Analyses of Hydrogen Storage Materials and On-Board Systems

Project ID # ST002

Updated Cryogenic and Compressed Hydrogen Storage System Cost Assessments

DOE Annual Merit Review
June 7-11, 2010

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Reference: D0268

Timeline

- Start date: June 2004
- End date: Sept. 2010
- 90% Complete

Barriers

- A. System Weight and Volume
- B. System Cost
- K. System Life Cycle Assessments

Budget

- Total project funding
  - DOE share = $1.8M
  - No cost share
- FY09 = $261k
- FY10 = $300k

Collaboration

- Design and performance assessment: Argonne and other National Labs
- Technical input: Centers of Excellence and other developers
- Review: Tech Teams and other stakeholders

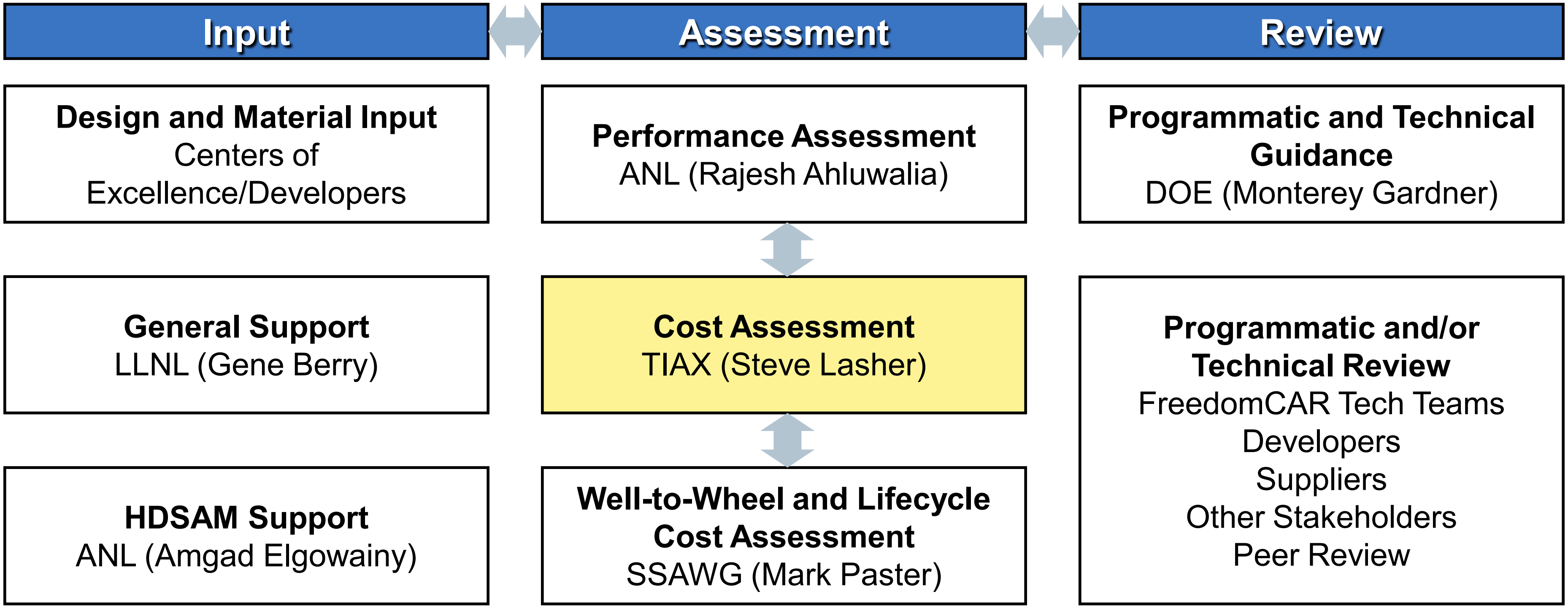
This project provides an independent cost assessment of the hydrogen storage technologies being developed for the DOE Grand Challenge.

Project Objectives	Description	Barriers Addressed
Overall	Help guide DOE and developers toward promising R&D and commercialization pathways by evaluating the status of the various on-board hydrogen storage technologies on a consistent basis	Develop and demonstrate viable H_2 storage for transportation applications
On-Board Storage System Assessment	Evaluate or develop system-level designs for the on-board storage system to project: 1) Bottom-up factory cost 2) Weight and volume (ANL lead)	A. System Weight and Volume B. System Cost
Off-Board Fuel Cycle Assessment	Evaluate or develop designs and cost inputs for the fuel cycle to project: 1) Refueling cost 2) Well-to-Tank energy use and GHG emissions (ANL lead)	K. System Life Cycle Assessments

Last year's objective was to evaluate a MOF-based system and update our other cryogenic and compressed storage assessments.

Past Year Objectives	Description	Barriers Addressed
On-Board Storage System Assessment	Evaluate bottom-up factory cost, weight and volume for the following: 1) MOF177 tanks (preliminary) 2) LH_2 tanks (finalize) 3) Cryo-compressed tanks (update) 4) 350 and 700 bar tanks (update)	A. System Weight and Volume (ANL lead) B. System Cost (TIAX lead)
Off-Board Fuel Cycle Assessment	Review cost assessment of Ammonia Borane (first fill only) and work with SSAWG to evaluate well-to-tank energy use and GHG emissions for the following: 1) MOF177 tanks (preliminary) 2) Cryo-compressed tanks 3) 350 and 700 bar tanks 4) Cold gas (preliminary)	K. System Life Cycle Assessments (SSAWG lead)

We collaborate with various partners to ensure our assessments are consistent, transparent and relevant.



Input	Assessment	Review
Design and Material Input Centers of Excellence/Developers	**Performance Assessment** ANL (Rajesh Ahluwalia)	**Programmatic and Technical Guidance** DOE (Monterey Gardner)
General Support LLNL (Gene Berry)	**Cost Assessment** TIAX (Steve Lasher)	**Programmatic and/or Technical Review** FreedomCAR Tech Teams Developers Suppliers Other Stakeholders Peer Review
HDSAM Support ANL (Amgad Elgowainy)	**Well-to-Wheel and Lifecycle Cost Assessment** SSAWG (Mark Paster)	

The on-board cost and performance assessments are based on detailed technology review and bottom-up cost modeling.

Technology Assessment

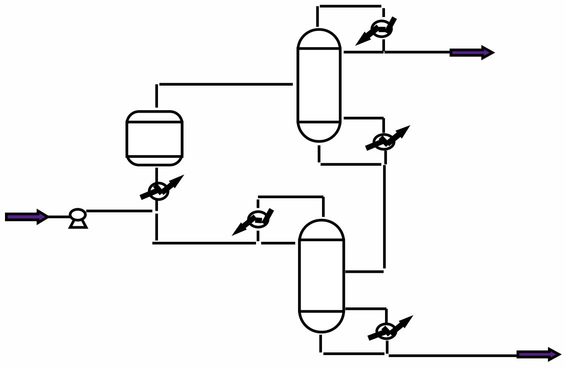
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Design Assumptions
- Obtain Developer Input

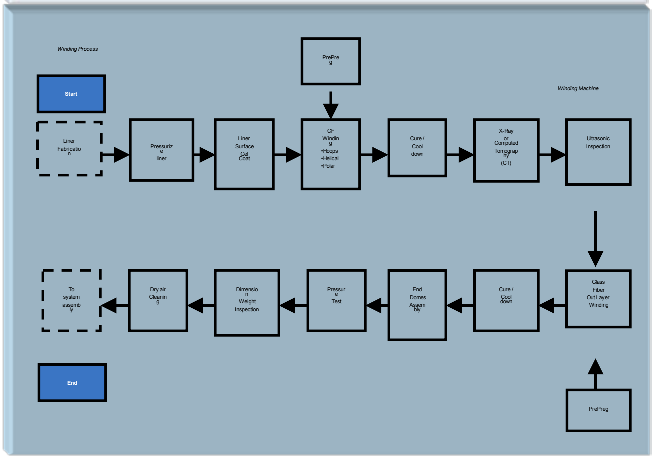
Cost Model and Estimates

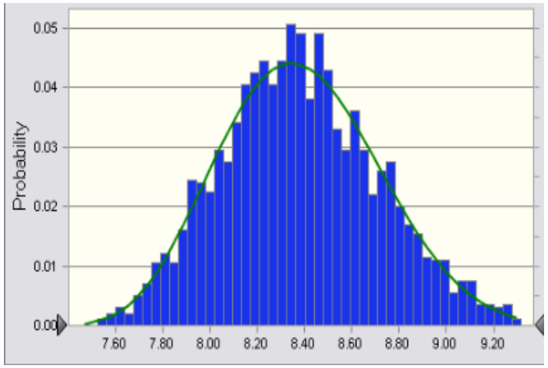
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Processing Costs
- Develop Bulk Cost Assumptions

Overall Model Refinement

- Obtain Developer and Industry Feedback
- Revise Assumptions and Model Inputs
- Perform Sensitivity Analyses (single and multi-variable)



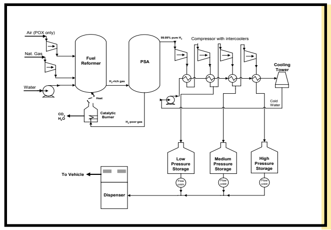




BOM = Bill of Materials

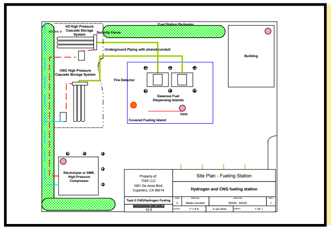
The off-board assessment makes use of existing models to calculate cost and performance for each technology on a consistent basis.

Conceptual Design



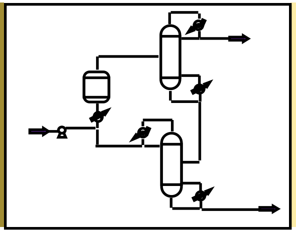
- System layout and requirements

Site Plans



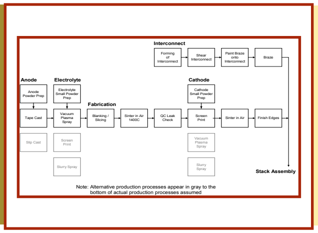
- Safety equipment, site prep, labor and land costs

Process Simulation



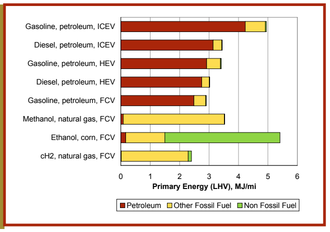
- Energy requirements
- Equipment size/specs

Capital Cost Estimates



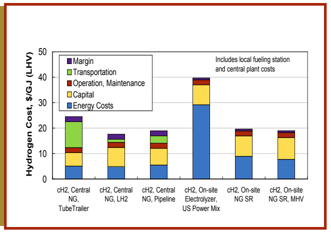
- High and low volume equipment costs

ANL/GREET Model



- WTT energy use
- WTT GHG

TIAX/H2A Model



- Equivalent hydrogen selling price

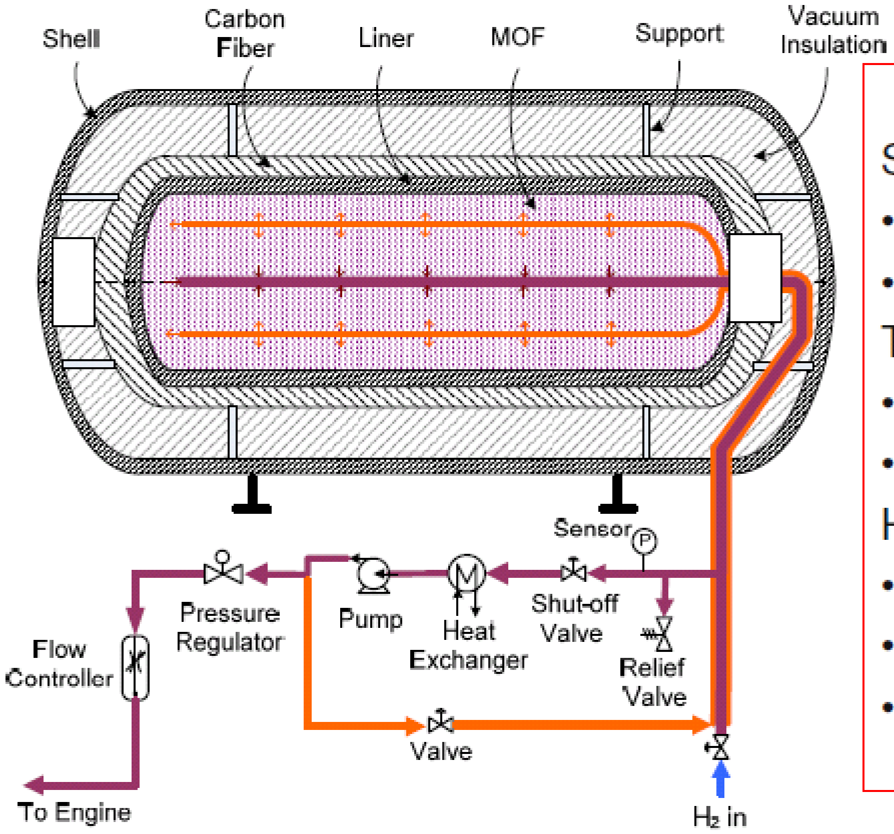
We conducted on-board assessments of MOF177, liquid, cryo-compressed, and compressed hydrogen systems since the last Review.

- Completed preliminary, high-volume (500,000 units/yr) on-board system factory cost assessments of MOF177 and liquid hydrogen tank systems[1]
  - MOF177 = \$12 and \$16/kWh for 5.6 and 10.4 kg useable H_2
  - LH_2 = \$8.0 and \$5.4/kWh for 5.6 and 10.4 kg useable H_2
- Finalized high-volume on-board system factory cost assessments of cryo-compressed and compressed tank systems[1]
  - Cryo-compressed = \$12 and \$8.4/kWh for 5.6 and 10.4 kg useable H_2
  - 350 bar = \$13/kWh for 5.6 kg useable H_2
  - 700 bar = \$20/kWh for 5.6 kg useable H_2
- Worked with Mark Paster and other Storage Systems Analysis Working Group (SSAWG) members to evaluate well-to-tank energy use and GHG emissions for the following[1]:
  - MOF177 tanks (preliminary)
  - Cryo-compressed tanks
  - 350 and 700 bar tanks
  - Cold gas (preliminary)
- Completed review of Dow's latest Ammonia Borate 1st fill cost projections

[1] Based on ANL's performance assessment and input from industry.

