DOE Hydrogen Delivery Analysis
and High Pressure Tanks
R&D Project Review Meeting
February 8-9, 2005
Argonne National Laboratory

Hydrogen Delivery Infrastructure Option Analysis

Project Kick Off Meeting

SOW, Budget, Schedule

Tan-Ping Chen

Project Team

- **Real world infrastructure project experience**
  - **Air Liquide**
  - **GTI**
  - **Nexant**
- **Technology forward looking expertise**
  - **Tiax**
  - **NREL**
- **Ultimate users to advise on H2 infrastructure path**
  - **ChevronTexaco Technology Venture (CTTV)**
  - **Pinnacle West (PW)**

Current Gas Station Operation in US

- 220 million cars for 280 million people = roughly 1 car/person
- Gasoline dispensed per station = 2,000 gallons/d
- Gasoline filled in the station = 8-10 gallons/car
- Cars pulled in per station = 200-250/d
- Fueling peaks at the morning and afternoon rush hours
- People do refueling close to home and work place
- The typical driving distance to refueling is 2-3 miles
- Maximum acceptable distance between gas stations on national highway is 25 miles (according to GM)
- 170,000 gas stations in US; 100 major metro areas for 70% population; 120 stations for a large city; 130,000 mile national highway

Vision on H_2 Economy Evolution (1)

- **When crude oil is approaching depletion and its price becomes high, vehicles can still drive with gasoline/diesel derived from tar sand, oil shale, and coal derived liquids for 100-250 years**
- **These alternative gasoline/diesel sources are probably cheaper than hydrogen and, more importantly, does not invoke fueling infrastructure change**
- **H_2 economy will most likely happen only if the government and public mandates GHG reduction and/or zero emissions**
- **By then, if H_2 cost (production & delivery) can be reduced to a level close to the alternative gasoline/diesel cost and meanwhile FCV cost and on-board storage volume can be reduced to acceptable levels, the H_2 economy could take off**

Vision on H_2 Economy Evolution (2)

- **There would be a market penetration threshold level for the H_2 economy to proceed, i.e. enough fueling stations for FCV**
- **Energy companies will invest in these stations only if H_2 and FCV are clearly going to move forward**
- **Nexant team can decide this threshold level in the study based on the maximum acceptable driving time to the station**
- **Government will allow phase-in period of several years for this initial buildup**
- **Gas stations will coexist with H2 stations until the full H2 economy is reached**
- **Before the threshold, there will be commercial stations for technology validation or fleet operations**

Vision on H_2 Economy Evolution (3)

- **GM says that the threshold is 11,700 stations (6,500 & 5,200 for metro areas & highway, respectively) or 7% of existing gas stations, other studies say 10%**
- **Let us use GM's number & 1,000 kg/d H2 dispensed per station (FCV is twice efficient as ICE), we need 11.7 million kg/d H2**
- **If we build large H2 plants at 250,000 kg/d each (100 million scfd), we need 50 plants in US**
- **As the transition to H2 economy will invoke huge investment even for the initial build up, it will accelerate to completion once the energy companies decide to pursue it (similar to the switch from horse carriages to automobiles)**
- **Due to this reason, energy companies will build the production and delivery infrastructure based on a longer term vision to minimize transition waste and cost**

Vision on H_2 Economy Evolution (4)

- **If NG is still available and allowed to be used for many many years at that point, NG pipelines will not be available to ship H2; the possible options are then:**
  - **On-site generation by SR or electrolyzer**
  - **Central H2 plant to deliver LH/GH/H2 carriers by truck/rail/(new) pipeline**
  - **H2 blending into NG pipelines with separation at the end**
- **If NG is close to depletion or not allowed (due to carbon emission) at that point, then the use of NG pipelines for H2 delivery is an additional option but on-site SR is not an option**
- **If NG will be depleted during the course of H2 infrastructure buildup (assume to be over a long duration); then we will face a complex situation**

A Few Notes on H_2 Economy

- On-site generation by solar will mostly not prevail due to huge space required for solar reception; probably also true for wind
- When H2 economy starts, power from RE (especially wind) might be cost competitive with that from FE because FE at that point is expected to be more expensive and have CO2 sequestration cost penalty
- Central production plants could be small if RE is used
- Most REs are harvested only as electricity. The issue is to deliver electricity for on-site H_2 generation or to deliver H_2 directly?
- Oil pipelines will be gradually out of service when H2 economy proceeds; they can be used to transport GH or H2 carriers
- If on-board H_2 storage is not CG, then a whole new ball game

Is Existing NG Network Good for H_2 Delivery?

