Analyses of Hydrogen Storage Materials and On-Board Systems

Project ID # ST1

Cryo-compressed and Liquid Hydrogen System Cost Assessments

DOE Merit Review
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Reference: D0268

Timeline

- Start date: June 2004
- End date: June 2009
- 54% Complete

Barriers

- Barriers addressed
  - B. Cost
  - C. Efficiency
  - K. System Life Cycle Assessments

Budget

- Total project funding
  - DOE share = $1.5M
  - No cost share
- FY07 = $170k
- FY08 = $350k (plan)

Collaboration

- Argonne and other National Labs
- Centers of Excellence and other developers
- Tech Teams and other stakeholders

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

Objective	Description	Technology Focus		
		2004-2006	2007	2008
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 Assessment	Evaluate or develop system-level designs to estimate weight, volume, and bottom-up factory cost for the on-board storage system	• Sodium Alanate • SBH	• Liquid H_2 • Cryo-compressed H_2 • Compressed H_2 (update)*	• AC • Liquid HC • Ammonia Borane
Off-Board Assessment	Evaluate or develop designs and cost inputs to estimate refueling cost and Well-to-Tank energy use and GHG emissions for the fuel chain	• Liquid H_2 • Compressed H_2	• SBH*	• Liquid HC • Ammonia Borane

* Results presented in Backup Slides.
Note that previously analyzed systems will continually be updated based on feedback and new information.

SBH = Sodium Borohydride, HC = Hydrocarbon, AC = Activated Carbon

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

Technology Assessment

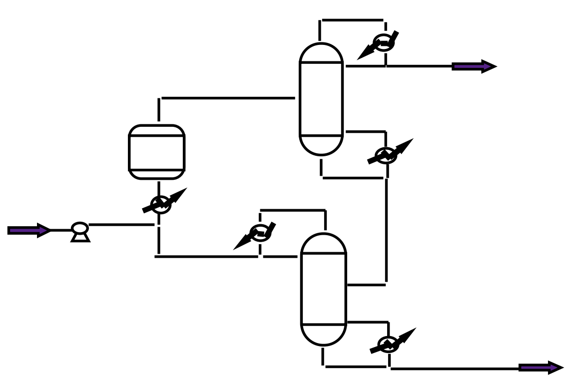
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Design Assumptions
- Obtain Developer Input

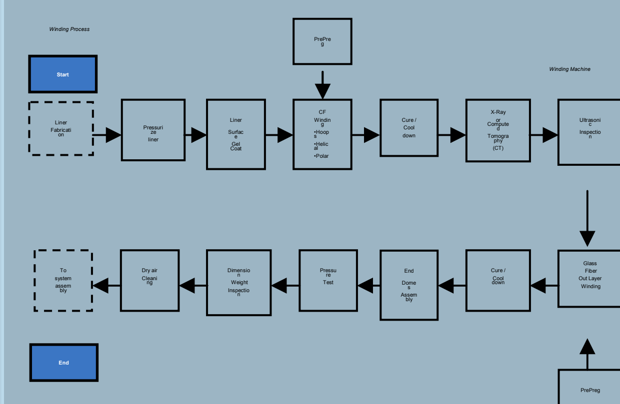
Cost Model and Estimates

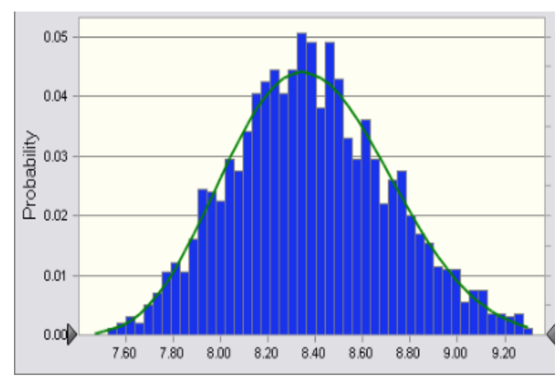
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Processing Costs
- Develop Bulk Cost Assumptions

