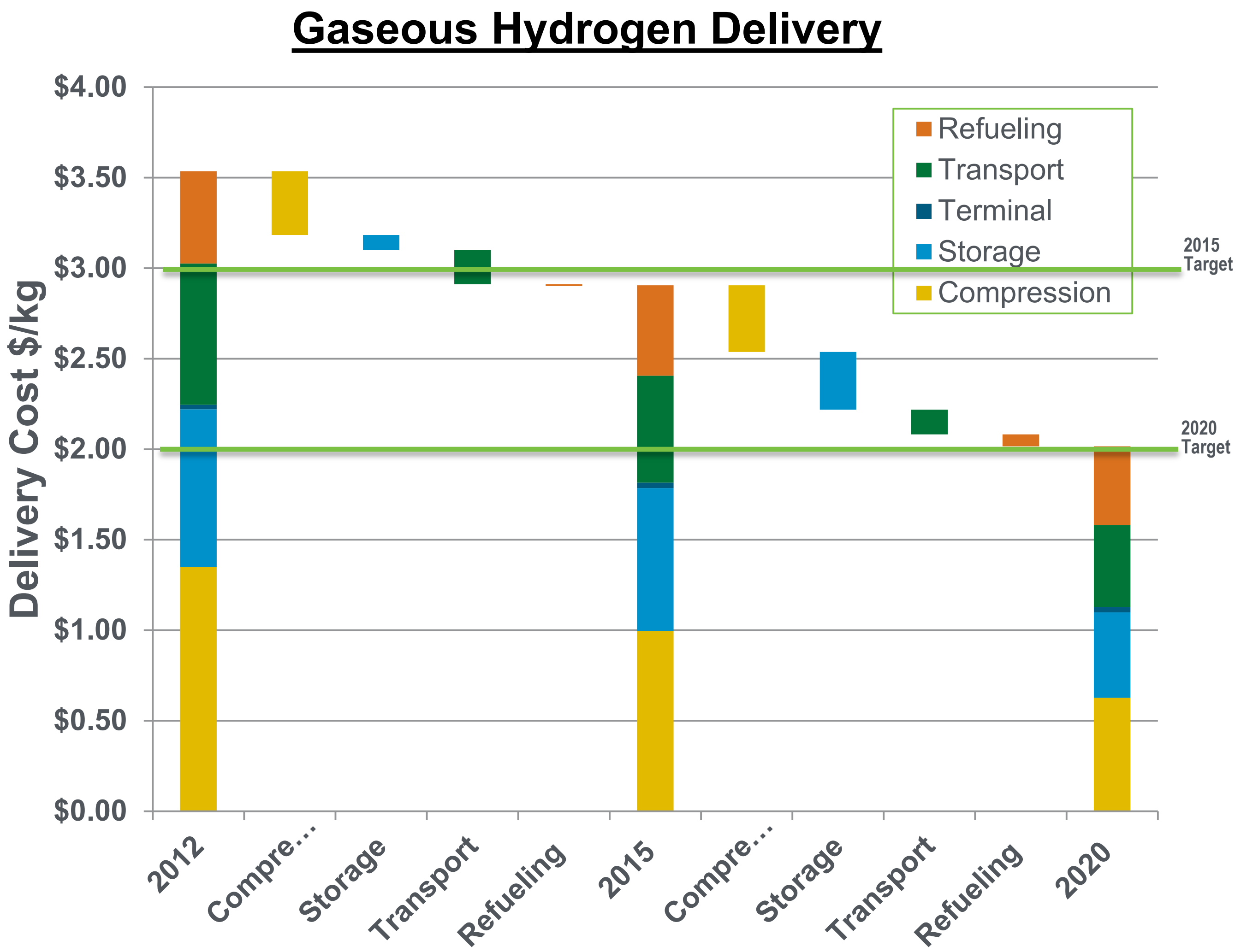
Updated waterfalls show that CSD cost reduction is a key activity to achieve the 2015 delivery target



HDSAM V2.32 (2007$) analysis using the following assumptions:

