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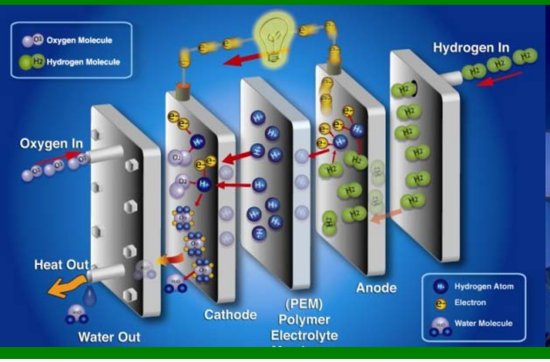
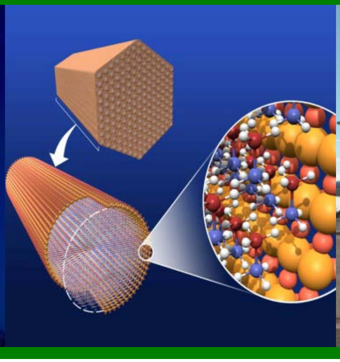




Hydrogen Delivery

Monterey Gardiner

2010 Annual Merit Review and Peer Evaluation Meeting
(8 June 2010)

Goal and Objectives

Goal: ***Develop technologies to deliver hydrogen at reduced cost.***

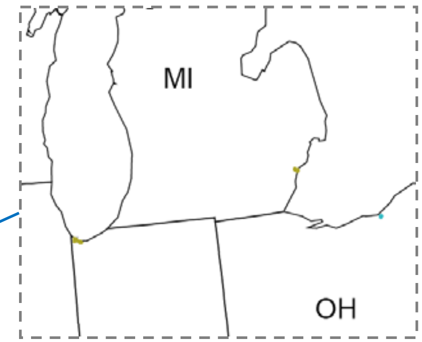
Current Target of $1/gge or ~kg under evaluation.

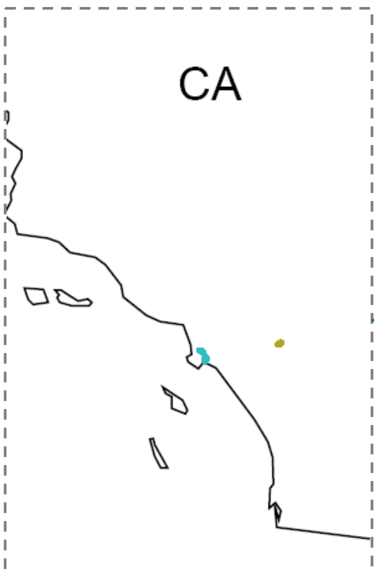
Near-term:

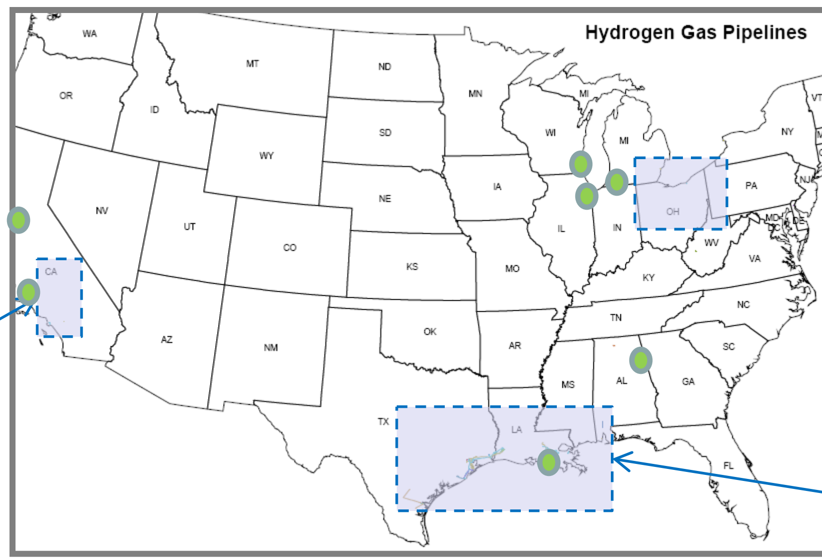
- ***Tanker trucks (liquid)***
- ***Tube Trailers (gas)***