- **In US: 86,000 miles oil pipelines to 133 refineries, 91,000 miles refined oil pipelines to 1,400 dispatch terminals, 100,000 tank trucks deliver 350 million g/d gasoline/diesel to gas stations, $1 trillion spent on this infrastructure**
- **If FCV is twice efficient as ICE, H_2 demand = 175 million kg/d or 21 trillion Btu/d**
- **NG consumption in US = 700 million NM^3/d or 26 trillion Btu/d**
- **NG when used for H_2 delivery, the capacity is derated by 30%**
- **So, the existing NG network has about the right capacity for H_2 delivery at full H_2 economy**
- **Can use only the transmission/trunk lines; the plastic distribution lines need to be replaced by steel lines, which go only to the H_2 fueling stations**

Questions to Be Answered in This Project

- **Pipeline delivery is the choice at high H_2 demand but:**
  - Are there better options (novel H_2 carriers, methanol/ethanol)?
  - For options still in development, what are their cost reduction potentials?
  - Should DOE fund the R&D for these options?
- **When will the pipeline delivery become the choice?**
  - The threshold demand level required?
  - Transition solutions between the threshold and full H_2 economy?
- **What are the options for rural area?**
- **How to do the transition smoothly at least cost?**
  - Need to also consider the fueling station transition
- **Can we build upon the existing delivery infrastructure?**
- **Just how much are the infrastructure capital requirements?**
  - For both the transition and full H_2 economy periods
  - What R&D should DOE fund to significantly reduce these costs; including the compression/storage at fueling stations ?

Project Assumptions

- **H2 economy will prevail and proceed**
  - ONL is doing dynamic modeling to determine the H2 economy future based on cost competitiveness with other modes of energy supplies, including the supply-demand factors and impacts of policies/regulations/incentives
  - A major objective of our project is to provide good database for various delivery scenarios considered in the dynamic modeling
- **H2 required will be produced only in central plants for delivery to fueling stations** - i.e. excluding on-site production
- **Consider only H2 demand for LDV**
  - Stationary energy can be provided by carbon free power
  - Transportation cannot use carbon free power unless electric car technology is back; there is no C-free fuel for transportation, except H2
  - Why not HDV? H2 fuel for trucks to delivery GH/LH?
  - Why not H2 for stationary if H2 cost can be reduced?

Delivery Options

Option 1: Dedicated pipelines for GH delivery

Option 2: Existing NG/oil pipelines for GH delivery

Option 3: Existing NG pipelines by blending in GH

Option 4: Truck or rail delivery of GH

Option 5: Truck, rail, or pipeline transport of LH

Option 6: Use of novel H2 carriers

Option 7: Methanol/Ethanol as H2 carriers

Project 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

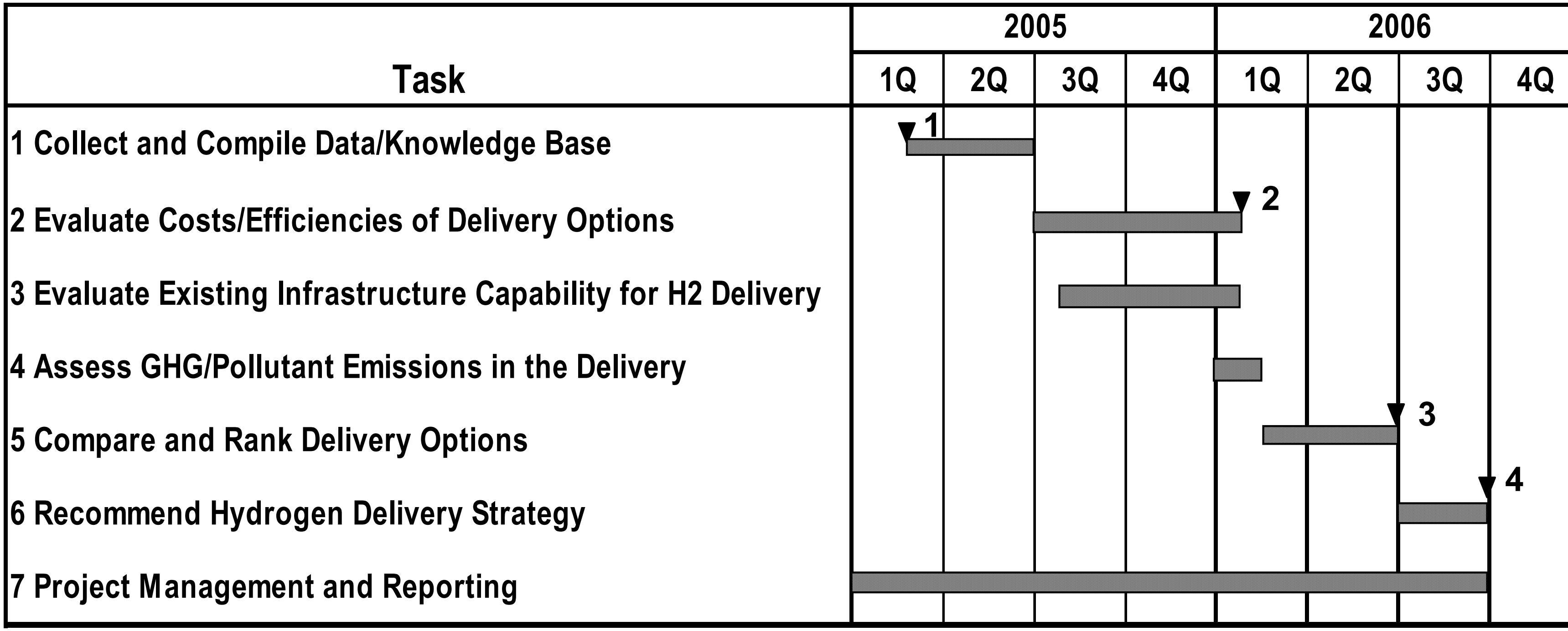
Task 4: Assess GHG and Pollutant Emissions in Each Delivery Option