Overall Model Refinement

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







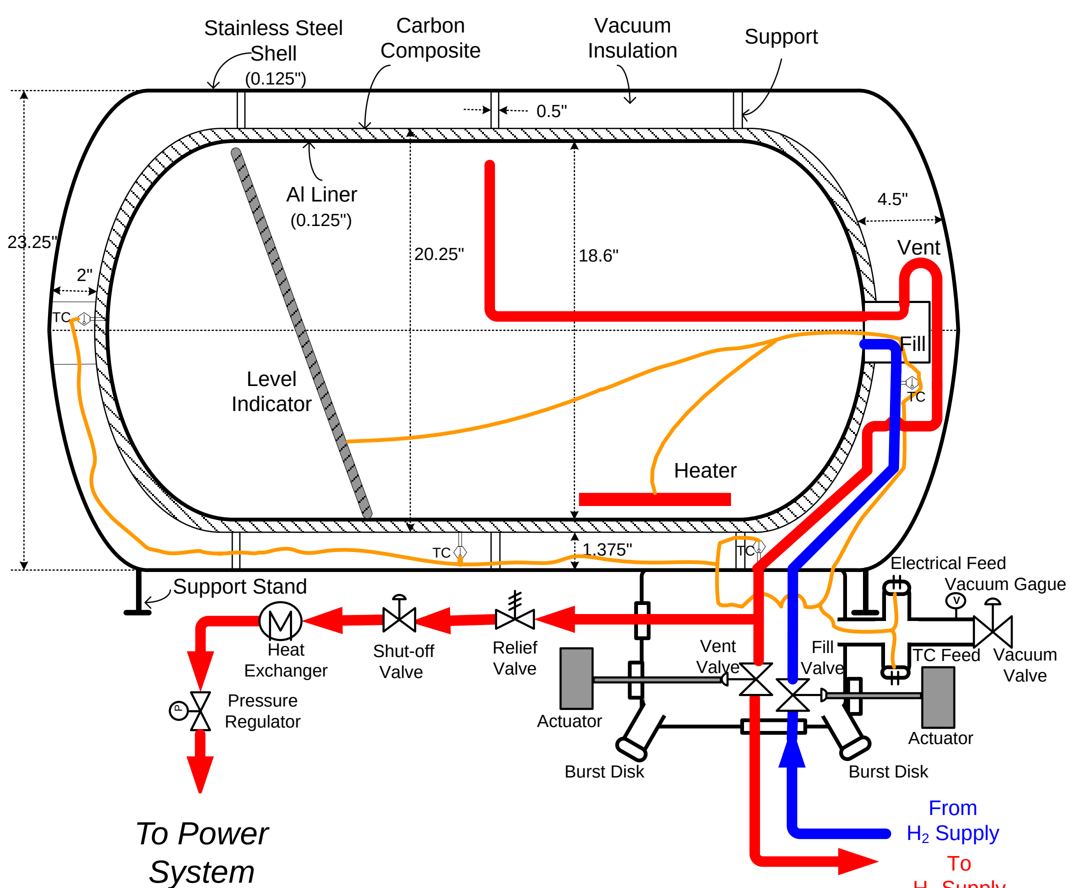
BOM = Bill of Materials

We completed on-board cryogenic system assessments and updated compressed and SBH cost estimates since the last Review.

- Completed cryo-compressed and preliminary liquid hydrogen (LH_2) on-board storage system cost assessments
  - Based on the LLNL 2nd generation cryo-compressed system with modifications
  - Included processing and detailed component cost estimates
  - Updated carbon fiber cost based on industry feedback ($13/lb fiber)
  - $14/kWh and $8/kWh (preliminary) for cryo-compressed and LH_2, respectively
- Updated compressed hydrogen (cH_2) on-board storage system estimates
  - Based on Tech Team and industry feedback for pressure requirements and material cost ($13/lb fiber)
  - $17/kWh and $27/kWh for 5,000 and 10,000 psi storage, respectively
- Updated Sodium Borohydride (SBH) on-board and off-board system estimates
  - Based on latest information provided by developers (primarily MCell and Rohm and Haas)
  - The higher SBH concentration assumed by MCell results in reduced on-board system size, but still does not meet the DOE 2010 targets
  - New off-board regeneration pathways could reduce costs, but the resulting selling price is still in excess of the goal of $2-3 kg/$H_2$ using the base case assumptions

The LLNL second generation tank design was the basis of our cryo-compressed storage system cost assessment.

