Cost Analyses of Hydrogen Storage Materials and On-Board Systems

Project ID # ST002

Updated Hydrogen Storage System Cost Assessments

DOE Annual Merit Review
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Reference: D0268

Timeline

- Start date: June 2004
- End date: March 2012
- 95% complete

Barriers

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

Budget

- Total project funding
  - DOE share = $2.1M
  - No cost share
- FY10 = $300k
- FY11 = $300k

Partners

- Project lead: TIAX
- 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 technologies being developed for DOE's Hydrogen Storage Sub-Program.

Project Objective	Barriers and Targets Addressed	Current Impact on Barriers and Targets	Previous Impact on Barriers and Targets
Overall	Develop and demonstrate viable H_2 storage for transportation applications	Help guide DOE and developers toward promising R&D and commercialization pathways by evaluating status of the various on-board hydrogen storage technologies on a consistent basis	
Assess On-Board Storage Systems	A. System Weight and Volume (ANL Lead) B. System Cost (TIAX Lead)	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)	Finalize bottom-up factory cost, weight and volume for the following storage systems: 1) 350 and 700 bar compressed 2) Liquid carrier 3) MOF-177 4) AX-21
Assess Off-Board Fuel Cycles	K. System Life Cycle Assessments (SSWAG Lead)	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)	Finalize review of Dow's ammonia borane first fill and spent fuel regeneration cost analysis

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

Technology Assessment

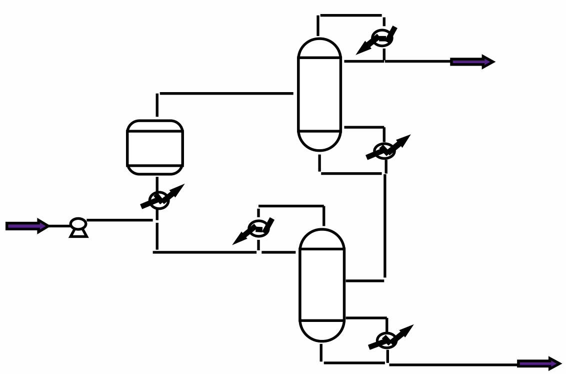
- Perform literature search
- Outline assumptions
- Develop system requirements and design assumptions
- Obtain developer input

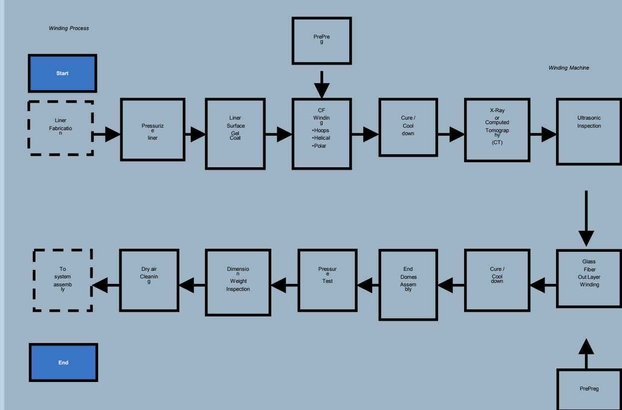
Cost Model and Estimates

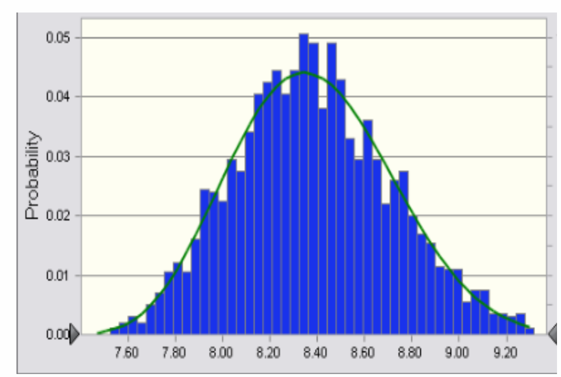
- Develop BOM
- Specify manufacturing processes and equipment
- Determine material and processing costs
- Develop bulk cost assumptions

Overall Model Refinement

- Obtain developer and industry feedback
- Revise assumptions and model inputs
- Perform sensitivity analyses (single and multi-variable)



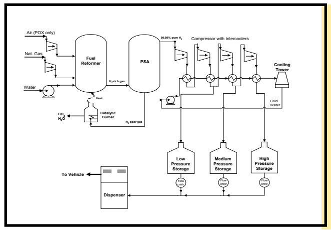




BOM = Bill of Materials

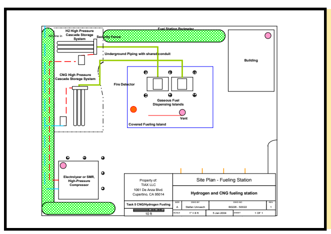
The off-board assessment makes use of existing models to calculate cost and performance for each technology on a consistent basis.

Conceptual Design



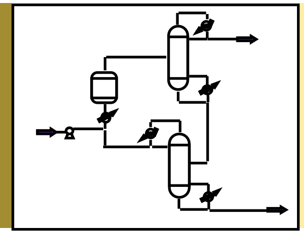
- System layout and requirements

Site Plans



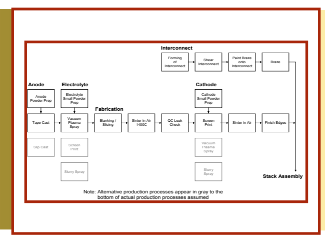
- Safety equipment, site prep, labor and land costs

Process Simulation



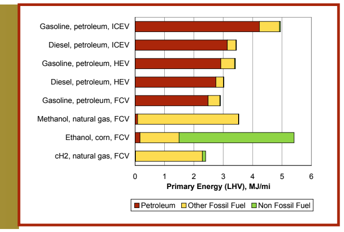
- Energy requirements
- Equipment size/specs

