DOE and FreedomCAR & Fuel Partnership Hydrogen Delivery and On-Board Storage Analysis Workshop
January 25, 2005
Washington DC

Hydrogen Delivery Infrastructure Option Analysis

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Presentation Outline

- Project Background
- Knowledge Collected and Preliminary Results for Each Delivery Option
- Summary of Observations
- Next Step

Project Background

Delivery Options

Option 1* **GH delivery by new pipelines**

Option 2 **Converting NG/oil pipelines for GH delivery**

Option 3 **Blending GH into NG pipelines**

Option 4* **GH tube trailers**

Option 5* **LH tank trucks**

Option 6 **Use of novel H2 carriers** (alanate; chemical hydride; liquid hydrocarbon; metal hydride in powder or brick form)

Option 7 **Methanol/ethanol/ammonia as H2 carriers**

* Options already incorporated in the H2A component and scenario models

Objectives

- **Refine technical and cost data in H2A component and scenario models based on industrial experience**
- **Explore new options to reduce H2 delivery cost**
- **Expand H2A component and scenario models to include new options**
- **Provide basis to recommend H2 delivery strategies**

Tasks

Task 1 **Collect/Compile Data and Knowledge Base**

Task 2 **Evaluate Current/Future Efficiencies and Costs for Each Delivery Option**

Task 3 **Evaluate Existing Infrastructure Capability for H2 Delivery**

Task 4 **Assess Emissions in Each Delivery Option**

Task 5 **Compare and Rank Delivery Options Based on Expansion of H2A Component & Scenario Models**

Task 6 **Recommend Hydrogen Delivery Strategies**

Task 7 **Project Management and Reporting**

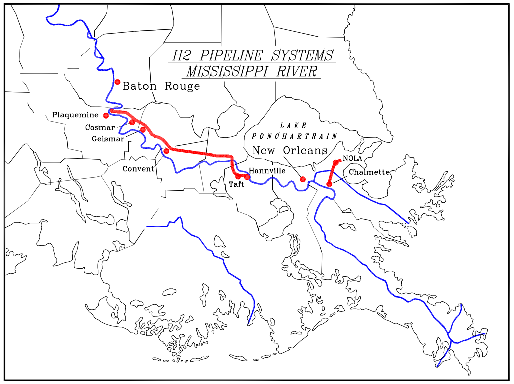
Schedule, Budget, and Status

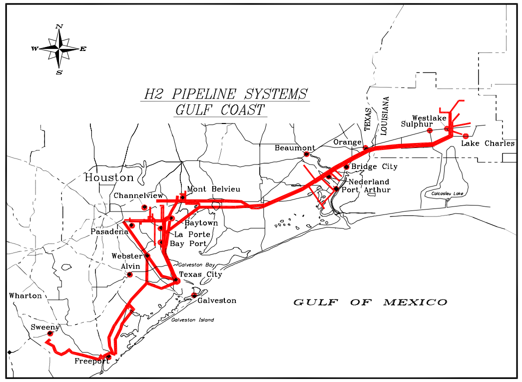
- **Project Schedule**
  - ✓ Start: November 2004
  - ✓ End: March 2007
- **Project Budget**
  - ✓ $1.5 million
  - ✓ Increase to $1.7 million with addition of ANL and PNL
- **Status**
  - ✓ Completed Task 1 (Review Existing H2A Models; Compile Knowledge Base)
  - ✓ Midst of Task 2 (Evaluate Each Delivery Option)

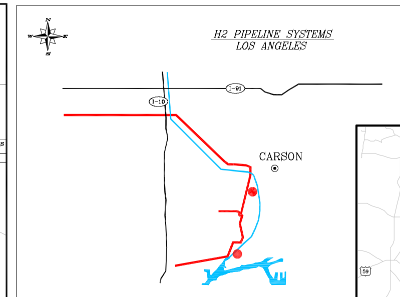
Knowledge Collected and Preliminary Results

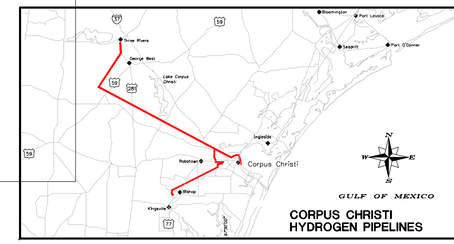
GH Delivery by New Pipelines

H2 Pipeline Delivery Experience *(from Air Liquide)*









- Transmission lines
  - 600 miles exist in US
  - 10-18" lines (100,000-500,000 kg/d)
  - Size range envisioned for H2 economy @ full penetration
  - $0.5-2MM/mile
  - Only 2-5% more than NG line costs (refinement for H2A model): pipe material is not more exotic; but better welding needed
- Compression station
  - Reciprocating compressor only
  - Compressor cost: 100-150% more than NG
  - Installed cost: 50-100% more (refinement for H2A model)
- Distribution lines
  - None built; borrow NG experience
  - Dominated by labor cost (>80% of total)
  - Very high total cost: $ 0.75-1.5 MM/mile (being incorporated by H2A model)

Pipeline Safety

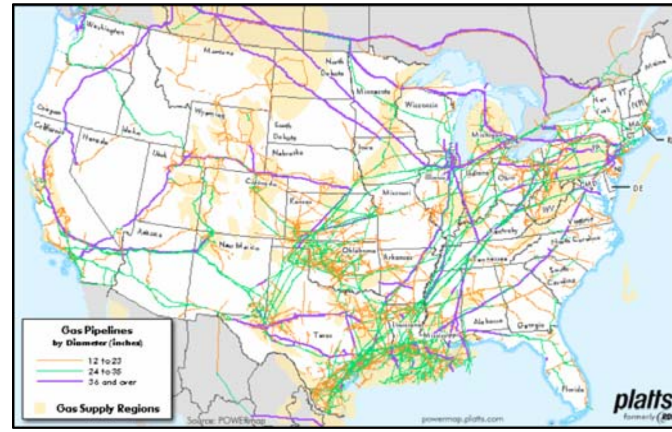
- 4 DOT pipeline location classifications (49 CFR 192)
- Higher classification:
  - Higher population density
  - Allowable pipe stress decreases
  - Number of isolation valves increases
  - Frequency of leak check & line patrol increases
- Regulation for using odorants
  - DOT does not require for transmission
  - NG transmission lines: interstate lines use no odorants; lines in a state might require (such as CA)
  - NG distribution lines: gas companies usually use for Class 3 & 4
- No odorants used in current H2 pipelines
- Conventional sulfur-based odorants not suitable
  - Molecules are too large compared with H2
  - Will precipitate and deposit on the pipe wall
  - Removal prior to use in FCV adds cost
- Several sulfur-free odorants being developed by JARI (Japanese Automobile Research Institute) hold promise

Minimize Right of Way Cost

- Transmission lines
  - DOT (49 CFR 192) allows mixed energy transmission
  - General engineering practice: 50’ easement on either side of the line
  - H_2 lines can be installed next to existing oil/NG lines to avoid ROW cost
  - H_2 and NG/oil lines need to separate at least 12” but separate owners of the line might want 20’ apart to avoid interferences and disputes
- Distribution lines
  - Share utility trenches within cities to minimize ROW cost
  - City owns utility trenches
  - Local utility leases ROW from the city through franchise fee
  - City inspects mainly the repaving, but might occasionally the line quality

Differences from Natural Gas Pipelines

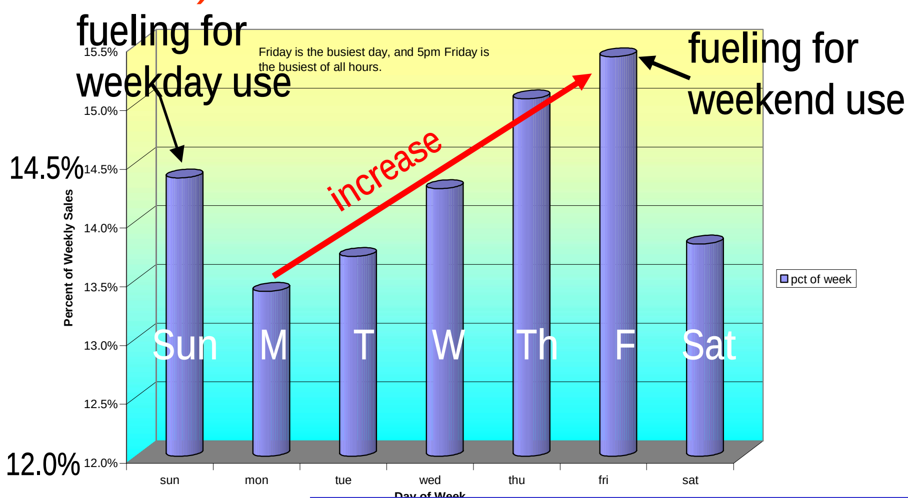
- Freedom to site central H_2 production; while NG resource locations are given & fixed
  - Coal shipped across country; CO_2 seq. sites all over US
  - Biomass in most states (except those of desert climate)
  - MeOH/NH_3 produced from NG but ultimately from coal
  - Ethanol from Midwest but trucked across country
  - Wind in US central corridor; best delivered as electrons
  - Hydro in NW region; best delivered as electrons
  - Solar in South region; best delivered as electrons
  - Nuclear power is available anywhere
- H_2 pipelines are shorter & smaller
  - Production sites likely close to major cities (<100 miles)
  - 10-18" lines (100,000-500,000 kg/d H_2) vs. 12-48" NG lines
  - Consist with H2A scenario model
- Metal distribution lines (300 psi?)

