Analyses of Compressed Hydrogen On-Board Storage Systems

Compressed and Cryo-Compressed Hydrogen Storage Workshop

February 14, 2011

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Reference: D0268

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

Project Objectives	Description
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
On-Board Storage System Assessment	Evaluate or develop system-level designs for the on-board storage system to project bottom-up factory costs
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)

Over the course of this project, we have evaluated on-board and off-board hydrogen storage systems for 11 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	√	√		√	√	√	√ *	√	√		
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	√	√		√	√	√	√ *	√	√		
	Analysis update	√			√	√	√		√	√		

* Preliminary results

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

(grey box) = Not part of current SOW

WIP = Work in progress

Recently Completed and Planned Analyses

Technology	Status
Compressed H_2: Type III & Type IV tanks;1-tank and 2-tank design, 350 and 700 bar	Completed final report, Aug 2010 – Type III & multi tank systems
Cryo-compressed Gen 3	Completed final report, Dec 2009
Metal Organic Framework (MOF-177)	Completed final report, Dec 2010 – revisited storage media cost
Activated Carbon (AX-21)	Completed final report, Dec 2010 – reflects new ANL analysis
Liquid Hydrogen Carrier, LCH2	Completed final report, Sept 2010 – misc updates to incorporate APCI feedback and reflect updated assumptions
Off-board Ammonia Borane (AB), first fill & regen	Reviewed cost analyses of first fill and regen pathways developed by Dow Chemical in 2009 & Aug 2010.
Cold Gas - Preliminary (e.g., 400 bar, 200 K)	Supported analysis of WTT costs & performance.
Liquid Hydrogen (LH_2)	Draft report completed January 2010. Reviewed with BMW April 2010. Further work on hold.
Compressed H2 (350 & 700 Bar, Type IV tanks, and 350 Bar, Type III tank) at alternate production volumes	Planned, FY'11
MOF-5	Planned, FY'11 (*Requires ANL input*)
Alternate (pyrolyzed polymer) sorbents	Planned, FY'11 (*TBD*)
Revise prior analyses based on new carbon fiber winding/placement processes and/orlower cost fibers	Planned, FY'11 (*TBD, depends on data availability*)
Alane Regen	Planned, FY'11 (*TBD – requires ANL updates*)
Alane 1st-fill	Planned, FY'11 (*TBD – requires ANL updates*)

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

Technology Assessment

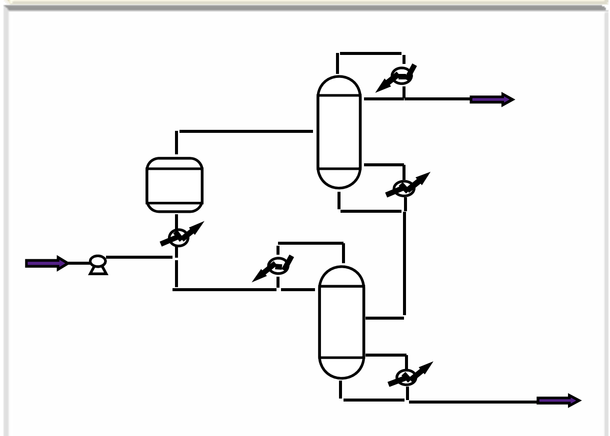
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Design Assumptions
- Obtain Developer Input