1.) City Size 1.5M

2.) 10% Market Penetration

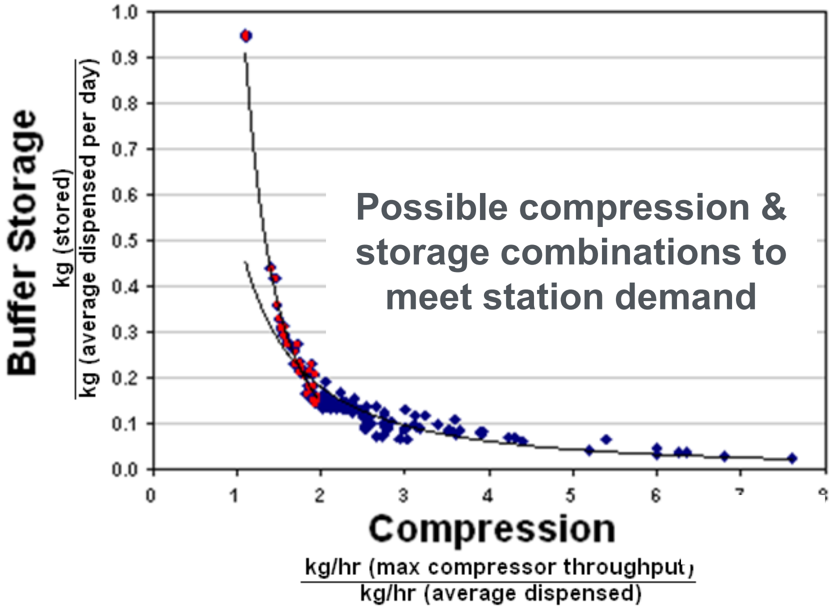
3.) 750 kg/day (743 gge/day) station size

4.) 700 bar fills from a cascade storage bank

5.) The hydrogen source is a central production facility located 62 miles from the city

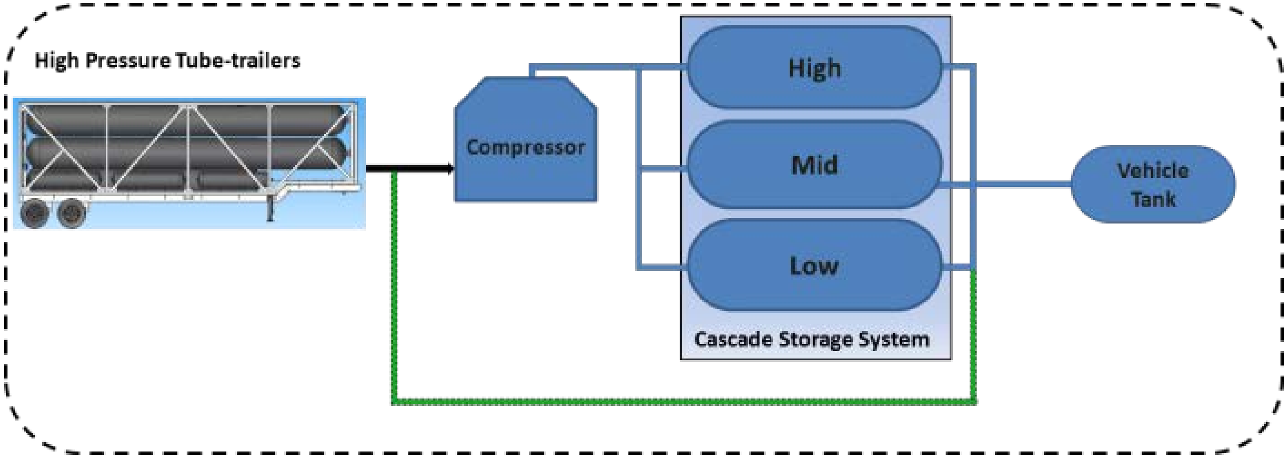
2013 Progress: Analysis

Optimized station design through use of high pressure tube trailers can reduce capital at the forecourt by ~40% (ANL)



Possible compression & storage combinations to meet station demand

Analysis efforts have show the potential to significantly reduce the cost of CSD at the forecourt by choosing the optimal compression ratio to storage capacity and by optimizing the number of cascade storage banks and utilization of high pressure tube trailers.