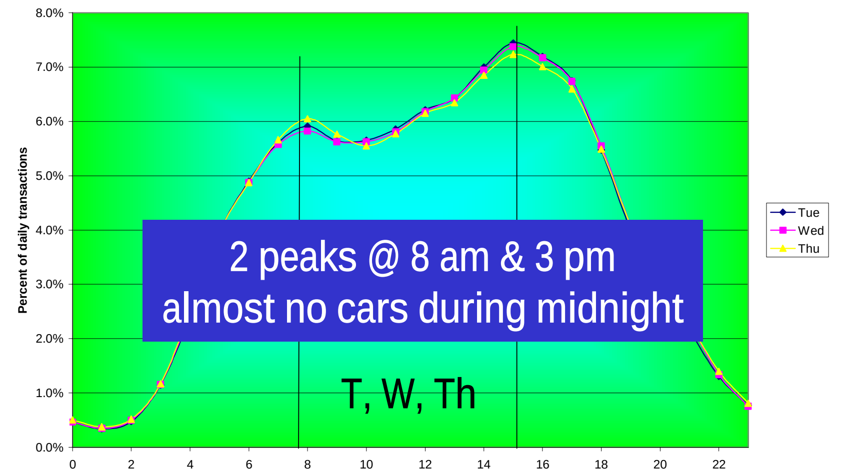


NG pipelines from resources to users

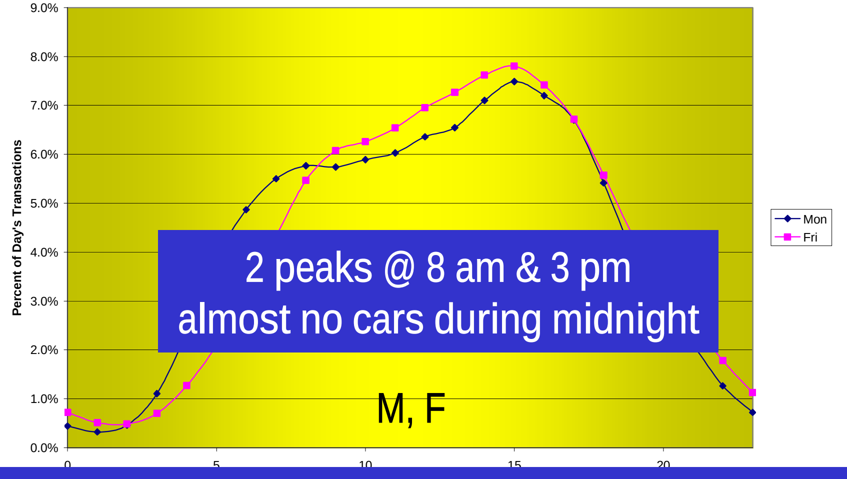
100 metropolitans for 70% US population

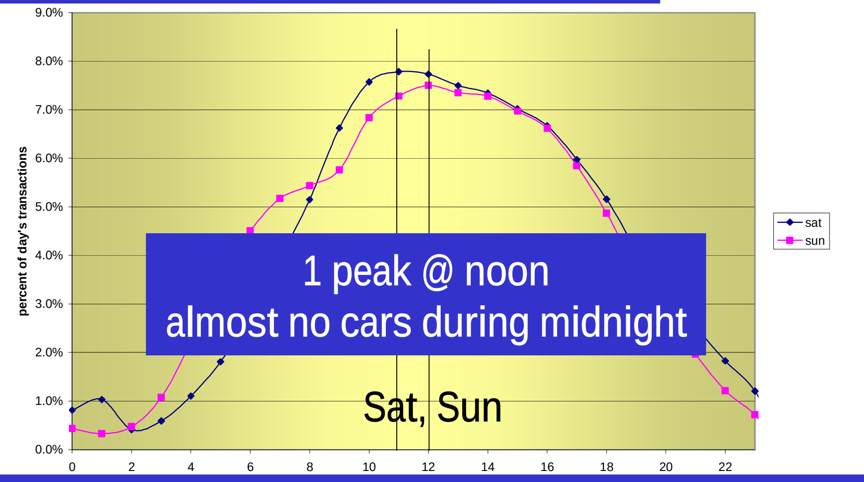
Current Gas Station Fueling Profile (from Chevron)





Peak to average ratio: 1.07:1 in daily variation and 2:1 in hourly variation



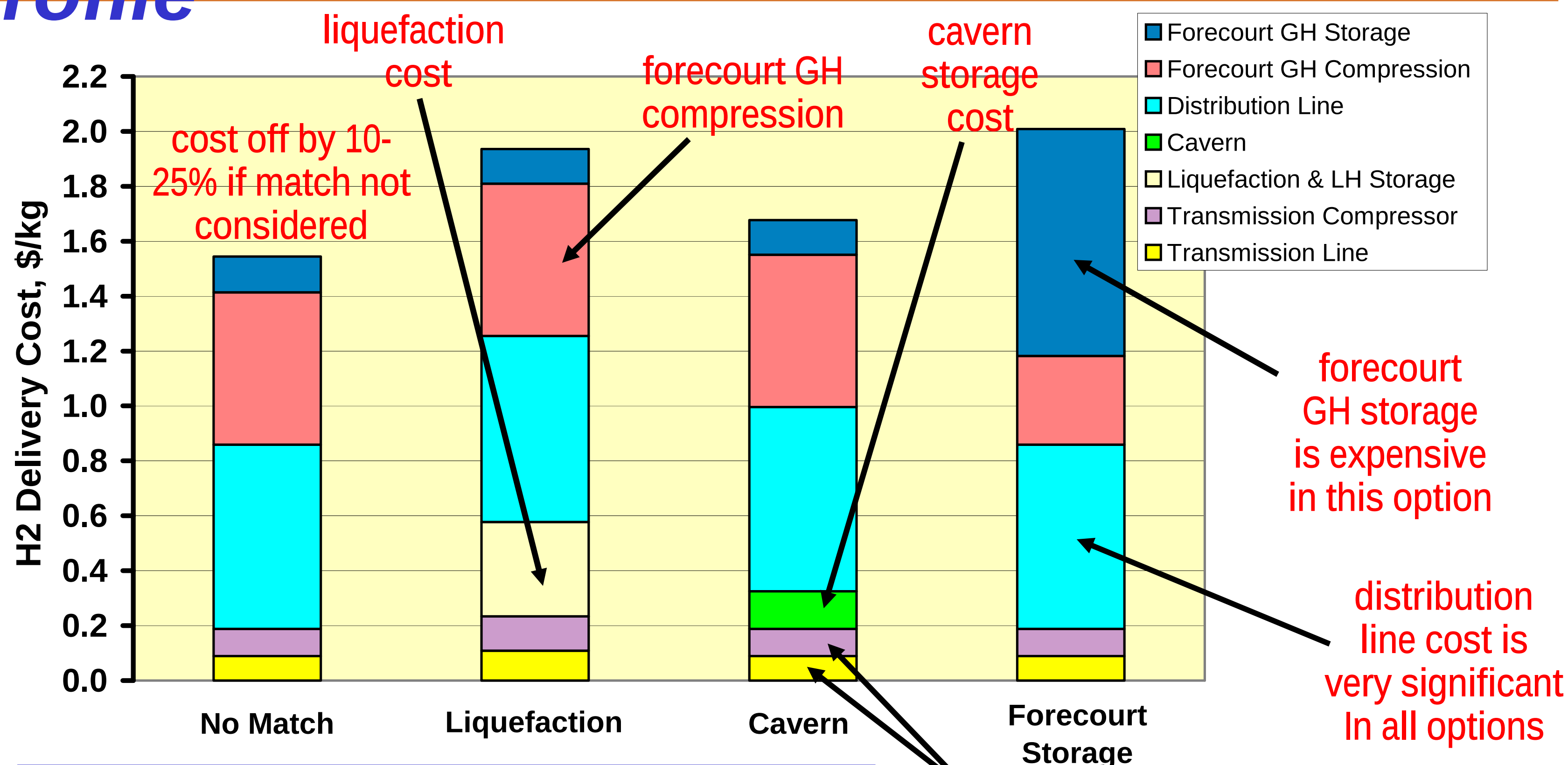


Also seasonal variation! Winter need is 70% and 90% of summer in the US North and South, respectively.

Match Forecourt Fueling Profile

- H2 supply at forecourt is limited by central production plant: cannot match profile at will as CNG stations
- Options for GH pipeline delivery to meet the profile:
  - At central production plant: large liquefaction unit & LH storage
  - Use pipeline as storage; <3% for 100 mile long pipeline
  - Use underground caverns for storage; not always applicable
  - At forecourt: on-site GH storage
- LH or H2 carriers served also for on-board storage are more cost effective to match the profile
  - Liquid and solid are easier and cheaper to store than gas
  - The high gas storage cost also applies for on-site H2 production (NG reforming; electrolyzer; reforming of methanol/ethanol/NH3)
  - GH pipeline might not the most cost effective long-term delivery option if the forecourt profile matching is realistically considered

Comparison of Options to Match Fueling Profile

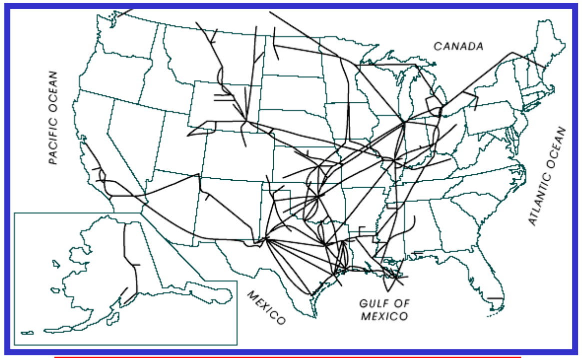


- H2 demand: 200 MMSCFD (474,000 kg/d)
- 5000 psig on-board GH storage
- Transmission: 100 miles; 1,000 psi in, 600 psi out
- Forecourt: 320 stations; 300 psi H2 in
- Distribution line: 640 miles