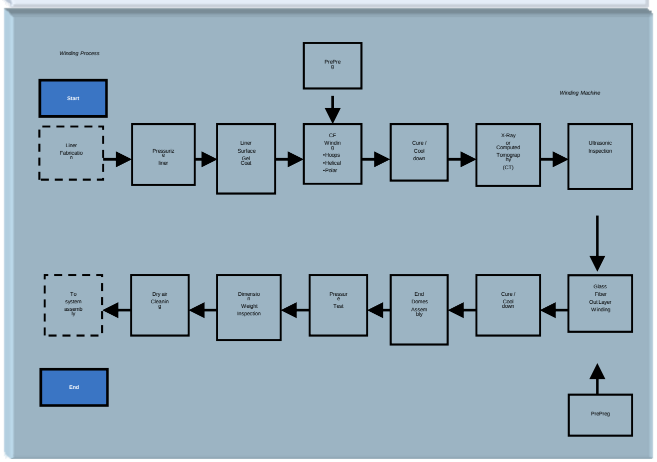
Cost Model and Estimates

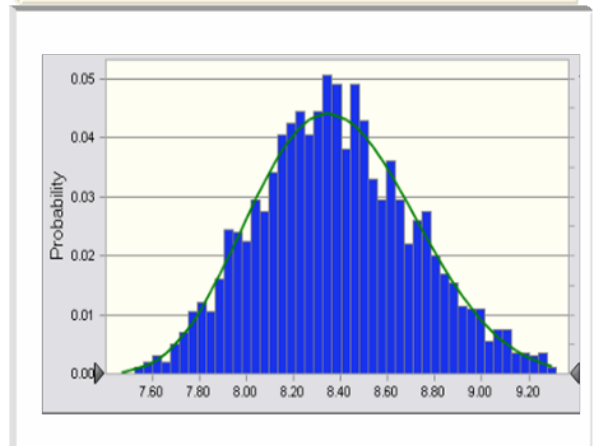
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Processing Costs
- Develop Bulk Cost Assumptions

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 high volume (500,000 units/year) manufactured cost for all H_2 storage systems is estimated from raw material prices, manufacturing costs, and purchased balance of plant component costs