Capital Cost Estimates



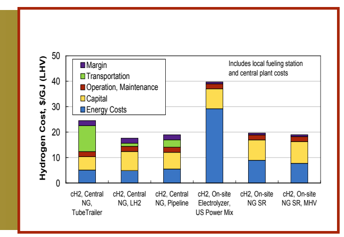
- High and low volume equipment costs

ANL/GREET Model



- WTT energy use
- WTT GHG

TIAX/H2A Model



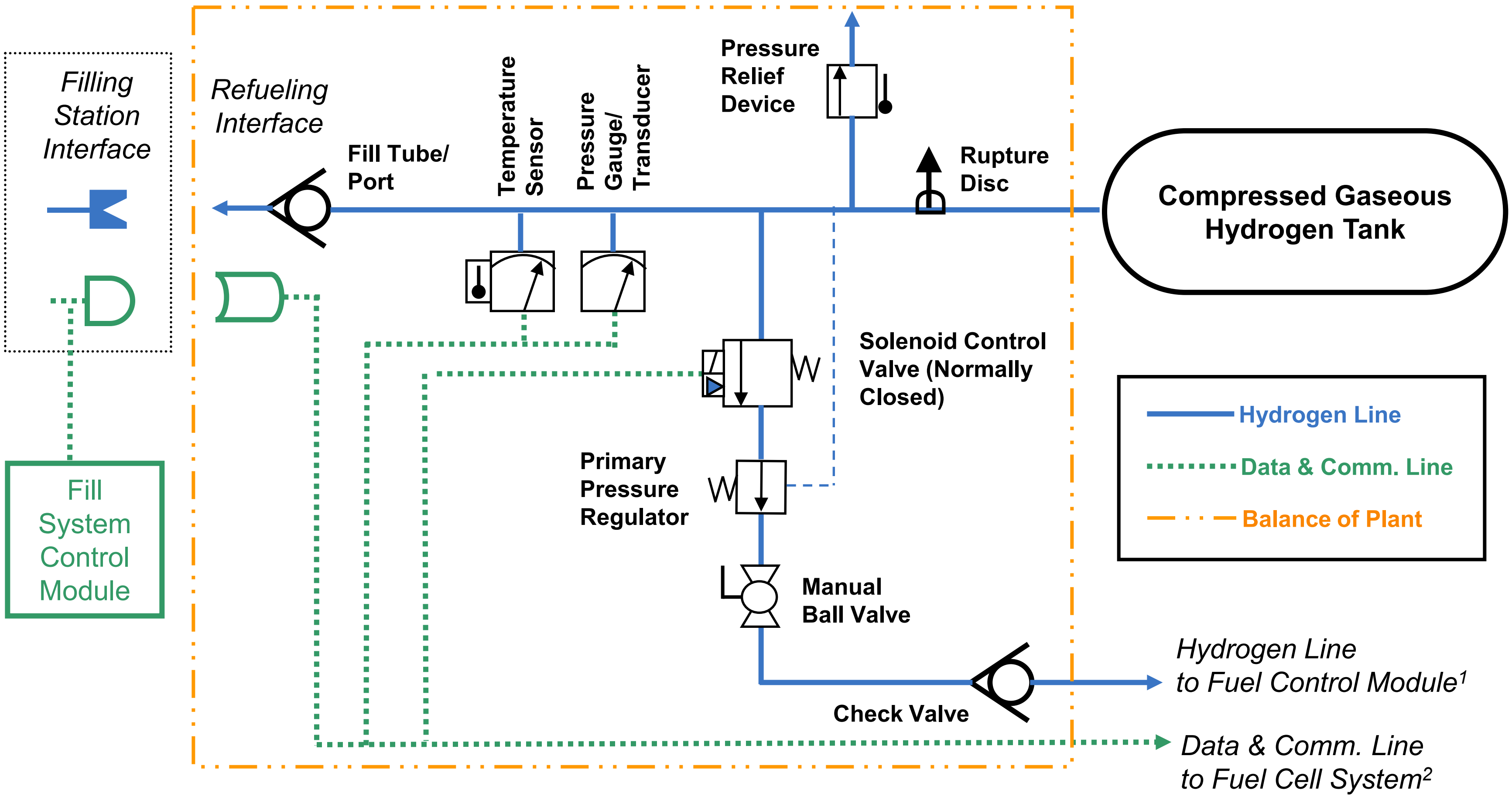
- Equivalent hydrogen selling price

Finalized assessments of compressed gas, liquid carrier, MOF and activated carbon. Began low-volume manufacturing cost analysis for compressed gas.

- Finalized high-volume factory cost assessments of compressed gas systems (5.6 kg usable H_2)[1]
  - 350 bar, Type III = \$17/kWh and \$17/kWh for one- and two-tank systems
  - 700 bar, Type III = \$21/kWh and \$21/kWh for one- and two-tank systems
  - 350 bar, Type IV = \$15/kWh and \$16/kWh for one- and two-tank systems
  - 700 bar, Type IV = \$19/kWh and \$19/kWh for one- and two-tank systems
- Finalized high-volume factory cost assessments of liquid carrier and sorbent systems[1]
  - Liquid carrier = \$16/kWh for 5.6 kg usable H_2 system
  - MOF-177 = \$16/kWh and \$12/kWh for 5.6 and 10.4 kg usable H_2 systems
  - AX-21 = \$27/kWh and \$18/kWh for 50 and 250 atm systems (5.6 kg usable H_2)
- Completed preliminary, low-volume factory cost assessments of 350 bar and 700 bar, one-tank, Type IV compressed gas system (5.6 kg usable H_2)[1]
  - 10,000 units/yr = \$29/kWh – 350 bar; \$36/kWh – 700bar
  - 30,000 units/yr = \$26/kWh – 350 bar; \$33/kWh – 700 bar
  - 80,000 units/yr = \$20/kWh – 350 bar; \$25/kWh – 700 bar
  - 130,000 units/yr = \$18/kWh – 350 bar; \$22/kWh – 700 bar
  - 500,000 units/yr = \$15/kWh – 350 bar; \$19/kWh – 700 bar
- Finalized review of cost assessments for ammonia borane first fill & regeneration processes

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

Our assessments are based on system schematics and bill of materials generated through discussions with tank developers.



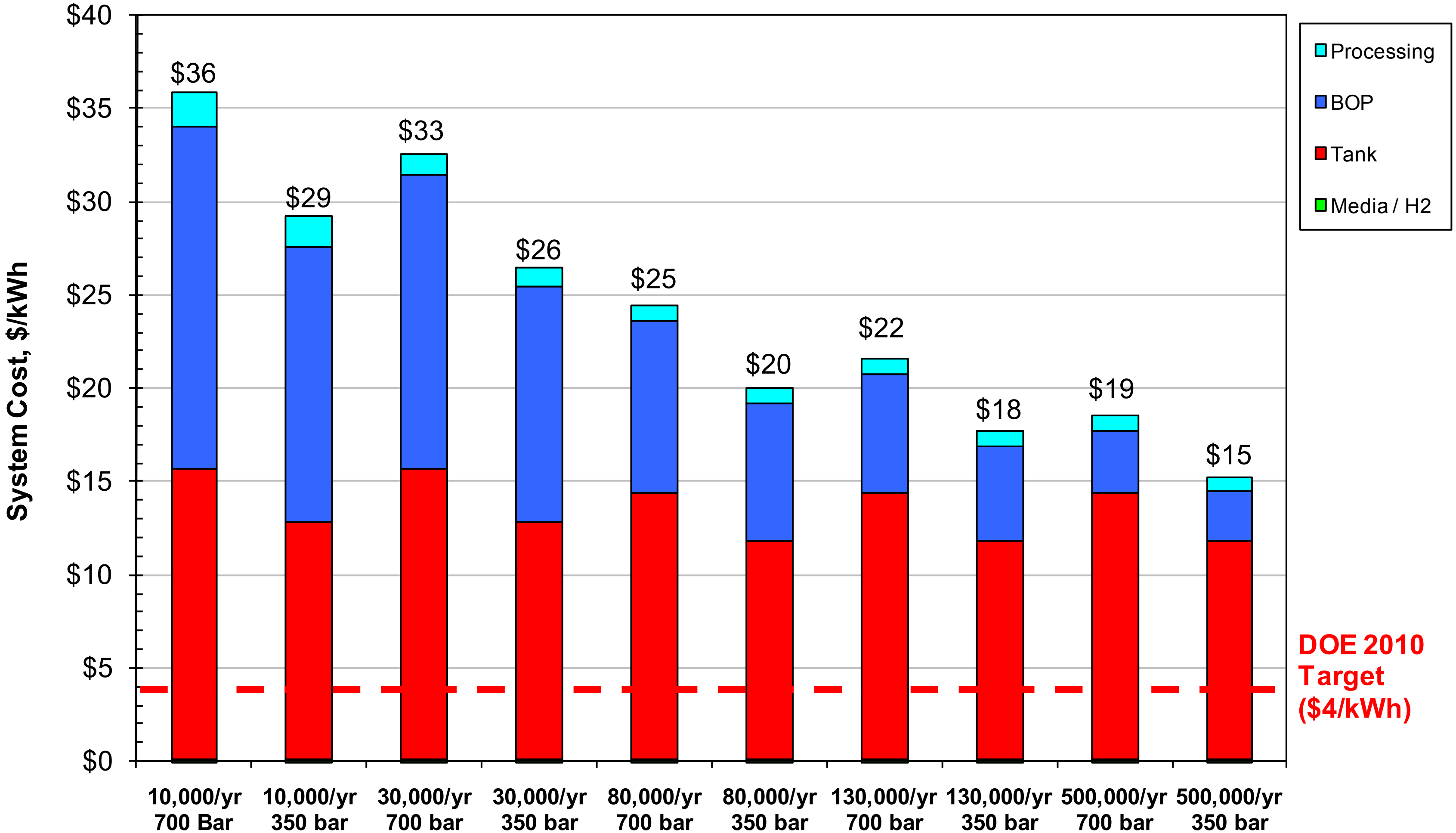
[1] Schematic based on the requirements defined in the draft European regulation "Hydrogen Vehicles: On-Board Storage Systems" and US Patent 6,041,762.
[2] Secondary Pressure Regulator located in Fuel Control Module of the Fuel Cell System.