Task 5: Compare and Rank Delivery Options

Task 6: Recommend Hydrogen Delivery Strategies

Task 7: Project Management and Reporting

Project Schedule



Major Milestones:

1. Project kickoff meeting
2. 1st project review meeting (review results of Tasks 1 and 2)
3. 2nd project review meeting (review results of Tasks 3, 4, and 5)
4. Final project review meeting (review results from Task 6)

Task 1: Collect Data & Knowledge Base

Subtask 1.1: GH/LH delivery by pipeline/truck/rail

Subtask 1.2: NG pipeline

Subtask 1.3: Novel H2 carrier technologies

Subtask 1.4: H2/NG separation technologies

Subtask 1.5: Use of Hythane

Subtask 1.6: Methanol/Ethanol as H2 carrier

Subtask 1.7: Fueling station operation requirements

Subtask 1.8: Previous system analysis/modeling

Subtask 1.1: H2 Pipeline/Truck/Rail Delivery (AL)

GH pipeline

- **Survey of existing lines in US:** location/length/diameter, material, flow rate, pressure, compression station, power consumption, emissions, capital cost, O&M requirements, etc.
- **Project experiences**: leakage prevention, maintenance tools, conversion of oil/gas lines for GH, etc.
- **Issues to address:** H2 embrittlement, codes/standards, odorants, etc.
- **Potential technology improvements:** compressors, new leak detection methods, etc.; key players; improvements potential

GH/LH truck/rail

- **Survey of existing delivery operations in US:** delivery distance/frequency, cart/trailer/tank holding capacity and material, energy consumption for gas compression/liquefaction/delivery, leakage/boil-off, emissions, capital cost, O&M requirements, etc.
- **Potential technology improvements:** light weight/cheaper/better thermal insulation cart/trailer/tank, more efficient liquefaction processes, etc.

Subtask 1.2: NG Pipelines (GTI)

- **Transmission lines**
  - **Survey of existing lines in US:** location/length/diameter, material, flow rate, pressure, compression station, power consumption, leakage, emissions, capital cost, O&M requirements, transaction among pipeline owners, line ages, refurbishment, etc., including network map and relevant statistics
  - **Issues to address:** ability to isolate portion to facilitate H2 transport, how to connect H2 production plants with the NG network; solicit interest and expected returns from line owners to participate in H2 economy; survey of right of way (ROW) for transmission lines
- **Trunk lines & distribution system**
  - **Survey of existing operations in US:** location/length/diameter, material, flow rate, pressure letdown stations, leakage, emissions, capital cost, O&M requirements, interface with pipeline owners, etc.
  - **Issues to address:** ability to isolate portion to facilitate H2 transport; material compatibility to deliver H2; survey of right of way (ROW) in urban area and rural area

Subtask 1.3: Novel H2 Carriers (Tiax)