We used on-board system definitions and designs developed by ANL[1] as the basis of our factory cost assessments.

MOF177 On-Board Storage System – Adiabatic Liquid H_2 Refueling



Key System Requirements

Storage Medium

- 5.6 kg recoverable H_2
- 4-bar minimum delivery P

Type-3 Containment Vessel

- 2.25 safety factor
- 5,500 P and T cycles

Heat Transfer System

- 1.5 kg/min H_2 refueling rate
- 1.6 g/s H_2 min flow rate
- 1.3 W in-leakage rate through MLVSI

Source: Argonne National Laboratory[1]

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[1] R K Ahluwalia, T Q Hua and J-K Peng, "On-Board and Off-Board Performance of Hydrogen Storage in Metal-Organic Frameworks", Storage System Analysis Working Group Meeting, 24 February 2010

Example of key design assumptions for the MOF177 tank system:

Design Parameter	Base Case Value	Basis/Comment
Sorbent material	MOF177	Design assumption
Nominal pressure	250 bar	ANL design assumption; optimized for storage densities
Minimum (empty) pressure	4 bar	Design assumption; required to meet DOE delivery pressure target
Usable LH_2 storage capacity	5.6 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range for midsized (5.6 kg) and larger vehicle (10.4 kg)
Recoverable hydrogen (fraction of stored hydrogen)	95%	ANL calculation based on hydrogen storage density at maximum and minimum pressure and temperature conditions
Tank size (water capacity)	91 L	ANL calculation for 5.6 kg useable H_2 capacity (5.9 kg total H_2 capacity)
Safety factor	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure
L/D ratio	2.0	Consistent with other cryo-tank assessments and discussions with LLNL and SCI, 2008; based on the outside of the CF wrapped tank
Carbon fiber type	Toray T700S	Discussions with LLNL, Quantum and other developers, 2008; assumed to have a composite strength of 2,550 MPa for 60% fiber by volume
Translation strength factor	86%	ANL assumption based on discussions and data from Quantum, 2004-09
Tank liner thickness	8.6 mm Al	ANL calculation based on cycle analysis for AL6061-T6 alloy, 5,500 PT cycles, 125% NWP
Insulation type	MLVSI	Aluminized Mylar sheets, Dacron spacer, 10^{-5} torr
Minimum temperature	-173 ºC	ANL design assumption; optimized for storage density
Vacuum gap	12.7 mm	ANL calculation to achieve ~1.3 W heat transfer rate with MLVSI
Outer shell	3.2 mm Al	Discussions with LLNL and industry, 2008-10

We based the cost of purchased raw materials on raw material databases and discussions with suppliers.

Raw Material Cost Estimates, $/kg	Base Cases	Comment/Basis
Hydrogen	3.0	Consistent with DOE H_2 delivery target
MOF177	15.4	Based on the high-volume price projection for AX21; high-volume projections for MOF177 are not available
Aluminum (6061-T6)	9.6	Bulk price from Alcoa (2009)
Carbon fiber (T700S) prepreg	36.6	Discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb, $13/lb base case); 1.27 prepreg/fiber ratio (Du Vall 2001)
Multi-layer vacuum insulation (MLVI)	50 ($0.15/ft^2)	Discussion with MPI (2007)
Stainless steel (304)	4.7	Average monthly costs from Sep ’06 – Aug ’07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Standard steel	1.0	Estimate based on monthly costs for 2008-2009 (MEPS International 2009)

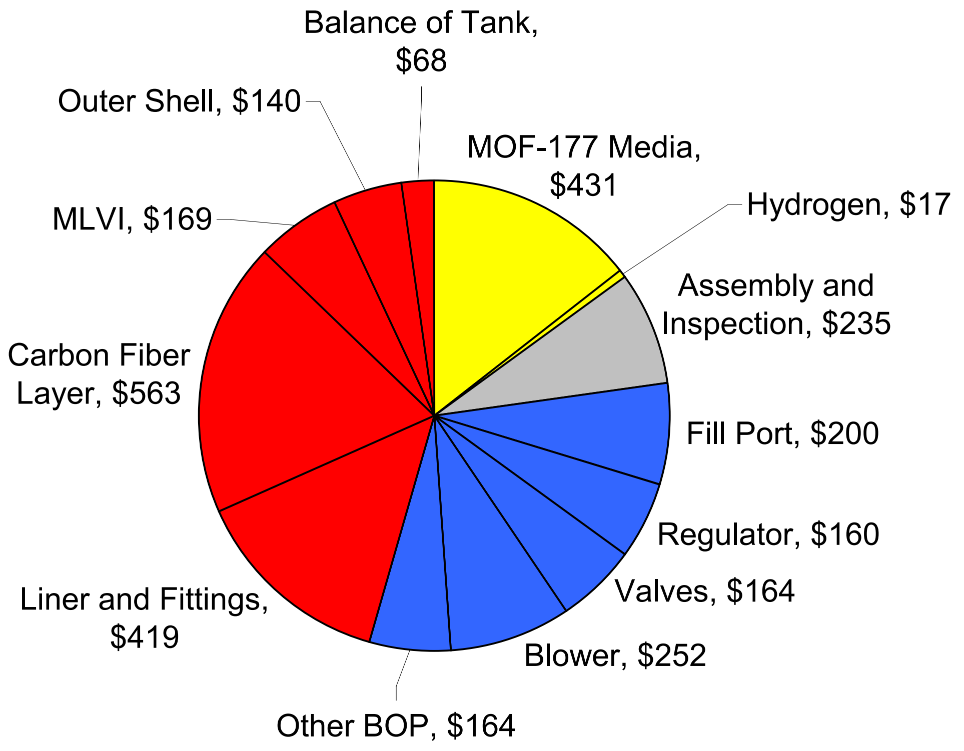
In the case of MOF177, high-volume raw material price projections are not available, so a substitute material price projection was used.

Material and processing cost are estimated assuming high-volume manufacturing (i.e., 500,000 units/yr) for each storage technology.

MOF177 Base Case Factory Cost	Material Costs	Processing Costs
Hydrogen	$17	(purchased)
MOF177	$431	(purchased)
Cryogenic Vessel	$1,117	$242
Liner & Fittings	*$319*	*$100*
Carbon Fiber Layer	*$537*	*$26*
MLVI	*$62*	*$106*
Outer Shell	*$131*	*$9*
Balance of Tank	*$68*	*(purchased)*
Fill Port	$200	(purchased)
Regulator	$160	(purchased)
Valves	$164	(purchased)
Blower	$252	(purchased)
Other BOP	$164	(purchased)
Final Assembly & Inspection	-	$235
Total Factory Cost	**$2,505**	**$477**

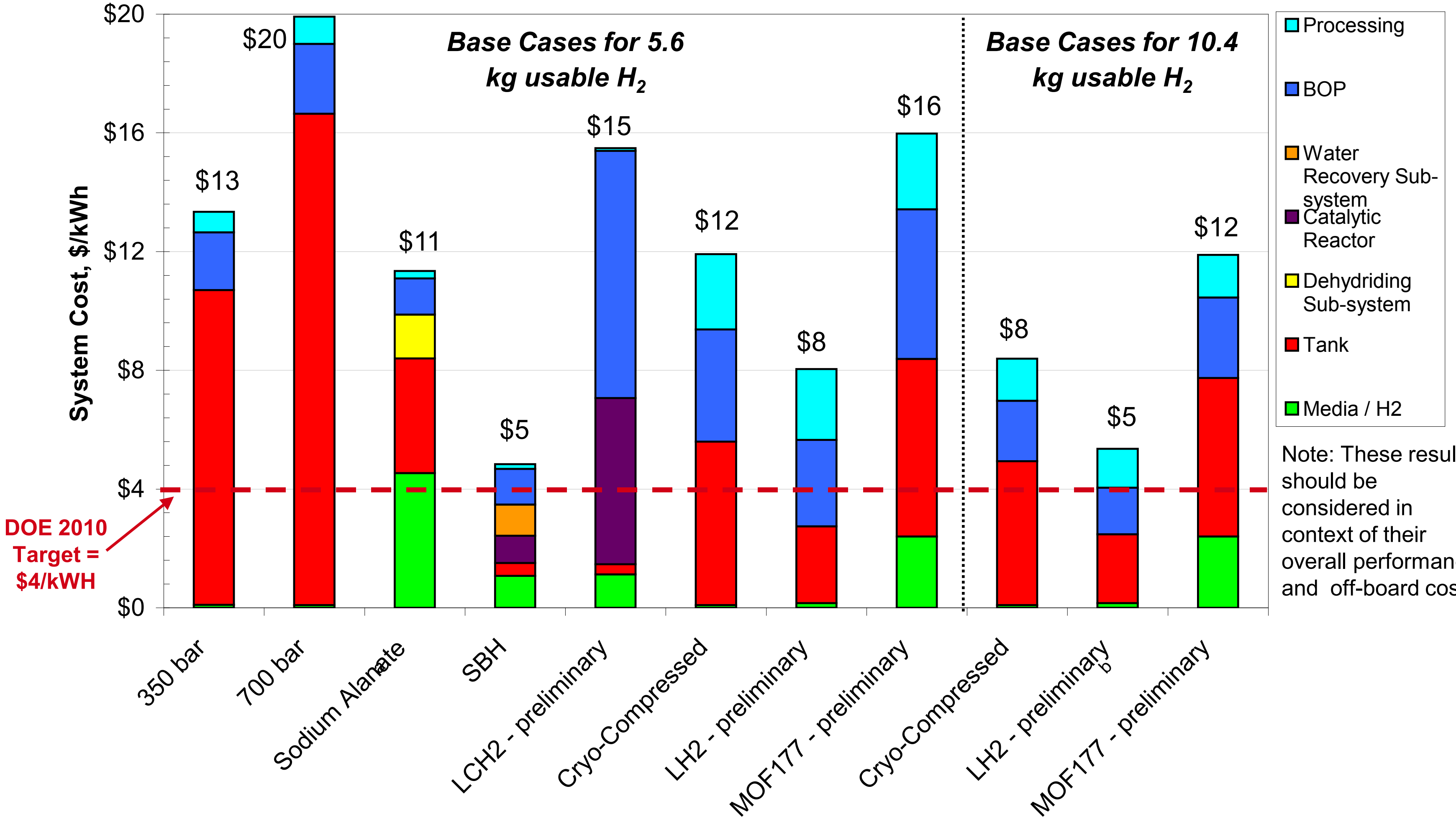
MOF177 Base Case Factory Cost[1] = $2,982

$16.0/kWh based on 5.6 kg usable LH_2



[1] Cost estimate in 2005 USD. Includes processing costs.

Compressed, cryo-compressed, LH_2 and MOF177 costs are projected to be 2 to 5 times higher than the 2010 target for 5.6 kg systems.



Note: These results should be considered in context of their overall performance and off-board costs.

Note: not all hydrogen storage systems shown are at the same stage of development, and each would have different on-board performance characteristics.

[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

[b] The larger tank (10.4 kg useable H2) LH2 case is not applicable for most vehicular application due to its excessive volume.

These results should be considered in context of their overall well-to-wheel performance and lifecycle costs.

15% Mkt. Penetration G NG	WTW Hydrogen Cost ($/kg)	WTW Energy Efficiency (%)	WTW Ownership Costs ($/mile)	WTW GHG (gms/mile)	Volume Efficiency (gms-H2/L)	Storage System Cost $/vehicle
350 Bar P-T5000	$4.84	56.7	$0.13	197	17.8	$2,499
700 Bar P-T5000	$5.22	54.2	$0.16	209	25.6	$3,730
CcH2 LH2 Truck	$4.89	40.3	$0.12	296	41.8	$2,219
Cold Gas P-T5000	$4.60	52.2	$0.14	219	27.1	$3,431
MOF 177	$4.89	40.1	$0.15	297	33.9	$3,577
Conventional Gasoline Vehicle	$2.30-$3.00/gal (1)		$0.07-$0.09	~330		
Hybrid Gasoline Vehicle	$2.30-$3.00/gal (1)		$.04-$.05	~210		

Source: Mark Paster[1]

We collaborated with the SSAWG to evaluate a hand-full of technologies based on WTW efficiency, GHG emissions, and ownership cost. These results will be presented by Mark Paster later in this session.

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[1] M. Paster, et al, "SSAWG Base Case Storage Systems WTW Analysis", Storage System Analysis Working Group Meeting, April 2010

Last year, we collaborated closely with ANL and numerous developers and other stakeholders participating in the DOE Grand Challenge.

- Argonne National Laboratory (ANL)
  - Frequent email exchanges and monthly conference calls with DOE
  - MOF177, LH_2, Cryo-compressed, 350 and 700 bar on-board system designs
- Storage Systems Analysis Working Group, including H_2 Storage Centers of Excellence, Ford, GM, ANL, DOE, Mark Paster
  - Presented at monthly SSAWG conference calls and meetings
  - SSAWG reviewed assumptions and results for various technologies
  - Worked with Mark Paster and others on Cold Gas off-board assessment and WTW/Lifecycle Cost assessments for MOF177, Cryo-compressed, 350 and 700 bar
- Stakeholders (FreedomCAR Tech Teams, BMW, LLNL, Quantum, etc.)
  - Email exchanges and presented during conference calls
  - MOF177, LH_2, Cryo-compressed, 350 and 700 bar on-board system designs
  - Stakeholders reviewed assumptions and results and provided feedback and recommendations
- DOW Chemical
  - Email exchanges and conference calls to discuss Ammonia Borane off-board cost assessment

We have completed certain aspects of on-board and off-board evaluations and updates for 11 hydrogen storage technologies.

Analysis To Date		cH_2	Alanate	MgH_2	SBH	LCH_2	CcH_2	LH_2	AC	MOF-177	Cold Gas	AB
On-Board	Review developer estimates	√	√	▨	√	√	√	√	√	√	▨	▨
	Develop process flow diagrams/system energy balances (ANL lead)	√	√	▨	√	√	√	√	▨	√	▨	▨
	Performance assessment (ANL lead)	√	√	▨	√	√	√	√ *	▨	√ *	▨	▨
	Independent cost assessment	√	√	▨	√	√	√	√ *	WIP	√ *	▨	▨
Off-Board	Review developer estimates	√	▨	√	√	√	√	√	▨	▨	√	√
	Develop process flow diagrams/system energy balances	√	▨	√	√	√	▨	▨	▨	▨	√	√
	Performance assessment (energy, GHG)[a]	√	▨	▨	√	√	▨	▨	▨	▨	√	▨
	Independent cost assessment[a]	√	▨	▨	√	√	▨	√	▨	▨	√	▨
Overall	Ownership cost projection[a]	√	▨	▨	√	√	▨	√	▨	√	√ *	▨
	Solicit input on TIAX analysis	√	√	▨	√	√	√	√ *	WIP	√ *	▨	▨
	Analysis update	√	▨	▨	√	▨	√	WIP	▨	WIP	▨	▨

* Preliminary results under review.