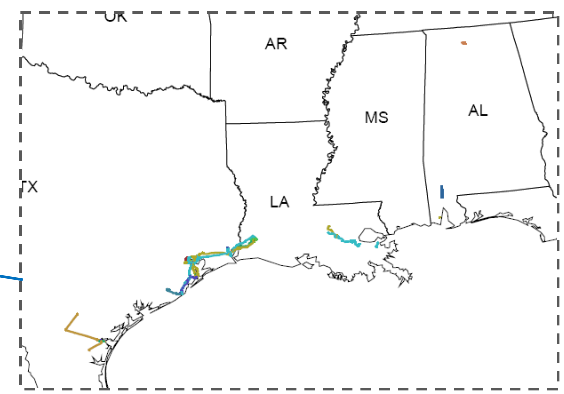
Longer-term:

- ***Pipelines***
- ***Tanker trucks (liquid)***
- ***Tube Trailers (gas)***









Existing liquefaction sites in the U.S.

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

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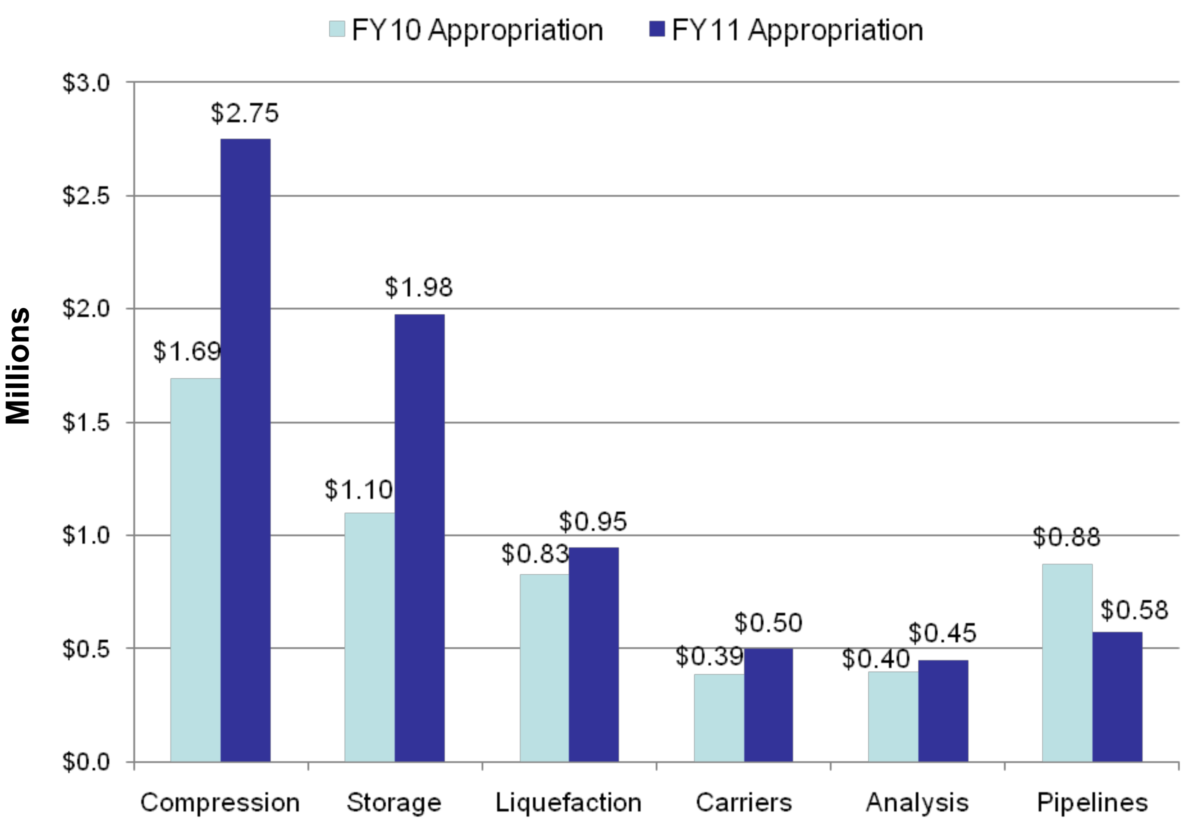
FY 2010 Appropriation = $4.5 M