Knowledge Collected and Preliminary Results

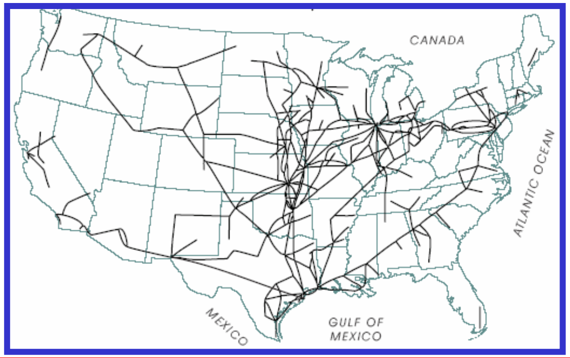
Converting NG/Oil Pipelines for GH Delivery

Lines Available for Conversion



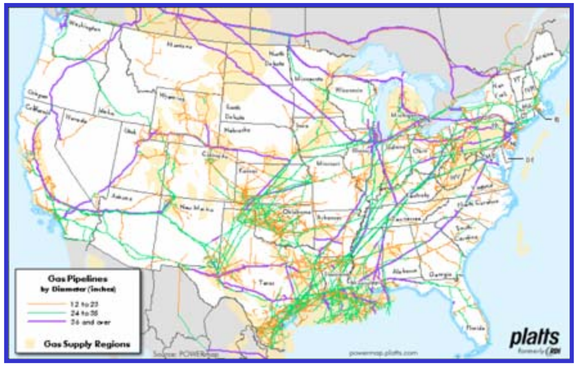
Crude Oil Pipelines

- Main US crude production: Alaska, TX, CA
- Lines to transport crude
  - Gulf area to Midwest refineries
  - CA to Gulf Coast refineries
- Availability for conversion
  - Near term: lines from depleted oil field
  - Long term: all lines



Petroleum Product Pipelines

- Lines to transport petroleum products
  - Gulf Coast refineries to Midwest
  - Gulf Coast refineries to East coast
- Availability for conversion
  - Near term: none
  - Long term: all lines



Natural Gas Pipelines

- Transmission lines available for conversion
  - Near term: none
  - Long term: all lines
- Distribution lines available for conversion
  - Not amenable to conversion if the lines are plastic or have low pressure rating

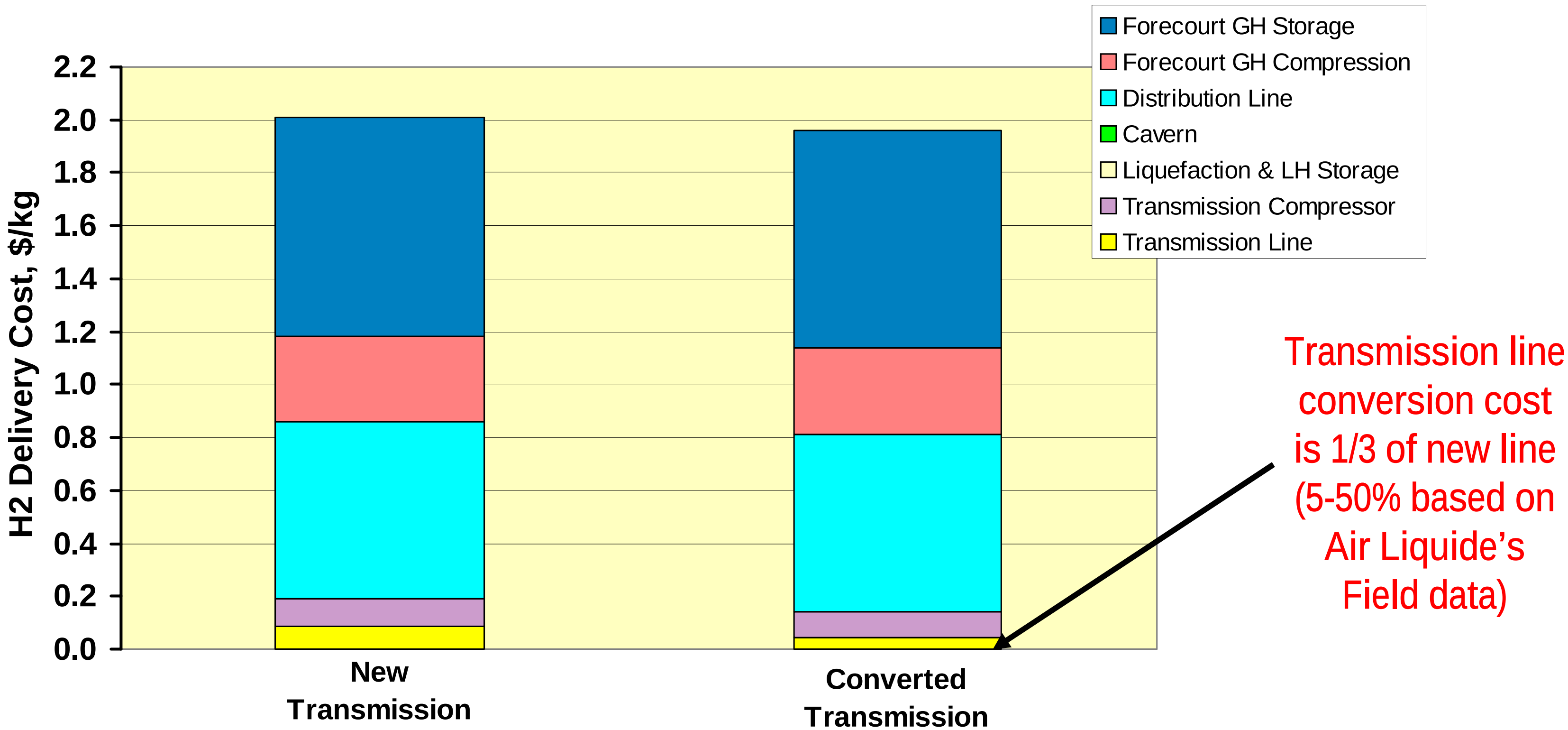
Capacity Adjustment After Conversion

- Line operating pressure de-rated by 50%
  - Caution taken due to embrittlement of H2 in carbon steel pipes
  - Operating pressure is 35% rather than typical 72% of allowable stress
- 20-25% less energy delivered (excluding pressure de-rating):

	Natural Gas	H_2
Volume of Gas Delivered (SCFH)	***7.0 MM***	***18.4 MM***
LHV Energy Delivered (BTU/Hr)	***6,391 MM***	***5,060 MM***
Less Compression Energy (BTU/Hr)	***(20) MM***	***(69) MM***
Net Energy Delivered (BTU/Hr)	***6,371 MM***	***4,991 MM***

- Overall, delivery capacity is de-rated by 60%

Economics for Converting Existing Lines



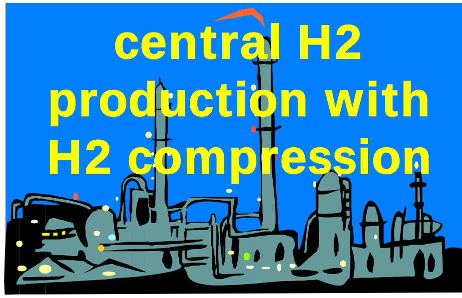
- H2 demand: 200 MMscfd (474,000 kg/d)
- 5000 psig on-board GH storage
- Transmission: 100 miles; 1,000 psi in, 600 psi out
- Forecourt: 320 stations; 300 psi H2 in
- Distribution line: 640 miles

Saving by using existing pipeline infrastructure does not reduce GH pipeline transport cost too much because pipeline is a very small component of the whole delivery cost

Knowledge Collected and Preliminary Results

Blending GH into NG Pipelines

Basic Concept



1,000 psi

600 psi

NG/H2 separation at city gate

NG to Existing Distribution System

300 psi

New H2 Distribution Lines

H2 in blended fuel needs to be <10%

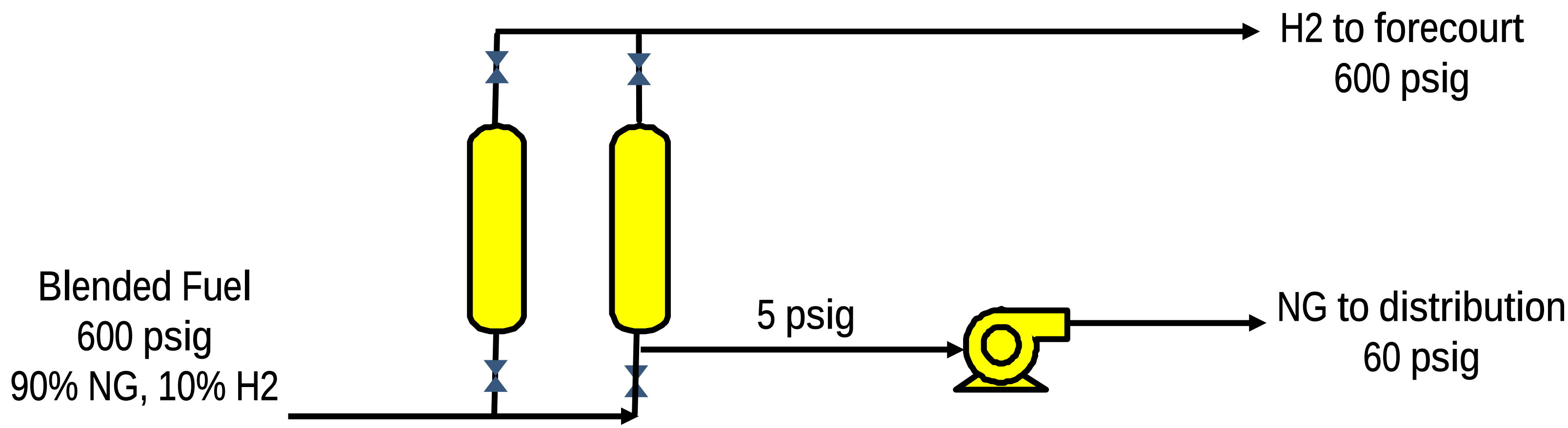
- Fulfill NG delivery obligation: not much room for H2
- Capacity constraint faced by NG pipelines now
- Compatible with NG pipeline materials & safety
- 95% NG pipelines have gas take in the last 50-100 miles prior to city gate
- Deviate <5% from NG spec:

	NG Spec.	10% mix
HHV, Btu/SCF	950	940
Wobbe Index, Btu/SCF	1,300	1,245

Separation Processes Considered

Technology	Responsible
PSA	Air Liquide
Membrane	Air Liquide
H2 Absorber	TIAX
Methane Hydrate	GTI
Proprietary Process	Air Liquide

PSA Separation Process

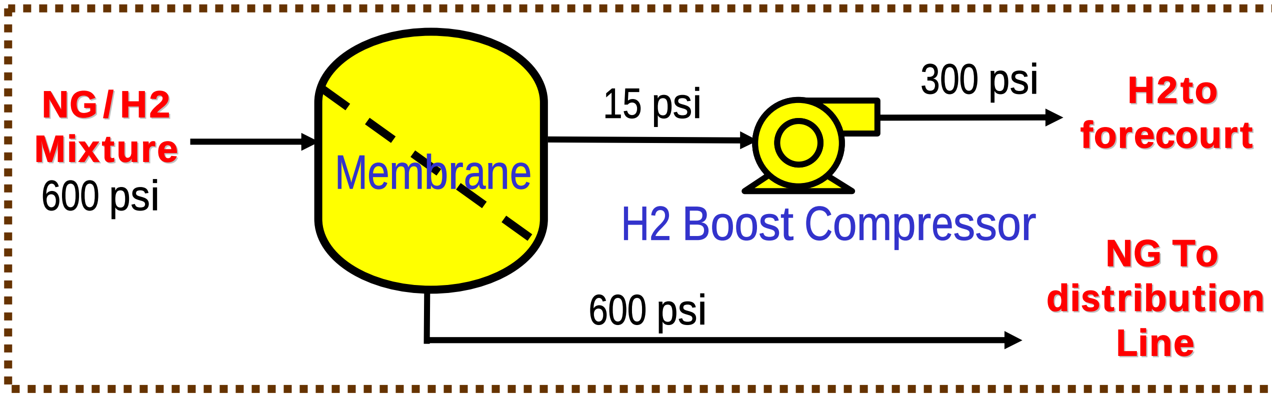


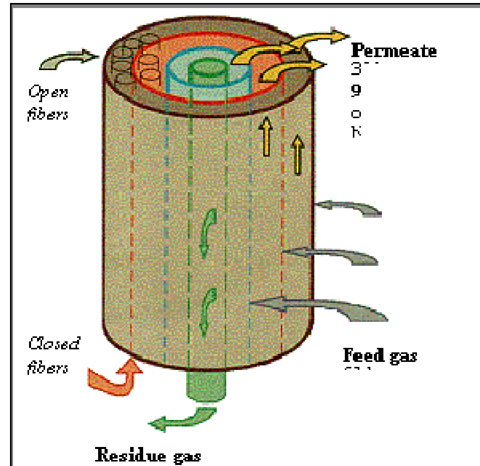
- System operation
  - Heavier compounds (i.e. NG & odorant) in the blended fuel are absorbed
  - H2 leaves at high pressure to go to forecourt without further compression
  - Part of H2 produced used to purge NG absorbed; NG leaves at low pressure
- Can produce high purity H2 for FCV
- Low H2 content (10%) in the feed increases the number of adsorbent beds & amount of purge gas required
- H2 recovery is estimated to be very low in the 20% range
- This separation option is not further considered

Membrane Separation Process

Relative Permeation Rates

Fast — H_2O — He — **H_2** — NH_3 — CO_2 — H_2S — O_2 — Ar — CO — N_2 — **CH_4** — C_2H_4 — C_3H_8 — Slow



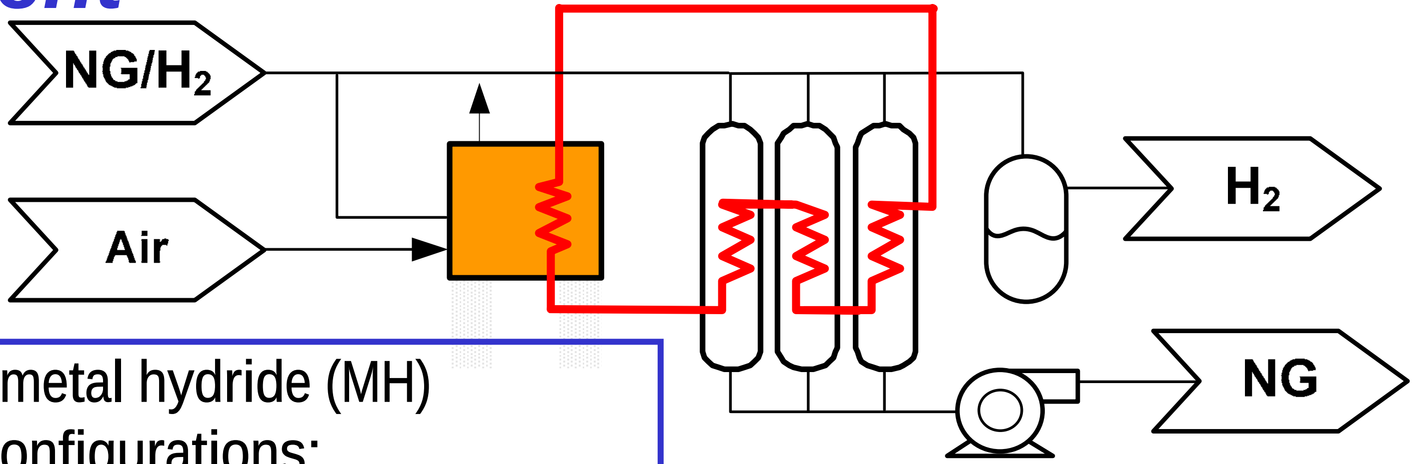


Air Liquide's MEDAL polymer membrane process

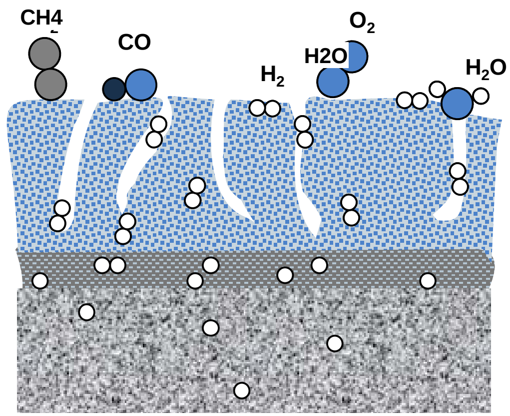
	Temp, C	Mechanism
Polymer	<100C	Molecular Diffusion
Porous Ceramic	200-600	Molecular Sieve
Metallic (Pd Alloys)	300-600	Atomic Diffusion
Porous Carbon	500-900	Molecular Diffusion
Dense Ceramic	600-900	Ionic Transfer

- Polymer membranes
  - Commercial (Air Products, Linde, BOC, Air Liquide)
  - Potential to adapt large gas flow
  - Cannot produce high purity H2 with 10% H2 in the blended fuel feed
- Metallic membrane
  - Commercial (J. Matthey, Aleghany Technology, Walther Juddah Tech)
  - Limited by precious metal cost to small-scale special applications
  - Cheaper ZrNi to replace Pd is under development (Bend Research, Japanese Nat Inst Material NIMCR)
- Porous/dense ceramics & porous carbon are far from commercial