[a] Work with SSAWG, ANL and SSAWG participants on WTT analysis.

▨ = Not part of current SOW

WIP = Work in progress

TIAX

For the remainder of the contract, we will focus on incorporating stakeholder feedback and submitting final reports for each technology.

- Incorporate feedback and finalize on-board cost assessments and reports (with ANL) for MOF177 and LH_2 options
  - Final reports for 350 bar, 700 bar and cryo-compressed are complete but will be updated
- Complete updated assessments and final reports (with ANL) for previously evaluated technologies:
  - 2-tank system for 350 and 700 bar
  - Liquid hydrogen carrier (LCH_2)
  - Gen 4 cryo-compressed (CcH_2)
- Complete new assessments and final reports (with ANL) for additional technologies:
  - Activated carbon (AC)
  - MOF5 or other advanced sorbent
  - Alane
- Complete off-board cost review for ammonia borage (AB) and other technologies as requested by DOE and integrate with overall performance and on-board cost results
- Continue to work with DOE, SSAWG, Centers of Excellence, other analysis projects, developers, Tech Teams and other stakeholders (as necessary) to revise and improve system models

Thank You

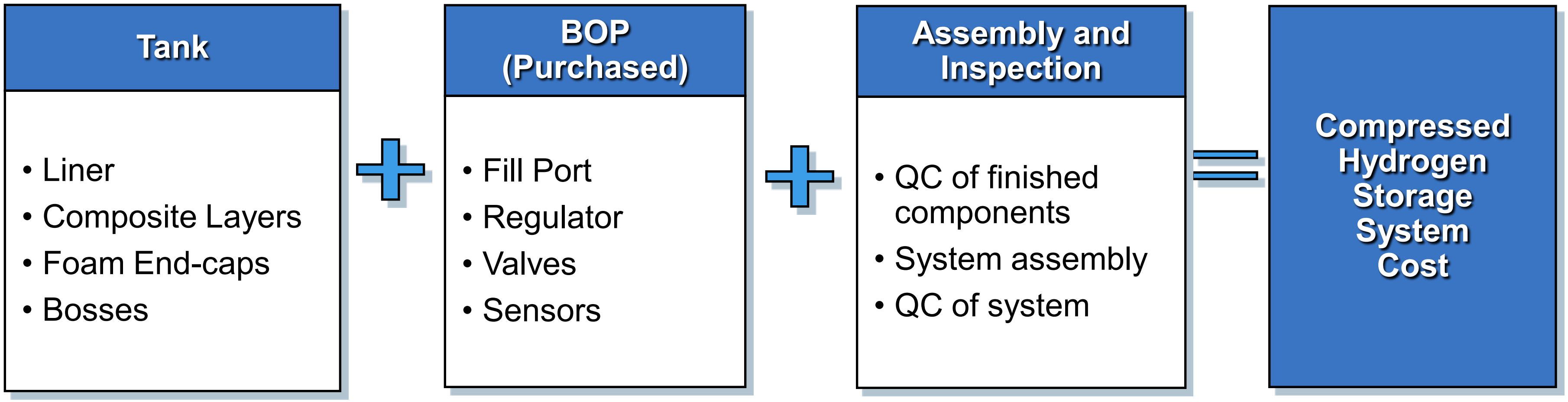
Questions?

Additional Approach Slides

The high volume (500,000 units/year) manufactured cost for all H_2 storage systems is estimated from raw material prices, capital equipment, labor, and other operating costs.

BOP Bottom-up Costing Methodology

- ➢ Develop Bill of Materials (BOM)
- ➢ Obtain raw material prices from potential suppliers
- ➢ Develop production process flow chart for key subsystems and components
- ➢ Estimate manufacturing costs using TIAX cost models (capital equipment, raw material price, labor rates)



Tank

- Liner
- Composite Layers
- Foam End-caps
- Bosses

+

BOP (Purchased)

- Fill Port
- Regulator
- Valves
- Sensors

+

Assembly and Inspection

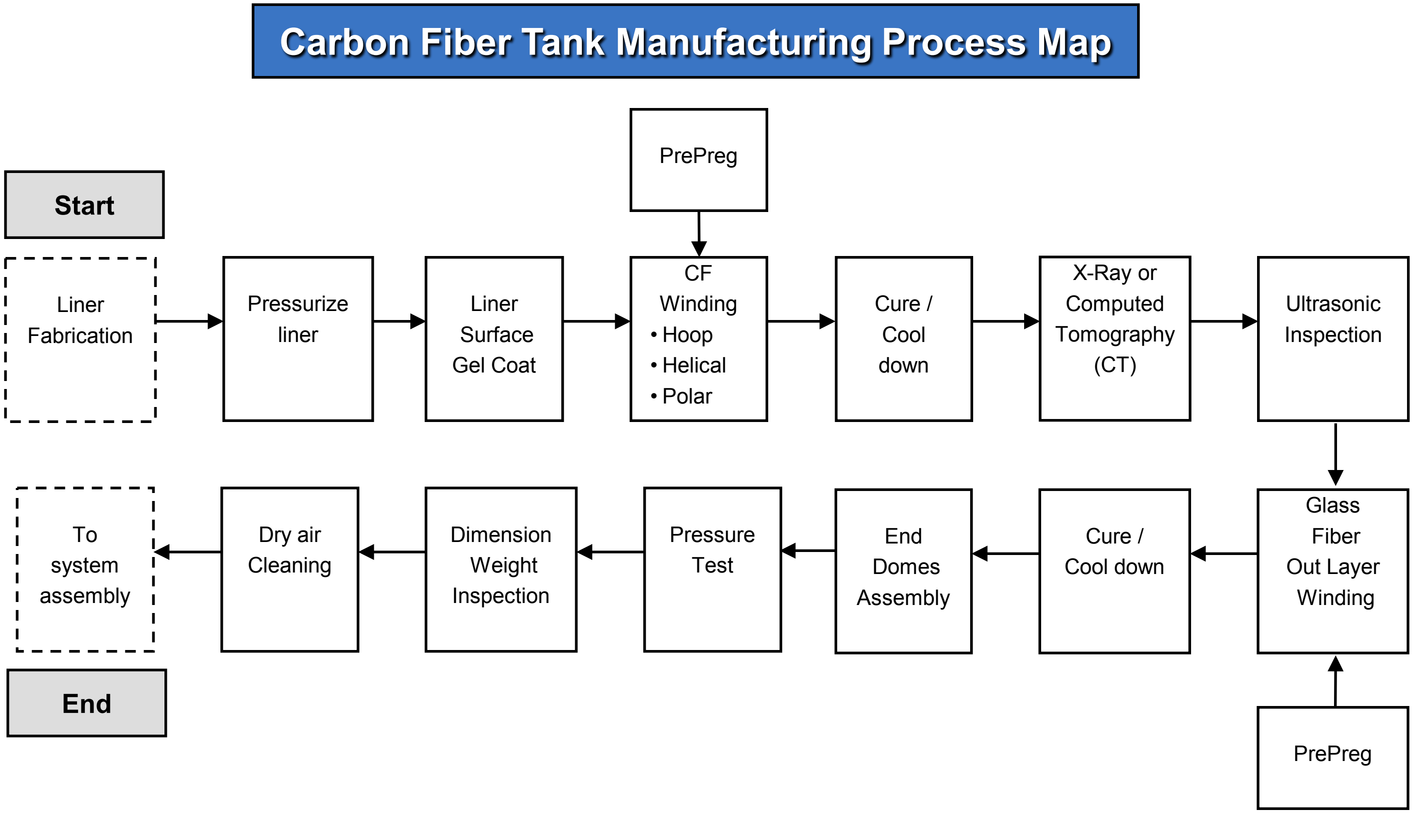
- QC of finished components
- System assembly
- QC of system

=

Compressed Hydrogen Storage System Cost

We modeled material and manufacturing process costs for the compressed tanks, while the BOP is assumed to be purchased.

The high-pressure compressed tanks require composite winding steps that are well established by the Compressed Natural Gas Industry.

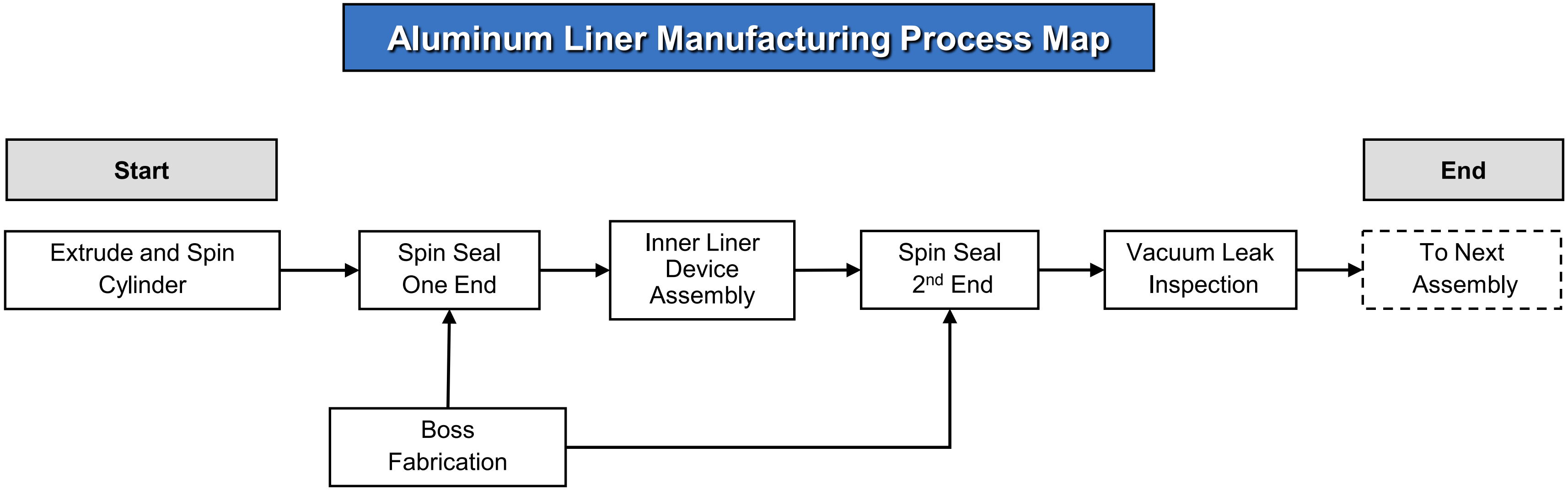


We also assume the system manufacturer purchases pre-impregnated (i.e., "prepreg") carbon fiber composite as apposed to raw carbon fiber.[1]

Note: About 60 winding machines would be required for 500,000 350-bar tanks per year; about 100 machines would be required for 700-bar tanks.

[1] See Appendix for details.

The cryo-compressed tanks also require an aluminum “liner” fabricated using standard pressure vessel manufacturing processes.



Aluminum Liner Manufacturing Process Map

Start

Extrude and Spin Cylinder

Spin Seal One End

Inner Liner Device Assembly

Spin Seal 2nd End

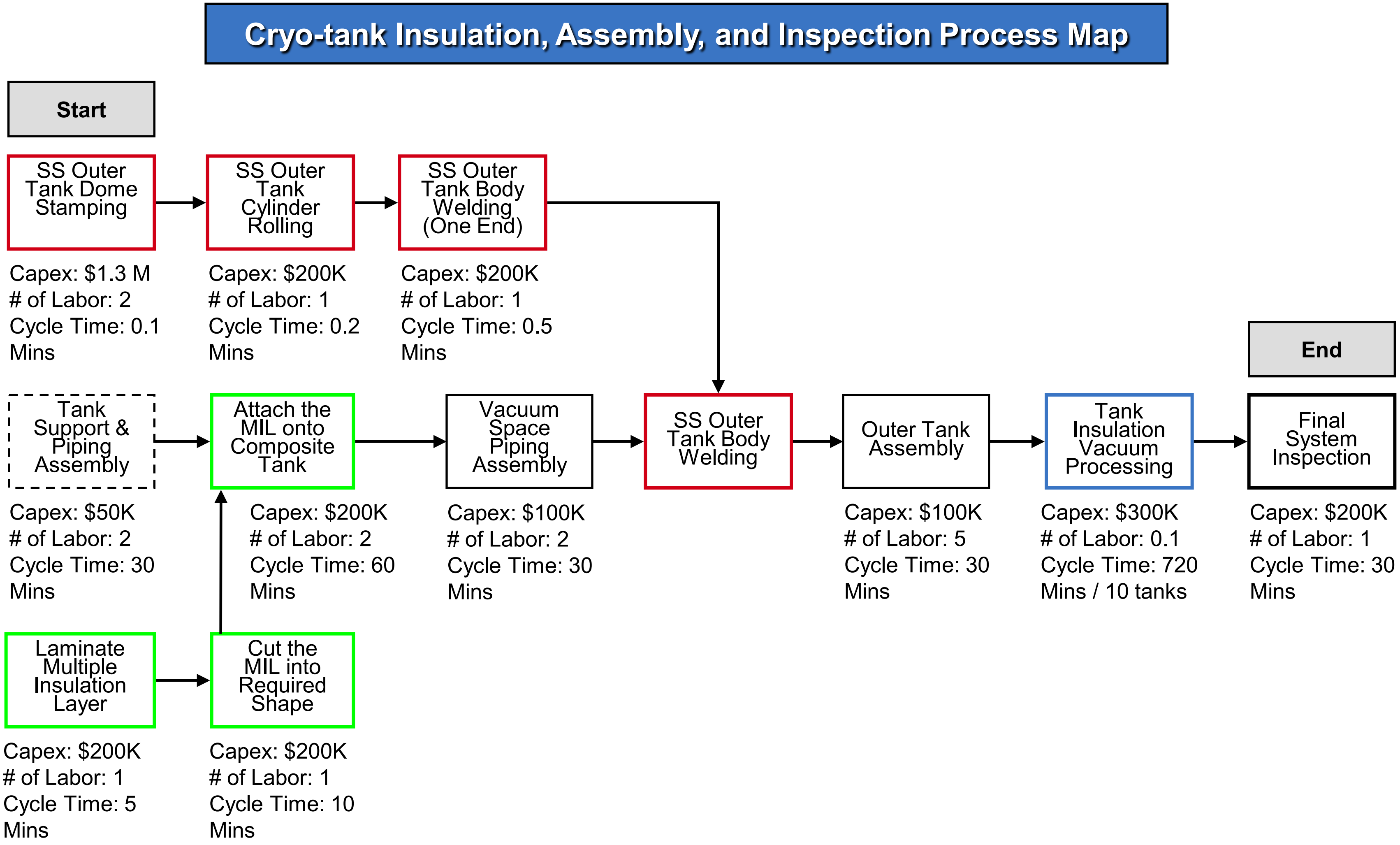
Vacuum Leak Inspection

To Next Assembly

End

Boss Fabrication

Finally, multi-layer vacuum insulation (MLVI) for all cryo-tanks requires a vacuum shell and labor intensive assembly process.