FY 2011 Appropriation = $7.2 M



EMPHASIS

- **Reducing compression cost**
  - Centrifugal compression system design using "off the shelf parts"
  - High RPM system to reduce size and cost while increasing efficiency
  - High pressure/temperature test bed to develop coatings and materials
  - Electrochemical – SBIR
- **Higher capacity truck delivery**
  - Large volume/high pressure gas
  - High pressure, low temperature using glass fibers
- **Advanced liquefaction**
  - Leveraging Ortho-Para conversion
  - Helium cycle with novel heat exchanger configuration
  - Solid state cooling
- **Analysis**
  - Refine 700 bar and cryocompressed cost
  - Evaluating pathways and largest cost contributors
  - Evaluating purification costs

Challenges

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

Project Category	Goal (Targets to be met by 2020)	Status*
Tube Trailers	Reach H_2 delivery cost target of $1/gge Reduce capital cost to <$200,000 Increase capacity to 1100 kg through the use of carbon fiber or low-cost glass fiber	$2.85-$3.15/gge (high volume demand projection Completed system design for 1100 kg capacity with glass fibers and small scale prototype development Completed testing of carbon fiber tank with a capacity of 600 kg
Pipelines	Reach H_2 delivery cost target of $1/gge Decrease cost/mile to <$490K	$2.20-$2.35/gge (high volume demand projection) Cost/mile (steel): $1M/mile; cost/mile (FRP): $600K/mile
Liquefaction	Reach H_2 delivery cost target of $1/gge Decrease installed capital cost to $100M Increase energy efficiency to 87%	$2.70 - $2.90 (high volume demand projection) Installed capital cost: $170M Energy efficiency: 40%
Compression	Reduce capital cost to $6.2M (transmission compression) Increase energy efficiency to >98% Cost contribution: $0.25/kg H_2	Centrifugal pipeline package cost: $4.5M (projected) Energy efficiency: 98% (projected) Cost contribution: $0.60/kg H_2
Bulk Storage	Reduce cost of storage tank to $300/kg H_2 stored Increase volumetric capacity to >0.035 kg H_2/liter of storage volume	Storage tank cost: $820/kg H_2 stored Volumetric capacity: 0.025 kg H_2/liter of storage volume
Carriers	Show a viable carrier material (liquid, non-toxic) Decrease delivery cost contribution to <$1/gge Increase carrier H_2 content to 13.2% by weight	N-ethylcarbazole delivery cost: $4.75 N-ethylcarbazole H_2 content by weight: 5.8%

***DOE estimates—not publicly vetted**

Target and Status costs are projected high volume costs

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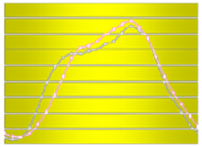
Major Challenges of Delivery Pathways

- Tube Trailers
  - Tube Trailer capacity
  - Capital cost
  - Regulatory issues
- Pipelines
  - Managing Embrittlement (steel pipelines) to reduce material and costs
  - Capital and labor cost (automated welding and inspection)
  - New materials—fiber reinforced pipe
  - Hydrogen quality
- Liquid Hydrogen via Truck
  - Energy intensity of liquefaction
  - Boil off
  - Modularity, and Capital cost