BOP Bottom-up Costing Methodology

- Develop Bill of Materials (BOM)
- Obtain raw material prices from potential suppliers
- Develop manufacturing process map 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

+

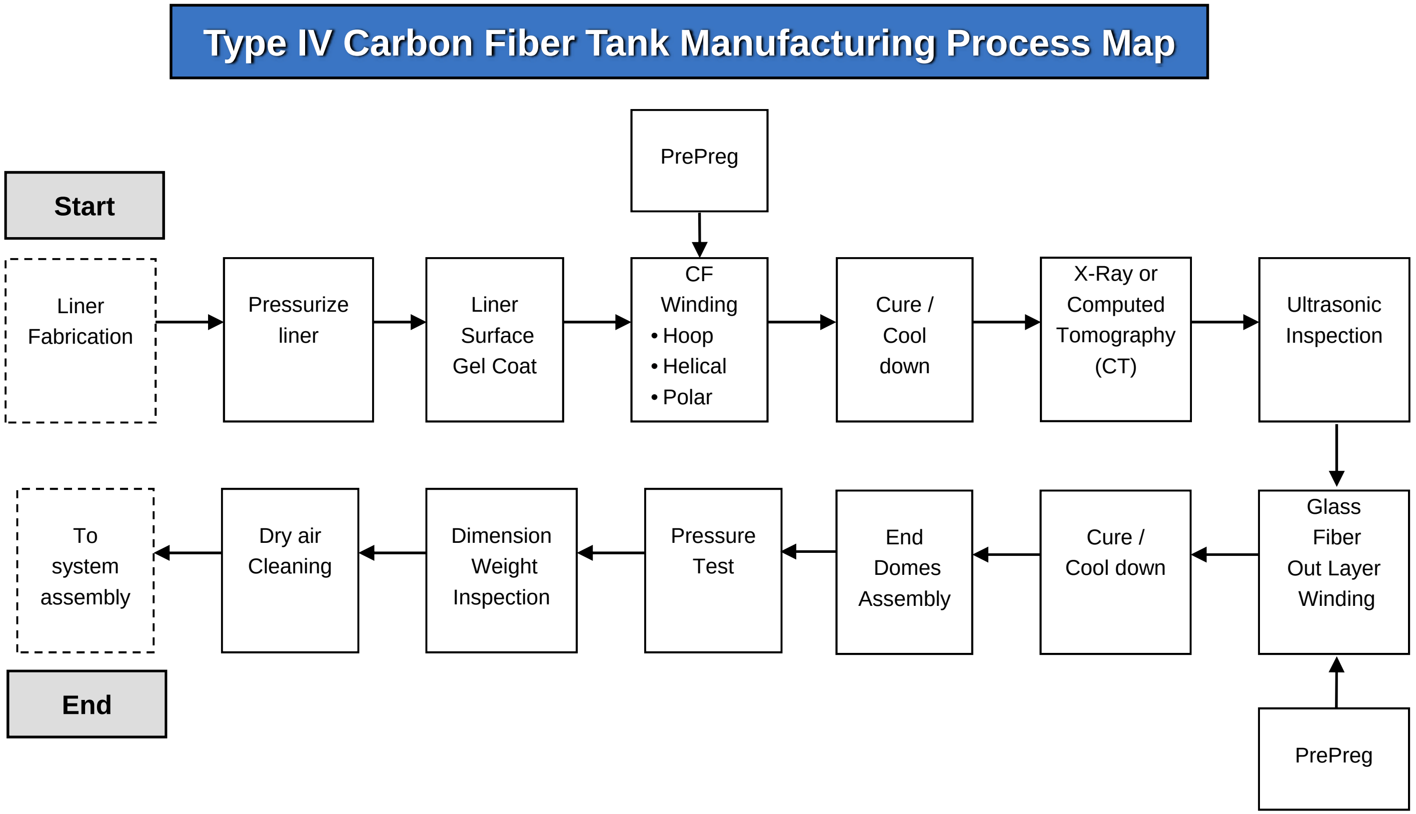
Assembly and Inspection
- QC of finished components
- System assembly
- QC of system