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

Raw Material Cost Estimates, 2005$/kg	Base Cases	Comment/Basis
Hydrogen	3.0	Consistent with DOE H_2 delivery target
HDPE liner	1.6	Plastics Technology (2008), deflated to 2005$
Aluminum (6061-T6)	9.6	Bulk price from Alcoa (2009), deflated to 2005$
Carbon fiber (T700S) prepreg	36.6	Discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb); 1.27 prepreg/fiber ratio (Du Vall 2001); confirmed with discussions in 2011
Glass fiber prepreg	4.7	Discussions with AGY (2007) for non-structural fiber glass, deflated to 2005$
Foam end caps	6.4	Plastics Technology (2008), deflated to 2005$
Stainless steel (304)	4.7	Average monthly costs from Sep ’06 – Aug ’07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Standard steel	1.0	Estimate based on monthly cost range for 2008-2009 (MEPS International 2009), , deflated to 2005$

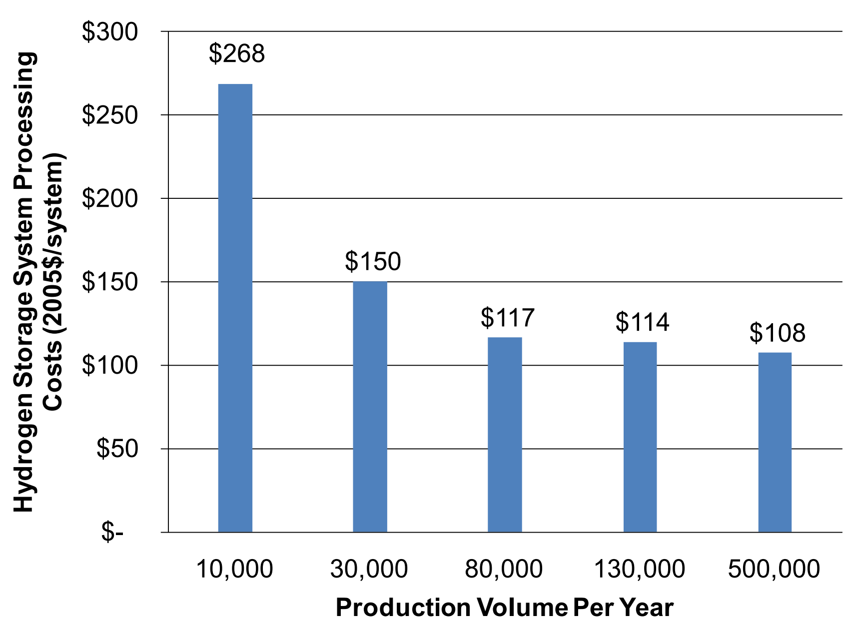
Note: for tank design assumptions see technical back-up slides

Currently, projections for 500,000 units/year of compressed systems do not meet the DOE 2010 cost target. In the near term, lower production volumes of 10,000 units/year may cost nearly twice as much as high volumes.



The TIAX manufacturing model optimizes processes at each production volume to determine processing costs. Production cost curves for BOP components are based on projections from suppliers.

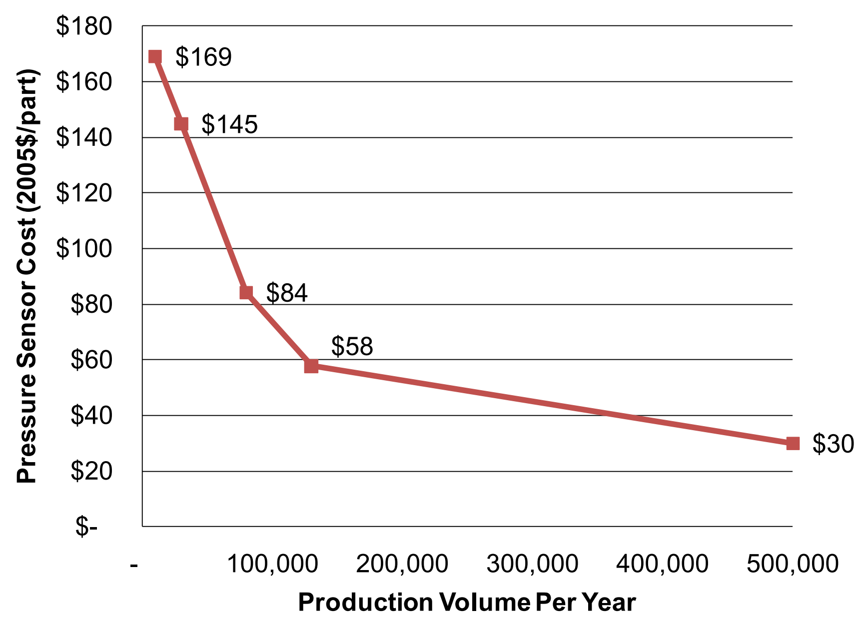
Type IV 350-bar Tank Processing Portion of Factory Cost[1] at Varying Volumes



[1] Cost estimate in 2005 USD. Includes processing and inspection costs for tank only.

BOP = Balance of Plant

Type IV 350-bar Pressure Sensor Cost[1,2] at Varying Volumes



[1] Cost estimate in 2005 USD. Includes processing costs.
[2] Based on cost estimates from a supplier of hydrogen vehicle pressure sensors

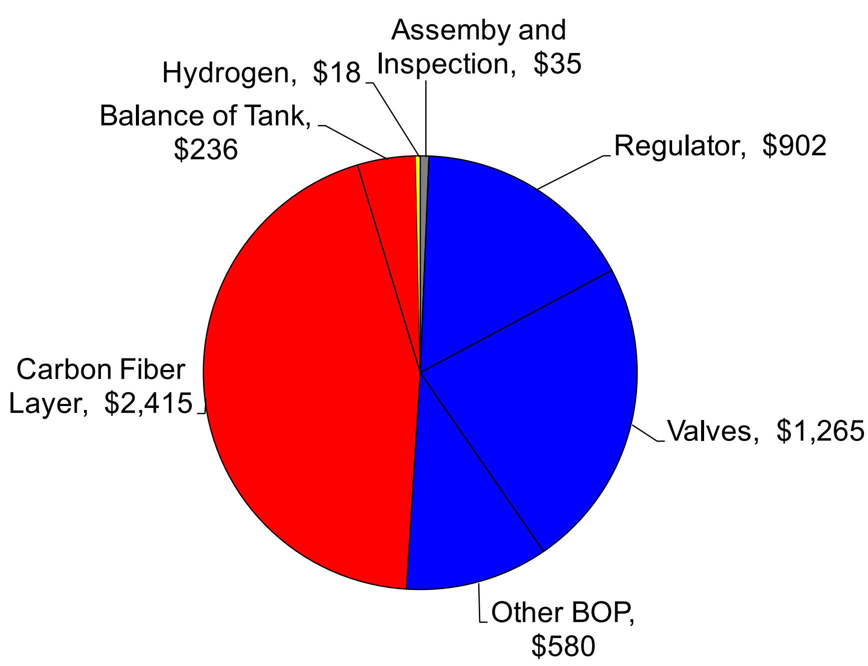
Material and processing cost are estimated for low-volume manufacturing (10,000 units/year) for compressed H_2 storage.