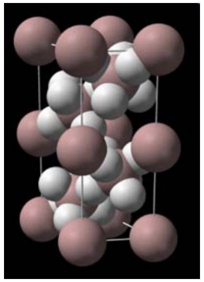
Analysis

Pipelines

Liquefaction

Tube Trailers

Compression



Carriers

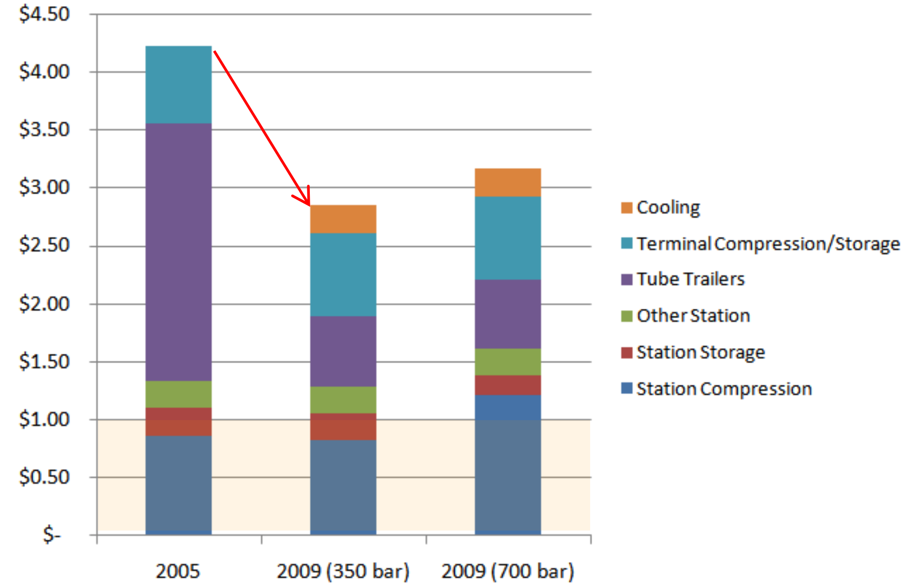
Dispensers

Tube Trailers (Gaseous Hydrogen)

2009 Modeled High-Volume Hydrogen Delivery Cost: **$2.85 – $3.15/gge (preliminary estimate)**

Recent Progress ***(Lincoln Composites and Livermore National Laboratory):***

- **Higher capacity with carbon fiber Doubled capacity to 600 kg H_2**
  - **Demonstrated large scale dome molding, tubular welding, and filament winding of tanks**
- **Trailer with glass fibers**
  - **Demonstrated stronger glass fibers at lower temperatures to project reduced delivery tank costs**
  - **Identified pathway to triple capacity : 1,100 kg H_2**
  - **Potential for up to 50% trailer cost reduction**



Future Work:

- **High performance glass fiber composite pressure vessels**
- **High pressure hydrogen tank for storage and gaseous truck delivery**
- **CF testing and failure analysis**
- **Integrated alloy/concrete vessel design and fabrication for low-cost storage at the station**

2010 Progress & Accomplishments

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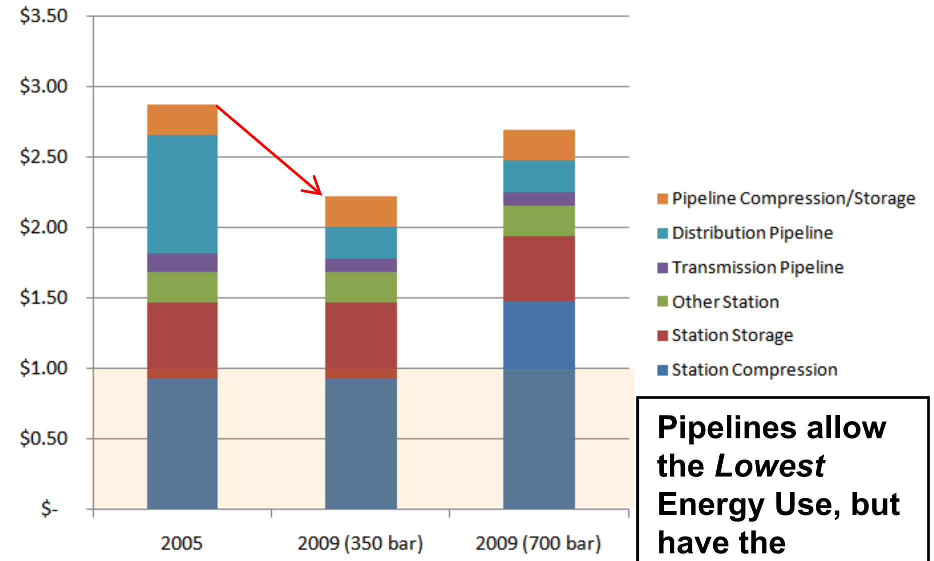
Pipelines (Gaseous Hydrogen)

2009 Modeled High-Volume Hydrogen Delivery Cost: **\$2.20 – \$2.35/gge (preliminary estimate)**

Projected Pipeline Cost: **FRP: \$600k/mile; Steel: \$1M/mile**

Recent Progress:

- **No degradation after eight months of accelerated-aging (equal to five years at room temperature)**
- **Hydrogen compatibility testing with commercial FRP pipeline specimens**
- **FRP passed blow-down testing**
- **Predicted leakage rate < 0.02% per year, surpassing target of 0.5% per year**
- **Measured leakage rate ≅ 0.5 kg H_2/yr/joint**



Pipelines allow the *Lowest* Energy Use, but have the *highest* station Cost!