2013 Progress: Pipelines for H_2(g) Delivery

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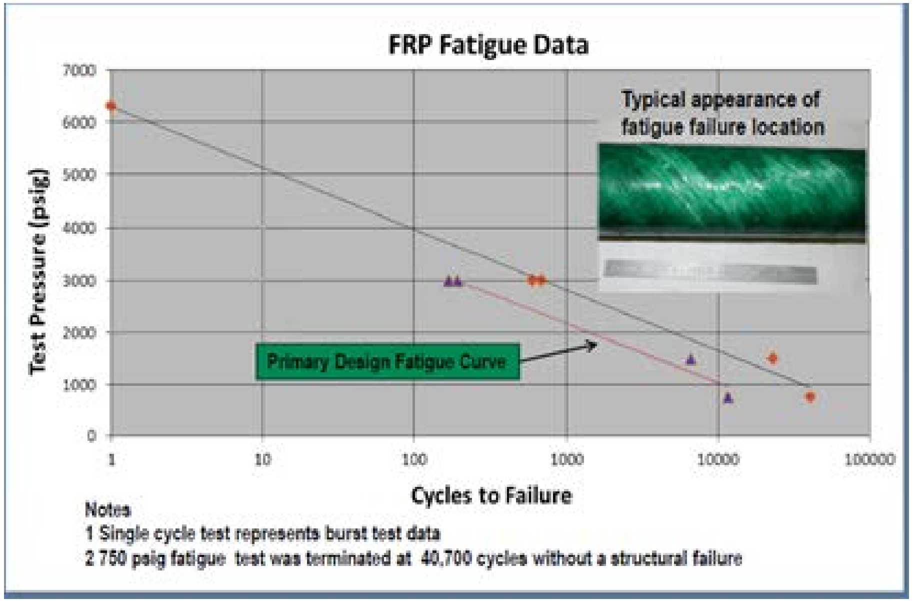
Steel and fiber reinforced polymer (FRP) pipeline work

FRP pipeline testing (SRNL)

Can reduce installation costs by 20 – 40%

- ✓ Fatigue testing completed over the range of 750 to 3000 psig
- ✓ Calculated FRP fatigue design curve from data
- ✓ Report submitted to ASME for inclusion in B31.12

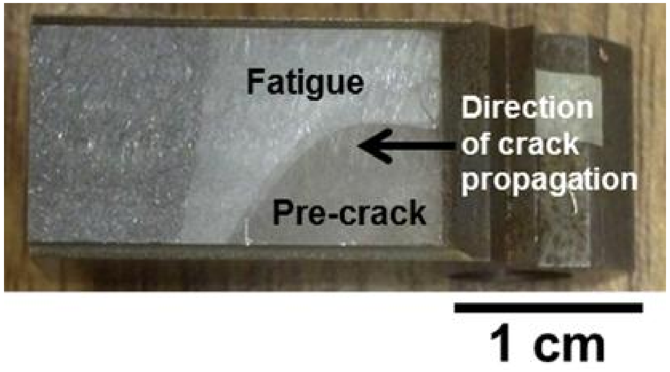


Notes
1 Single cycle test represents burst test data
2 750 psig fatigue test was terminated at 40,700 cycles without a structural failure

Hydrogen embrittlement of steel (SNL)

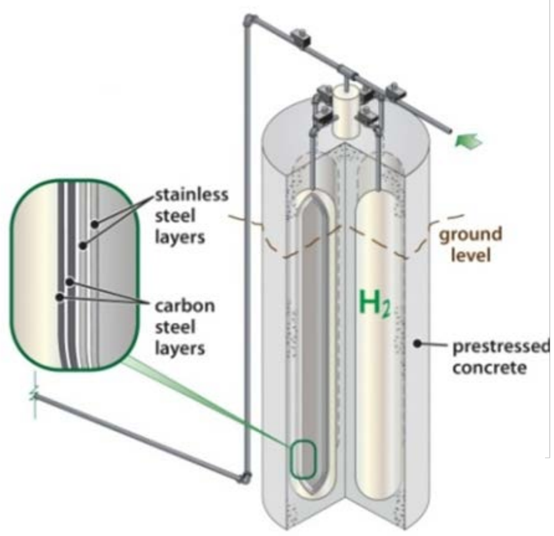
New models to predict hydrogen embrittlement in steel pipelines validated

