Delivery Tech Team

Oak Ridge National Laboratory
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Team Members

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Mission

- Provide a forum for the Partnership to help advance research aimed at developing low cost, safe, and energy efficient hydrogen delivery systems
- Catalyze the development of hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power

Useful Facts

- 1 kg H_2 = 1 gallon gasoline
- Eff_{FCV} = 2-3 x Eff_{ICEV} = 1.2-1.4 x Eff_{HEV}
- Energy Density
  - 10,000 psi H_2 = 1.3 kWhr/l
  - LH2 = 2.3 kWhr/l
  - Gasoline = 9.7 kWh/l

Delivery Scope

From the end point of central (or distributed) production (200 psi H_2) to and including the dispenser at a refueling station or stationary power site

(Includes forecourt compression, storage and dispensing)

FreedomCAR & Fuel Partnership

Delivery Roadmap

- ✓ Goal and Objectives
- ✓ Technology Status: Pathways and Components
- • Pathway Pros & Cons
- • Transition Issues,
- ✓ Research Strategy
- ✓ Barriers
- ✓ Targets
- • Conceptual R&D Paths

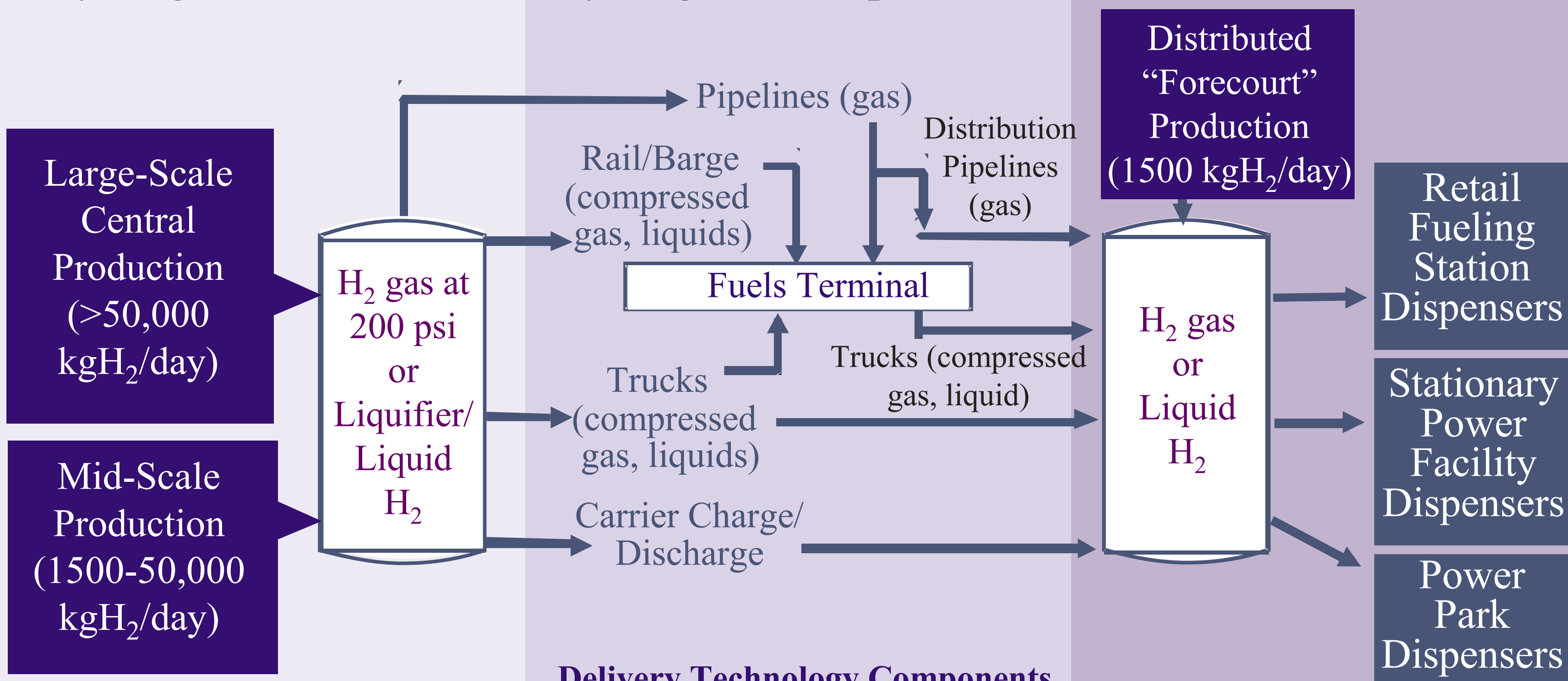
Completion by January, 2004

Technical Objectives

- By **2006**, define a cost-effective and energy-efficient hydrogen delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power.
- By **2010**, develop technologies to reduce the cost of hydrogen delivery from central and semi-central production facilities to the gate of refueling stations and other end users to <***$0.90/kg*** of hydrogen.
- By **2010**, develop technologies to reduce the cost of compression, storage, and dispensing at refueling stations and stationary power sites to less than ***<$0.80/kg*** of hydrogen.
- By **2015**, develop technologies to reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to <***$1.00/kg*** of hydrogen in total.
- By **2015**, develop technologies to reduce the cost of hydrogen delivery during the transition to <***$xx/kg*** of hydrogen.

Hydrogen Delivery Infrastructure

Hydrogen Production | Hydrogen Transportation | End-Use Station



Delivery Technology Components
- Storage at Production Site
- Liquefier
- Carrier Production/Regeneration

Delivery Technology Components
- Pipelines (transmission & distribution)
- Trucks, Rail, Barges
- Compressors
- Liquid and Gaseous Storage Tanks
- Geologic Storage
- Terminals