Future Work:

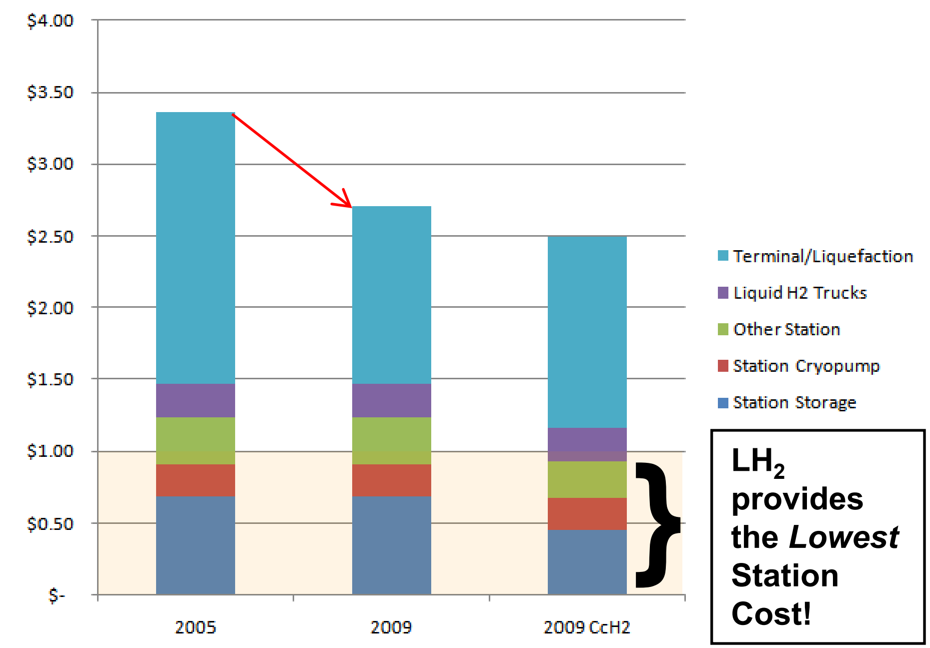
– **Address steel embrittlement issues**
– **FRP: on-site manufacturing and increased automation**
– **H_2 permeability and integrity of pipelines**

Liquid Hydrogen via Truck

***2009 Modeled High-Volume Hydrogen Delivery Cost*: $2.70 – $2.90/gge (preliminary estimate)**

Recent Progress Praxair and Heracles:

- Ortho-Para Approach to Liquefaction
  - Created computer model to determine ortho-para energy reduction potential
  - Developed test bed to validate model results
- Active Magnetic Regenerative Liquefier
  - Constructing lab prototype for cooling from 290 K to 120 K (LN_2)
  - Demonstration and independent verification planned third quarter



Future Work:

- Increasing efficiency (Active Magnetic Regenerative Liquefier and advanced processes)
- Cryo-pump testing
- Reduced boil-off
- Improved insulation