LLNL 2nd Gen Design with ANL Modifications



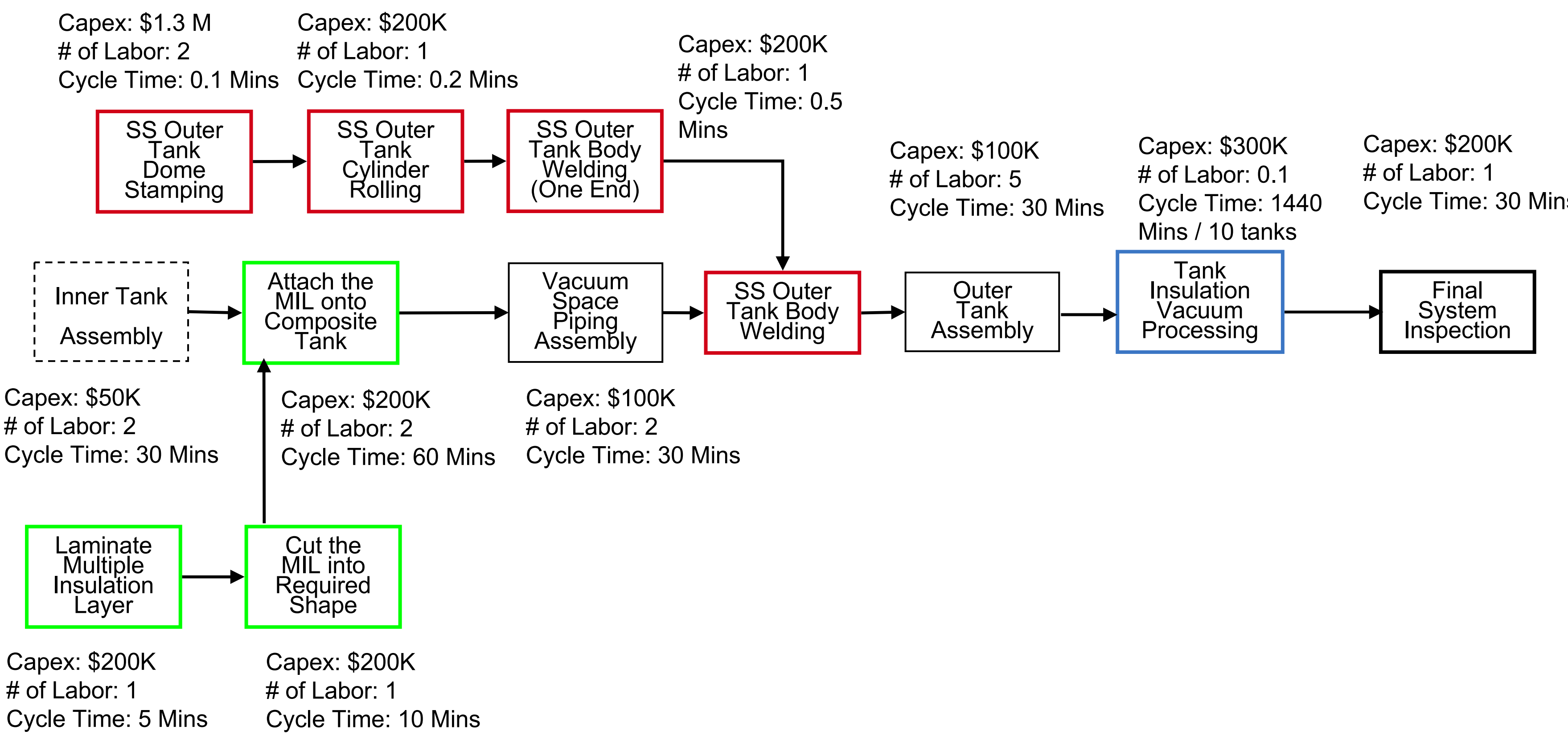
Key Cryo-compressed Tank Specifications

- 151 L (38 gal, 10.7 kg) LH_2
- -253 ºC min temp
- 5,000 psi (~350 bar) max pressure
- 3 mm (0.118") thick Al liner
- 12 mm (0.47") T700S carbon fiber, 60% fiber vol, 2.25 SF, 82% translation strength
- 40 mm (1.57") vacuum gap w/ 40 layer of MLVI, 10-5 torr, ~1 W HT rate
- 3 mm (0.118") thick SS304 outer shell

Additional modifications were made based on literature and developer feedback.