Delivery Technology Components
- Carrier Transfiguration
- Separation/Purification
- Storage Tanks
- Compression/Vaporization
- Fuel Dispensers

Crosscutting Delivery Technology Components
- Sensors & Controls
- Health & Human Safety
- Codes & Standards
- Right of Ways/Permitting

Research Areas

– Pathways
  - Gaseous Hydrogen Delivery
  - Liquid Hydrogen Delivery
  - Carriers

Including mixed pathways

– Components

Pipelines	Terminals
Compression	Separations/Purification
Liquefaction	Dispensers
Liquid and Gaseous Tanks	Carrier Transformations
Geologic Storage	Mobile Fuelers
GH2 Tube Trailers, Cryogenic Liquid Trucks, Rail, Barge, Ships	Other Forecourt Issues

Budget

- FY04: $0.25M
- FY05: ~$4M

Why Federal Support?

- Current H_2 markets do not justify extensive delivery R&D
- High risk research and significant breakthroughs required to achieve objectives

Delivery Projects

- Delivery Analysis
  - H2A delivery effort (ANL, NREL, J. Ogden)
  - Nexant collaborative project
- Compression
  - ANL: Novel screw compressor
  - HERA: Hydride compression (integrated with production distr. production project)
- Liquefaction
  - GEECO: Advanced turbo compression/expansion
  - NCRC: Magnetic liquefaction

Delivery Projects (Cont'd)

- Off-Board Storage
  - GTI: Forecourt analysis/underground liquid storage
  - LLNL: Composites for high pressure storage and tube trailers
- Pipelines (H_2 and Mixed H_2/NG)
  - National lab projects (ORNL, SRNL)
  - SECAT collaborative project
  - U. of Illinois
  - CTC: PA dongressionally directed
  - NG infrastructure: GTI
- Carriers
  - APCI, UTRC, Penn State U: liquid hydrocarbon

Risk

Current costs for hydrogen delivery are \$4-\$9/kg of H_2

The objective is <\$1/kg

Targets	2003 Status	2015 Target
Transmission Pipeline Capital (\$/mile)	\$1.20	\$0.80
Forecourt Compression		
Cost Contribution (\$/kg of H_2)	\$0.60	\$0.25
Reliability	Unknown	>99%
Forecourt Storage Cost Contribution (\$/kg of H_2)	\$0.70	\$0.20
Carrier (weight % H_2)	3%	13%

Challenges/Needs

- Forecourt Compression and Storage Costs
  - Attracting research in compression is challenging
  - Need a breakthrough in high pressure storage or carrier system for low pressure storage
- Transition
  - Low volumes means much higher delivery costs
  - Need a breakthrough: liquefaction, higher pressure tube trailers, or a liquid carrier approach