On-board System Cost Breakout – Compressed Gas	Type IV 350-bar one-tank – 10,000/yr		Type IV 700-bar one-tank – 10,000/yr	
	Material, $	Processing, $	Material, $	Processing, $
Hydrogen	$18	(purchased)	$18	(purchased)
Compressed Vessel	$2,383	$268	$2,917	$296
Liner & Fittings	*$20*	*$89*	*$14*	*$89*
Carbon Fiber Layer	*$2,301*	*$114*	*$2,855*	*$142*
Glass Fiber Layer	*$30*	*$27*	*$23*	*$27*
Foam	*$32*	*$12*	*$25*	*$12*
Inspection	-	*$26*	-	*$26*
Regulator	$902	(purchased)	$1,127	(purchased)
Valves	$1,265	(purchased)	$1,580	(purchased)
Other BOP	$580	(purchased)	$715	(purchased)
Final Assembly & Inspection	-	$35	-	$35
Total Factory Cost	**$5,148**	**$303**	**$6,357**	**$331**

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

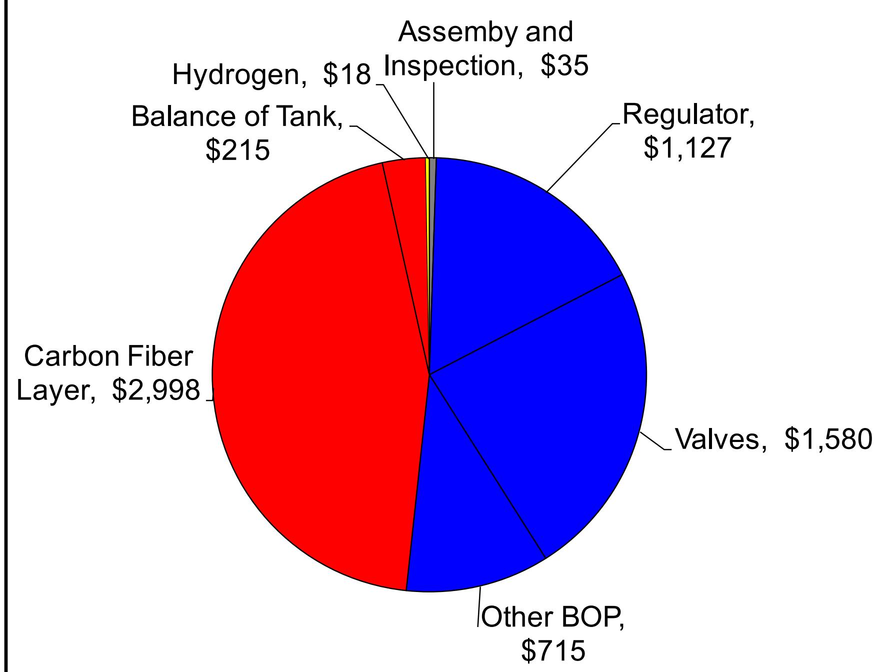
Material and processing costs are estimated for low-volume manufacturing (10,000 units/year) for compressed storage systems.

Type IV 350-bar 10,000/yr
Factory Cost[1] = $5,450
$29.2/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

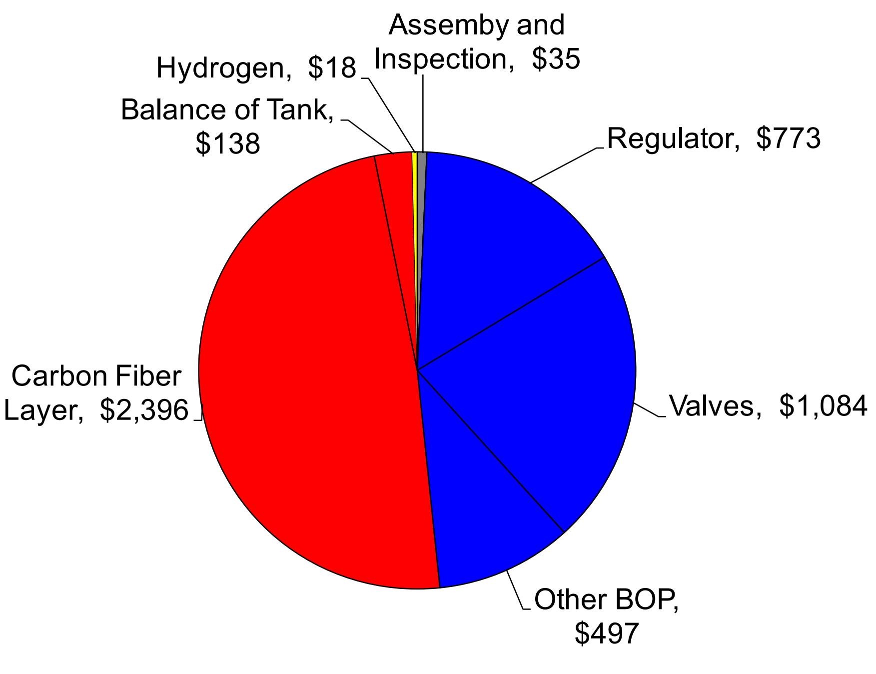
Type IV 700-bar 10,000/yr
Factory Cost[1] = $6,690
$35.9/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

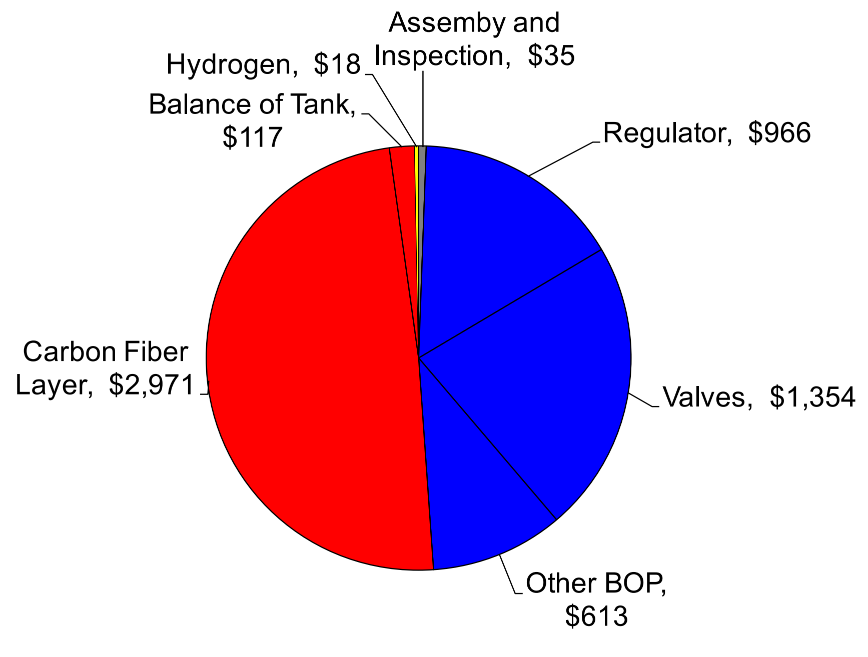
Material and processing costs are estimated for low-volume manufacturing (30,000 units/year) for compressed storage systems.

Type IV 350-bar 30,000/yr
Factory Cost[1] = $4,940
$26.5/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

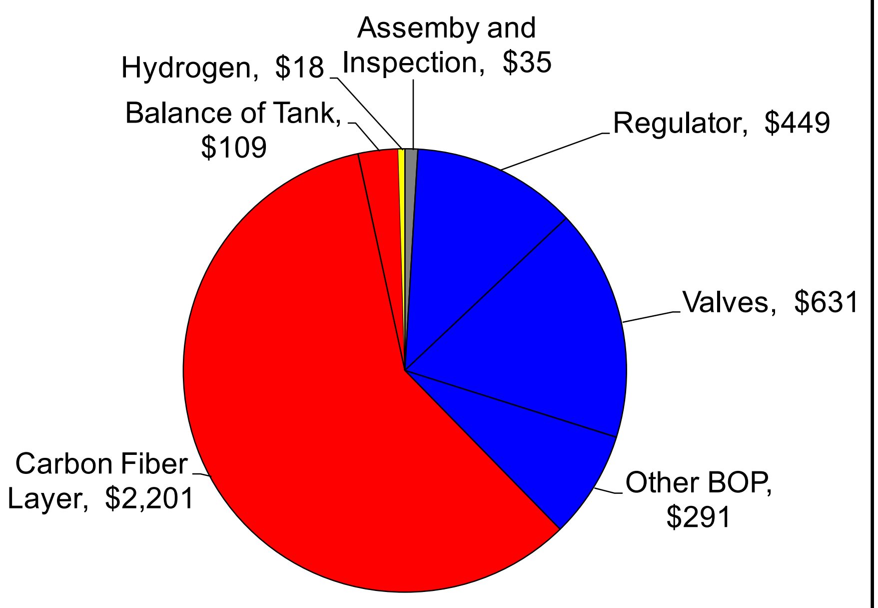
Type IV 700-bar 30,000/yr
Factory Cost[1] = $6,080
$32.6/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