Processing and assembly/inspection costs were generated by developing process maps, and obtaining developer feedback.

Processing Steps for Cryo-tank Insulation, Assembly, and Inspection



The costs of key processing steps were estimated from capital equipment, labor, and other operating costs assuming high volumes (500,000 units/year) and a high level of automation.

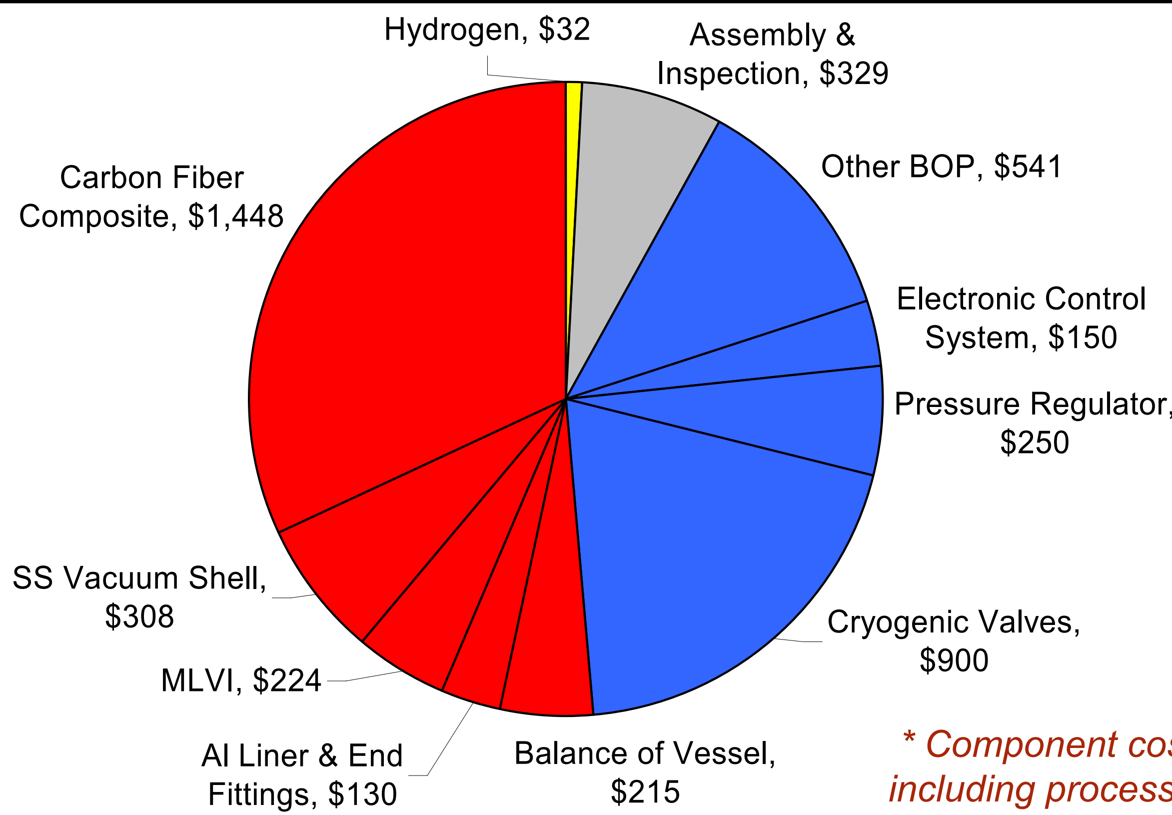
Cryo-compressed Key Processing Steps	Process Cost per Tank	% of Total Processing Cost
Al Liner Fabrication, Assembly, & Inspection	$76	13%
Carbon Fiber Winding Process	$56	10%
SS Vacuum Shell Fabrication	$14	2%
MLVI Wrapping	$108	18%
In-vessel Assembly	$42	7%
Ex-vessel Assembly	$128	22%
Vacuum Processing	$119	20%
Final Inspection	$40	7%
Total	**$583**	**-**

Processing costs make up 13% of the total cryo-compressed system cost.