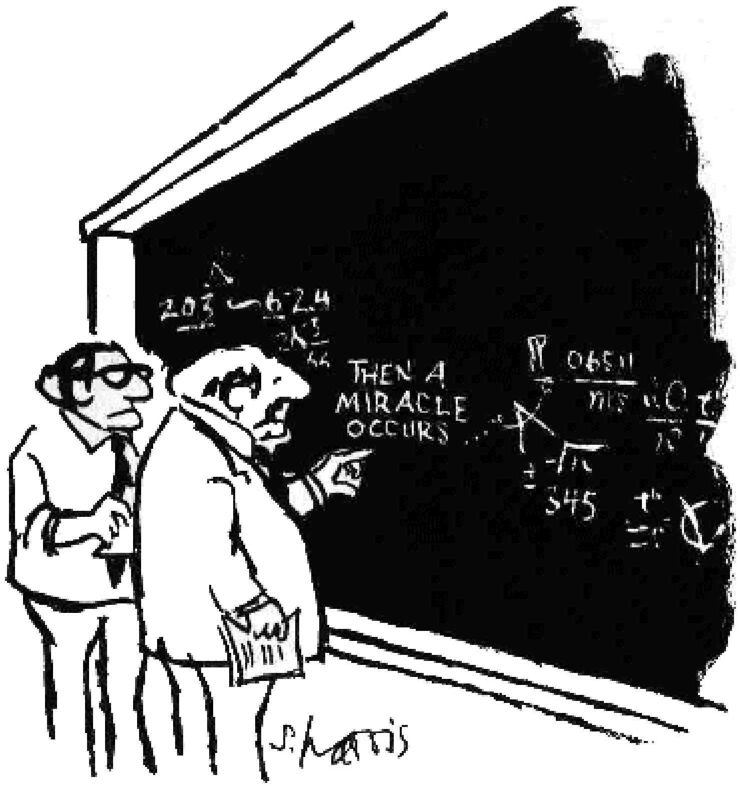
Pipeline Needs

- Use of Existing Pipelines?
- Step-Change Technologies
  - Materials
  - Joining
  - Lower labor costs
- Implement Early in Transition?
- ROW
- Suitable Geologic Storage?

Key DTT Learnings for FY06 and Beyond

- Forecourt costs are significant and need to be reduced
- The transition and long term are very different hurdles for delivery
  - Liquefaction breakthrough?
  - High pressure tube trailers?
  - Carriers?
- Pipelines are the current low cost pathway for the long term, but:
  - Must resolve embrittlement, and find reasonable cost ROW
  - Reduce the capital with alternative materials and or joining technology
  - How to move to pipelines (at least transmission) earlier?
- Can carriers change the delivery paradigm?
- Storage needs for market demand fluctuations need further understanding
  - NG relies heavily on geologic storage

FreedomCAR & Fuel Partnership



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Back-Up Slides

Hydrogen Delivery Targets

Category	2003	2005	2010	2015
Total Capital Cost ($M/mile)[2]	$1.20	$1.20	$1.00	$0.80
Pipelines: Distribution				
Total Capital Cost ($M/mile)[2]	$0.30	$0.30	$0.25	$0.20
Pipelines: Transmission and Distribution				
Reliability (relative to H_2 embrittlement concerns, and integrity)[3]	Undefined	Undefined	Understood	High (metrics TBD)
H_2 Leakage[4]	Undefined	Undefined	<2%	<0.5%
Compression: Transmission				
Reliability[5]	92%	92%	95%	>99%
Hydrogen Energy Efficiency (%)[6]	99%	99%	99%	99%
Capital Cost ($M/compressor)[7]	$18	$18	$15	$12
Compression: At Refueling Sites				
Reliability[5]	Unknown	Unknown	90%	99%
Hydrogen Energy Efficiency (%)[6]	94%	94%	95%	96%
Contamination[8]	Varies by Design	Varies by Design	Reduced	None
Cost Contribution ($/kg of H_2)[9,10]	$0.60	$0.60	$0.40	$0.25