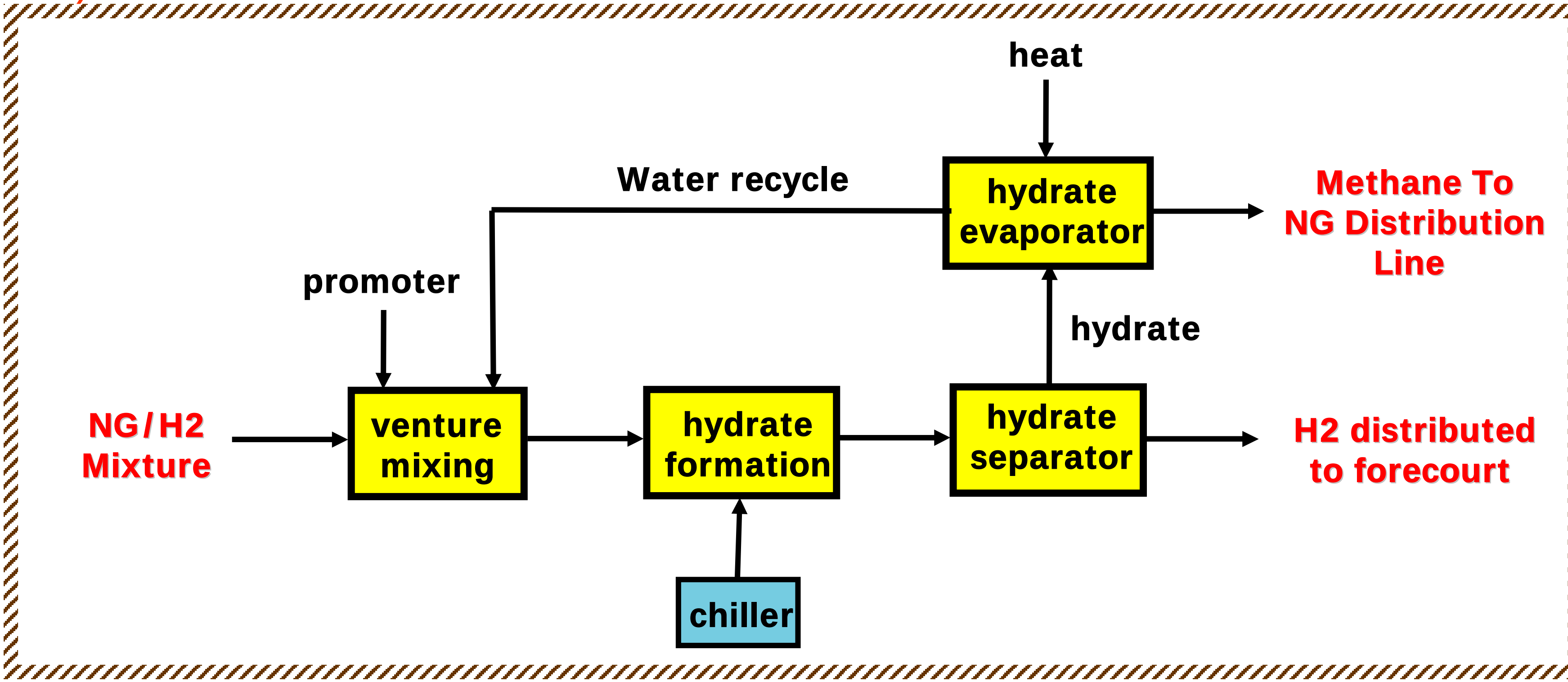
Separation Process Using MH as H2 Sorbent



- Sorbent: metal hydride (MH)
- System configurations:
  - Fixed bed swing absorber; pumped slurry
  - Fired heater drives H_2 from MH
- Key issue: MH deactivation by CH_4 and CO in blended fuel
- Solution: Porous fluorinated layer to allow only small H2 molecules to reach MH
- Not commercial; cost estimate on-going



Methane Hydrate Separation Process *(from GTI)*

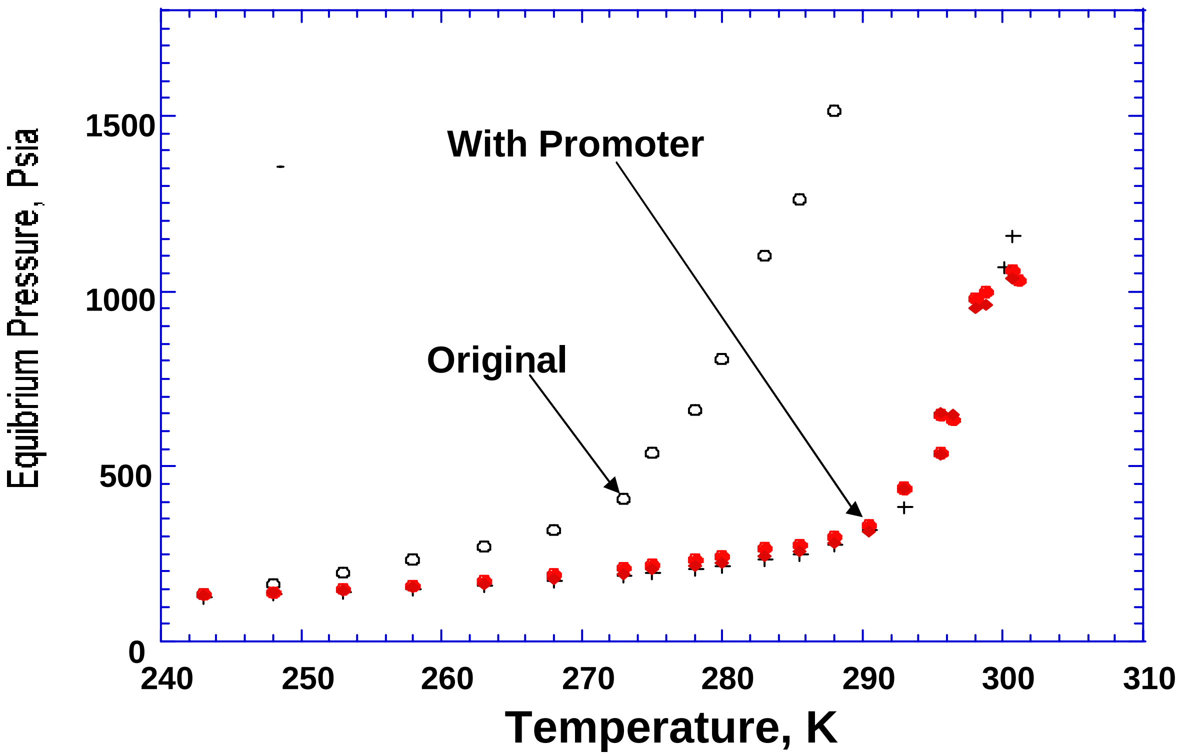


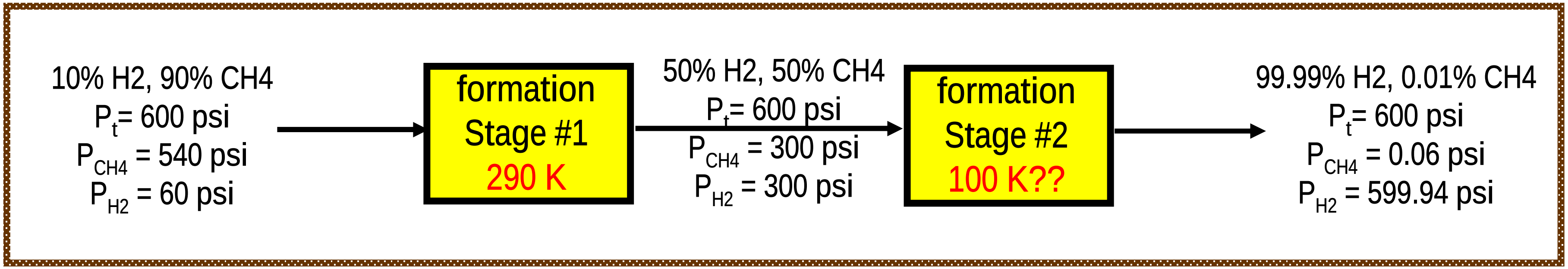
Methane hydrate balls

Methane hydrate powder

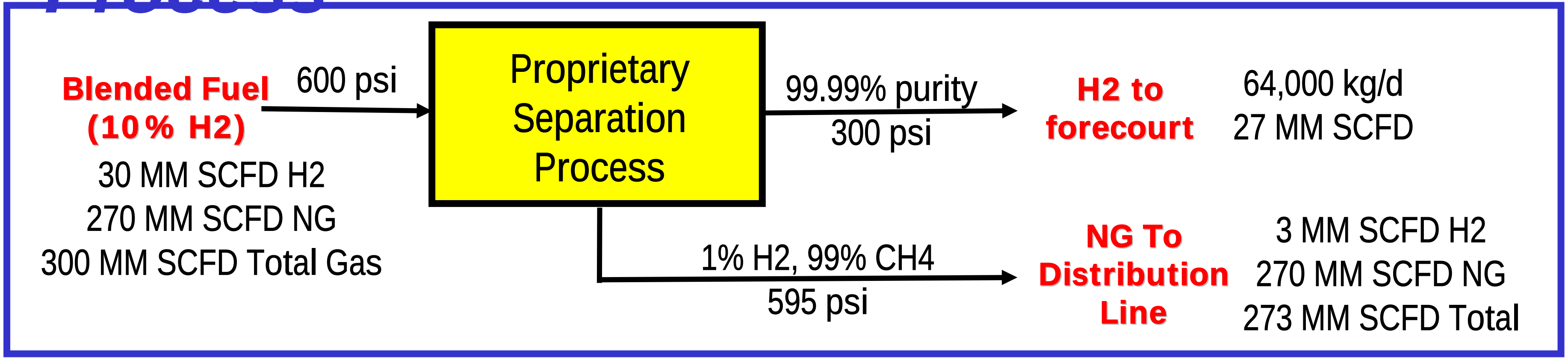
Methane Hydrate Operating Conditions *(from GTI)*

- Equilibrium: at reactor outlet condition
- Extremely low last stage temp: due to very high H2 purity required
- No chance to improve it: dictated by equilibrium
- Not practical to pursue further