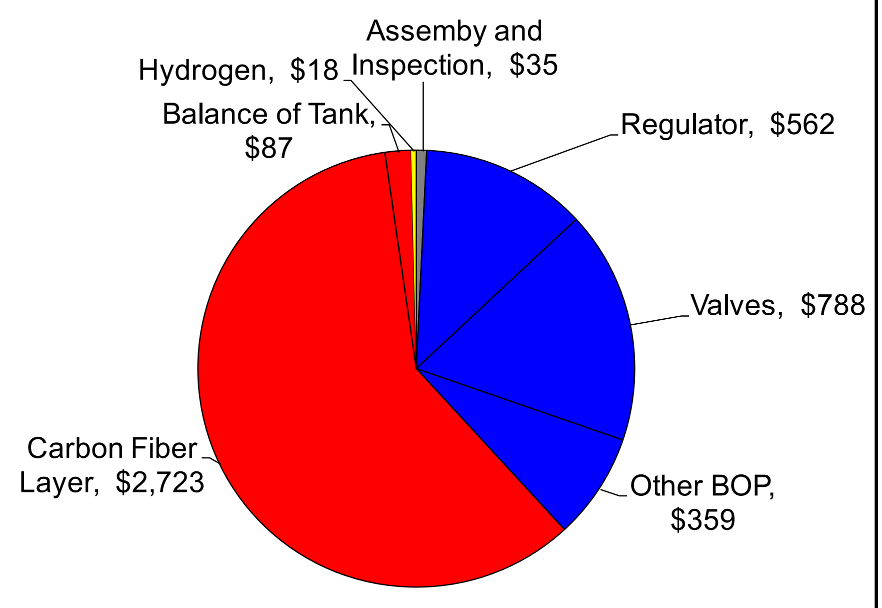
Material and processing costs are estimated for mid-volume manufacturing (80,000 units/year) for compressed storage systems.

Type IV 350-bar 80,000/yr
Factory Cost[1] = $3,740
$20.0/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

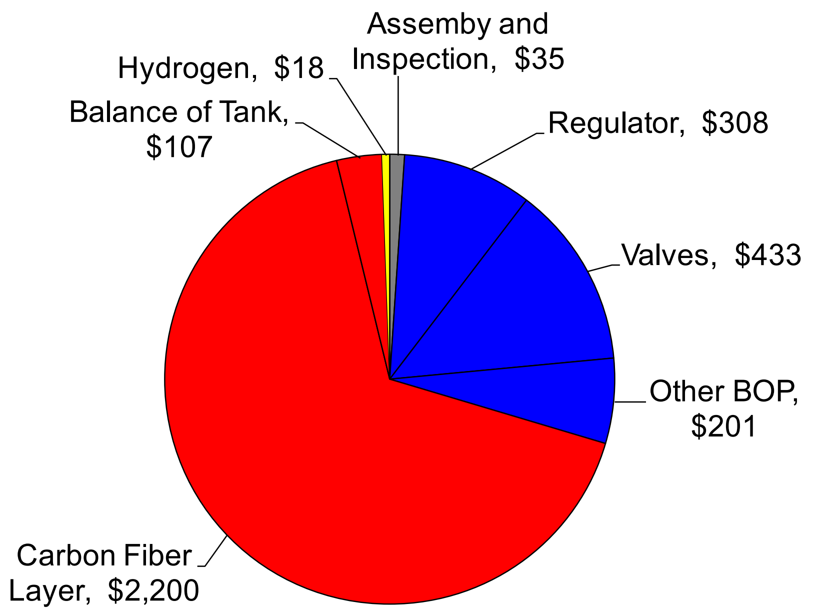
Type IV 700-bar 80,000/yr
Factory Cost[1] = $4,580
$24.5/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

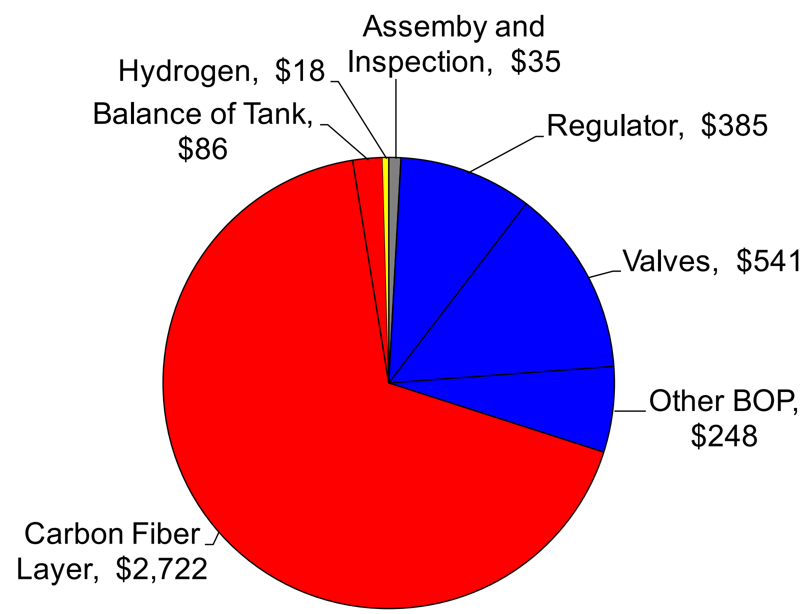
Material and processing costs are estimated for mid-volume manufacturing (130,000 units/year) for compressed storage systems.

Type IV 350-bar 130,000/yr
Factory Cost[1] = $3,310
$17.8/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

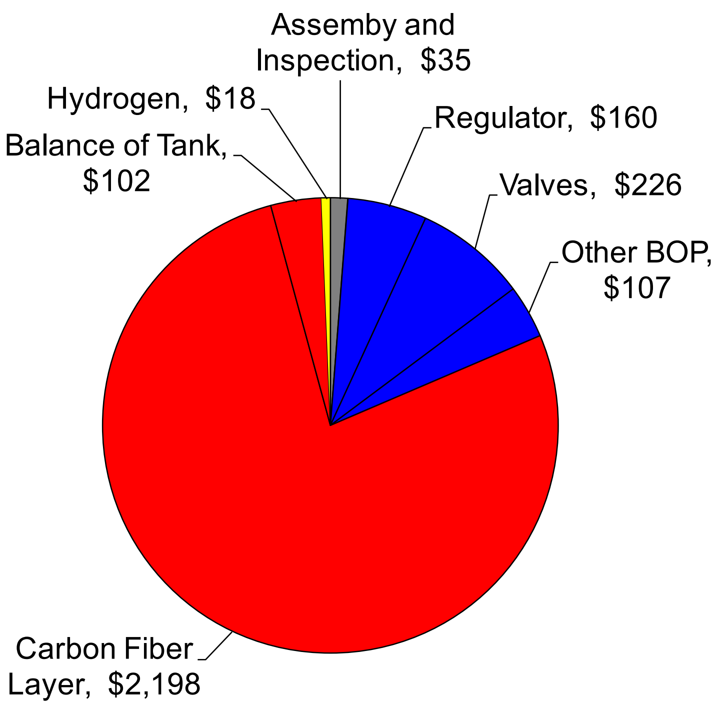
Type IV 700-bar 130,000/yr
Factory Cost[1] = $4,040
$24.6/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

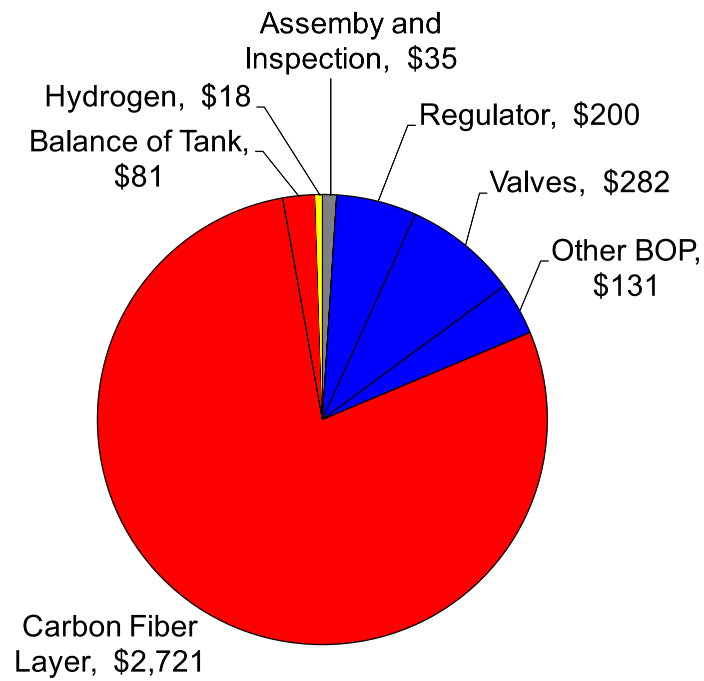
Material and processing costs are estimated for high-volume manufacturing (500,000 units/year) of compressed storage systems.