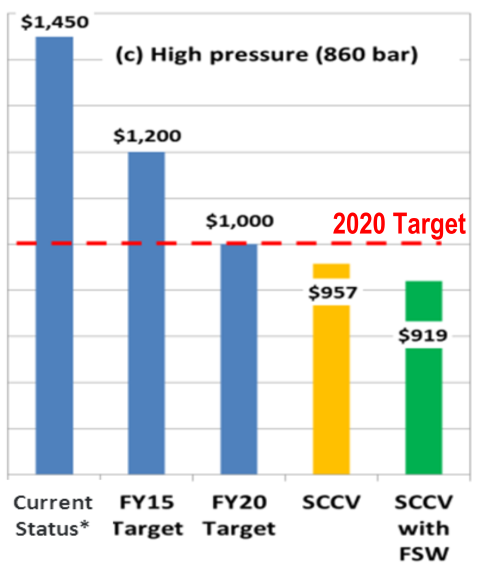
- ✓ Created and validated a model to quantify the effect of O_2 on H_2-accelerated fatigue crack growth
- ✓ Completed initial measurements of fatigue crack growth laws for pipeline steel girth weld in H_2 gas and found non-uniform crack fronts – additional testing to be performed



2013 Progress: Forecourt CSD – Near Term

Demonstrated that high pressure steel-concrete composite vessel (SCCV) for hydrogen storage can exceed the 2020 cost target (ORNL)





*Based on 2011 advances projected to high volume

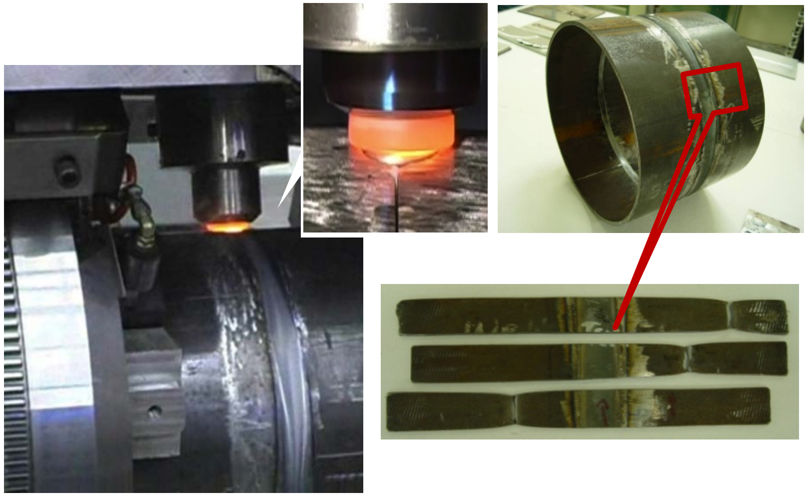
Quantified the benefits of multi pass friction stir welding (FSW)

FSW: automated welding process which reduces labor costs and does not require the use of consumables

- ✓ Superior joint strength shown through tensile sample testing
- ✓ Reduced cost by $38/kg through use of FSW

Design Completed – Prototype quoted

- ✓ Optimized design at a 50/50 split between steel and concrete
- ✓ Initiated hydrogen permeation testing of the multi-layer design
- ✓ Completed and published a report on the manufacture of the vessel



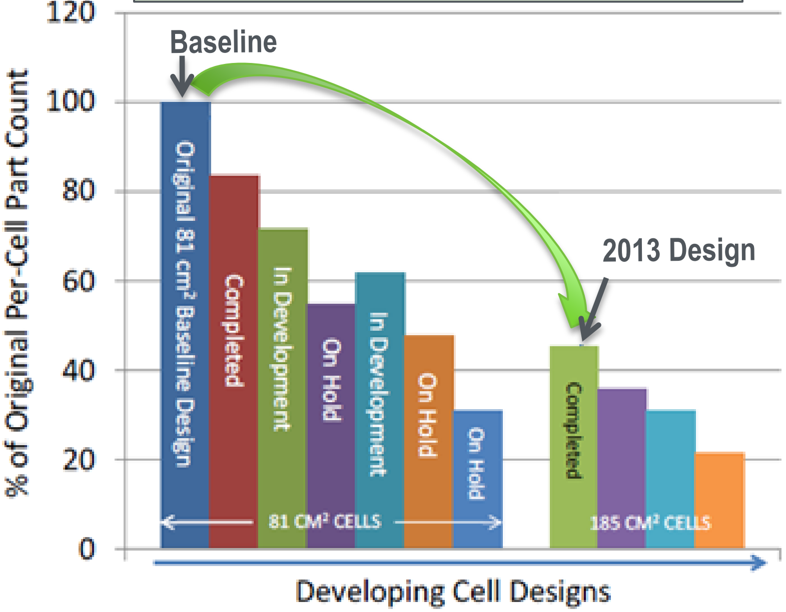
2013 Progress: Forecourt CSD – Long Term