Liquefaction				
Small-Scale (30,000 kg H_2/day) Cost Contribution (\$/kg of H_2)[11]	\$1.80	\$1.80	\$1.60	\$1.50
Large-Scale (300,000 kg H_2/day) Cost Contribution (\$/kg of H_2)[11]	\$0.75	\$0.75	\$0.65	\$0.55
Small-Scale (30,000 kg H_2/day) Electrical Energy Efficiency (%)[11,12]	25%	25%	30%	35%
Large-Scale (300,000 kg H_2/day) Electrical Energy Efficiency (%)[11,12]	40%	40%	45%	50%
Carriers				
H_2 Content (% by weight)[13]	3%	3%	6.6%	13.2%
H_2 Content (kg H_2/liter)			0.013	0.027
H_2 Energy Efficiency (From the point of H_2 production through dispensing at the refueling site)[6]	Undefined	Undefined	70%	85%
Total Cost Contribution (From the point of H_2Production through dispensing at the refueling site—\$/kg of H_2)	Undefined	Undefined	\$1.70	\$1.00
Storage				
Refueling Site Storage Cost Contribution (\$/kg of H_2) [10,14]	\$0.70	\$0.70	\$0.30	\$0.20
Geologic Storage	Feasibility Unknown	Feasibility Unknown	Verify Feasibility	Capital and operating cost <1.5X that for natural gas on a per kg basis
Hydrogen Purity[15]	>98% (dry basis)			

Hydrogen Delivery Targets (Table Notes)

1. All dollar values are in 2003 U.S. dollars

2. The 2003 status is based on data from True, W.R.,"Special Report: Pipeline Economics", Oil and Gas Journal, Sept. 16, 2002, pp 52-57. This article reports data on the cost of natural gas pipelines as a function of pipe diameter. It breaks the costs down by materials, labor, misc. and right of way. It is based on a U.S. average cost. A 15 inch pipe diameter was used for transmission and 2.5 inch for distribution. It was assumed that hydrogen pipelines will cost 30% more than natural gas pipelines based on advice from energy and industrial gas companies and organizations. The targeted cost reductions for 2010 and 2015 assume the right of way costs do not change.

3. Pipeline reliability used here refers to maintaining integrity of the pipeline relative to potential hydrogen embrittlement or other issues causing cracks or failures. The 2015 target is intended to be at least equivalent to that of today's natural gas pipeline infrastructure.

4. Hydrogen leakage based on the hydrogen that permeates or leaks from the pipeline as a percent of the amount of hydrogen put through the pipeline. The 2015 target is based on being equivalent to today's natural gas pipeline infrastructure based on the article: David A. Kirchgessner, et al, "Estimate of Methane Emissions from the U.S. Natural Gas Industry", *Chemososphere,* Vol.35, No 6, pp1365-1390, 1997.

5. Compression reliability is defined as the percent of time that the compressor can be reliably counted on as being fully operational. The 2003 value for transmission compressors is based on information from energy companies that use these types and size of compressors on hydrogen in their own operations.

6. Hydrogen energy efficiency is defined as the hydrogen energy (LHV) out divided by the sum of the hydrogen energy in (LHV) plus all other energy needed for the operation of the process.

Hydrogen Delivery Targets (Table Notes)

7. The 2003 value is based on data from" Special Report: Pipeline Economics", Oil and Gas Journal, Sept. 4, 2000, p 78. The compressor capital cost data was plotted vs. the power required for the compressor using the natural gas transmission compressor data provided. The capital cost was increased by 30% as an assumption for higher costs for hydrogen compressors. The power required was calculated assuming 1,000,000 kg/day of hydrogen flow with an inlet pressure of 700 psi and an outlet pressure of 1,000 psi.

