Hydrogen Delivery Infrastructure
Option Analysis

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This presentation does not contain any proprietary or confidential information
Presentation Outline

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

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<th>GH delivery by new pipelines</th>
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<td>Converting NG/oil pipelines for GH delivery</td>
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<td>Option 4*</td>
<td>GH tube trailers</td>
</tr>
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<td>Option 5*</td>
<td>LH tank trucks</td>
</tr>
<tr>
<td>Option 6</td>
<td>Use of novel H2 carriers (alanate; chemical hydride; liquid hydrocarbon; metal hydride in powder or brick form)</td>
</tr>
</tbody>
</table>

* Option 7 Methanol/ethanol/ammonia as H2 carriers

* Options already incorporated in the H2A component and scenario models carriers
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
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
  - H2 lines can be installed next to existing oil/NG lines to avoid ROW cost
  - H2 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 H₂ production; while NG resource locations are given & fixed**
  - Coal shipped across country; CO₂ seq. sites all over US
  - Biomass in most states (except those of desert climate)
  - MeOH/NH₃ 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

- **H₂ pipelines are shorter & smaller**
  - Production sites likely close to major cities (<100 miles)
  - 10-18” lines (100,000-500,000 kg/d H₂) vs. 12-48” NG lines
  - Consist with H₂A scenario model

- **Metal distribution lines (300 psi?)**
Current Gas Station Fueling Profile (from Chevron)

<table>
<thead>
<tr>
<th>Day of Week</th>
<th>Sun</th>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of Weekly Sales</td>
<td>12.0%</td>
<td>13.5%</td>
<td>15.0%</td>
<td>14.5%</td>
<td>14.0%</td>
<td>13.5%</td>
<td>12.0%</td>
</tr>
</tbody>
</table>

**Day of Week Sales Profile**

- Friday is the busiest day, and 5pm Friday is the busiest of all hours.
- Tue, Wed, Thu Profiles
  - 2 peaks @ 8 am & 3 pm
  - almost no cars during midnight
- Saturday and Sunday Profile
  - 1 peak @ noon
  - almost no cars during midnight

**24 hour day**

- 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

Transmission line and compression costs are small in comparison with distribution and forecourt costs.
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):

<table>
<thead>
<tr>
<th></th>
<th>Natural Gas</th>
<th>H₂</th>
</tr>
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<tbody>
<tr>
<td>Volume of Gas Delivered (SCFH)</td>
<td>7.0 MM</td>
<td>18.4 MM</td>
</tr>
<tr>
<td>LHV Energy Delivered (BTU/Hr)</td>
<td>6,391 MM</td>
<td>5,060 MM</td>
</tr>
<tr>
<td>Less Compression Energy (BTU/Hr)</td>
<td>(20) MM</td>
<td>(69) MM</td>
</tr>
<tr>
<td>Net Energy Delivered (BTU/Hr)</td>
<td>6,371 MM</td>
<td>4,991 MM</td>
</tr>
</tbody>
</table>

- 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

Transmission line conversion cost is 1/3 of new line (5-50% based on Air Liquide’s Field data)

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

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:

<table>
<thead>
<tr>
<th></th>
<th>NG Spec.</th>
<th>10% mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHV, Btu/SCF</td>
<td>950</td>
<td>940</td>
</tr>
<tr>
<td>Wobbe Index, Btu/SCF</td>
<td>1,300</td>
<td>1,245</td>
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</tbody>
</table>
## Separation Processes Considered

<table>
<thead>
<tr>
<th>Technology</th>
<th>Responsible</th>
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<tbody>
<tr>
<td>PSA</td>
<td>Air Liquide</td>
</tr>
<tr>
<td>Membrane</td>
<td>Air Liquide</td>
</tr>
<tr>
<td>H2 Absorber</td>
<td>TIAX</td>
</tr>
<tr>
<td>Methane Hydrate</td>
<td>GTI</td>
</tr>
<tr>
<td>Proprietary Process</td>
<td>Air Liquide</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Fast</th>
<th>H₂O</th>
<th>He</th>
<th>H₂</th>
<th>NH₃</th>
<th>CO₂</th>
<th>H₂S</th>
<th>O₂</th>
<th>Ar</th>
<th>CO</th>
<th>N₂</th>
<th>CH₄</th>
<th>C₂H₄</th>
<th>C₃H₆</th>
<th>Slow</th>
</tr>
</thead>
</table>

### Membrane Process Flow

- **NG/H₂ Mixture 600 psi**
- **15 psi**
- **Membrane**
- **300 psi**
- **H₂ to forecourt**
- **NG To distribution Line**
- **600 psi**

**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 H₂ from MH
- Key issue: MH deactivation by CH₄ and CO in blended fuel
- Solution: Porous fluorinated layer to allow only small H₂ molecules to reach MH
- Not commercial; cost estimate ongoing
Methane Hydrate Separation Process

(from GTI)

NG/H2 Mixture → venture mixing → hydrate formation → hydrate separator → Methane To NG Distribution Line

- Water recycle
- promoter
- heat

- chiller

H2 distributed to forecourt

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

10% H2, 90% CH4
- $P_t = 600$ psi
- $P_{CH4} = 540$ psi
- $P_{H2} = 60$ psi

formation Stage #1
- $290$ K

50% H2, 50% CH4
- $P_t = 600$ psi
- $P_{CH4} = 300$ psi
- $P_{H2} = 300$ psi

formation Stage #2
- $100$ K??

99.99% H2, 0.01% CH4
- $P_t = 600$ psi
- $P_{CH4} = 0.06$ psi
- $P_{H2} = 599.94$ psi
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

<table>
<thead>
<tr>
<th>Technology</th>
<th>Forecourt Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alanate</td>
<td>Dehydrogenate to produce GH</td>
</tr>
<tr>
<td>Chemical Hydride</td>
<td>React with H2O to produce GH</td>
</tr>
<tr>
<td>Liquid Hydrocarbon</td>
<td>Pump to on-board fuel tank</td>
</tr>
<tr>
<td>Flowable Powder</td>
<td>Pump to on-board fuel tank</td>
</tr>
<tr>
<td>Bricks</td>
<td>Load as on-board fuel tank</td>
</tr>
</tbody>
</table>
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 $H_2$
  \[ XH_2 + H_2O = XO + 2H_2 \quad X = Mg, Li, Na, NaB \]
- Hydrogen yield: 7-11%
- Regeneration
  - Electrolytic process
  - Processes of using reducing gases
Liquid Hydrocarbon as Carrier

- 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 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% H₂ for powder and bricks, respectively.
- Forecourt requires solids transport system, inert gas supply.
- Hydrogen recovered from vehicle, presumably with waste heat.
Truck Delivery Bases

- GH @ 2700 psi
- GH @ 7000 psi
- LH
- Bricks
- Flowable Powder
- Chemical Hydride
- Alanate
- Liquid HC

H2 Delivered by Truck, 1,000 kg

Trailer Cost, 1,000 $
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 H2 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

<table>
<thead>
<tr>
<th>Year</th>
<th>Activities</th>
</tr>
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</table>
| 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 |