Cryo-tank Insulation, Assembly, and Inspection Process Map

Start

SS Outer Tank Dome Stamping

Capex: $1.3 M
# of Labor: 2
Cycle Time: 0.1 Mins

SS Outer Tank Cylinder Rolling

Capex: $200K
# of Labor: 1
Cycle Time: 0.2 Mins

SS Outer Tank Body Welding (One End)

Capex: $200K
# of Labor: 1
Cycle Time: 0.5 Mins

Tank Support & Piping Assembly

Capex: $50K
# of Labor: 2
Cycle Time: 30 Mins

Attach the MIL onto Composite Tank

Capex: $200K
# of Labor: 2
Cycle Time: 60 Mins

Vacuum Space Piping Assembly

Capex: $100K
# of Labor: 2
Cycle Time: 30 Mins

SS Outer Tank Body Welding

Outer Tank Assembly

Capex: $100K
# of Labor: 5
Cycle Time: 30 Mins

Tank Insulation Vacuum Processing

Capex: $300K
# of Labor: 0.1
Cycle Time: 720 Mins / 10 tanks

Final System Inspection

Capex: $200K
# of Labor: 1
Cycle Time: 30 Mins

End

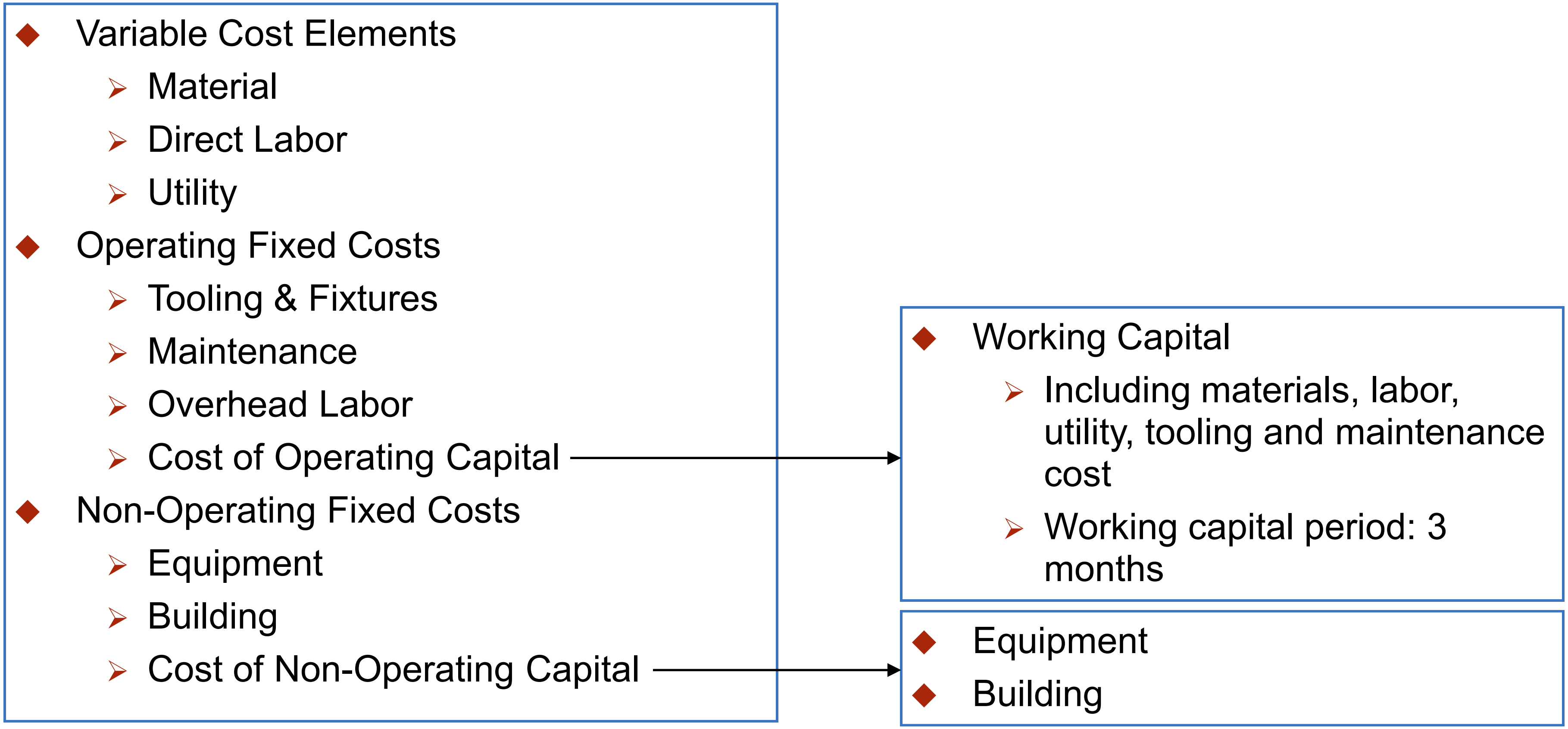
Laminate Multiple Insulation Layer

Capex: $200K
# of Labor: 1
Cycle Time: 5 Mins

Cut the MIL into Required Shape

Capex: $200K
# of Labor: 1
Cycle Time: 10 Mins

We assume 100% debt financed with an annual interest rate of 15%, 10-year equipment life, and 25-year building life.



- Variable Cost Elements
  - Material
  - Direct Labor
  - Utility
- Operating Fixed Costs
  - Tooling & Fixtures
  - Maintenance
  - Overhead Labor
  - Cost of Operating Capital
- Non-Operating Fixed Costs
  - Equipment
  - Building
  - Cost of Non-Operating Capital

- Working Capital
  - Including materials, labor, utility, tooling and maintenance cost
  - Working capital period: 3 months

- Equipment
- Building

We developed BOP cost projections for high-volume production using the Delphi method with validation from Top-down and Bottom-up estimates.

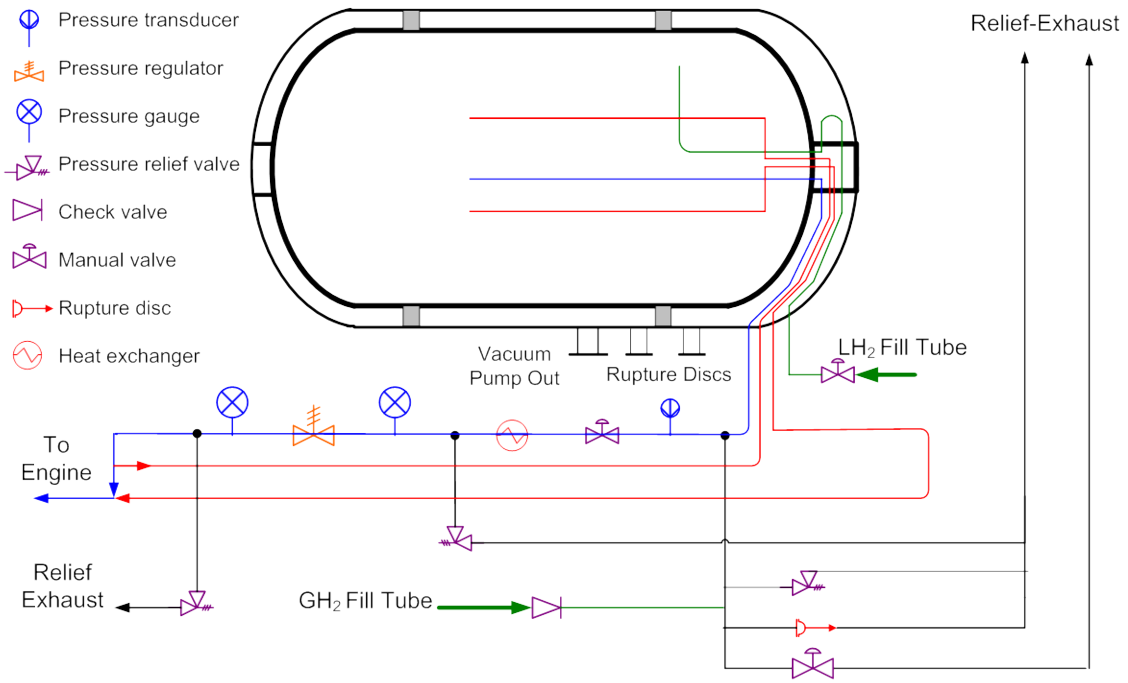
- We obtained input from developers on their cost projections for BOP components
  - Tank developers are considering the issue of automotive scale production
  - But, they do not produce tanks at such large scales today
- Some feedback from Automotive OEMs was that these projections did not account for process or technology changes that would be required for automotive scale production
  - High pressure components are often built-to-order or produced in low volumes, so “processing costs” are typically high
  - Vendor quotes contain unspecified markups, which can be substantial in the industry these devices are currently used (unlike the automotive industry, purchasing power of individual buyers is not very strong)
  - Low-volume quotes are sometimes based on laboratory and/or custom components that often exceed the base case system requirements
- Therefore, we developed BOP cost projections that were more in-line with OEM estimates for high-volume production using the Delphi method with validation from:
  - Top-down estimates - high-volume discounts applied to low-volume vendor quotes using progress ratios
  - Bottom-up estimates - cost modeling using DFMA® software plus mark-ups

BOP costs were reduced significantly this year based on industry feedback.

Additional Cryo-compressed Assessment Slides

This year, we evaluated the cost of two cryo-compressed storage systems based on LLNL’s Gen 3 design capable of storing 5.6 and 10.4 kg usable LH_2.

LLNL Gen 3 Design with ANL Modifications



Gen 3 Cryo-compressed Tank Modifications from Gen 2

- Two tank sizes: 80.8 & 151 liters (5.6 kg & 10.4 kg usable LH_2)
- Reduced pressure vessel rating: 272 bar (4,000 psi) max pressure
- Increased Al liner thickness: 9.5 mm
- Reduced insulation: 10 & 17 mm vacuum gap w/ MLVI, 10^{-5} torr (~1.5 W HT rate)
- Vacuum valve box eliminated
- Better packaging

Additional modifications assumed for high-volume production

- Cryogenic valves assumed to be electronically controlled
- Added liquid level sensor[1]
- Valves and tubing assumed for in-tank heat exchange system

- Assumed low-carbon steel instead of SS304 for outer shell to save cost
- Did not include electronic boards and computer
- Insulated LH_2 fill/gas vent port included

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[1] Other methods of accounting of fuel could be used (e.g. close mass -balance accounting with flow sensor).

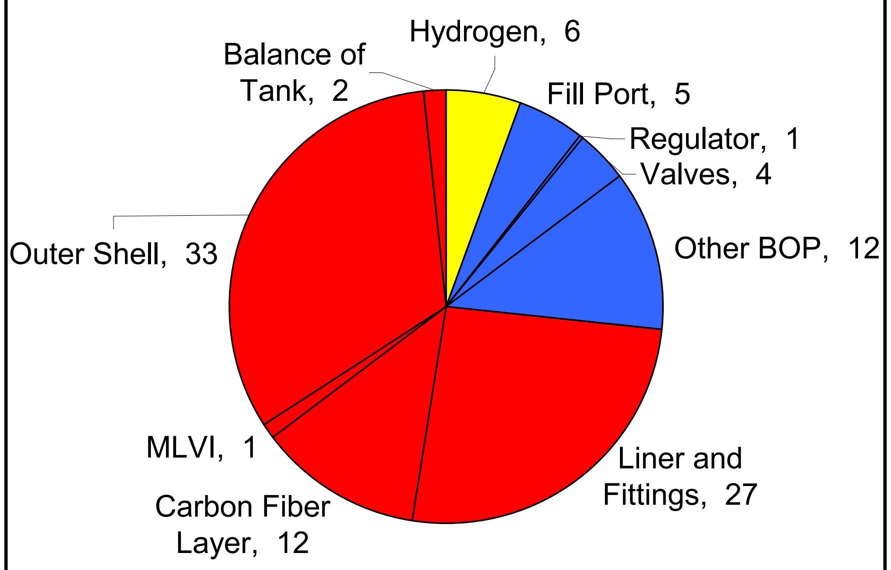
Key Design Assumptions: Cryo-compressed Tank

Design Parameter	Base Case Value	Basis/Comment
Nominal pressure	272 bar	Design assumption based on discussions with LLNL
Maximum (filling) pressure[1]	340 bar	125% of nominal design pressure is assumed required for dormancy
Minimum (empty) pressure	4 bar	Design assumption; required to meet DOE delivery pressure target
Usable LH_2 storage capacity	5.6 and 10.4 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range for midsized vehicle (5.6 kg) and LLNL tank design (10.4 kg)
Recoverable hydrogen (fraction of stored hydrogen)	97%	ANL calculation based on hydrogen storage density at maximum and minimum pressure and temperature conditions
Tank size (water capacity)	81 and 151 L	ANL calculation for 5.6 kg and 10.4 kg useable H_2 capacity (5.7 and 10.7 kg total H_2 capacity)
Safety factor	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure
L/D ratio	2.0	Consistent with other cryo-tank assessments and discussions with LLNL and SCI, 2008; based on the outside of the CF wrapped tank
Carbon fiber type	Toray T700S	Discussions with LLNL, Quantum and other developers, 2008; assumed to have a composite strength of 2,550 MPa for 60% fiber by volume
Translation strength factor	86%	ANL assumption based on discussions and data from Quantum, 2004-09
Tank liner thickness	9.5 mm Al	ANL assumption based on discussions with LLNL and SCI design, 2008
Insulation type	MLVSI	Aluminized Mylar sheets, Dacron spacer, 10^{-5} torr
Minimum temperature	-253 ºC	ANL assumption; typical for liquid hydrogen storage
Vacuum gap	10 and 17 mm	ANL calculation to achieve ~1.5 W heat transfer rate with Mylar layers
Outer shell	3.2 mm Steel	Discussions with LLNNL and industry, 2008-09

[1] Tank design based on nominal pressure not maximum pressure.