=

Compressed Hydrogen Storage System Cost

We modeled material and manufacturing process costs for the compressed tanks, while assuming that the BOP is purchased.

The Type IV tanks require composite winding steps that are well established and mature technologies within 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.

Manufacturing process costs are calculated by amortizing the cost of each unit operation over the life of the plant

- 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 →

- Financial Assumptions
  - 100% debt financed
  - Interest rate = 15%
  - 10 yr equipment life
  - 25 year building life
- Working Capital
  - Including materials, labor, utility, tooling and maintenance cost
  - Working capital period: 3 months
- Equipment
- Building

Each unit operation has associated costs for capital equipment, buildings, labor, utilities, etc., which are amortized over the expected plant life and production volume to develop a per-unit manufacturing cost.

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
- Feedback from some Automotive OEMs suggested 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.

We also developed low and high estimates for the cost of purchased raw materials for input to the sensitivity analysis and adjusted to 2005$.

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
HDPE liner	0.9	1.8	3.6	Low and high are half and double the base cases, respectively
Carbon fiber (T700S) prepreg	18.5	36.6	44.9	Low assumes 68% fiber (wt.) at $10/lb and 32% epoxy at $5/lb;[a] High is based on discussion w/ Toray (2007) re: T700S fiber at $16/lb and 1.27 prepreg/fiber ratio (Du Vall 2001)
Glass fiber prepreg	3.8	5.0	7.5	Low and high are 75% and 125% of the base cases, respectively
Foam end caps	3.5	7.0	14	Low and high are half and double the base cases, respectively
Stainless steel (304)	2.4	4.7	9.4	Low and high are half and double the base cases, respectively
Standard steel	0.5	1.0	2.0	Low and high are half and double the base cases, 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).