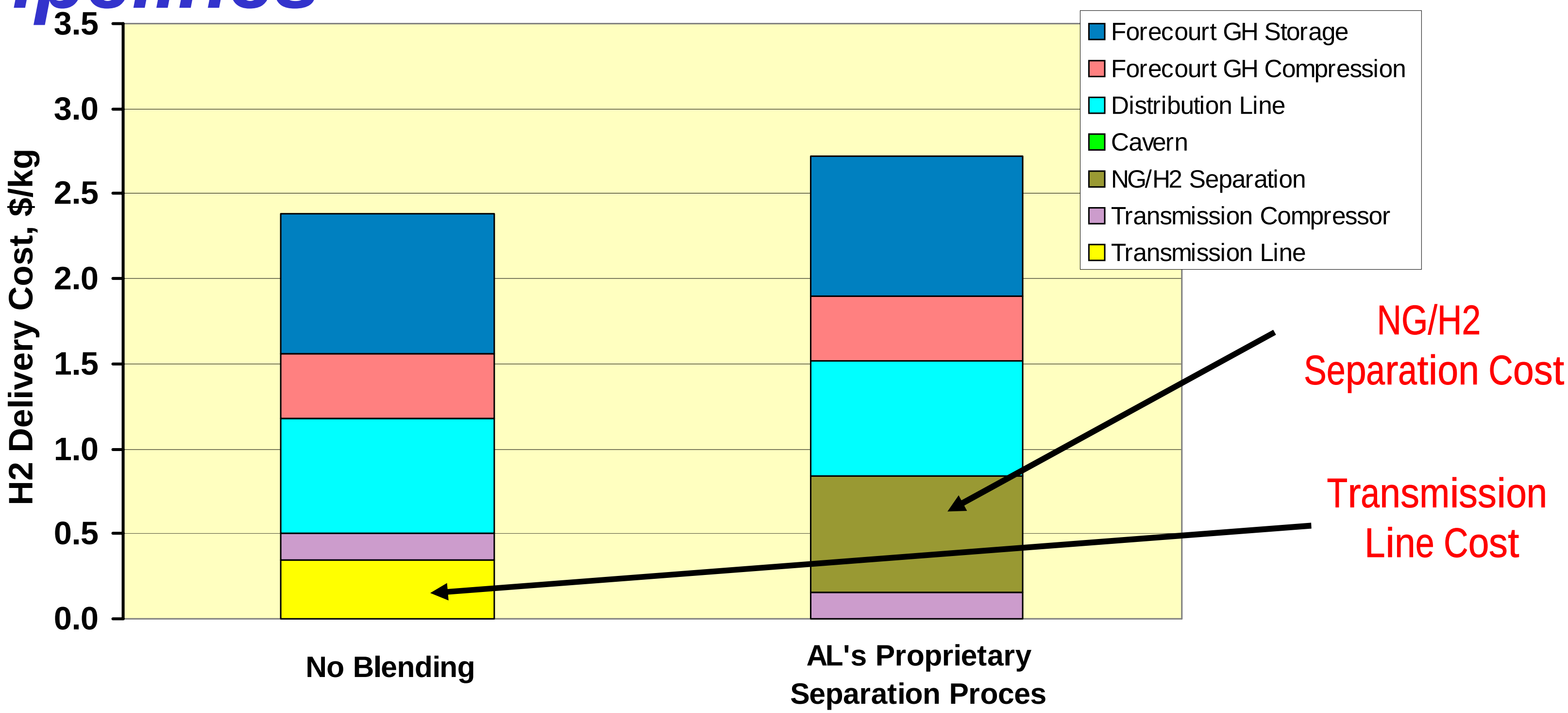


Air Liquide's Proprietary Separation Process



- Can produce high purity H2 from low H2 content blended fuel
- Process components based on mature technologies
- High H2 recovery: 90%
- Only 5 psi pressure loss for NG
- Odorant in NG line: does not show up in the high purity H2 produced
- For 64,000 kg/d H2 delivered to forecourt:
  - capital: $44 million
  - power consumption: 11 MW
  - O&M: $3.7 million

Economics of Blending GH into NG Pipelines



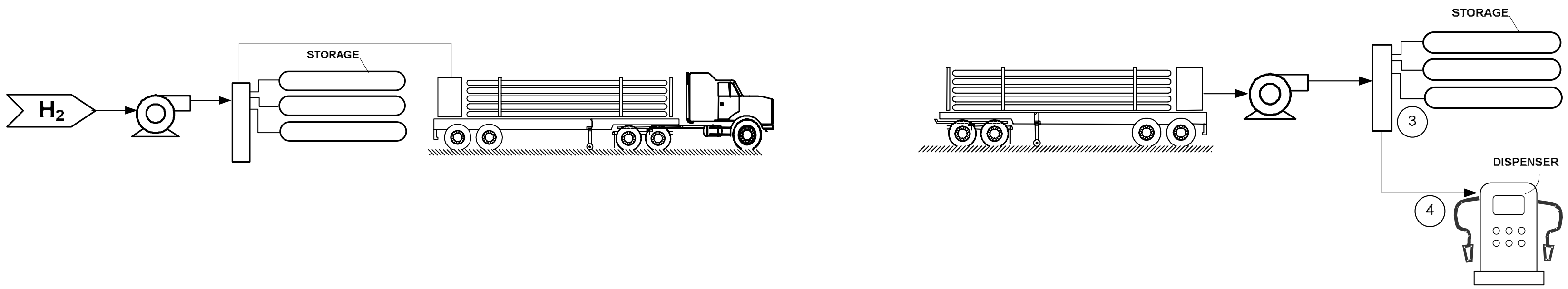
- H2 demand: 27 MMscfd (64,000 kg/d)
- 5000 psig GH on-board storage
- Transmission: 100 miles; 1,000 psi in, 600 psi out
- Forecourt: 43 stations; 300 psi H2 in
- Distribution line: 86 miles

- *AL's process is not economical when central production is 100 mile away from city gate*
- *It becomes cost effective when the central production is >175 miles away from city gate*

Knowledge Collected and Preliminary Results

GH Tube Trailers

GH Tube Trailer Delivery Experience & Issues

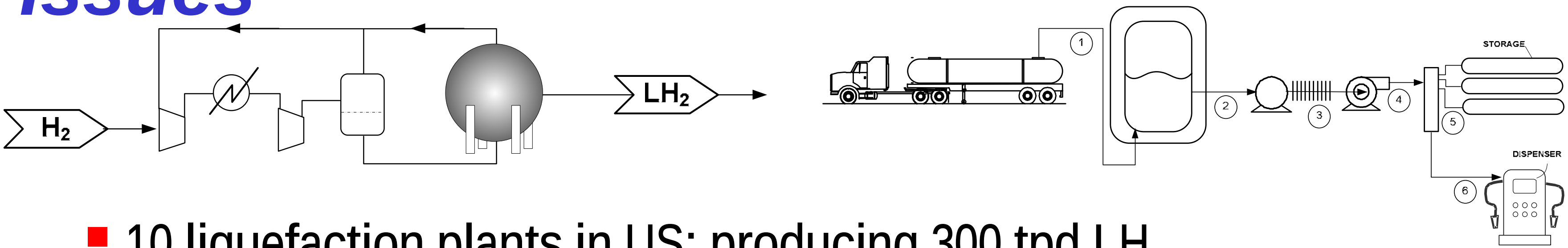


- 1500 tube trailers in services in US
- Tube trailers incorporated in H2A model
  - 2700 psi tube trailer in actual use (carry 9-36 tubes; 20-38' long,; 92 ft3 for 38' tube; 700 lb H2 total; $165K trailer cost)
  - 7000 psi tube trailer being offered (carry 1 tube of composite materials; 918 ft3; 1445 lb H2 total; $350K trailer cost)
- Refill terminal at central production: need 6 day LH storage to cover scheduled /unscheduled shutdown of GH production

Knowledge Collected and Preliminary Results

LH Tank Trucks

LH Tank Truck Delivery Experience & Issues



- 10 liquefaction plants in US; producing 300 tpd LH
- LH tank truck delivery already incorporated in H2A model
  - LH tank truck (deliver 8000 lb H2; $650K trailer cost)
  - Liquefaction plant:: 8-14.5 kWh/kg H2 (refining it as function of plant size)
  - LH pump rather than GH compressor
- Sub-cooled liquid to avoid boil-off during tank truck delivery
- No need of LH distribution terminal
  - 6-10% loss during unloading at terminal
  - LH will be dispatched from central production to forecourt directly
- 3 day storage is sufficient to match forecourt demand profile
- Magnetic liquefaction in development (Prometheus, Astronautics)
  - Can reduce power consumption to 7 kWh/kg H2 (twice of theoretical)
  - Capital is 2/3 of conventional process

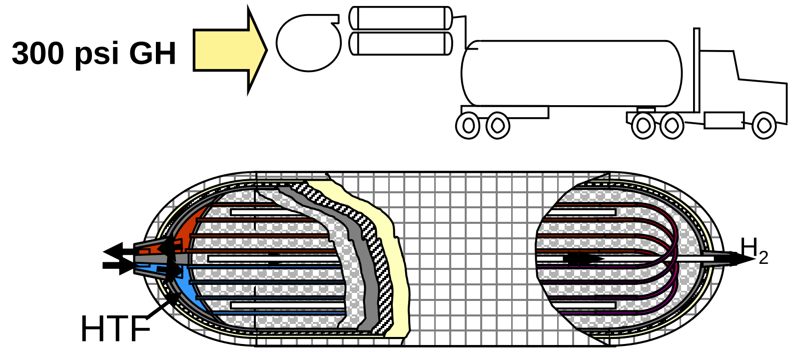
Knowledge Collected and Preliminary Results

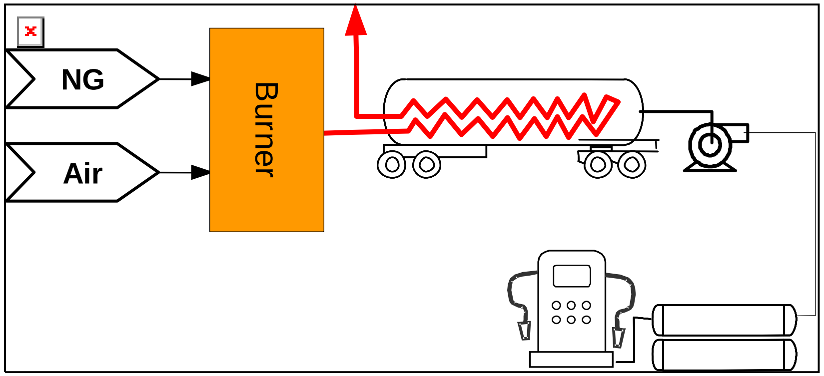
Novel H2 Carriers

Novel Carriers Considered

Technology	Forecourt Processing
▪ Alanate	▪ Dehydrogenate to produce GH
▪ Chemical Hydride	▪ React with H2O to to produce GH
▪ Liquid Hydrocarbon	▪ Pump to on-board fuel tank
▪ Flowable Powder	▪ Pump to on-board fuel tank
▪ Bricks	▪ Load as on-board fuel tank