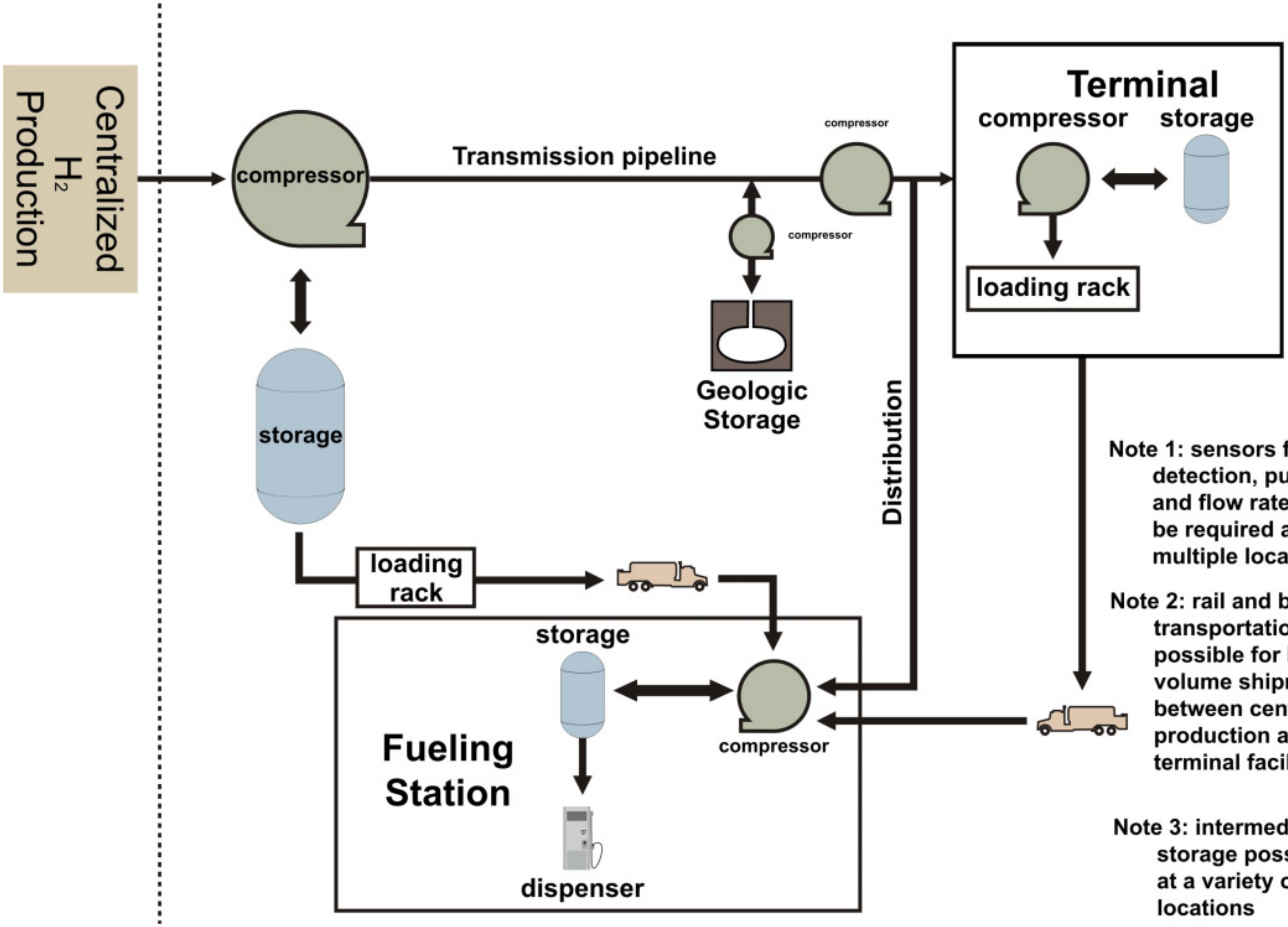
8. Some gas compressor designs require oil lubrication that results in some oil contamination of the gas compressed. Due to the stringent hydrogen purity specifications for PEM fuel cells, the 2015 target is to ensure no possibility of lubricant contamination of the hydrogen from the compression needed at refueling stations or stationary power sites since this compression is just prior to use on a vehicle or stationary power fuel cell.

9. The 2003 value is based on utilizing the H2A Forecourt (refueling station) Model spreadsheet tool for a 1500 kg/day distributed natural gas hydrogen production case (www,eere.energy.gov/hydrogenandfuelcells). The standard H2A financial input assumptions were used. It was assumed that two compressors would be needed due to the currently unknown reliability of forecourt compressors, at a total installed capital cost of $600k. The electricity required assumed an isentropic energy efficiency of 70% and an electricity price of $.07/kWhr. The compression operation was assumed to have a fractional share of the forecourt fixed costs based proportional to its capital and the total capital cost of the forecourt.

10. For 2003 and 2005, it is assumed that the hydrogen delivery pressure to the vehicle is 5000 psi. For 2010 and 2015, it is assumed that the hydrogen delivery pressure to the vehicle is 1500 psi or less based on the on-board vehicle storage program (Section 3.3) being successful in meeting it's targets.