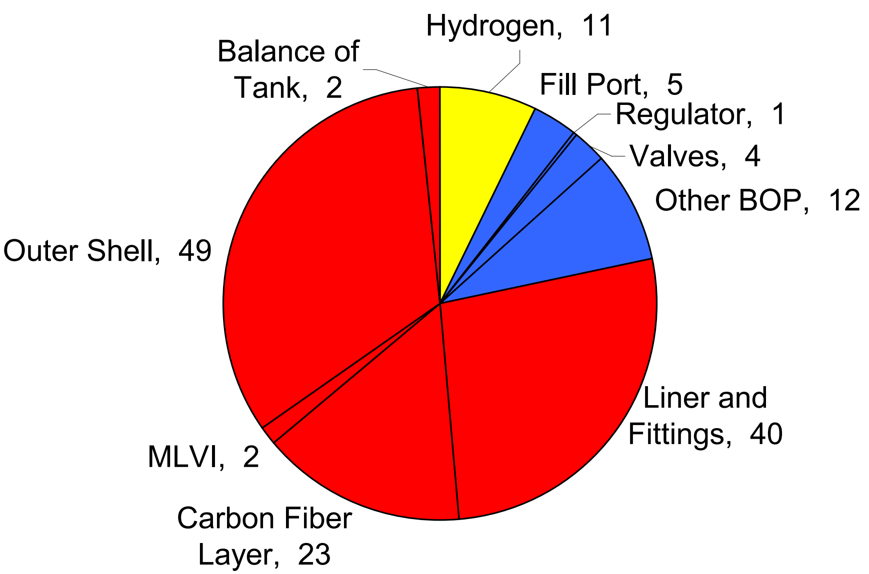
For the base case conditions, the outer shell accounts for about 30% of the total weight of the 5.6 kg and 10.4 kg systems.

5.6 kg CcH_2 Base Case Weight = 102 kg
5.5 wt% based on 5.6 kg usable LH_2



**Weights in kg*

10.4 kg CcH_2 Base Case Weight = 149 kg
7.0 wt% based on 10.4 kg usable LH_2



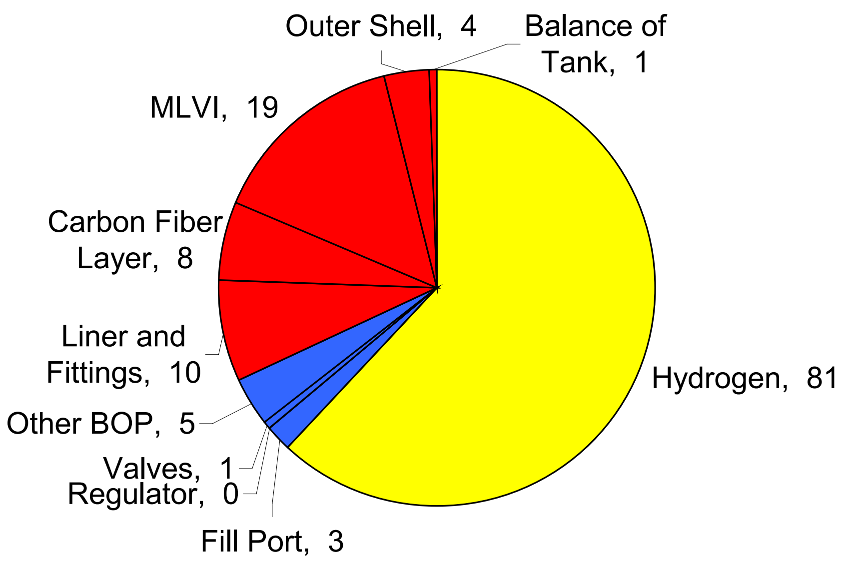
**Weights in kg*

Weight savings of over 20% can be realized if aluminum rather than standard steel is used for the outer shell, but system cost would go up by about 15%.

On-board Assessment Results *Volume Breakout – Base Cases*

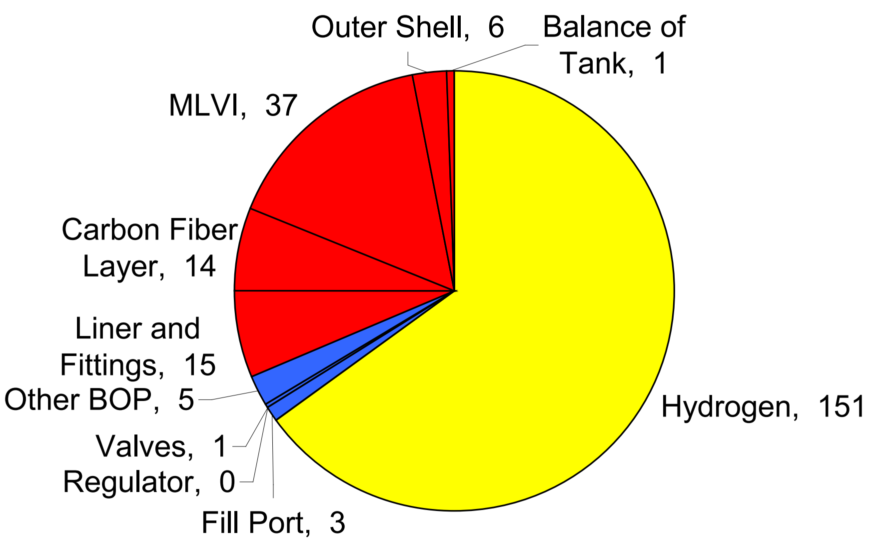
For the base case conditions, the stored hydrogen accounts for about 65% of the total volume of the 5.6 kg and 10.4 kg systems.

5.6 kg CcH_2 Base Case Volume = 131 L
43 g H_2/L based on 5.6 kg usable LH_2



**Volumes in L*

10.4 kg CcH_2 Base Case Volume = 232 L
45 g H_2/L based on 10.4 kg usable LH_2



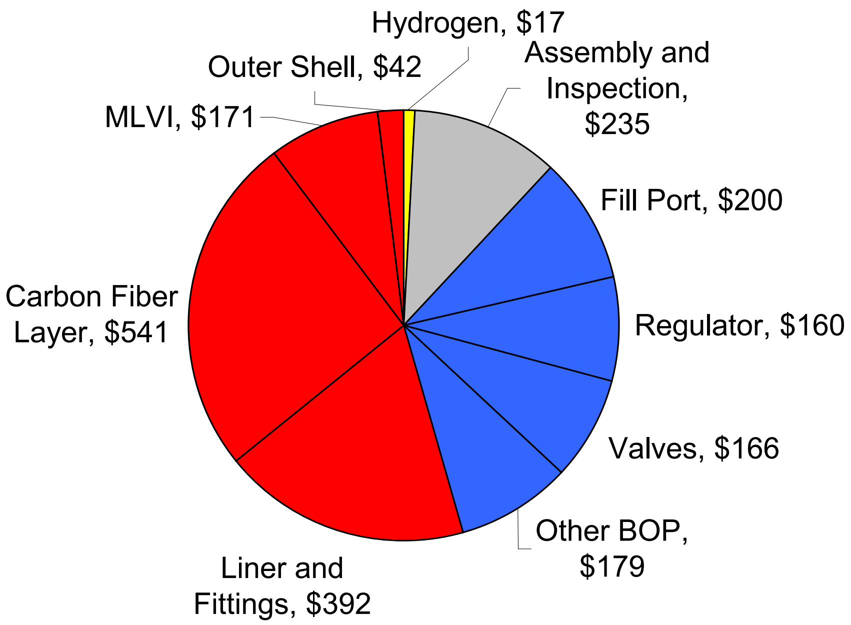
**Volumes in L*

Note: Volume results do not include void spaces between components (i.e., no packing factor was applied).

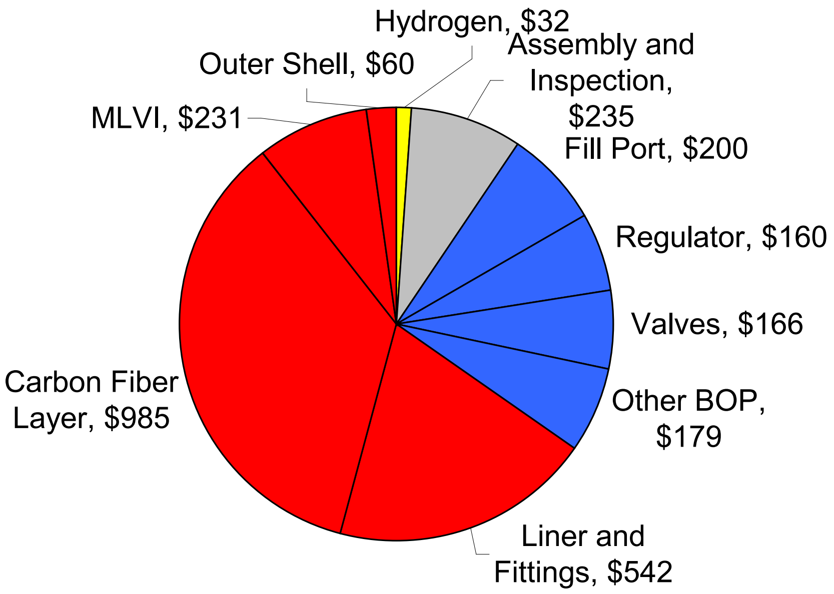
Volumetric, weight and cost savings can be realized if the Al liner thickness is reduced from the base case assumption of 9.5 mm.

The carbon fiber layer is the most expensive single component and accounts for about 25% and 35% of the base case 5.6 and 10.4 kg systems costs.

5.6 kg CcH_2 Base Case Factory Cost[1] = \$2,200
\$12/kWh based on 5.6 kg usable LH_2



10.4 kg CcH_2 Base Case Factory Cost[1] = \$2,900
\$8/kWh based on 10.4 kg usable LH_2



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[1] Cost estimate in 2005 USD. Includes processing costs.

The BOP components account for about 30% and 25% of the base case 5.6 and 10.4 kg system costs, respectively.

Processing cost makes up about 15-20% of the total system cost due to the time-consuming processing steps, even at assumed high production volumes.

Key Processing Steps – Cryo-compressed Tank	5.6 kg Base Case	10.4 kg Base Case
Liner Fabrication, Assembly, & Inspection	$99	$103
Carbon Fiber Winding Process	$25	$40
MLVI Wrapping	$106	$108
Outer Shell Fabrication	$7	$7
In-vessel Assembly	$42	$42
Ex-vessel Assembly	$93	$93
Vacuum Processing	$59	$59
Final Inspection	$40	$40
Total	**$473**	**$494**

The larger tank size increases the cost of the liner fabrication, carbon fiber winding, and MLVI wrapping processes.

We used sensitivity analysis to account for design assumptions that are either not very well established or could change significantly in the near future.

Design Parameter	Low	Base Cases	High	High/Low Comments/Basis
Safety factor	1.80	2.25	3.00	Based on discussions with Quantum and Dynatek (2005)
Composite tensile strength, MPa	2,300	2,550	2,940	Low 10% below base case; high assumes 60% of fiber strength based on fiber volume fraction
Translation strength factor	0.80	0.86	1.00	Low based on discussions with developers for similar pressure tanks (e.g., 350-bar); high assumes theoretical maximum
Tank liner thickness, mm	3.0	9.5	10.0	Based on discussions with developers

To account for the inherent uncertainty of the BOP cost projections, we developed “low” and “high” cost estimates for input to the sensitivity analysis.

Purchased Component Cost Est.	Low	Base Cases	High	High/Low Comments/Basis
Fill tube/port	$100	$200	$400	Low and high are one half and double the base case, respectively
Pressure regulator	$80	$160	$360	Low and high based on discussions with tank developers and vendors (2009)
Control valve	$37	$94	$190	Low and high based on discussions with tank developers (2009), Circle Seal (2009), and Valcor (2007)
Heat exchangers	$44	$50	$200	Low is sum of control valve and check valve low costs; high based on discussions with developers
Pressure transducer	$15	$30	$60	Low and high are half and double the base case, respectively
Vacuum pressure transducer	$15	$30	$60	Low and high are half and double the base case, respectively
Pressure relief valves	$20	$28	$130	Low and high based on discussions with tank developers, Flow Safe (2009), Ham-Let (2009), and Swagelock (2009) venders
Level sensor (in tank)	$10	$25	$100	Low assumes simpler technology; high based on discussions with developers
Pressure gauge (in engine feed zone)	$9	$17	$34	Low and high are half and double the base case, respectively
Boss and plug (in tank)	$12	$15	$100	Low is 75% of base case; high assumes more complicated processing requirement

We also developed low and high estimates for the cost of purchased raw materials for input to the sensitivity analysis.

Raw Material Cost Estimates, $/kg	Low	Base Cases	High	High/Low Comments/Basis
Hydrogen	1.5	3.0	6.0	Low and high are half and double the base case, respectively
Aluminum (6061-T6)	4.8	9.6	19.2	Low and high are half and double the base case, respectively
Carbon fiber (T700S) prepreg	18.5	36.6	44.9	Low based on 68% fiber (by weight) at $10/lb and 32% epoxy at $5/lb[a]; High based on discussion w/ Toray (2007) re: T700S fiber at $16/lb and 1.27 prepreg/fiber ratio (Du Vall 2001)
Multi-layer vacuum insulation	25	50	100	Low and high are half and double the base case, respectively
Stainless steel (304)	2.4	4.7	9.4	Low and high are half and double the base case, respectively
Standard steel	0.5	1.0	2.0	Low and high are half and double the base case, respectively

[a] Weighted raw material costs would be more relevant for a wet winding process, which may also alter fiber winding processing costs.