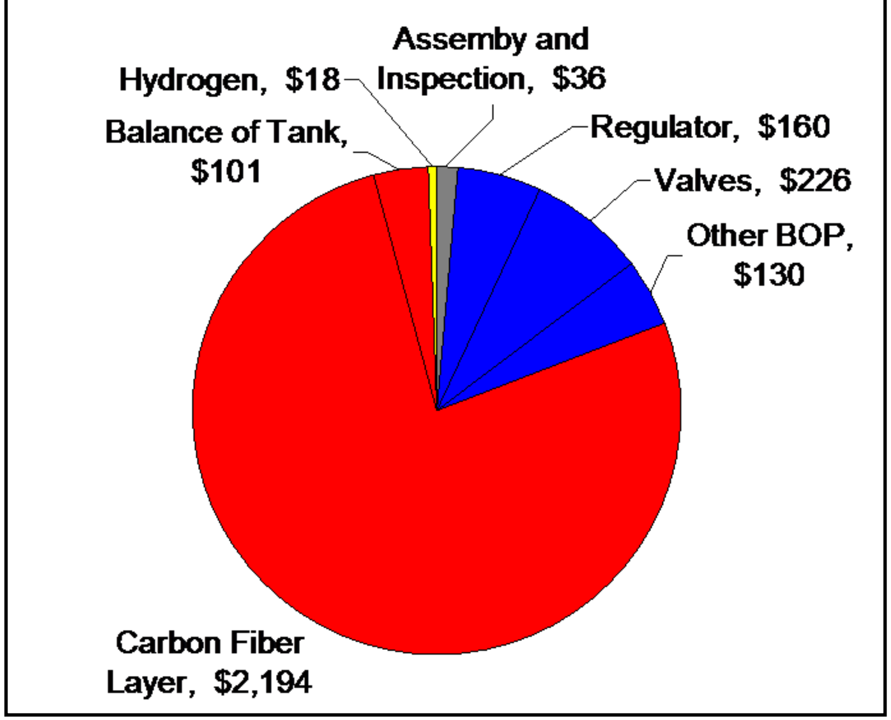
Carbon fiber is already produced at very high-volumes for the Aerospace industry, so it isn't expected to become significantly cheaper in the near term.[1]

The base case cost projections for the major BOP components range from $15-200 per unit assuming high-volume (i.e., 500,000 units/yr) production.

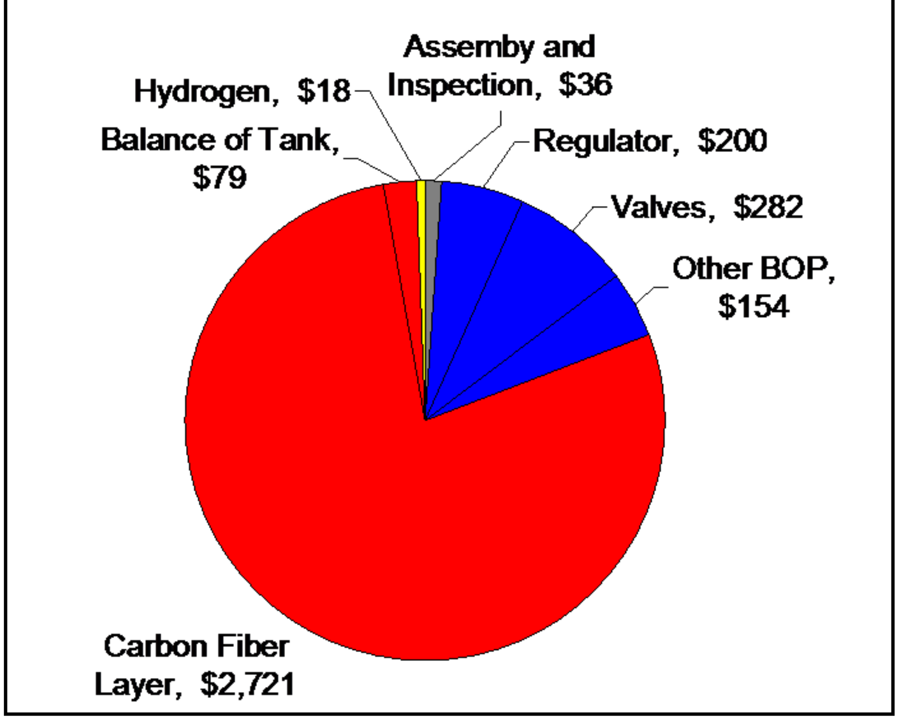
Purchased Component Cost Est. ($ per unit)	Low (350 / 700-bar)	Base Cases (350 / 700-bar)	High (350 / 700-bar)	High/Low Comments/Basis
Pressure regulator	$80 / $100	$160 / $200	$360 / $450	Low and high based on discussions with tank developers and vendors (2009)
Control valve	$93 / $117	$186 / $233	$372 / $466	Low and high are half and double the base cases, respectively
Fill tube/port	$25 / $32	$50 / $63	$100 / $125	Low and high are half and double the base cases, respectively
Pressure transducer	$15 / $19	$30 / $38	$60 / $76	Low and high are half and double the base cases, respectively
Pressure gauge	$9 / $9	$17 / $17	$34 / $34	Low and high are half and double the base cases, respectively
Boss and plug (in tank)	$12 / $15	$15 / $19	$100 / $125	Low is 75% of base case; high assumes more complex processing requirement