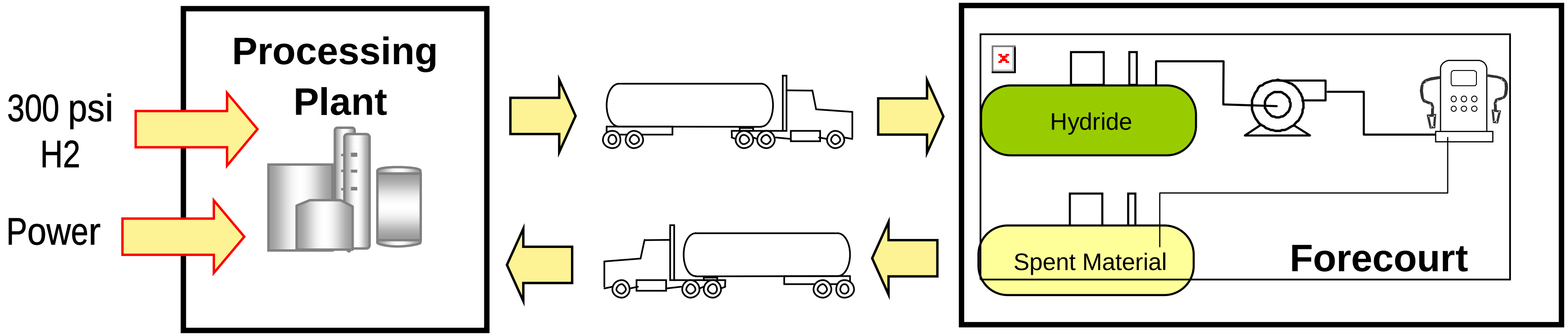
Alanate as Carrier





- Alanate (NaAlH4, LiAlH4, etc.) has high H2 content: 5.5% wt
- Suitable as carrier delivered by tank trucks
- Alanate burns vigorously upon contact with air
- Safer to leave in the trailer after disengaged from cab at forecourt
- Hydrogen is released after being heated at forecourt: process heat required = 6% of H2 energy
- Can match H2 demand profile at forecourt at will
- 1500 kg/d H2 demand at forecourt will require 1 trailers/d (1,500 Kg H2/trailer); minimum parking space required

Chemical Hydride as Carrier

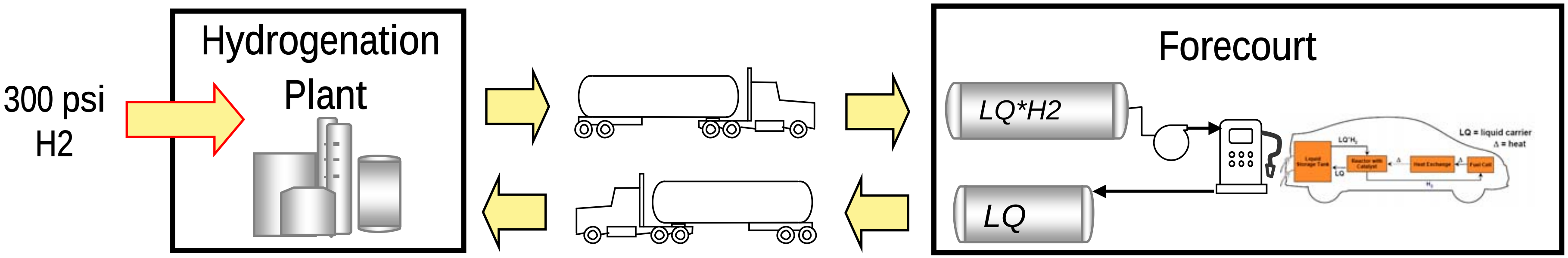


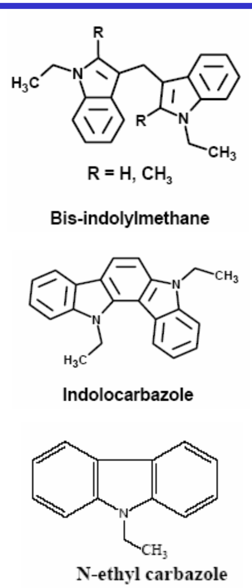
- Chemical hydride water solution reacts over catalyst on-board to release H_2

$$XH_2 + H_2O = XO + 2H_2 \qquad X = Mg, Li, Na, NaB$$

- Hydrogen yield: 7-11%
- Regeneration
  - Electrolytic process
  - Processes of using reducing gases

Liquid Hydrocarbon as Carrier

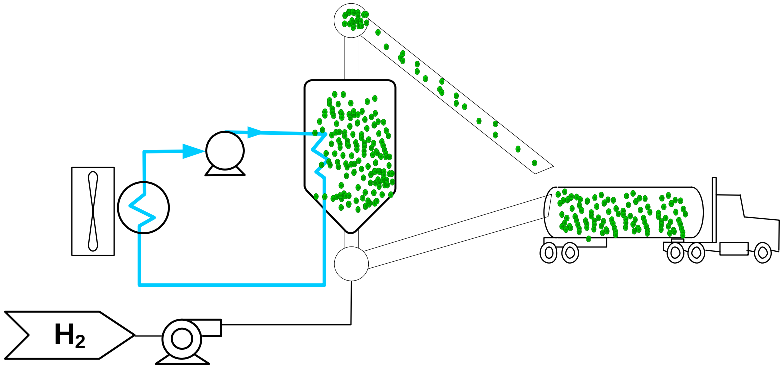




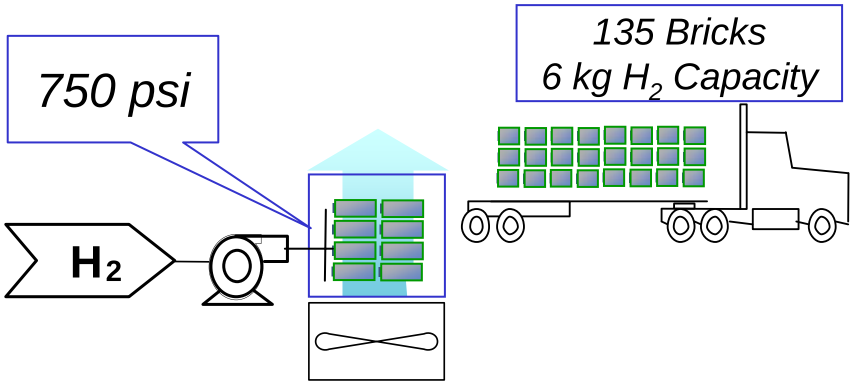
HC carriers explored by Air Products

- Very promising option
  - High H2 content: 5-6.5 wt%
  - Liquids are easier and safer to store
  - On-board storage avoids gas compress
  - No transition issue
- On-board dehydrogenation
  - Desirable to use FC waste heat (80 C); but succeeded so far only for 170 C
  - Intermediate solution: burn part of the on board H2 generated
  - On-going testing of various reactor designs, cyclic use capability, etc.
- Hydrogenation
  - Too complex for forecourt to handle; central processing allows effective use of the heat rejected
  - Operating condition: around 170 C, 1200 psi
  - No extensive tests yet
  - Design & cost estimate bases: Use refinery naphtha hydrogenation experience