Achieved a 50% reduction in the cost of electrochemical hydrogen compression (FCE)

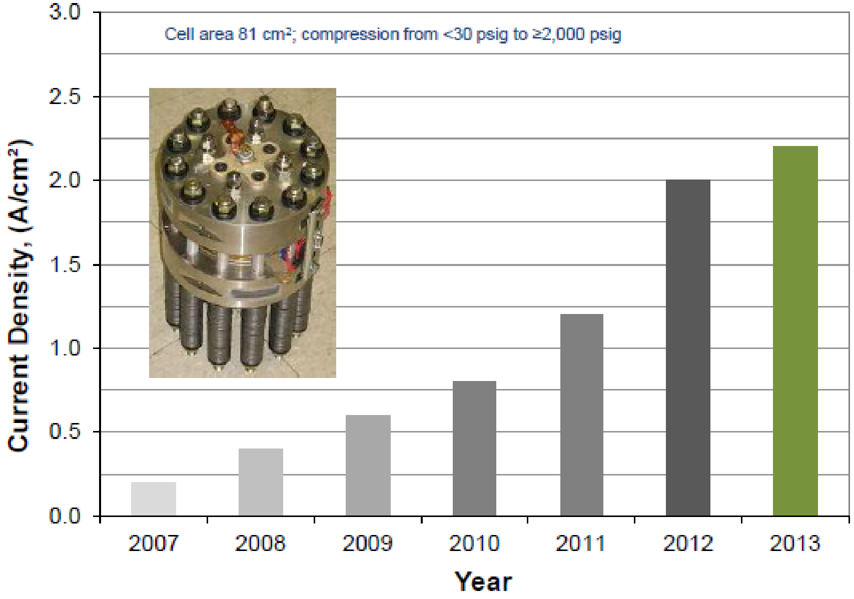
Electrochemical hydrogen compression has the potential to greatly increase reliability

- ✓ No moving parts, or oil as a source of contamination
- ✓ 50% decrease in single production unit cost achieved through lowering part count and increasing the current density and active area to increase the production rate while lowering the total cells per stack.

>50% decrease in parts count!



~10X increase in current density!



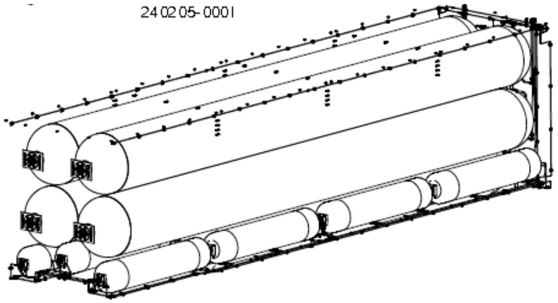
Highlights from Projects Completed in 2013

Hexagon Lincoln and Mohawk Innovative Technologies Inc.

Hexagon Lincoln

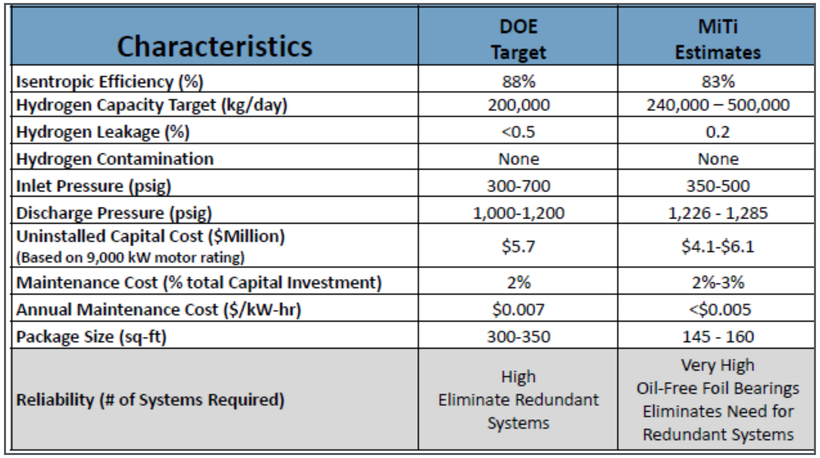
- ✓ Hexagon Lincoln's TITAN™ V Magnum Trailer System (originally designed for the 2010 targets) exceeds the DOE 2015 delivery capacity target
- ✓ 350 bar design shows promise toward the 2020 targets.