Cost estimates for Type III tanks and dual tank systems project a modest cost increase compared to the Type IV, single tank baseline.

Type IV 350-bar Factory Cost[1] = $2,865
$15.3/kWh based on 5.6 kg usable H_2 (6 kg stored H_2)



Type IV 700-bar Factory Cost[1] = $3,490
$18.7/kWh based on 5.6 kg usable H_2 (5.8 kg stored H_2)



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

These costs, adjusted for progress ratios of 85 to 90%, are consistent with industry factory cost projections for similar tanks at lower production volumes.

TIAX

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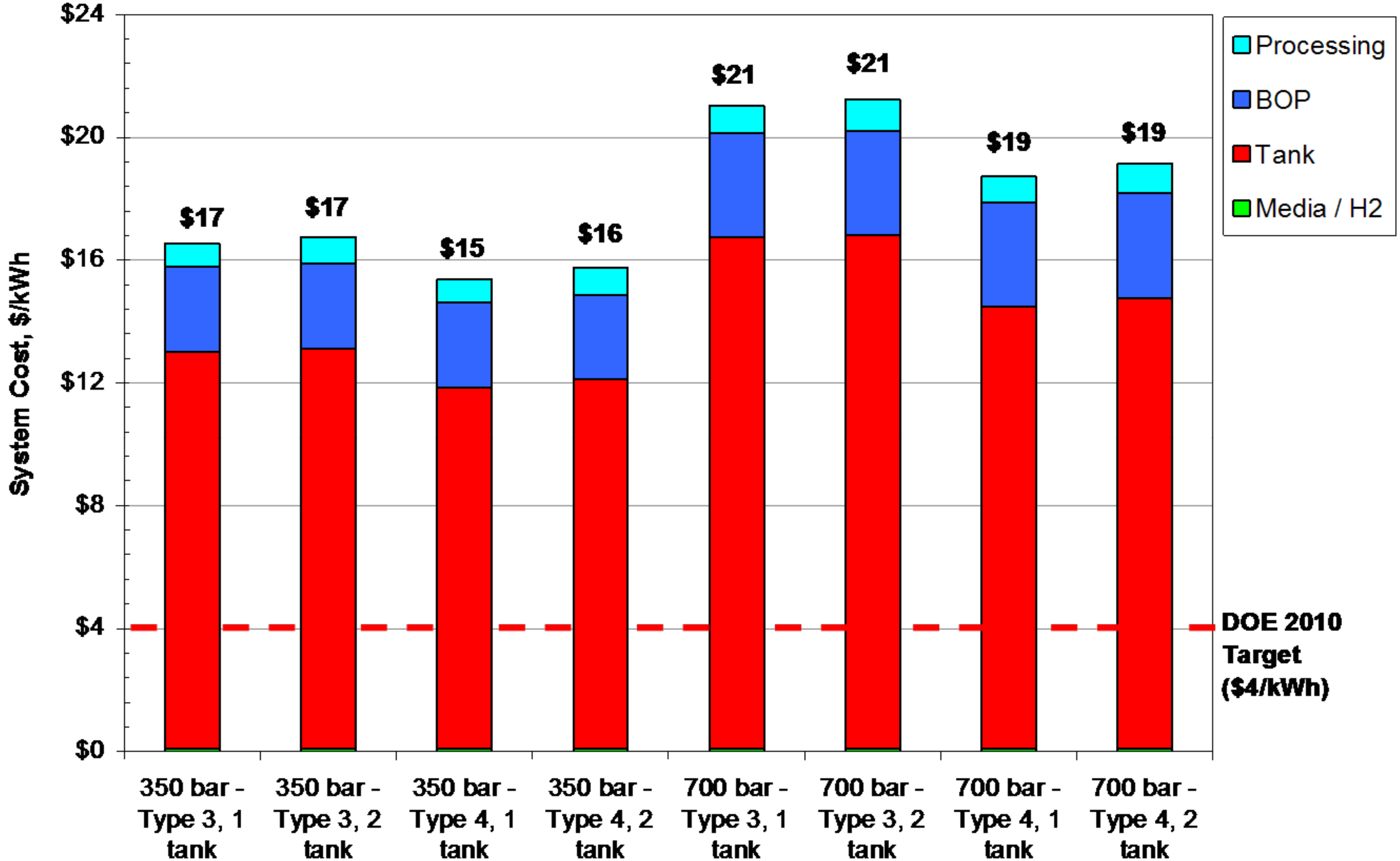
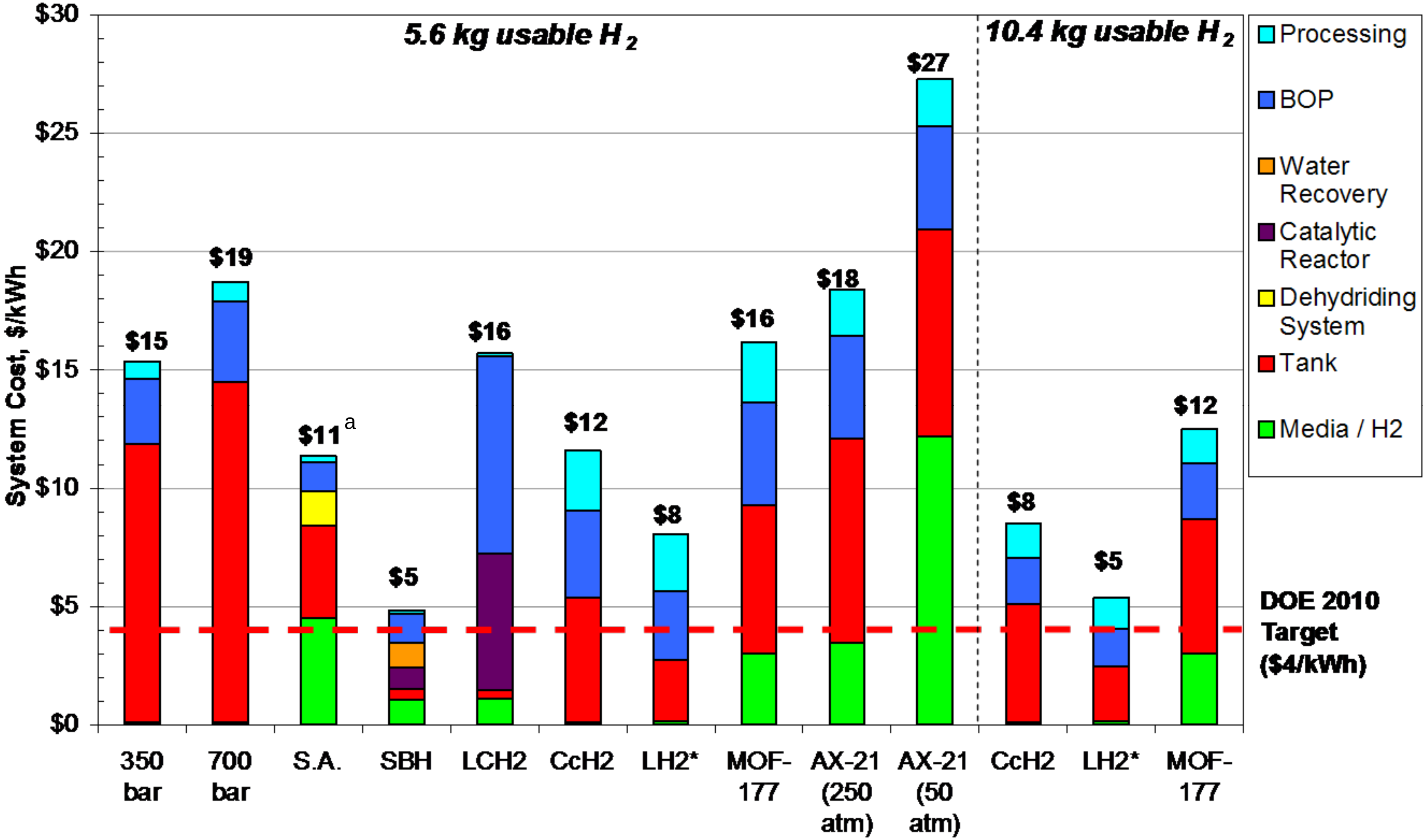