Type IV 350-bar 500,000/yr
Factory Cost[1] = $2,850
$15.3/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



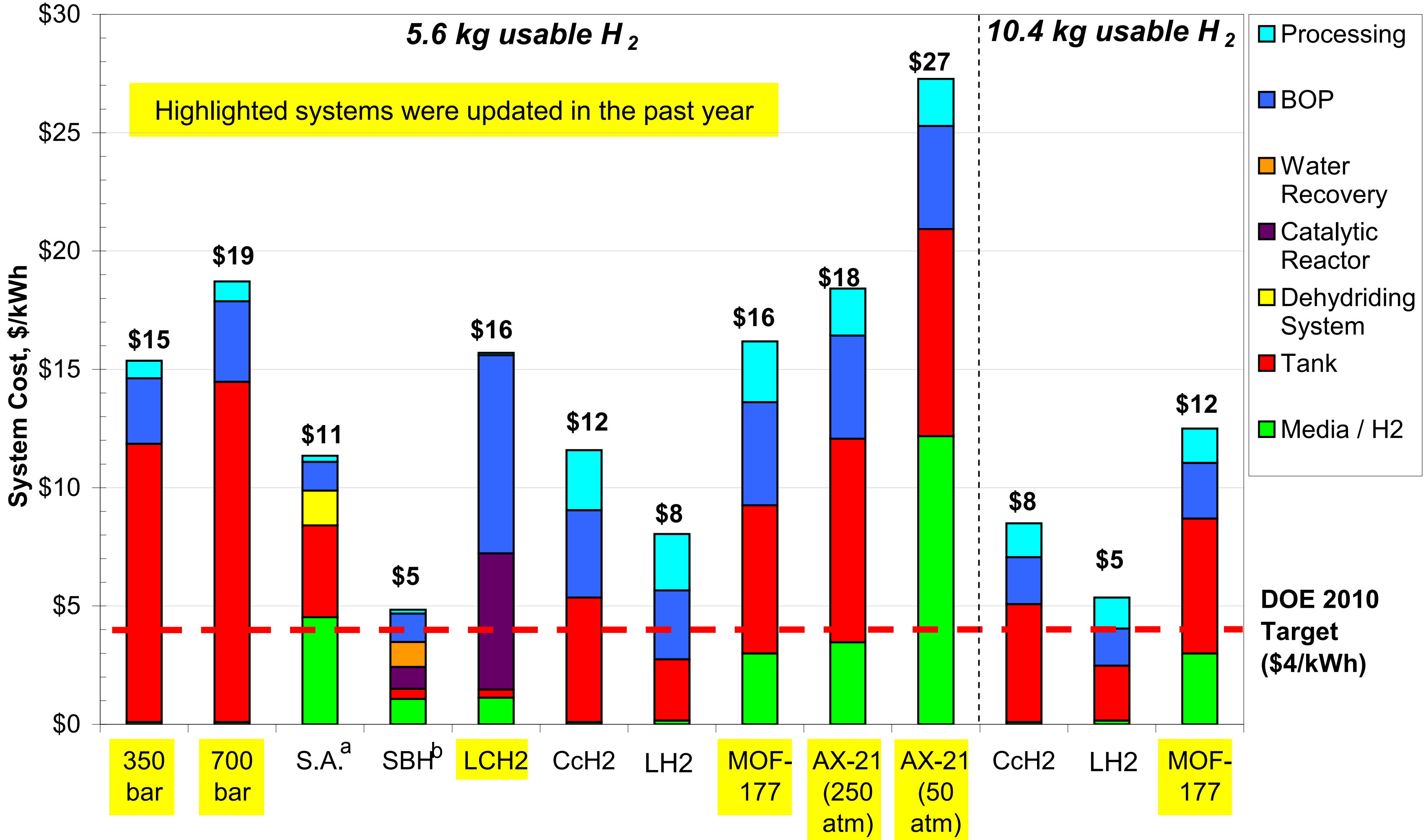
[1] Cost estimate in 2005 USD. Includes processing costs.

Type IV 700-bar 500,000/yr
Factory Cost[1] = $3,480
$18.6/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

Currently, none of the analyzed systems are projected to meet the DOE 2010 target of $4/kWh. These results should be considered in context of their overall well-to-wheel performance and lifecycle costs.



[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.
b SBH = Sodium borohydride, "A NO-GO decision was made on the hydrolysis of SBH for on-board application"

We collaborated closely with ANL and numerous developers and other stakeholders participating in the DOE Hydrogen Storage Sub-Program.

- Argonne National Laboratory (ANL)
  - MOF177, LH_2, cryo-compressed, 350- and 700-bar on-board system designs
- Manufacturers/Stakeholders (BMW, LLNL, Quantum, Dynetek, Lincoln Composites, Toray, Graphil, TohoTenex)
  - MOF177, LH_2, cryo-compressed, 350- and 700-bar on-board system designs
  - Stakeholders reviewed assumptions and results and provided feedback and recommendations
- DOE Hydrogen Storage Tech Developers
  - DOE Tech Developers reviewed assumptions and results for various technologies
  - Worked with SSAWG and others on Cold Gas off-board assessment and WTW/Lifecycle Cost assessments for MOF177, cryo-compressed, 350- and 700-bar
- DOW Chemical
  - Email exchanges and conference calls to discuss ammonia borane off-board cost assessment

For the remainder of the contract, we will focus on completing low-volume manufacturing cost analyses and assessing additional technologies as directed by DOE.

- Incorporate feedback and finalize on-board cost assessments and reports for low-volume manufacturing of compressed H_2 systems
  - Preliminary assessment of 350-bar and 700-bar, Type IV, one-tank system is complete but will be updated
  - Additional tank architectures (350- vs. 700-bar, Type III vs. Type IV, one- vs. two-tank systems) to be assessed with guidance from DOE
- Complete new assessments and final reports (with ANL) for additional technologies (MOF5 or other advanced sorbent)
- Continue to revise and improve system models and incorporate input from DOE, Hydrogen Storage Centers of Excellence, other analysis projects, tech developers, and other stakeholders (as necessary)

Over the course of this project, we have evaluated on-board and off-board hydrogen storage systems for 11 storage technologies.

- Relevance
  - Provides an independent cost assessment of the technologies being developed for DOE's Hydrogen Storage Sub-Program
  - Helps guide DOE and developers toward promising R&D and commercialization pathways by evaluating status of the various on-board hydrogen storage technologies on a consistent basis
- Approach – On-board cost and performance assessments are based on detailed technology review and bottom-up cost modeling combined with overall model refinement from industry and developer feedback
- Technical Accomplishments and Progress
  - Finalized high-volume factory cost assessment for compressed gas, liquid carrier, MOF177 and AX-21
  - Draft low-volume factory cost assessment of compressed gas Type IV, one-tank
- Collaborations – Active collaborations with ANL, Manufacturers/Stakeholders and DOE Hydrogen Storage Tech Developers
- Proposed Future Work – Finalize draft low-volume factory cost assessments for Type IV, one-tank systems, perform similar low-volume assessments for Type III compressed gas systems, and perform cost assessments for MOF5

Thank You

Questions?