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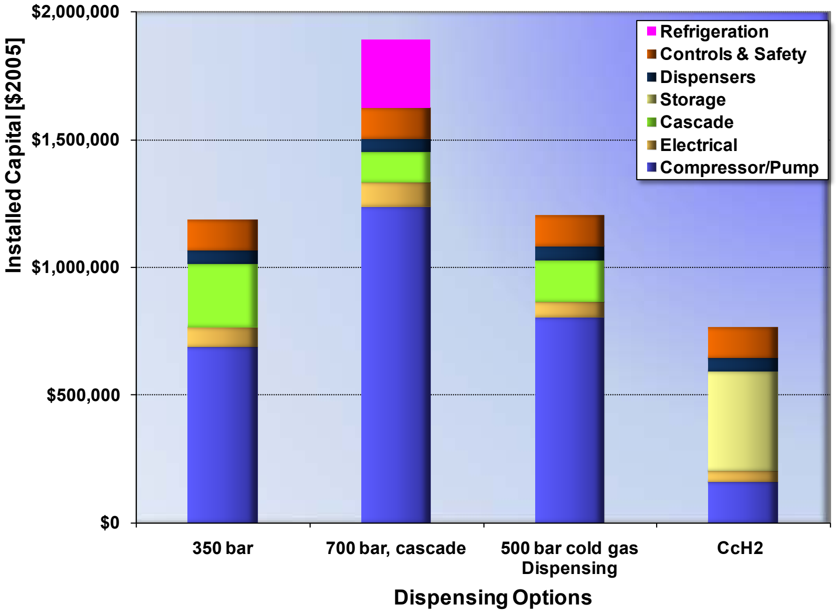
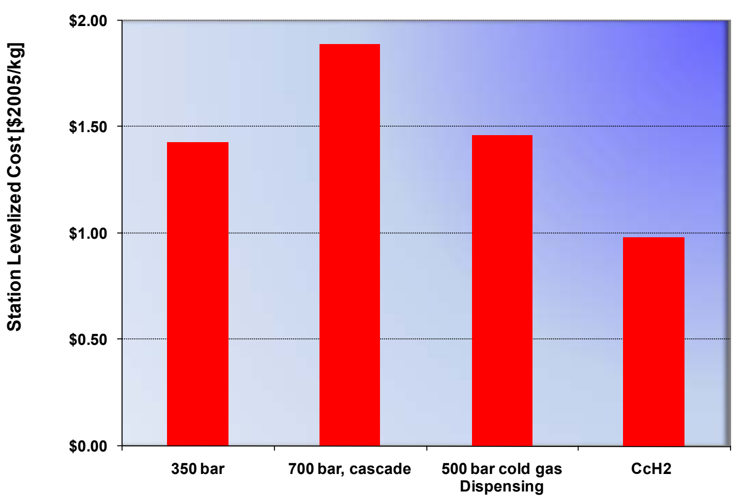
Analysis Updates
Fuel Stations Account for >Half Cost of GH_2 Delivery





- Installed capital of equivalent capacity H_2 stations ranges from $750k to $1.8 million.
- With no refrigeration and cascade and less storage, CcH_2 stations shift costs upstream.
- Installed capital for CcH_2 station is ~40% of 700-bar station: levelized H_2 cost is ~50%.
- LH_2 storage > 50% CcH_2 installed capital cost.
- 700-bar GH_2 with high pressure cascade is less expensive than booster-compressed 700-bar option (not shown).

- 500-bar cold gas station costs ~$0.50/kg >$CcH_2$ station dispensing of vaporized LH_2 (and ~$0.50/kg > 700-bar. GH_2 with cascade charging).
- Station cost for 500-bar cold GH_2 and 350-bar GH_2 ~$1.40/kg.
- But 500-bar cold GH_2 provides > energy density and longer driving range.
- All cost s are levelized 2005 $ for delivery only.

ANL: A. Elogwainy, M. Mintz

Compression Technology

***Projected 2009 Centrifugal Pipeline Compression Footprint Cost*: $4.5 m (versus DOE target: $6.2 m)**

Recent Progress:

- **Centrifugal Compression**
  - **Completed design criteria and performance specifications**
  - **Designed and began assembling a hydrogen centrifugal compressor using "off-the-shelf" parts**

Future Work:

- **Increase efficiency**
- **Reduce maintenance needs**
- **Centrifugal compression**
- **Ionic compression**

Progress Towards Meeting Technical Targets for Delivery of Hydrogen via Centrifugal Pipeline Compression*

Characteristic	DOE Target	Projection
Hydrogen Efficiency (btu/btu)	98%	98%
Hydrogen Capacity (kg/day)	100,000 to 1,000,000	240,000
Hydrogen Leakage (%)	<0.5	0.2
Hydrogen Purity (%)	99.99	99.99
Discharge Pressure (psig)	>1000	1285
Component Package Cost ($M)	6.2	4.5
Main Cost ($/kWh)	0.007	0.005
Package Size (sq. ft.)	300 to 350	175 to 200
Reliability (# systems required)	Eliminate redundant system	Modular systems with 240,000 kg/day with no redundancy required

Design projected to meet or exceed key targets

*Source: Concepts NREC, Compression Energy Record: http://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf

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.

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 ready room 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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