Flowable Powder & Bricks as Carrier



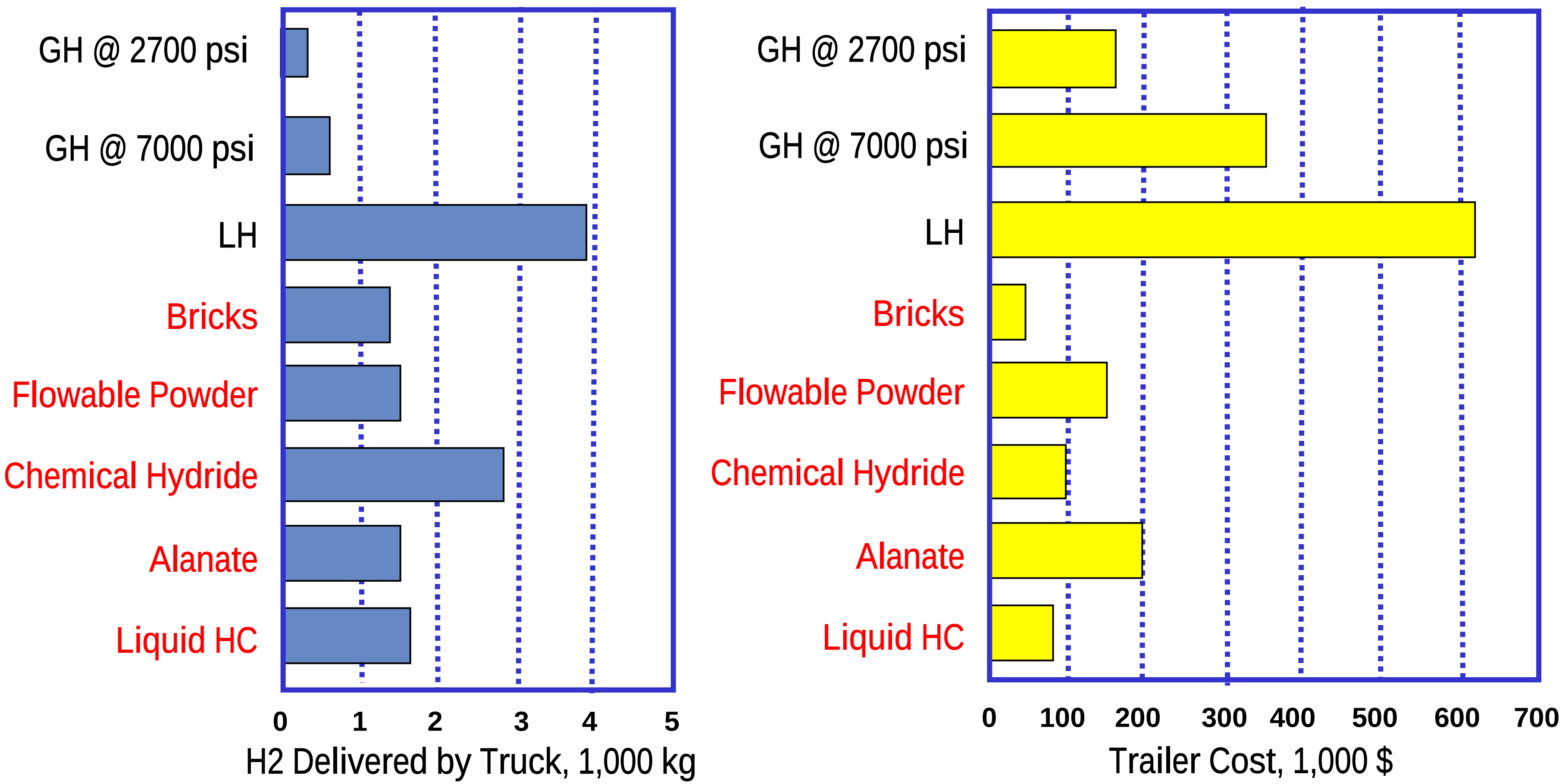
Flowable Powder Charging System



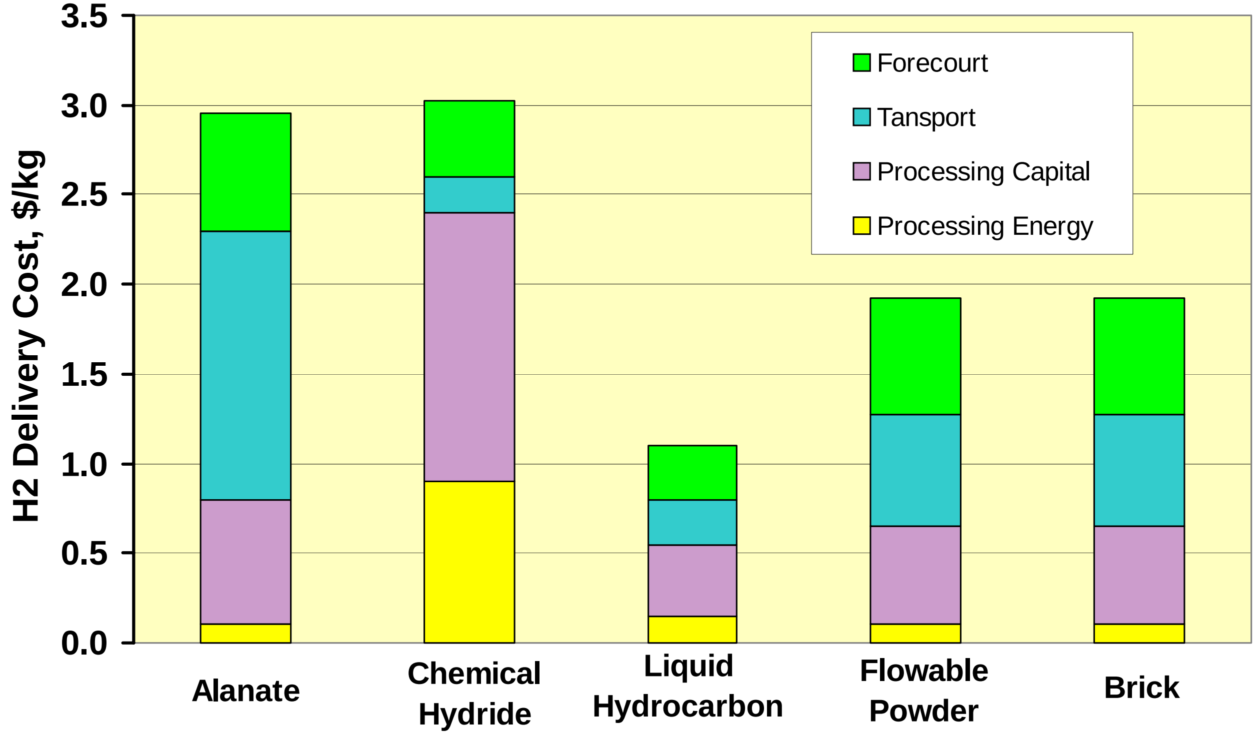
Brick Charging System

- Flowable powders and integrated tank systems (bricks) are options for delivering hydrogen adsorbed on solid materials
- Powder or bricks would be transported by truck
- Performance depends on achieving hydrogen mass storage performance
- Assumed 3.5% and 3% H_2 for powder and bricks, respectively
- Forecourt requires solids transport system, inert gas supply
- Hydrogen recovered from vehicle, presumably with waste heat

Truck Delivery Bases



Comparison of Novel Carriers



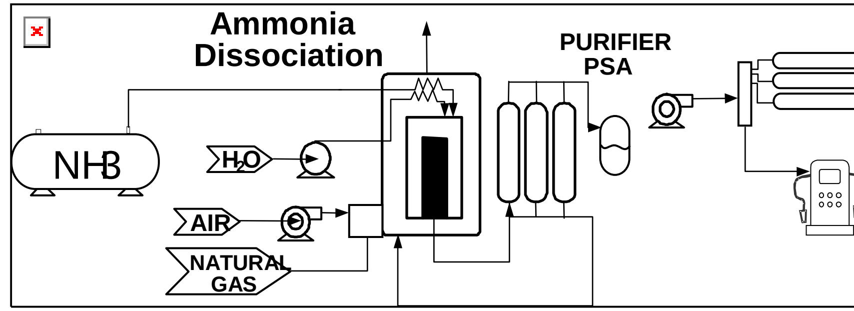
- All cases based on truck delivery from central processing plant 100 miles away from a large city requiring 200 million SCFD (474,000 kg/d) H2
- Liquid HC case might consider pipeline delivery to a city terminal with truck distribution to forecourt if central processing plant is located far away: delivery volume required is 8 times of gasoline
- Liquid HC case is most economical

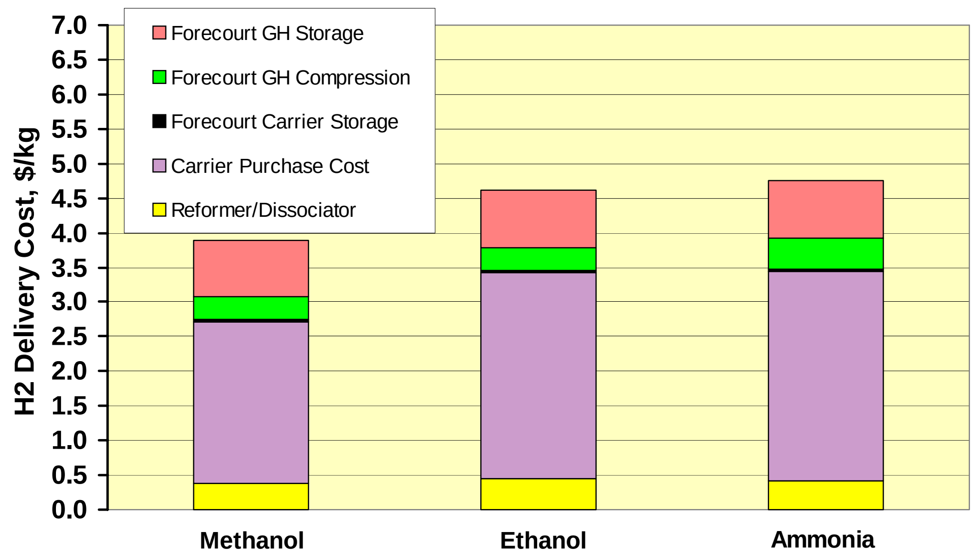
Knowledge Collected and Preliminary Results

Methanol/Ethanol/Ammonia as H_2 carriers

Methanol, Ethanol, Ammonia as Carrier

- On-board conversion to GH not practical, need ground conversion
  - Methanol: steam reforming
  - Ethanol: auto thermal reforming
  - Ammonia: dissociation
- For ammonia, unloading and setback distance at forecourt are major safety issues
- H2 production and delivery cannot be segregated; their economics can be assessed only jointly with the production infrastructure





Purchase cost, $/gallon
- Methanol: 0.95
- Ethanol: 1.55
- Ammonia: 0.76

1500 kg/d forecourt H2 demand; 5000 psi on-board GH storage

Summary of Observations

Summary

- **Forecourt H2 demand profile is a critical factor to consider in selecting delivery options**
- **Marginal cost advantage to convert existing NG/oil pipeline for H2 delivery if transmission line is short**
- **Blending H2 into existing NG line does not pay if the gas transmission distance is short**
- **Liquid hydrocarbons, such as that being developed by Air Products, hold the best promise**

Next Step

Future Activities

Year	Activities
FY2006	▪ Refine preliminary performance and cost estimate above for each delivery option ▪ Generalize the single point estimate as a function of delivery volume and distance ▪ Refine and expand H2A model
FY2007	▪ Evaluate existing H2 delivery infrastructure capability ▪ Estimate emissions for each delivery option ▪ Work with the production team & DOE to recommend hydrogen delivery strategies