	250 Bar (Available)	350 bar (Designed)	DOE 2015 Target	DOE 2020 Target
Delivery Capacity (Kg)	720	907	700	940
Capital Cost ($/kg)	744	710	730	575



Mohawk Innovative Technologies Inc.

- ✓ Successful prototype testing of oil free centrifugal pipeline compressor technology for hydrogen pipelines



Characteristics	DOE Target	MiTi Estimates
Isentropic Efficiency (%)	88%	83%
Hydrogen Capacity Target (kg/day)	200,000	240,000 – 500,000
Hydrogen Leakage (%)	<0.5	0.2
Hydrogen Contamination	None	None
Inlet Pressure (psig)	300-700	350-500
Discharge Pressure (psig)	1,000-1,200	1,226 - 1,285
Uninstalled Capital Cost ($Million) (Based on 9,000 kW motor rating)	$5.7	$4.1-$6.1
Maintenance Cost (% total Capital Investment)	2%	2%-3%
Annual Maintenance Cost ($/kW-hr)	$0.007	<$0.005
Package Size (sq-ft)	300-350	145 - 160
Reliability (# of Systems Required)	High Eliminate Redundant Systems	Very High Oil-Free Foil Bearings Eliminates Need for Redundant Systems

Single Stage Compressor and Motor Drive

Forecourt CSD Workshop

Workshop results will inform future programmatic decisions

- The workshop brought together approximately 30 experts form Industry and public sector to discuss the challenges to reducing the cost of hydrogen infrastructure at the forecourt and identify RD&D areas to address those challenges identified.
- The workshop sessions were organized into three topic areas, Compression, Storage, and Other and the top issues and activities from each session have been captured with a full report to follow during the AMR.

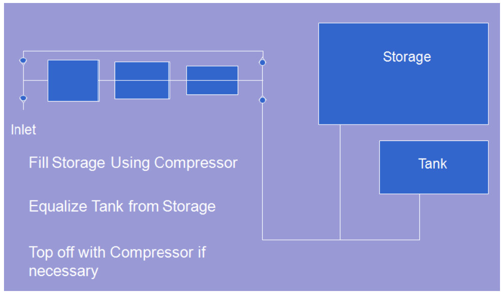
Key areas identified:

1.) Materials Research
- Dynamic seals
- Carbon fiber (cost and batch quality)
- Metallics

2.) Station Optimization Analysis
- Near, Mid and Long term markets
- Storage vs. Compression trade offs

3.) Metering, Quality & Performance Testing for Dispensing
- Meter accuracy
- Hydrogen quality measurement device
- Station dispensing test apparatus

4.) Data for codes and standards development
- Setback distances
- Tank cycle life