Technical Back-Up Slides

Example of key tank design assumptions for the compressed gaseous hydrogen storage system:

Design Parameter	Base Case Value	Basis/Comment
Nominal pressure	350 and 700 bar	Design assumptions based on DOE and industry input
Number of tanks	Single and dual	Design assumptions based on DOE and industry input – base case results reflect single tank systems
Tank liner	Type III (Aluminum) Type IV (HDPE)	Design assumptions based on DOE and industry input – base case results reflect Type IV tanks
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 FCEV 350 mile range for a midsized vehicle
Recoverable hydrogen (fraction of stored H_2)	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 specification (e.g., ISO/TS 15869)[1]
L/D ratio	3.0	Discussions with Quantum, 2008; based on the outside of the CF wrapped tank

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

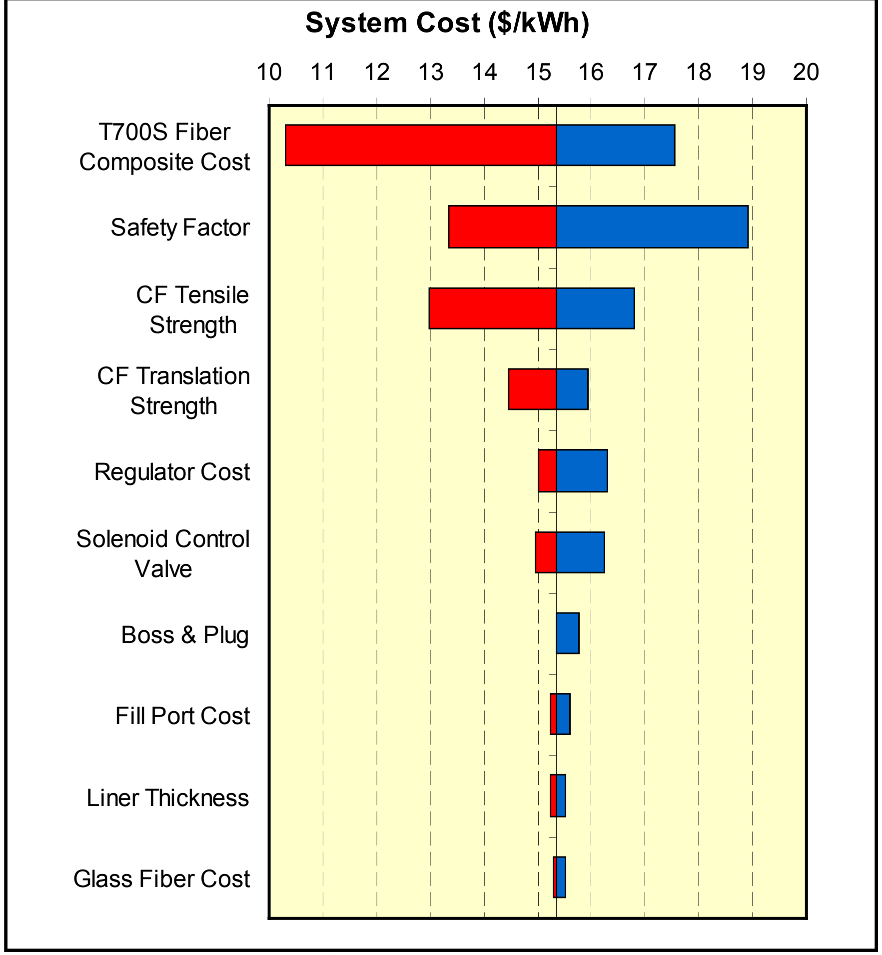
The cost of raw materials and cost projections for the major BOP components were developed through discussions with suppliers. The base case was estimated assuming high-volume (500,000 units/year) production.

Purchased Component and Carbon Fiber Cost Est. ($ per unit or lb)	10,000	30,000	80,000	130,000	500,000 (Base Case)	Comments/Basis – Base Case
Pressure regulator	$902	$773	$449	$308	$160	Industry feedback (2009) and DFMA® cost modeling software
Solenoid Control valves (3)	$1,048	$898	$522	$358	$186	Industry feedback (2009)
Fill tube/port	$282	$241	$140	$96	$50	Industry feedback (2009)
Pressure transducer	$169	$145	$84	$58	$30	Industry feedback validated with quotes and discussion with Taber Industries (2009)
Pressure gauge	$85	$72	$42	$29	$15	Based on quotes from Emerson Process Management/ Tescom/ Northeast Engineering (2009)
Boss and plug (in tank)	$85	$72	$42	$29	$15	Based on price estimate from tank developers (2009), validated with Al raw material price marked up
Other BOP[1]	$261	$224	$133	$94	$52	Industry feedback (2009)
Carbon fiber (T700S) prepreg	$39.9	$39.9	$36.6	$36.6	$36.6	Kept base case the same, increased low volume by high volume discount $1.50/lb

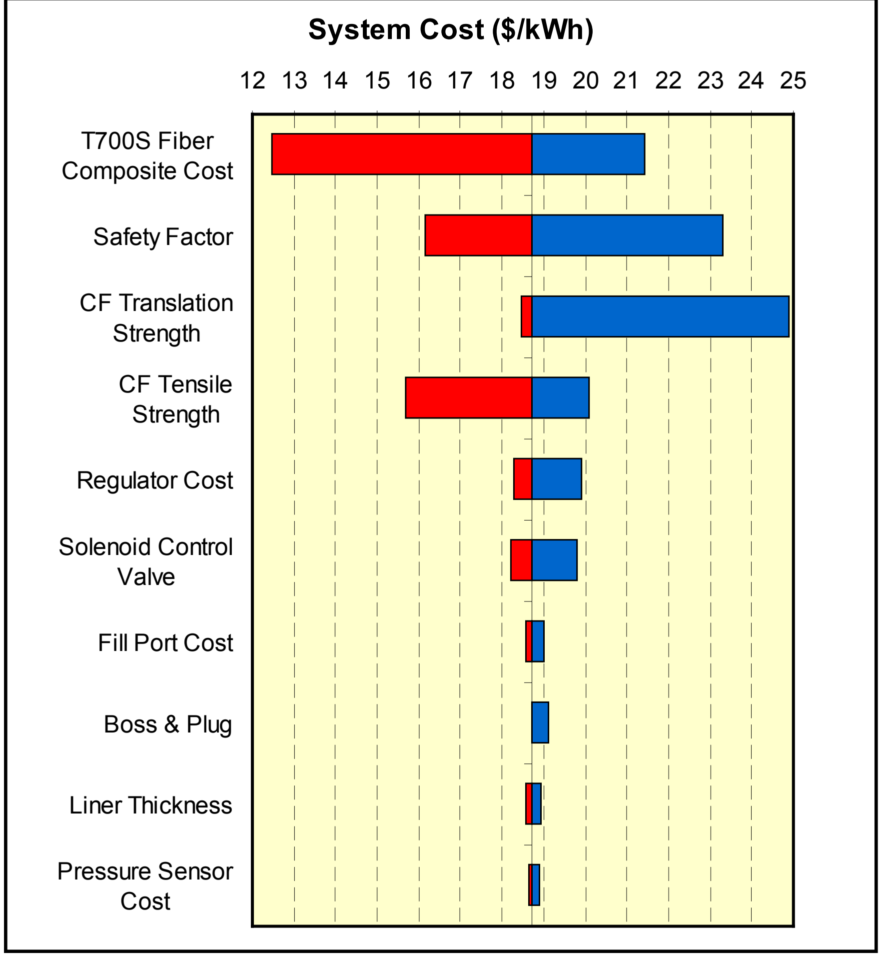
[1] Includes manual service vent valves (2), check valves (2), rupture disks (2), pipe assembly, bracket assembly, pressure relief devices (2), and gas temperature sensor.