11. The 2003 cost contribution and electrical energy efficiency was determined using the H2A Delivery Component Model spreadsheet using standard H2A financial input assumptions and the liquefaction spreadsheet tab (www.eere.energy.doe/hydrogenandfuelcells). The H2A spreadsheet information is based on data from other references sited in the H2A Delivery Component Model. References and a plot of liquefier capital cost as a function of capacity and a plot of actual energy used as a function of liquefier capacity are provided in the H2A Delivery Component model.

Gaseous Hydrogen Delivery Pathway

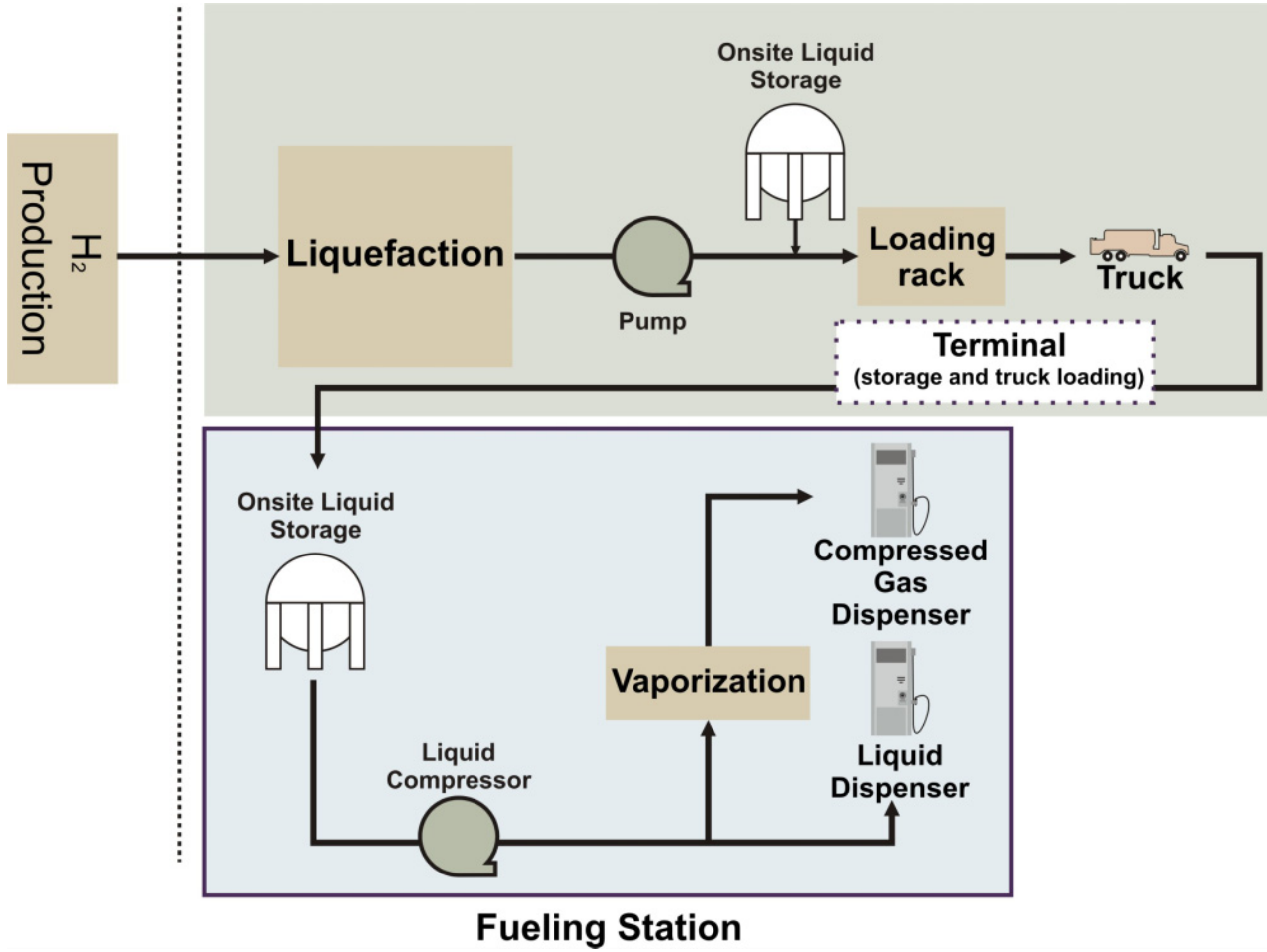


Note 1: sensors for leak detection, purity, and flow rate will be required at multiple locations