Class of Processes	Key Developers/Researchers
Reversible: Metal hydrides (such as $LaNi_5$ and Mg_2Ni) Alanates (such as $NaAlH_4$)	**Private:** Ovonics (ECD-Chevron), Ergenics, GfE (Metallurg Inc.), HERA, Advanced Materials, Hydrogen Components, UTRC, U. of Hawaii-SNL **National Labs:** SNL, ORNL, AMES, BNL, LLNL, SRTC, NASA-JPL
Irreversible: Chemical hydrides (such as LiH, NaH, and sodium borohydride)	**Private:** Millennium Cell, Powerball, Safe Hydrogen, Florida Solar Energy Center **National Labs:** ANL, INEEL, ORNL, LLNL, PNNL, LANL, SNL/BNL, SRTC
Advanced Reversible: Carbon nanotubes Boron nitride nanotubes	**Private:** U. of Pennsylvania, U. of Pittsburgh **National Labs:** NREL, ANL, ORNL
Other: Ammonia Sponge iron Naphthalene/decalin	**Private:** Carnegie Mellon University **National Labs:** LANL, ANL, INEEL, SRTC

- Advantages/disadvantages
- Development status (schedule, anticipated advancements)
- Cost/efficiency projection as a function of time
- Key issues/barriers and chance to overcome them

Subtask 1.4: H2/NG Separation Processes

- **Five Technologies:**
  - Pressure swing absorption, PSA (base case) - AL
  - Methane hydrate - GTI
  - Molecular sieve membrane separation - Tiax
  - Hydrogen sorbents, such as metal hydrides - Tiax
  - Metallic and ceramic transport membranes separation – Tiax
- **For each technology:**
  - Advantages/disadvantages
  - Development status (schedule, anticipated progress)
  - Cost/efficiency projection as a function of time
  - Key issues/barriers and chance to overcome them

Subtask 1.5: Use Hythane (PW)

- Hythane is a possible transition solution when FCV is not economically ready yet but there is need to get H2 economy going to eliminate CO2 emission
- If FCV is ultimately not economic, then H2 power ICE might be solution for GHG reduction/energy independence, even though not totally pollution free
- If NG/H2 is piped in together, homes/offices need to use Hythane as well; thus, Hythane may be practical only by blending in H2 into CNG at the fueling station
- Evaluate impacts of hythane use in ICE and power generation units: efficiency, emissions
- Review tests by Ford, GE, etc.
- Estimate equipment conversion costs

Subtask 1.6: MeOH/EOH as H2 Carrier (Nexant)

- **Large plants to produce MeOH/EOH from coal, NG, grains**
  - **Efficiency**
  - **Capital**
  - **O&M cost**
- **Existing pipelines/truck/rail used to transport methanol/ethanol**
- **Compact units at fueling station to reform methanol/ethanol to H2**
  - **Key players**
  - **Development status**
  - **Projected efficiency, capital, & O&M cost as a function of time**

Subtask 1.7: Fueling Station Operation (CTTV)

- **Number and locations of gas stations in US**
- **Typical gas station operation**
  - **Amount of gasoline dispensed per day**
  - **Frequency/time of the day for vehicles to come in for refueling**
- **The data will be used for:**
  - **A first cut estimate of the number and locations of H2 stations in US for a given market penetration level**
  - **Part of the determination for a representative H2 delivery distance to the H2 station**
  - **Sizing H2 storage requirements at the fueling station for each delivery option**

Subtask 1.8: Previous System Model (NREL, Tiax)

- **Hydrogen delivery options evaluated previously**
- **Efficiencies, costs, and emission data developed for the various options evaluated**
- **The system models developed in terms of database and methodology used (H2A, ANL, ONL, UC Davis, etc.)**
- **Delivery strategies recommended in the previous work**

Task 2: Current/Future Efficiencies and Costs

- **Subtask 2.1: Establish analysis basis (Nexant)**
  - Common starting point: 300 psig GH at production site, CG on FCV @10,000 psig (??)
  - System components include special requirements for each option to put all options on equal basis for comparison
  - Determine H2 production plant locations based on the energy resources available and the ability to do CO2 sequestration (in case of fossil fuel based) in different regions of US
  - Delivery volumes and distances: function of market penetration level, fueling station location (metro, highway, rural), and H2 production location
  - Cost estimate & economic analysis bases: same as H2A? Energy costs: function of penetration level??
- **Subtask 2.2: System design (Nexant, supported by AL, GTI, Tiax)**
  - Component sizing
  - Rating/performance changes if modifying existing fuel delivery systems
  - Utilities (power, fuel, water), chemicals/catalysts, etc. required
  - Develop generalized formula as function of H2 delivery volume and distance
  - Evaluate options and tradeoffs to reduce compression/storage cost at fueling stations
- **Subtask 2.3: Cost estimate (Nexant, supported by AL, GTI, Tiax)**
  - Component capital and O&M costs
  - Develop generalized formula as function of H2 delivery volume and distance