Storage

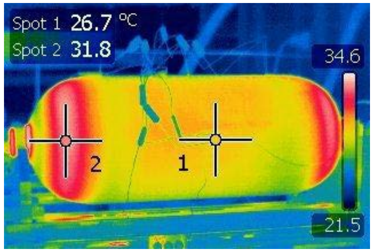
Inlet

Tank

Fill Storage Using Compressor

Equalize Tank from Storage

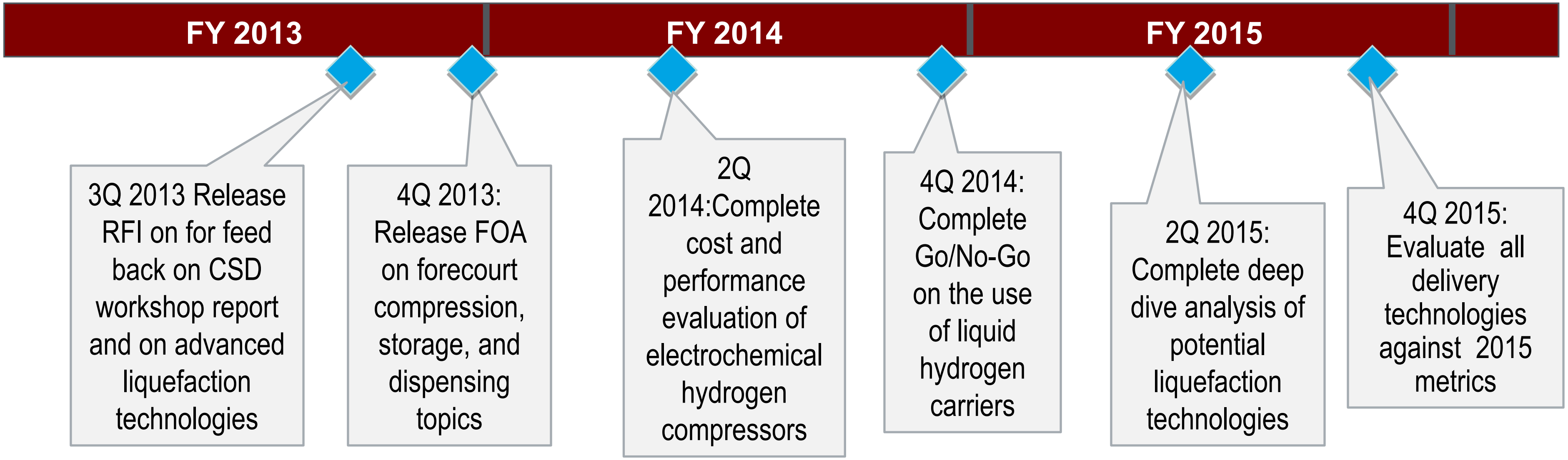
Top off with Compressor if necessary



Summary

Key milestones and future plans

- Published update MYRD&D Delivery Chapter
- Developed a forecourt delivery strategy to decrease forecourt capital cost by 40%
- Single stage prototype centrifugal compressor systems tested
- Established a fatigue design curve for FRP pipeline
- Lowered the cost of EHC by 50%
- Held a successful CSD workshop and released a report documenting the R&D needs
- Solicited and selected two SBIR topics on Hydrogen Dispensers



3Q 2013 Release RFI on for feed back on CSD workshop report and on advanced liquefaction technologies

4Q 2013: Release FOA on forecourt compression, storage, and dispensing topics

2Q 2014:Complete cost and performance evaluation of electrochemical hydrogen compressors

4Q 2014: Complete Go/No-Go on the use of liquid hydrogen carriers

2Q 2015: Complete deep dive analysis of potential liquefaction technologies

4Q 2015: Evaluate all delivery technologies against 2015 metrics

Participating Organizations/Collaborators

- **Analysis**
  - ANL
  - PNNL
- **Compression and Forecourt Technologies**
  - NREL
  - FuelCell Energy
  - LLNL
  - PNNL
  - ORNL
- **H_2 Liquid Delivery**
  - Linde Corporation
  - LLNL
  - Prometheus Energy
- **Tube Trailer Delivery**
  - Lincoln Composites
- **Pipelines & Pipeline Compression**
  - Concepts NREC
  - MITI
  - ORNL
  - SNL
  - SRNL
- **Sub-program Review**
  - BP
  - Chevron
  - Phillips 66
  - U.S. Department of Transportation
  - ExxonMobil
  - Praxair
  - Shell

For More Information:

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Angelo Cangialosi (Energetics, Inc.)

Session Instructions

- 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

- Deadline to submit your reviews is Friday, **May 24th at 5:00 pm EDT.**

- ORISE personnel are available on-site for assistance.
  - **Reviewer Lab Hours:**
    - Monday, 5:00 pm – 8:00 pm (Gateway ONLY)
    - Tuesday – Wednesday, 7:00 am – 8:00 pm (Gateway)
    - Thursday, 7:00 am – 6:00 pm (Gateway)
    - Tuesday – Thursday, 7:00 am – 6:00 pm (City)
  - **Reviewer Lab Locations:**
    - Crystal Gateway Hotel—*Rosslyn Room* (downstairs, on Lobby level)
    - Crystal City Hotel—*Roosevelt Boardroom* (next to Salon A)