Results to Date: Currently, none of the systems analyzed are projected to meet the DOE 2010 target of $4/kWh

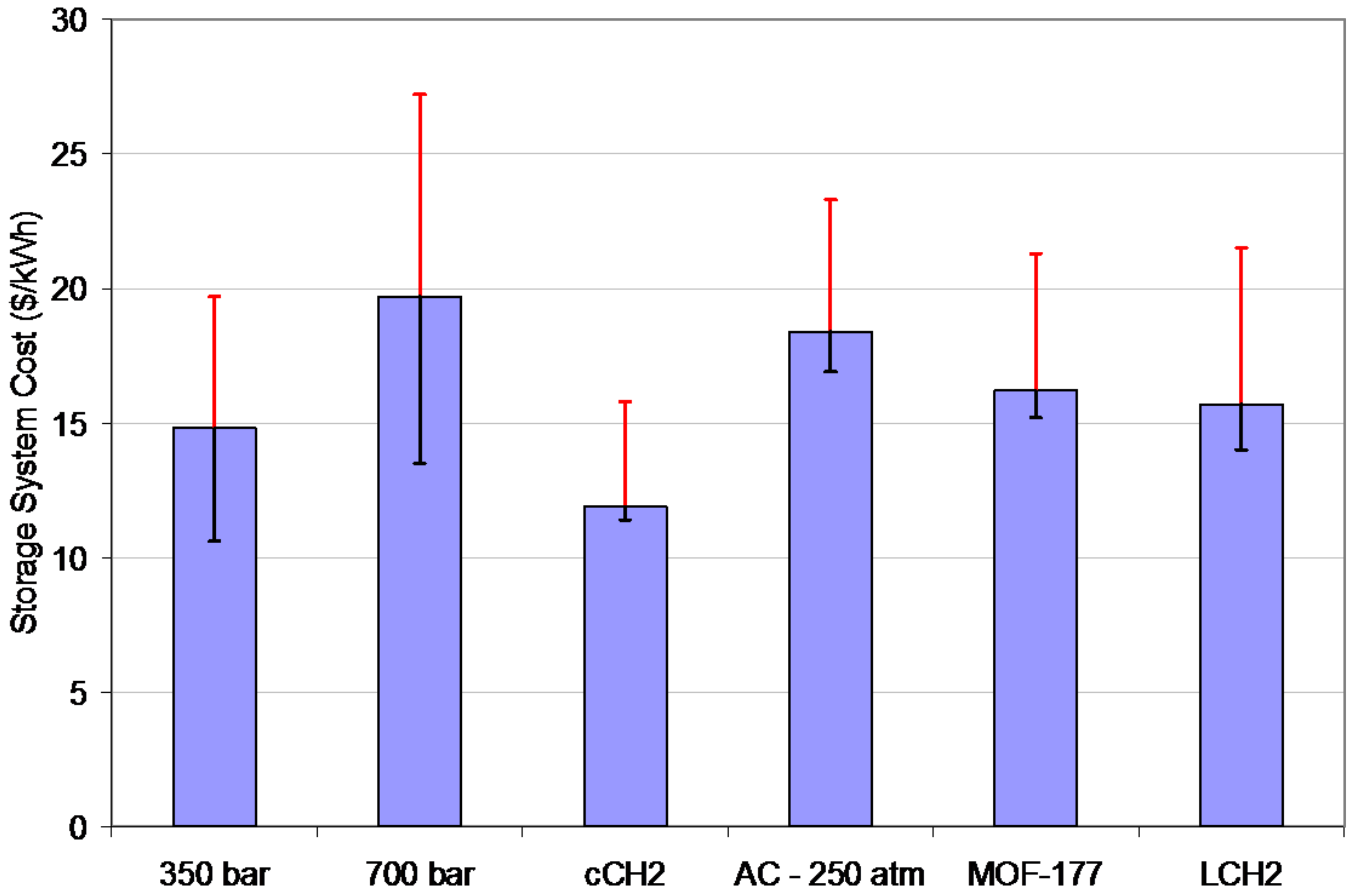


[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.
[*] Denotes a preliminary system cost estimate, to be reviewed before the conclusion of TIAX's analysis

Single variable and multi-variable ("Monte Carlo") sensitivity analysis are used to characterize the effect of uncertainty on our cost projections

- **Sensitivity analysis includes investigation of:**
  - Process assumptions – e.g., throughput, equipment cost
  - Raw material costs
  - Purchased balance of plant component costs
  - Design specifications – e.g., safety factor, material strength
- **In general, for high volume manufacturing, onboard storage system costs are most sensitive to raw material costs and design specifications**
- **Key cost drivers (cross-cutting):**
  - Carbon fiber cost
  - Aluminum liner thickness & cost
  - Safety factor
  - Carbon fiber translation/tensile strength
  - Balance of plant components – pressure regulator, fill port

Results of our Monte Carlo analysis show “high” costs that are typically 20 to 30% greater than the base case and “low” costs with <10% reduction



TIAX will work with DOE on an ongoing basis to identify FY2011 activities. Potential analyses include:

- Perform cost analysis at lower production volumes for compressed hydrogen storage systems
  - Production volumes are likely 10K, 50K, 80K, and 130K per year
  - Priority 1: 350 and 700 Bar Type IV tanks
  - Priority 2: 350 Bar Type III tanks
- Cost analysis on the Quantum/*Boeing manufacturing project* for combined Advanced Fiber Placement (AFP)/Fiber Winding (FW) (*depends on data availability*)
- Analysis of the ORNL/PNNL lower-cost/strength fibers (*depends on data availability*)

Adjustments to approach for lower volume production cost estimates

- Revisit high-volume manufacturing process assumptions
  - Discussions with tank developers, literature review, etc.
  - How does the manufacturing process change at lower volumes?
- Develop detailed manufacturing cost inputs
  - Identify how manufacturing process input assumptions change due to low volume process adjustments
  - Vendor quotes and cost modeling expertise
- Assess affect of scale on BOP and raw material costs
  - May be significant for BOP, minor for raw materials
- Incorporate new assumptions into cost model and review with stakeholders
- Perform single & multi-variable sensitivity analysis

Thank You

Questions?