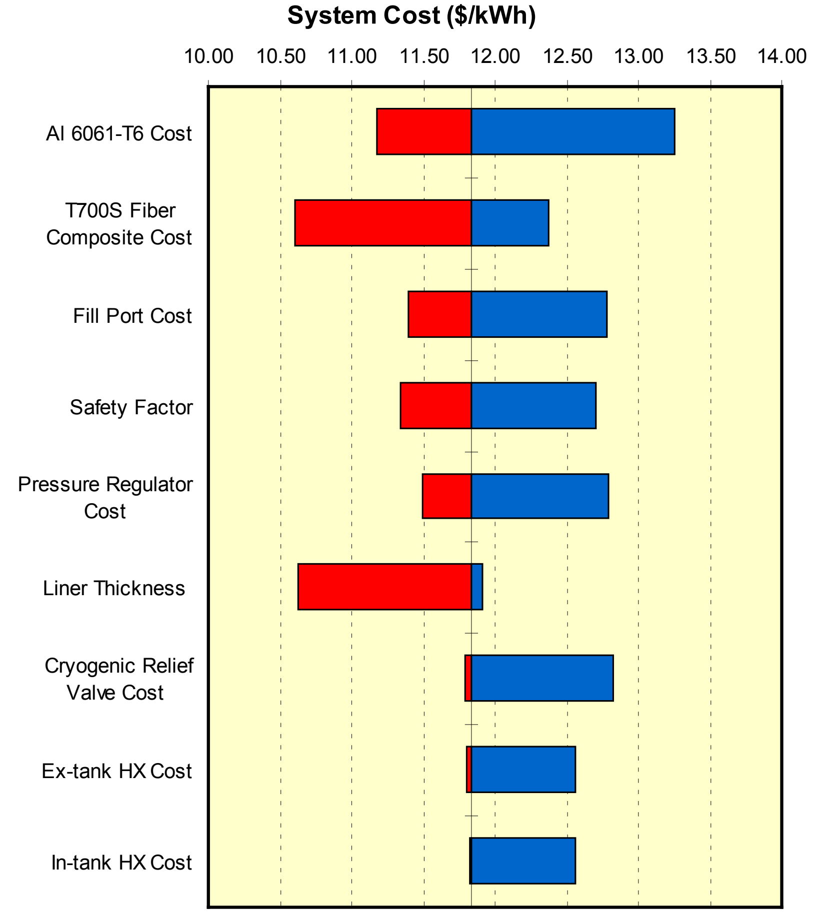
[1] However, there are DOE programs that are looking at ways to significantly reduce carbon fiber costs (e.g., Abdallah 2004).

Carbon fiber is already produced at very high-volumes for the Aerospace industry, so it isn't expected to become significantly cheaper in the near term.[1]

Single variable sensitivity analysis shows that aluminum and carbon fiber cost assumptions have the biggest impact on our system cost projections.

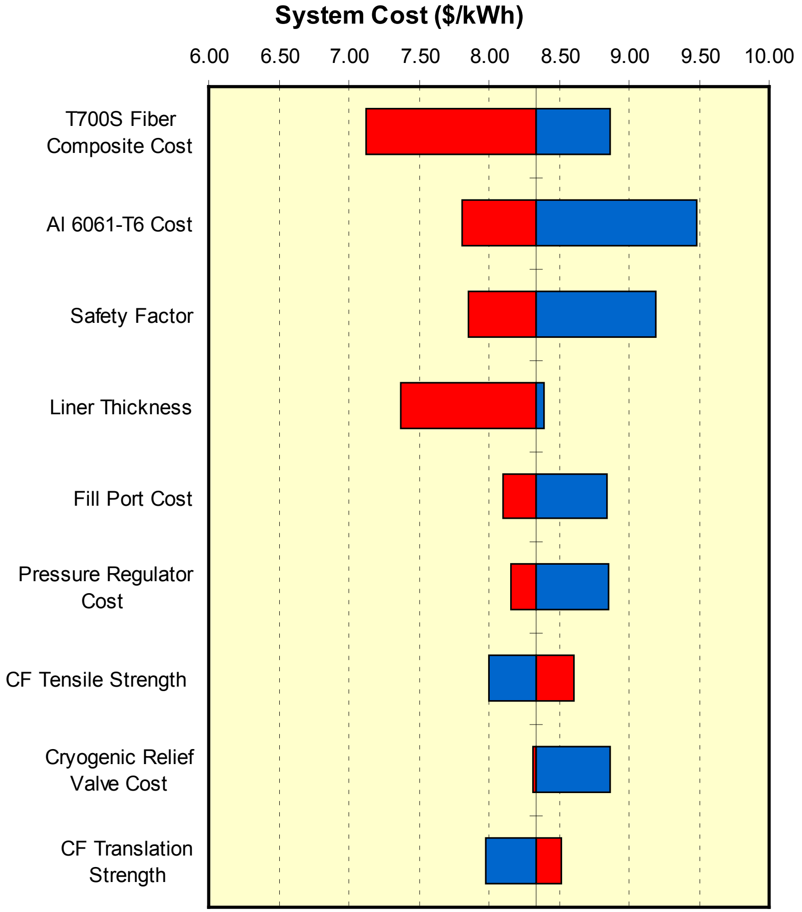
5.6 kg CcH_2 Single Variable Cost Sensitivity

based on 5.6 kg useable LH_2, $/kWh



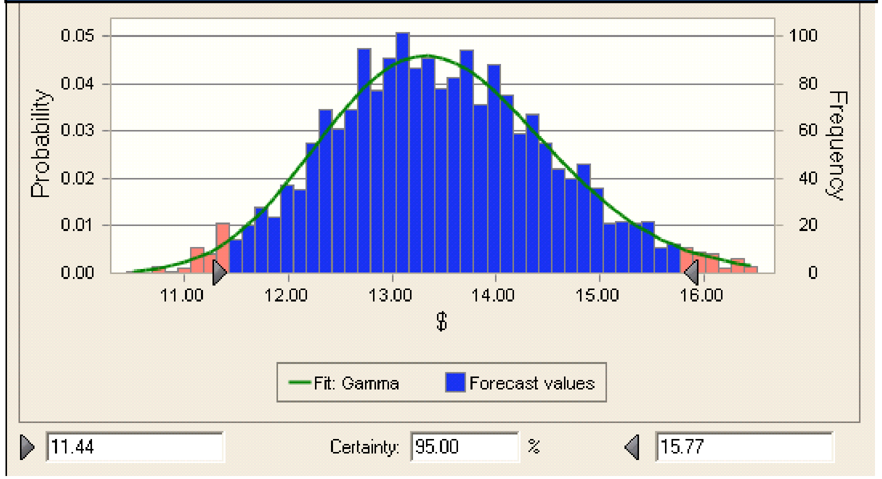
10.4 kg CcH_2 Single Variable Cost Sensitivity

based on 10.4 kg useable LH_2, $/kWh



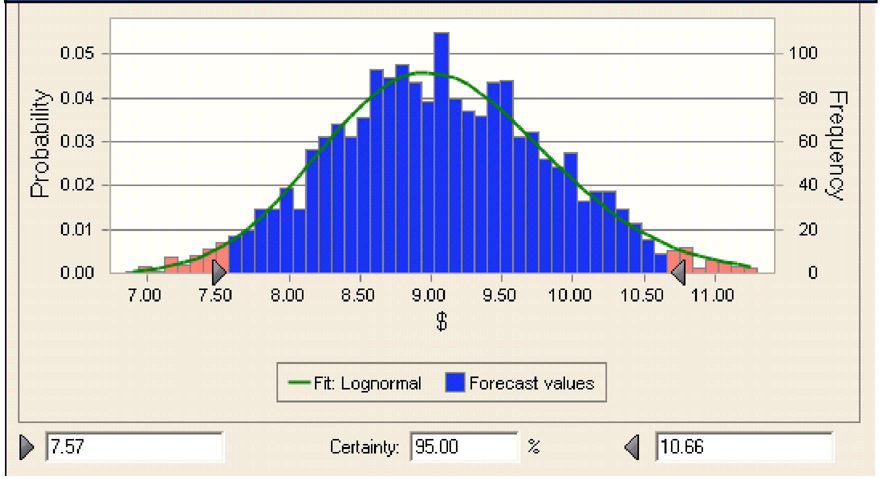
Multi variable sensitivity analysis shows the factory cost is likely to be between $11.4-15.8/kWh for 5.6 kg and $7.57-10.7/kWh for 10.4 kg tank systems.[1]

5.6 kg Multi Variable Cost Sensitivity
based on 5.6 kg useable LH_2, $/kWh



11.44 Certainty: 95.00 % 15.77

10.4 kg Multi Variable Cost Sensitivity
based on 10.4 kg useable LH_2, $/kWh



7.57 Certainty: 95.00 % 10.66

Base Case	11.9
Mean	13.5
Standard Deviation	1.08
"Low" Case[1]	11.4
"High" Case[1]	15.8

Base Case	8.39
Mean	9.07
Standard Deviation	0.80
"Low" Case[1]	7.57
"High" Case[1]	10.7

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[1] The ranges shown here are the 95% confidence interval based on the data fit.

Additional Compressed Hydrogen Assessment Slides (key inputs and cost results only)

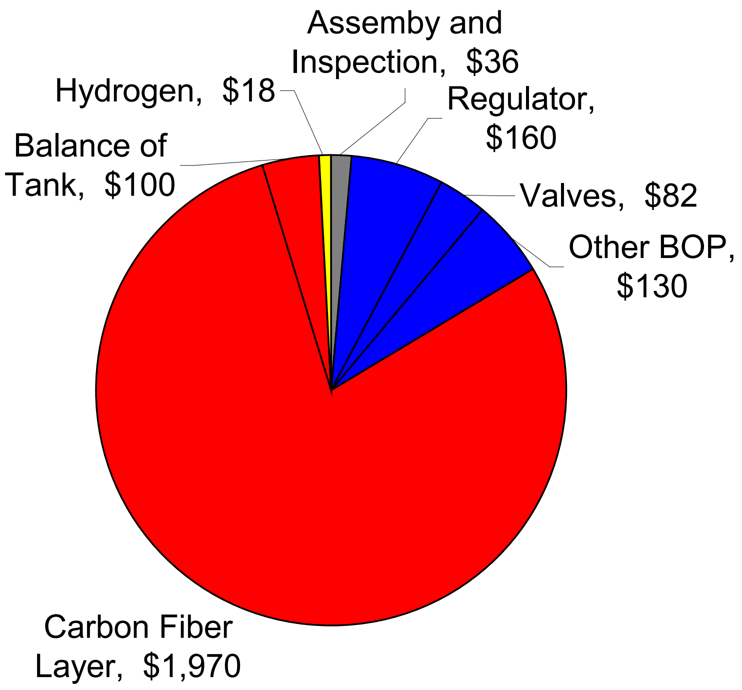
Key Design Assumptions: Compressed Gaseous Tanks

Design Parameter	Base Case Value	Basis/Comment
Nominal pressure	350 and 700 bar	Design assumptions based on DOE and industry input
Maximum (filling) pressure[1]	350-bar: 438 bar 700-bar: 875 bar	125% of nominal design pressure is assumed required for fast fills to prevent under-filling
Minimum (empty) pressure	20 bar	Discussions with Quantum, 2008
Usable H_2 storage capacity	5.6 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range for a midsized vehicle
Recoverable hydrogen (fraction of stored hydrogen)	350 bar: 93% 700 bar: 98%	ANL calculation based on hydrogen storage density at maximum and minimum pressure and temperature conditions
Tank size (water capacity)	350-bar: 258 L 700-bar: 149 L	ANL calculation for 5.6 kg useable H_2 capacity (6.0 and 5.8 kg total H_2 capacity for 350 and 700-bar tanks, respectively)
Safety factor	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure
L/D ratio	3.0	Discussions with Quantum, 2008; based on the outside of the CF wrapped tank
Carbon fiber type	Toray T700S	Discussions with Quantum and other developers, 2008; assumed to have a composite strength of 2,550 MPa for 60% fiber by volume
Translation strength factors	350-bar: 82.5% 700-bar: 63.0%	ANL assumption based on data and discussions with Quantum, 2004-09
Tank liner thickness	5 mm HDPE	Discussions with Quantum, 2008; typical for Type IV tanks
Overwrap	1 mm glass fiber	Discussions with Quantum, 2008; common but not functionally required
Protective end caps	10 mm foam	Discussions with Quantum, 2008; for impact protection

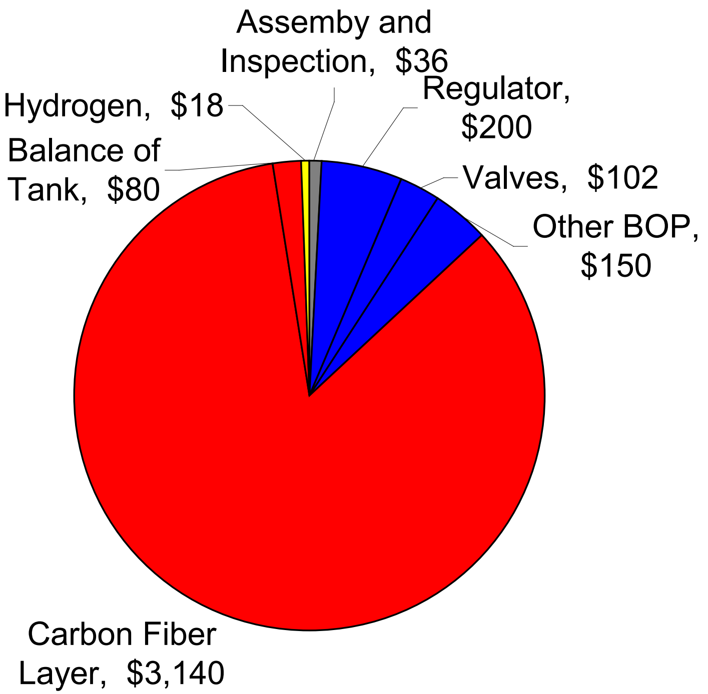
[1] Tank design based on nominal pressure not maximum pressure.

The carbon fiber composite layer accounts for about 75% and 80% of the base case 350-bar and 700-bar system costs, respectively.

350-bar Base Case Factory Cost[1] = $2,500
\$13/kWh based on 5.6 kg usable H_2 (6 kg stored H_2)



700-bar Base Case Factory Cost[1] = $3,700
\$20/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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[1] Cost estimate in 2005 USD. Includes processing costs.

These costs compare well to industry factory cost projections for similarly sized tanks at lower production volumes.

Processing cost makes up only 5% of the 350 and 700 bar system costs due to the assumed high production volumes and large number of purchased components.