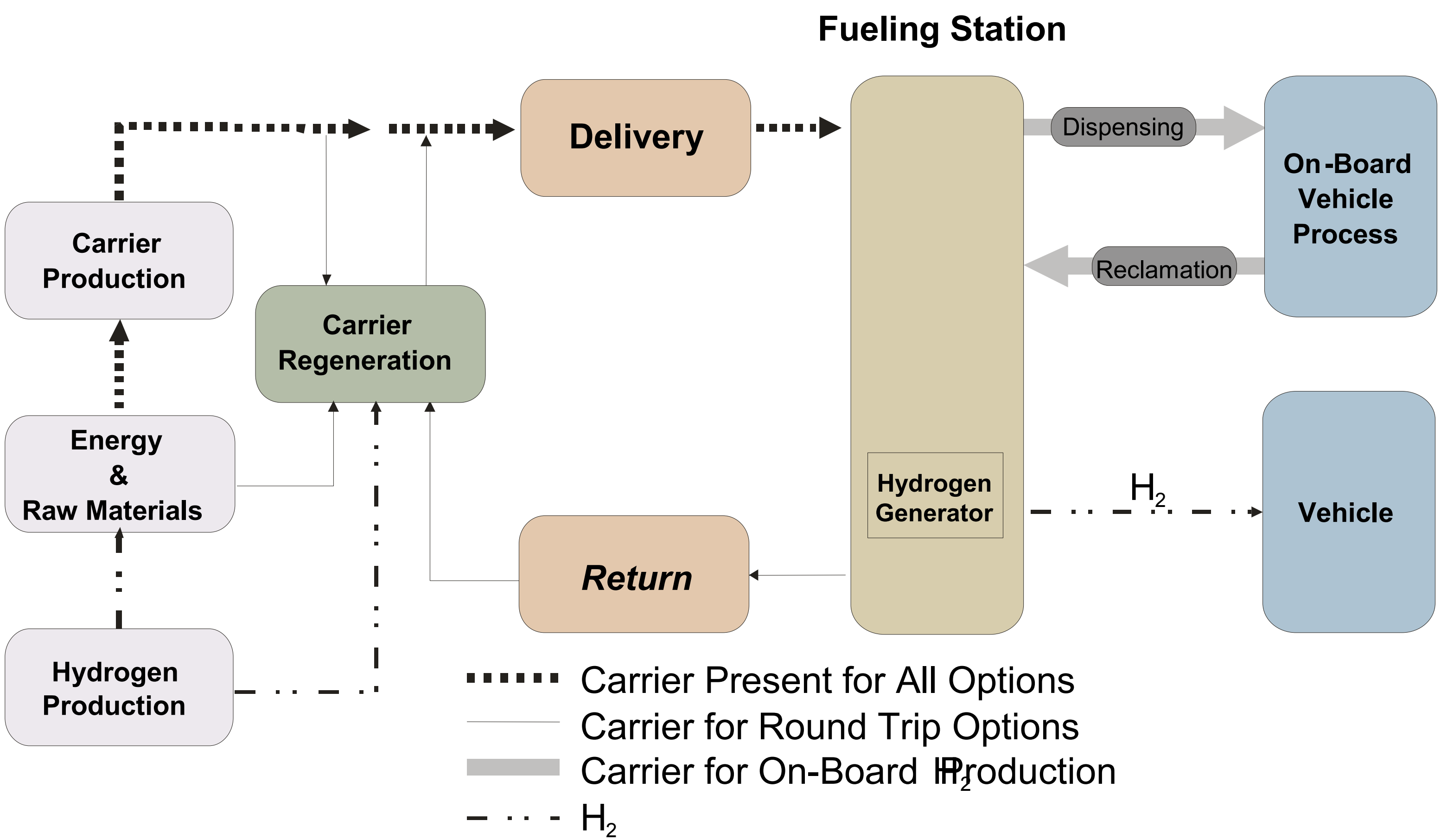
Note 2: rail and barge transportation is possible for large volume shipments between central production and a terminal facility