Task 3: Existing Infrastructure Capability

- Summarize capacities of existing H2 pipelines and LH/GH truck/rail delivery in US (AL)
- Estimate H2 delivery capacities by existing NG/oil pipelines in US thru:
  - Converting NG/oil lines to H2 lines (AL, GTI)
  - Blending in H2 into NG lines with separation at end – for transition period only (Tiax, AL)
  - Use NG/oil lines to transport methanol/ethanol or novel H2 carriers (Nexant, Tiax)
- Compare with the projected H2 demand buildup to determine the additional new infrastructure required (Nexant)
- Estimate the total capital required to modify the existing infrastructure (Nexant)

Task 4: GHG/Pollutant Emissions (Nexant)

- Life cycle approach to trace the emissions to the origin of the energy supply
- Power consumption in the delivery will be analyzed based on both fossil and renewable energy sources
- Develop generalized formula for the emissions as data base input to the delivery models
- Estimate total H2 leakages along the delivery chain to see whether it will reach the level for ozone destruction indicated by California Institute of Technology

Task 5: Rank Delivery Options

- **Expand NREL/ANL delivery models to include all the options considered and any supplemental database (NREL)**
- **For various combinations of market penetration levels and urban/rural scenarios, use the expanded models to crank out capital cost, O&M cost, delivery cost of H_2, and emissions for each delivery option (NREL)**
- **Rank and select the suitable options for various combinations of market penetration levels and urban/highway/rural scenarios (Nexant)**

Task 6: Recommend H2 Delivery Strategy

- **Estimate the cost required to build up the infrastructure (Nexant)**
- **Recommend the strategy (Nexant, CTTV, PW, NREL):**
  - **Options to take at different market penetration levels and for urban/rural scenarios**
  - **How to build upon existing infrastructure**
  - **How to do the transition at least cost**
  - **R&D to be funded by DOE**

Task 7: Project Management/Reporting *(Nexant)*

- Quarterly progress report to DOE?
- Topic report to DOE for Tasks 1-2
- Topic report to DOE for Tasks 3-5
- Final report at end of Task 6; including the delivery scenario/dynamic model

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 GHG and Pollutant Emissions in Each Delivery Option
Task 5: Compare and Rank Delivery Options
Task 6: Recommend Hydrogen Delivery Strategies
Task 7: Project Management and Reporting

Project Budget

- Proposed budget split between 2005 and 2006:

FY	Budget, $							
	Nexant	AL	GTI	TIAX	PW	CTTV	NREL	Total
2005	580,102	146,380	176,528	190,751	20,300	70,744	60,240	1,245,044
2006	129,800	15,820	8,857	15,042	9,500	35,280	62,160	276,459
Total	709,901	162,200	185,385	205,793	29,800	106,024	122,400	1,521,503

- AL, GTI, and Tiax will do bulk of their work in 2005
- PW, CTTV, and NREL, on the other hand, have significant amount of work in 2006
- Overall: 80% in 2005, 20% in 2006; based on 15 month schedule (2/1/05 to 4/30/06)
- Now, it is 19 month (3/1/05 to 9/30/06), budget reallocation necessary?

Summary/Action Items

- **Major changes from original SOW**
  - Reduced efforts in Tasks 1-5 due to some work already done by H2A
  - Expand Task 6 to include estimate of delivery infrastructure cost in US
  - Determine strategy based on % market penetration (1, 5, 10, 30, 70, 100%) rather than Year
  - Expand Subtask 2.2 to evaluate options and tradeoffs to reduce compression/storage cost at fueling stations
- **Coordinate with production infrastructure teams**
  - In the transition period, on-site generation (probably by reforming) to avoid building delivery infrastructure might be attractive when NG price is still reasonable; but the final conversion of fueling stations to use delivered H2 might be difficult.
  - If the delivery cost is too high or building the delivery infrastructure is cost prohibitive, on-site generation (probably by electrolysis) might be attractive in the full H2 economy period
  - How to coordinate with the production infrastructure teams to determine the overall strategy for H2 economy? Joint analysis for Tasks 5 & 6?
- **Next review meeting?**

Homework to Do

- Check with Air Products on H2 compressor up to 12,000 psig; issues involved, availability, vendors, chance for improvements
- Can liquid pump also handle this kind of delivery pressure?
- Get to EIA's web site on the energy resources and consumption rates (not just US but worldwide)