Key Processing Steps – Compressed Gas Tanks	350-bar Base Case	700-bar Base Case
Liner Fabrication	$11	$10
Carbon Fiber Winding Process	$75	$116
Glass Fiber Winding Process	$7	$6
Foam End Caps	$2	$1
Assembly and Inspection	$36	$36
Total	**$130**	**$170**

The higher, 700 bar pressure requirement, primarily increases the cost of the carbon fiber winding process.

350 and 700-bar system cost, weight and volume decreased (grav. and vol. capacities increased) due to revised assumptions compared to last year.

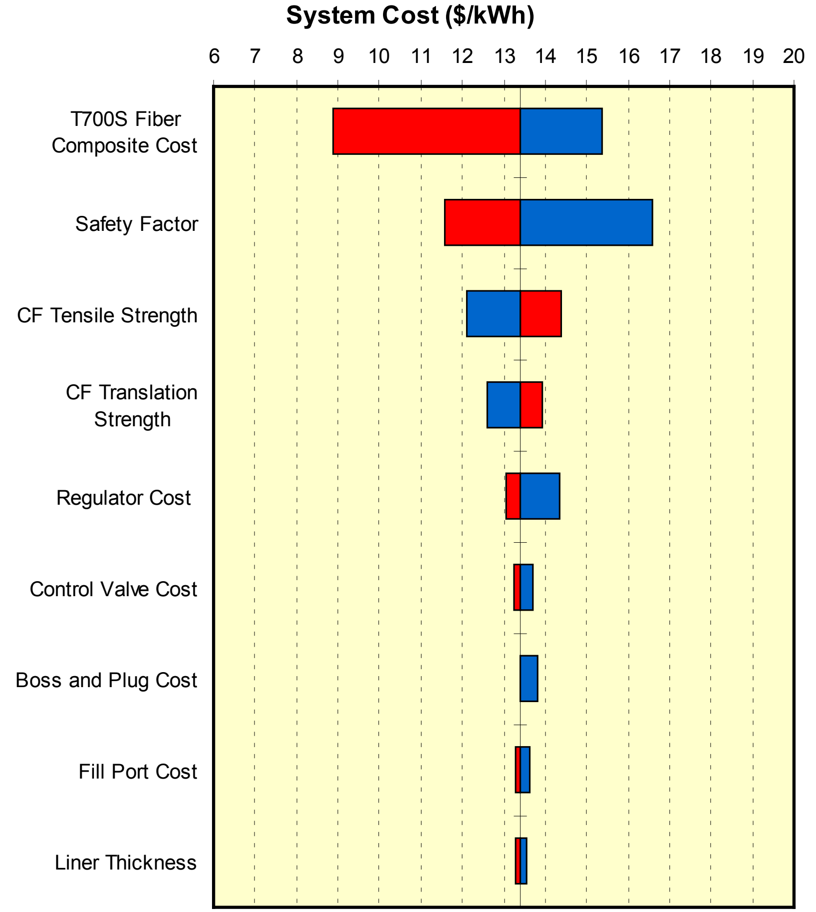
- The key changes resulting in the decreases was that the tank safety factor was applied to the *nominal* tank pressure rather than *max. filling* over pressure and most BOP costs were reduced based on industry feedback
- Changing the tank end dome shape based on ANL's latest performance analysis, also resulting in decreases
- Reducing the carbon fiber composite tensile strength partially offset the above adjustments
- Other changes to the tank design had a modest impact on the results (e.g., increasing safety factor, decreasing diameter, changing minimum pressure)

2009 Updated Results Compared to 2008 AMR Results	350-bar Base Case		700-bar Base Case	
	2009 / 2008	% Change	2009 / 2008	% Change
Gravimetric Capacity, wt%	6.0 / 5.3	13%	4.8 / 4.0	20%
Volumetric Capacity, g H_2/L	18 / 17	6%	25 / 23	9%
System Cost, $/kWh	13.4 / 17.1	-22%	20.0 / 26.7	-25%

Single variable sensitivity analysis shows that carbon fiber cost and safety factor assumptions have the biggest impact on our system cost projections.

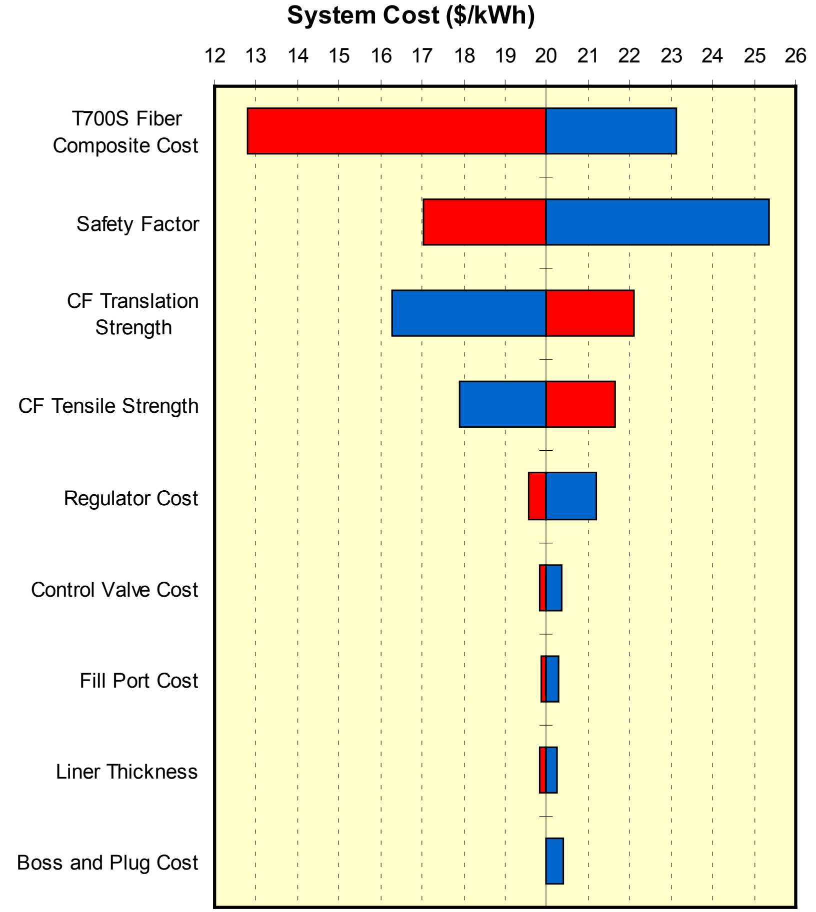
350-bar Single Variable Cost Sensitivity

based on 5.6 kg useable H_2, \$/kWh



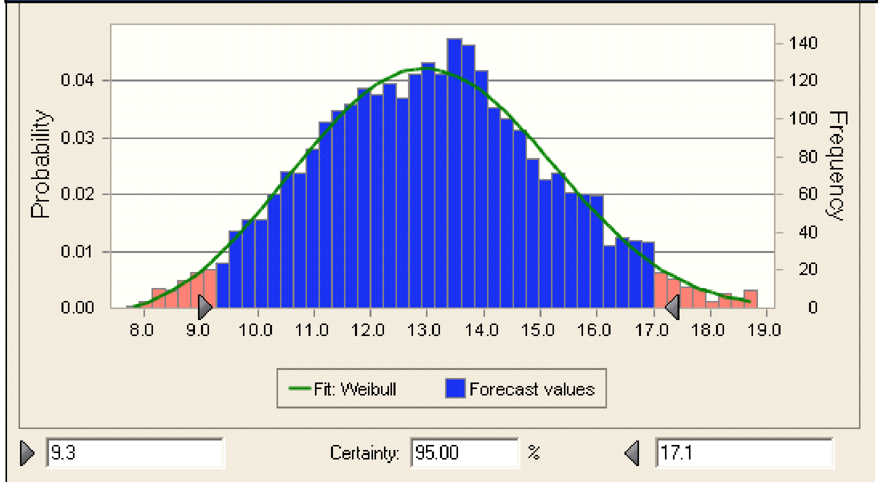
700-bar Single Variable Cost Sensitivity

based on 5.6 kg useable H_2, \$/kWh



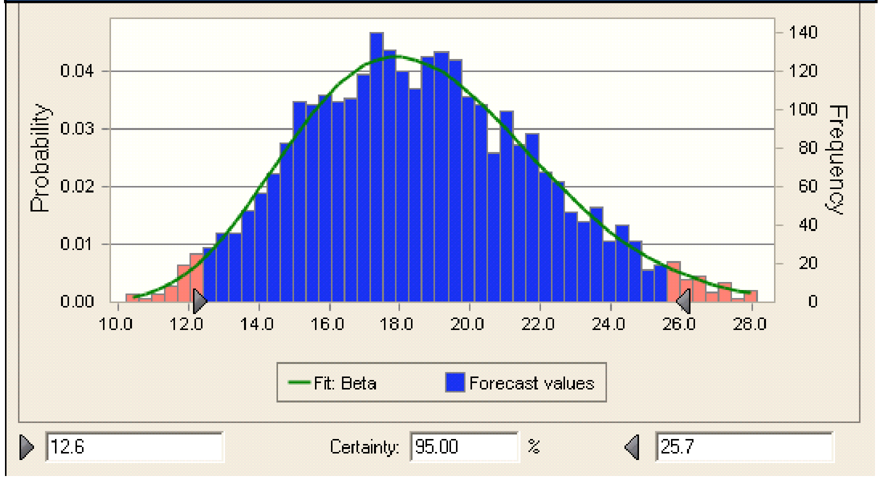
Multi variable sensitivity analysis shows the factory cost is likely to be between \$9.3-17.1/kWh for 350-bar and \$12.6-25.7/kWh for 700-bar tank systems.[1]

350-bar Multi Variable Cost Sensitivity
based on 5.6 kg useable H_2, \$/kWh



9.3 Certainty: 95.00 % 17.1

700-bar Multi Variable Cost Sensitivity
based on 5.6 kg useable H_2, \$/kWh



12.6 Certainty: 95.00 % 25.7

Base Case	13.4
Mean	13.1
Standard Deviation	2.10
"Low" Case[1]	9.30
"High" Case[1]	17.1

Base Case	20.0
Mean	18.6
Standard Deviation	3.40
"Low" Case[1]	12.6
"High" Case[1]	25.7

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[1] The ranges shown here are the 95% confidence interval based on the data fit.

Additional Liquid Hydrogen Assessment Slides (key inputs and cost results only)

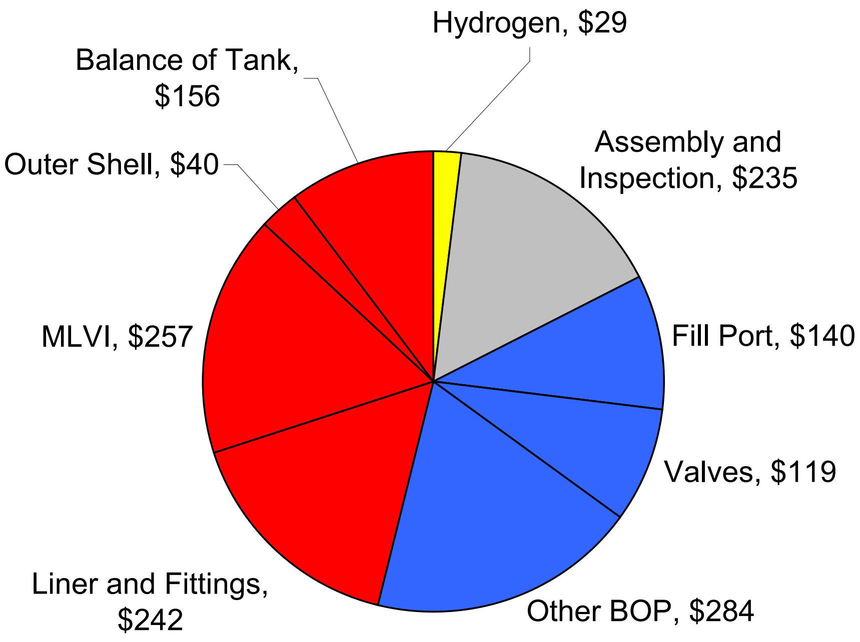
Key Design Assumptions: Liquid Hydrogen Tank

Design Parameter	Base Case Value	Basis/Comment
Maximum (venting) pressure	6 bar	Developer feedback; necessary to prevent excessive LH_2 boiloff
Minimum (empty) pressure	4 bar	Design assumption; required to meet DOE delivery pressure target
Usable LH_2 storage capacity[1]	5.6 and 10.4 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range for midsized (5.6 kg) and larger vehicle (10.4 kg)
Recoverable hydrogen (fraction of stored hydrogen)	57%	ANL calculation based on hydrogen storage density at maximum and minimum pressure and temperature conditions and 40% boil-off based on industry feedback
Tank ullage (fraction of total volume)	7.5%	ANL calculation; required to allow for thermal expansion of the liquid hydrogen
Tank size (water capacity)	168 and 312 L[1]	ANL calculation for 5.6 kg and 10.4 kg usable H_2 capacity (9.8 and 18.3 kg total H_2 capacity)
L/D ratio	2.0	Consistent with other cryo-tank assessments and discussions with LLNL and SCI, 2008; based on the outside of the inner tank
Inner tank thickness	3 mm Al	Discussions with industry, 2010
Insulation type	MLVSI	Aluminized Mylar sheets, Dacron spacer, 10^{-5} torr
Minimum temperature	-247 ºC	ANL calculation; saturation temperature at 4 bar
Vacuum gap	25 and 38 mm	ANL calculation to achieve ~1 W heat transfer rate with MLVSI
Outer shell	2 mm Steel	Discussions with industry, 2010

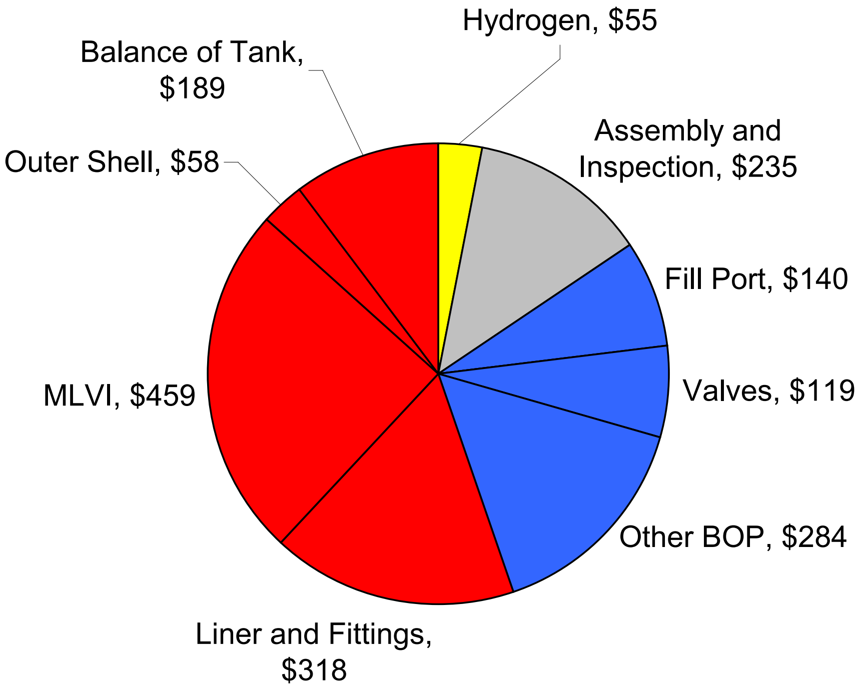
[1] Note that the larger tank (10.4 kg LH_2) case is not applicable for most vehicular application because of its excessive volume.