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

350-bar, Type IV, one-tank, 500,000/yr
Single Variable Cost Sensitivity
based on 5.6 kg usable H_2, \$/kWh

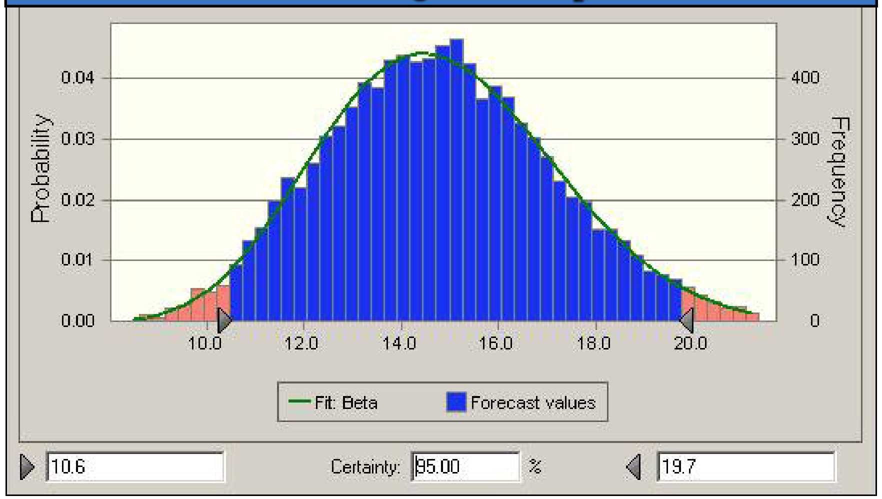


700-bar, Type IV, one-tank, 500,000/yr
Single Variable Cost Sensitivity
based on 5.6 kg usable H_2, \$/kWh

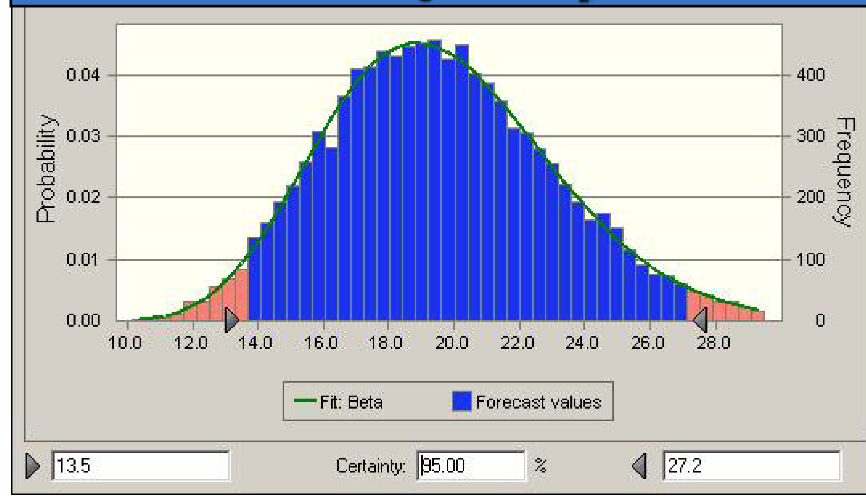


Monte Carlo simulations project that the factory cost is likely to be between \$10.6-19.7/kWh for 350-bar and \$13.5-27.2/kWh for 700-bar, Type IV, one-tank, 500,000/yr systems.[1]

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



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

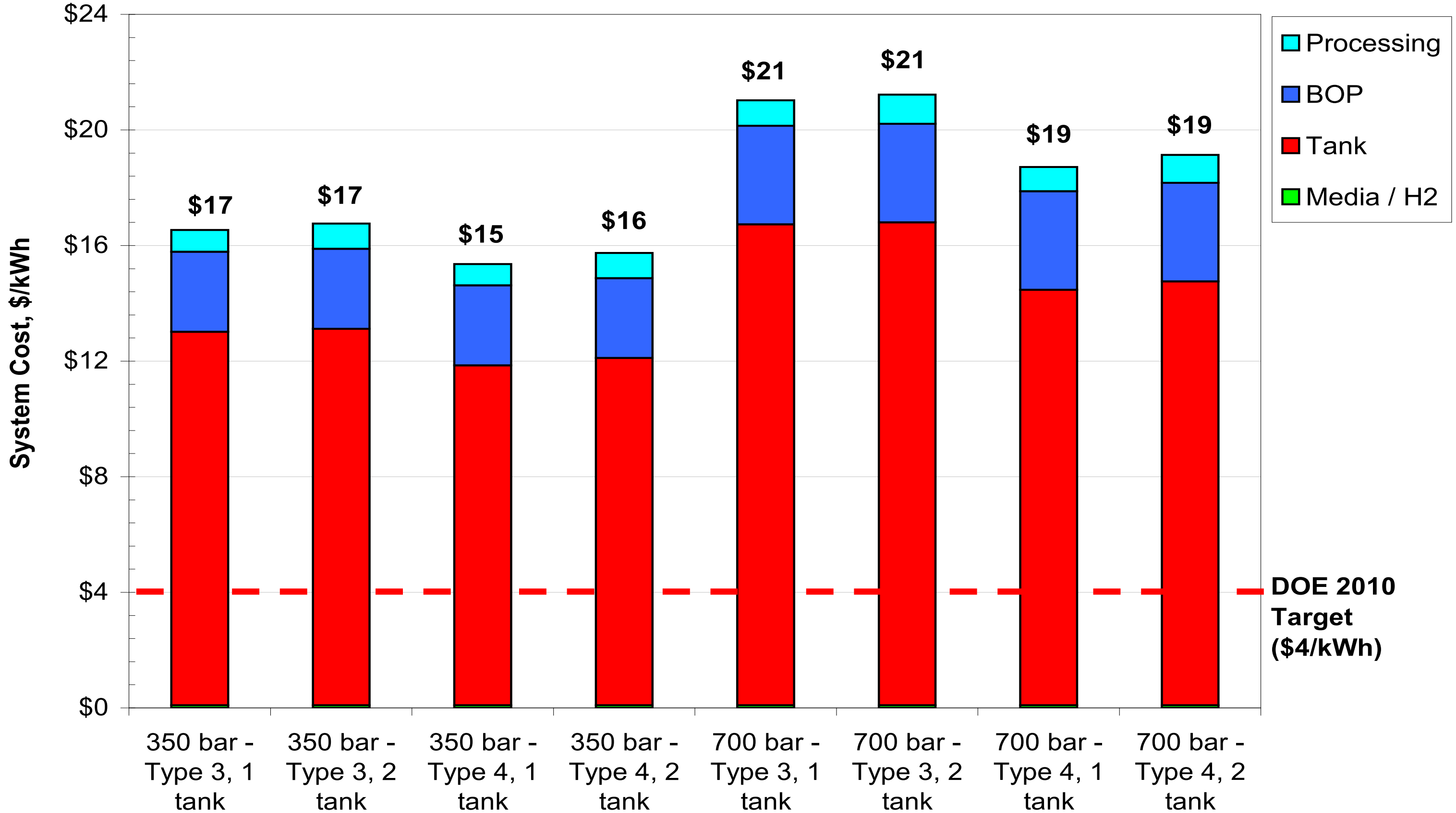


Base Case	15.4
Mean	14.8
Standard Deviation	2.3
"Low" Case[1]	10.60
"High" Case[1]	19.7

Base Case	18.7
Mean	19.7
Standard Deviation	3.5
"Low" Case[1]	13.5
"High" Case[1]	27.2

[1] The ranges shown here reflect the 95% confidence interval based on the probability distribution.

Cost estimates for Type III tanks and two-tank systems project a modest cost increase compared to the Type IV, one-tank baselines.



- Reduction in carbon fiber enabled by load-bearing qualities of Type III aluminum liner is more than offset by its higher cost, weight, and thickness compared to Type IV HDPE liner
- Tank for one-tank system has lower surface area-to-volume ratio than two-tank system, but advantage is largely offset by thicker walls required for one-tank system
- Two-tank system's BOP assumed similar to that of the single tank system, with sensitivity analysis