Note: Details provided in Backup Slides.

Carbon fiber and cryogenic valves are the dominant costs, accounting for approximately 50% of the overall system cost.

Cryo-compressed System Cost, 10.7 kg LH_2 Capacity (10.1 kg Usable[a]) = $4,527 ($13.6/kWh)[b]

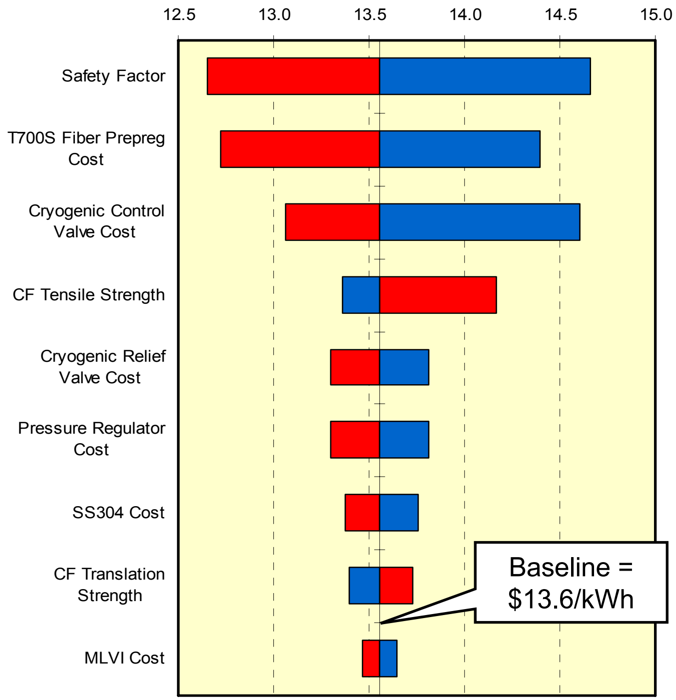


** Component costs including processing*

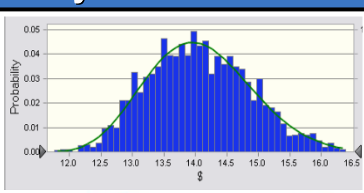
[a] Costs per kWh are based on a projected 10.1 kg (336 kWh) "usable" hydrogen assuming 94% drive cycle utilization (ANL 2006).
[b] The total system cost could be reduced by ~5% by using an aluminum shell rather than stainless steel.

Variability in the carbon fiber (CF) related costs and valve costs can significantly affect the overall cost of the cryo-compressed system.

Cryo-compressed System Factory Cost, \$/kWh (10.7 kg LH_2 Capacity)