Results show that the LH_2 system costs are relatively low and well distributed among the various components.

5.6 kg LH_2 Base Case Factory Cost[1] = $1,502
$8.0/kWh based on 5.6 kg usable LH_2 (9.8 kg stored LH_2)



10.4 kg LH_2 Base Case Factory Cost[1,2] = $1,856
$5.4/kWh based on 10.4 kg usable LH_2 (18.2 kg stored LH_2)



[1] Cost estimate in 2005 USD. Includes processing costs.
[2] Note that the larger tank (10.4 kg LH2) case is not applicable for most vehicular application because of its excessive volume.

BOP components account for 30-35% and the tank subsystem accounts for 45-55% of the base case system costs.

Processing cost makes up 25-30% of the LH2 system costs despite the assumed high production volumes and large number of purchased components.

Key Processing Steps – Liquid Hydrogen Tanks	5.6 kg Base Case	10.4 kg Base Case
Liner Fabrication, Assembly, and Inspection	$96	$97
MLVI Wrapping	$109	$114
Outer Shell Fabrication	$7	$7
Vacuum Processing	$59	$59
Final Assembly and Inspection	$176	$176
Total	**$446**	**$453**

Additional Off-board Assessment Slides

Cryo-compressed and compressed (350- and 700-bar) hydrogen off-board cost results were calculated using the base case delivery scenarios in HDSAM v2.06.

HDSAM Delivery Scenario Assumptions	350 and 700-bar Base Cases	Cryo-compressed Base Cases
Hydrogen Market	Urban	Urban
Market Penetration	30%	30%
City Selection	Indianapolis, IN (~1.2M people)	Indianapolis, IN (~1.2M people)
Central Plant H_2 Production Cost	\$1.50/kg H_2	\$1.50/kg H_2
Plant Outage/Summer Peak Storage	Geologic	Cryogenic liquid tanks
Transmission/Distribution Mode	Compressed gas pipeline	LH_2 tanker trucks (284 km round trip)
Transmission/Distribution Capacity	NA	4,100 kg LH_2
Refueling Station Size	1,000 kg H_2/day	1,000 kg H_2/day
Dispensing Temperature	350-bar = ambient (25ºC) 700-bar = -40ºC for fast fill	-253ºC
Dispensing Pressure	25% over-pressure for fast fill (up to 438 and 875 bar cH_2)	25% over-pressure for fast fill (up to 340 bar LH_2)
Hydrogen Losses	<1%	7.5% (0.5% each from liquefaction, storage and loading; 6% from unloading)
On-board Storage System	350-bar and 700-bar compressed gas	Cryogenic liquid and 272 bar compressed gas

The chemical hydride (i.e., SBH, LCH_2) off-board cost results were calculated using a modified version of the Delivery Components Carrier Model v34.

- Most financial assumptions are maintained from the original H2A Delivery Components Model
- New calculation tabs were added as part of the DOE Delivery Project for novel carriers, resulting in the H2A Deliver Components Carrier Model v34
  - Regeneration – calculates material regeneration costs based on capital and operating costs of a central plant and the storage capacity of the material
  - Storage Terminal – calculates required storage for fresh and spent materials
  - Trucking – calculates trucking costs for all novel carriers
  - Fueling Station – calculates fueling station costs for novel carrier storage and vehicle fueling
- These new calculation tabs were populated with inputs based on industry and developer feedback specifically for SBH (MCell, R&H)) and LCH_2 (APCI)
  - TIAX made initial estimates consistent with H2A methodology
  - Model and estimates were reviewed with developers
  - Model inputs and results were updated

"Ownership cost" provides a useful comparison metric that includes both on-board and off-board (i.e., refueling) costs on equal footing.

Simple Ownership Cost (OC) Calculation:

$$\boxed{OC = \frac{PC \times DF \times Markup}{Annual\ Mileage} + \frac{FC}{FE}}$$

PC = Purchased Cost of the On-board Storage System
DF = Discount Factor (e.g., 15%)
FC = Fuel Cost of the Off-board Refueling System
FE = Fuel Economy (e.g., 62 mi/kg)

Ownership Cost Assumptions	Gasoline ICEV	Hydrogen FCV	Basis/Comment
Annual Discount Factor on Capital	15%	15%	Input assumption
Manufacturer + Dealer Markup	1.74	1.74	Assumed mark-up from factory cost estimates[1]
Annual Mileage (mi/yr)	12,000	12,000	H2A Assumption
Vehicle Energy Efficiency Ratio	1.0	2.0	Based on ANL drive-cycle modeling
Fuel Economy (mpgge)	31	62	ICEV: Car combined CAFE sales weighted FE estimate for MY 2007[2]
H_2 Storage Requirement (kg H_2)	NA	5.6	Design assumption based on ANL drive-cycle modeling

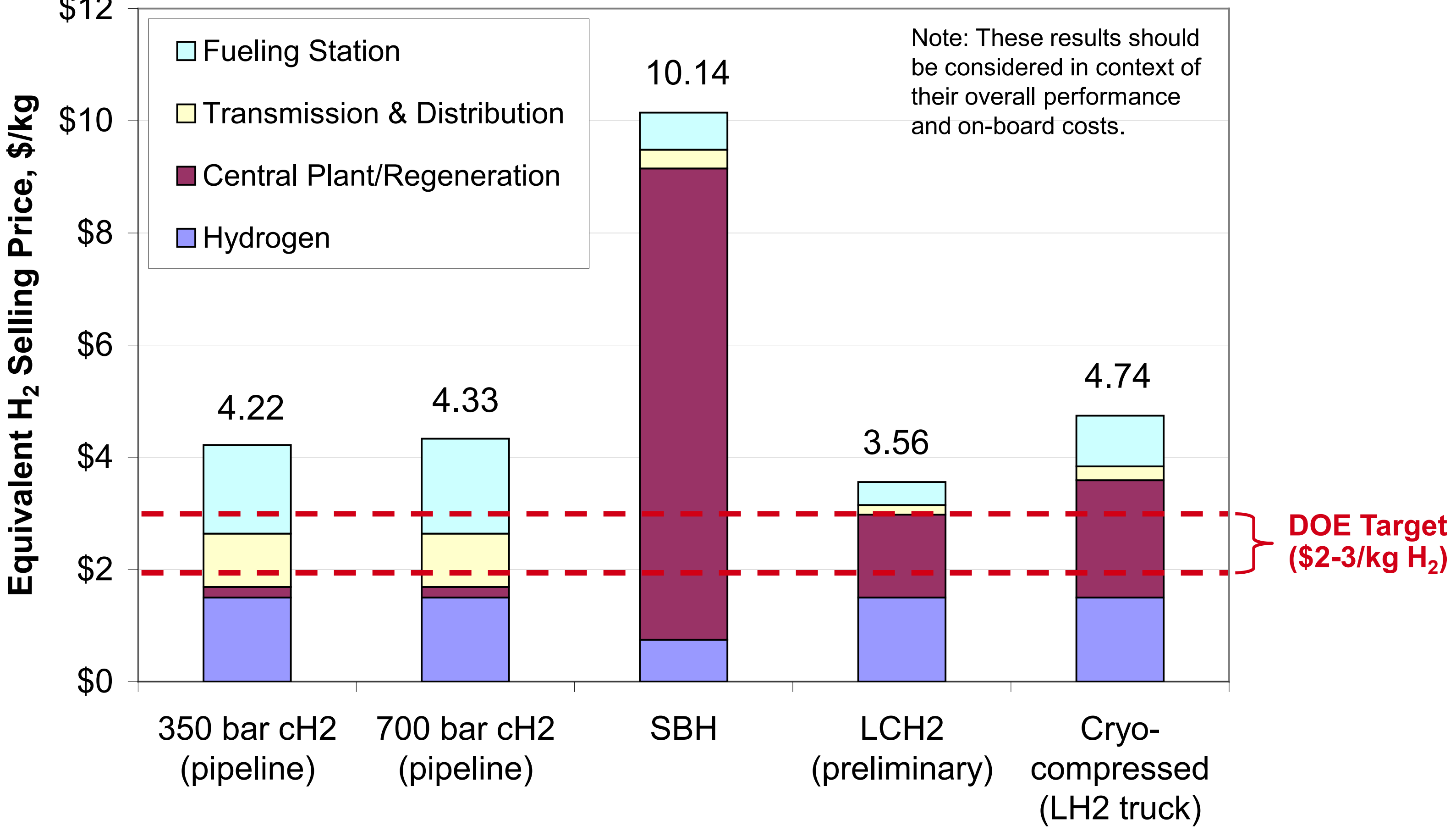
[1] Source: DOE, "Effects of a Transition to a Hydrogen Economy on Employment in the United States", Report to Congress, July 2008

[2] Source: U.S. Department of Transportation, NHTSA, "Summary of Fuel Economy Performance," Washington, DC, March 2007

The implicit assumption in this ownership cost assessment is that each fuel system and vehicle perform equally well and have the same operating lifetime.

The compressed system refueling costs are projected to be 1.5-2 times more expensive than the current DOE target range of $2-3/kg.

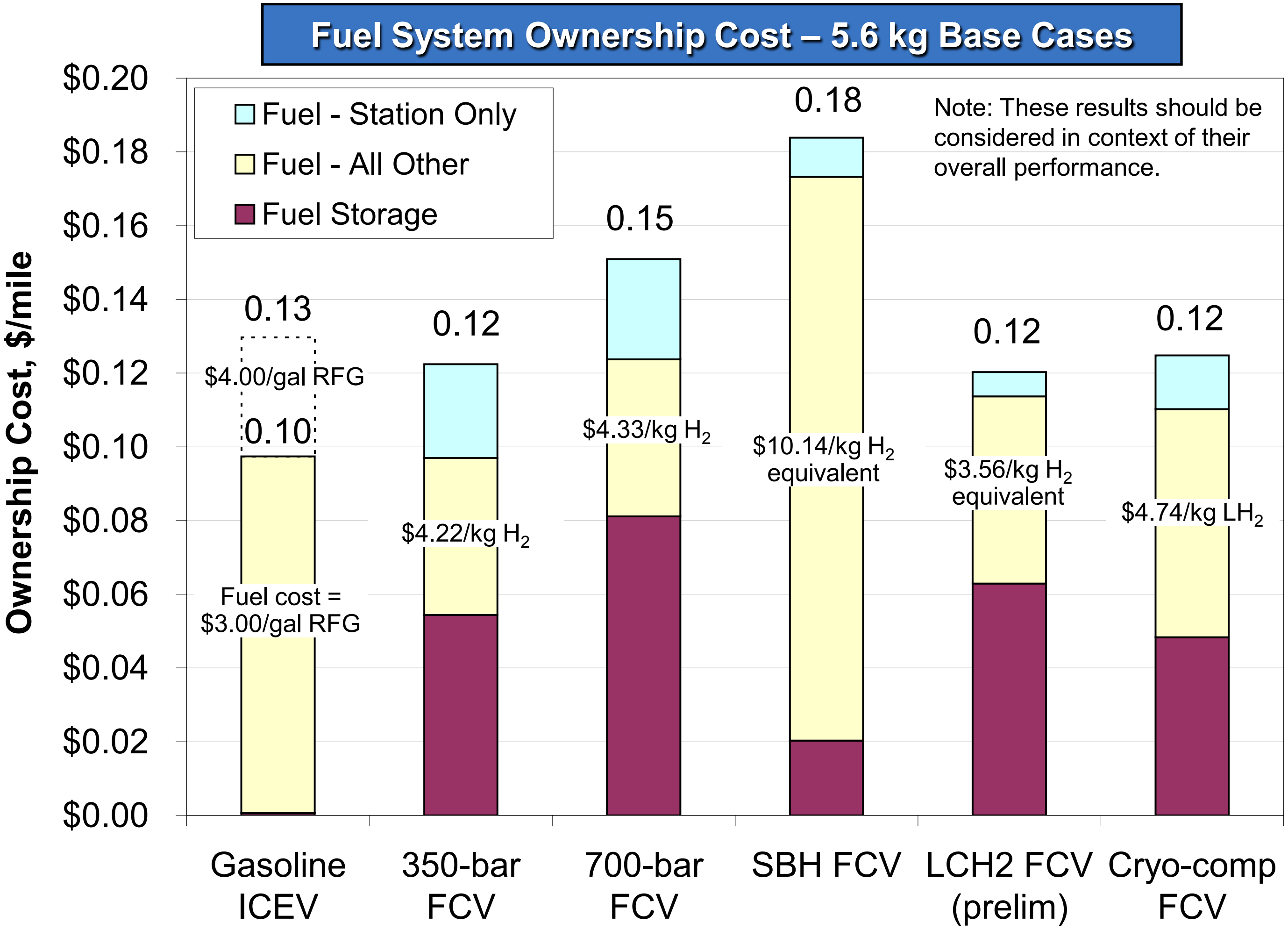
Refueling Cost Comparison – 5.6 kg Base Cases



Note: These results should be considered in context of their overall performance and on-board costs.

Note: 350-bar, 700-bar and cryo-compressed results were calculated using the base case delivery scenarios in HDSAM v2.06. SBH and LCH_2 results were calculated using a modified H2A Delivery Components Carrier Model v34. All fuel costs exclude fuel taxes.

Fuel system ownership cost for the base case compressed systems are projected to be 20-50% more expensive than gasoline at $3.00/gal.



Note: These results should be considered in context of their overall performance.

Note: All fuel costs exclude fuel taxes.