Note 3: intermediate storage possible at a variety of locations

Liquid Hydrogen Delivery Pathway



Hydrogen Carrier Delivery Pathway



NAS Report Recommendations

- Recommends concerted effort on Systems Analysis
  - First Task is Delivery Infrastructure options and trade-off analysis (in conjunction with Systems Integration/Analysis)
- Encourages fundamental research in materials for pipelines and other delivery infrastructure components
  - Key emphasis in the Roadmap and research projects initiated
  - Office of Science solicitation
  - Collaboration with EC NATURALHY Project and DOT
- Recommends initial focus on the transition and distributed production
  - Roadmap has a strong initial focus on Forecourt compression and storage research
- Delivery Infrastructure and cost need to be addressed
  - ~$4 M directed to Delivery R&D in FY05

Team Accomplishments

- Technology briefings: Petroleum, NG, LNG delivery; H_2 pipelines; H_2 compression; H_2 liquefaction and LH2 truck delivery; Carriers; Liquid and gaseous tanks; Geologic storage
- DRAFT Delivery Roadmap nearly completed
- Conducted two project reviews
  - H2A Delivery Project
  - ORNL pipeline project: Suresh Babu

Roadmap Status: Target Strategy

- Overall cost of delivery objectives will be set for the transition (<5% LDV market penetration) and longer term (>50% LDV market penetration)
- Targets will be for the Components

Key Objectives for FY05

- Complete comprehensive Roadmap and Targets
- Project Reviews and Guidance
- Identify R&D Portfolio Gaps

FY 2005 DTT Work Plan

- **January 3-6, 2005**
  - Pipeline Projects Review and working session
- **February 8-9, 2005**
  - Analysis Projects review and working session
- **March 9, 2005**
  - Project Reviews
- **April 6, 2005**
  - Project Reviews
- **May 2005**
  - at NHA Conference or DOE Program Review
- **June 1, 2005**
  - Project Reviews
- **July 13, 2005**
  - Carrier Projects Review
- **September 8-9, 2005**
  - Project Reviews

Hydrogen Delivery Targets (Table Notes)

12. Electrical energy efficiency is defined as the theoretical energy needed to liquefy the hydrogen divided by the energy actually needed in a hydrogen liquefaction plant. The theoretical energy is that energy needed to cool the gas to the liquefaction temperature and the energy needed for the ortho/para transition. The H2A Delivery Component Model (www.eere.energy.doe/hydrogenandfuelcells) provides the references and a plot of actual energy needed for current hydrogen liquefiers as a function of capacity.

13. The 2010 hydrogen content targets are based on transporting 1500 kg of hydrogen in a truck. Although regulations vary to some degree by state, a typical truck is limited to carrying 25,000 kg of load and/or 113,000 liters of volume. The minimum hydrogen content (% by weight and kg H2/liter) to achieve 1500 kg of hydrogen on the truck is determined by theses maximum loads allowable. Trucking costs with this hydrogen payload are such that this transport option would seem attractive relative to the delivery cost objectives. A typical refueling station of 1500 kg/day of hydrogen servicing hydrogen fuel cell vehicles would service the same number of vehicles as typical gasoline stations serve today. This delivery option would require one truck delivery per day which is also typical of today's gasoline stations. The 2015 targets are calculated in the same way but assuming 3000 kg per truck load so that the one truck could service two refueling stations. The total cost and attractiveness of this delivery option would depend on the cost of the total carrier delivery system including the cost of the operations of discharging the hydrogen at the refueling station and any carrier regeneration costs.

14. The 2003 value is based on utilizing the H2A Forecourt (refueling station) Model spreadsheet tool for a 1500 kg/day distributed natural gas case (www,eere.energy.gov/hydrogenandfuelcells). The standard H2A financial input assumptions were used. It was assumed that the hydrogen storage installed capital cost is $1.1M based on current technology and 1,100 kg of hydrogen storage. The storage operation was assumed to have a fractional share of the forecourt fixed costs based proportional to its capital and the total capital cost of the forecourt.

15. Based on current available PEM fuel cell information, the tentative contaminant targets are: <10ppb sulfur, <1 ppm carbon monoxide, <100 ppm carbon dioxide, < 1 ppm ammonia, < 100 ppm non-methane hydrocarbons on a C-1 basis, oxygen, nitrogen and argon can not exceed 2% in total, particulate levels must meet ISO standard 14787. Future information on contaminant limits for on-board storage may add additional constraints.