System Multi-variable Sensitivity Analysis

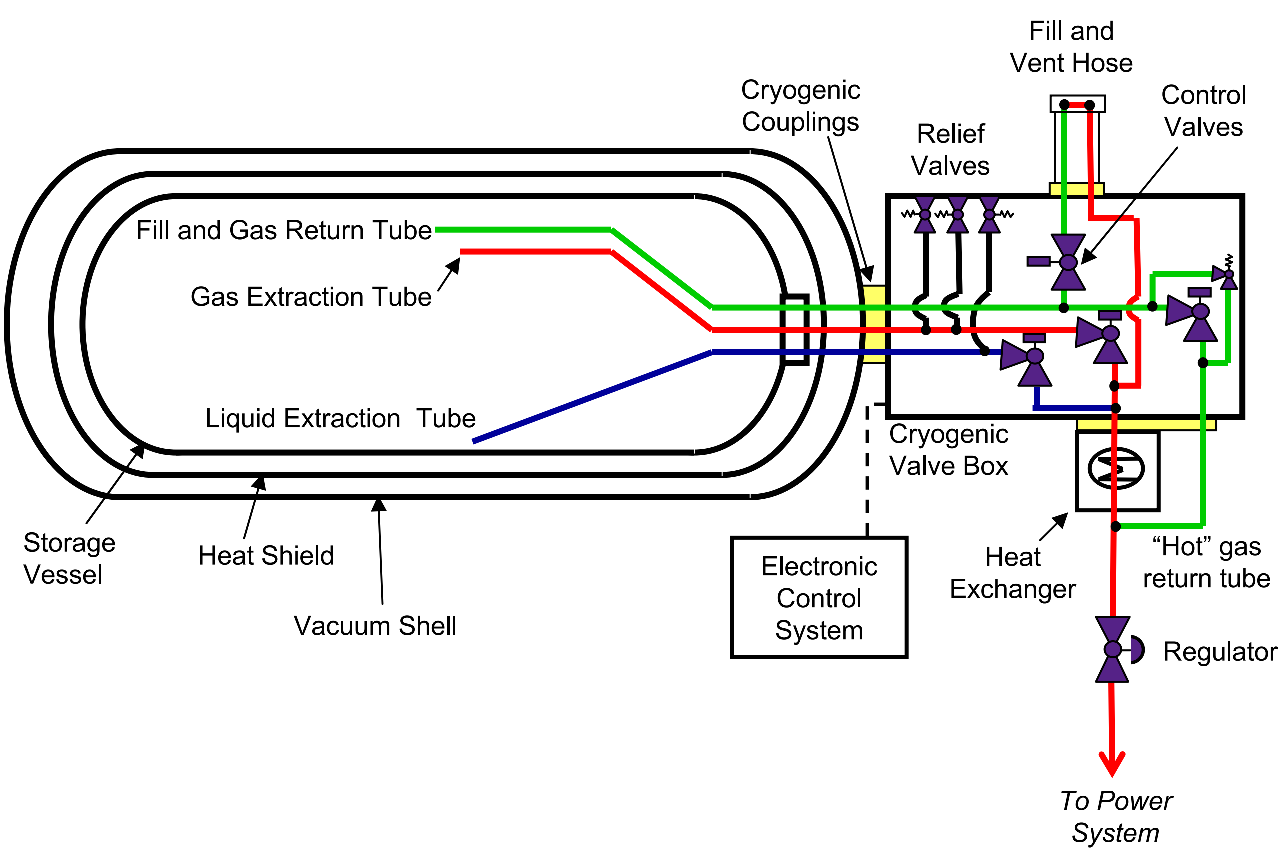


System Cost	\$/kWh
Mean	14.1
Std. Dev.	0.8
Baseline	13.6

Key Sensitivity Parameters	Cryo-Compressed			
	Base-line	Min	Max	Comments/Source
Safety Factor	2.35	1.80	3.0	◆ Baseline is typical industry standard; Min and Max based on discussions with Quantum and Dynatek (2005)
CF Prepreg (Fiber & Matrix) Cost (\$/lb)	16.6	12.8	20.4	◆ Based on discussion w/ Toray (2007) re: T700S fiber (\$10-\$16/lb, \$13/lb baseline) ◆ 1.27 prepreg/fiber ratio (DuVall 2001)
Cryogenic Control Valve Cost (\$)	150	100	250	◆ Discussions with Circle Seal (2007), Valcor (2007), and tank developers (2007)
CF Tensile Strength (MPa)	2,940	2,550	3,100	◆ Baseline from TIAX netting analysis using optimized wrap angle for pressure vessel geometry; Min from Toray T700S data sheet (2007); Max assumes 5% increase over baseline ◆ 60% fiber by volume assumed
Cryogenic Relief Valve Cost (\$)	75	40	150	◆ Discussions with Circle Seal (2007) and Swagelock (2007) venders
Pressure Regulator Cost (\$)	250	150	350	◆ Discussions with TESCOM vender and tank developers (2007)
SS304 Cost (\$/kg)	4.7	3.7	5.8	◆ Baseline, Min, and Max are the average, min, and max monthly costs, respectively, from Sep '06 – Aug '07 (MEPS International 2007) deflated to 2005\$s by ~6%/yr
CF Translation Strength (%)	81.5%	78%	85%	◆ Based on Quantum (2005) for 5,000 psi CF tanks
MLVI Cost (\$/kg)	50	35	65	◆ Estimates based on discussions with MPI (2007)

The cryo-compressed tank design was used as a starting point for the liquid hydrogen system cost assessment.

Sketch of Key LH_2 System Components

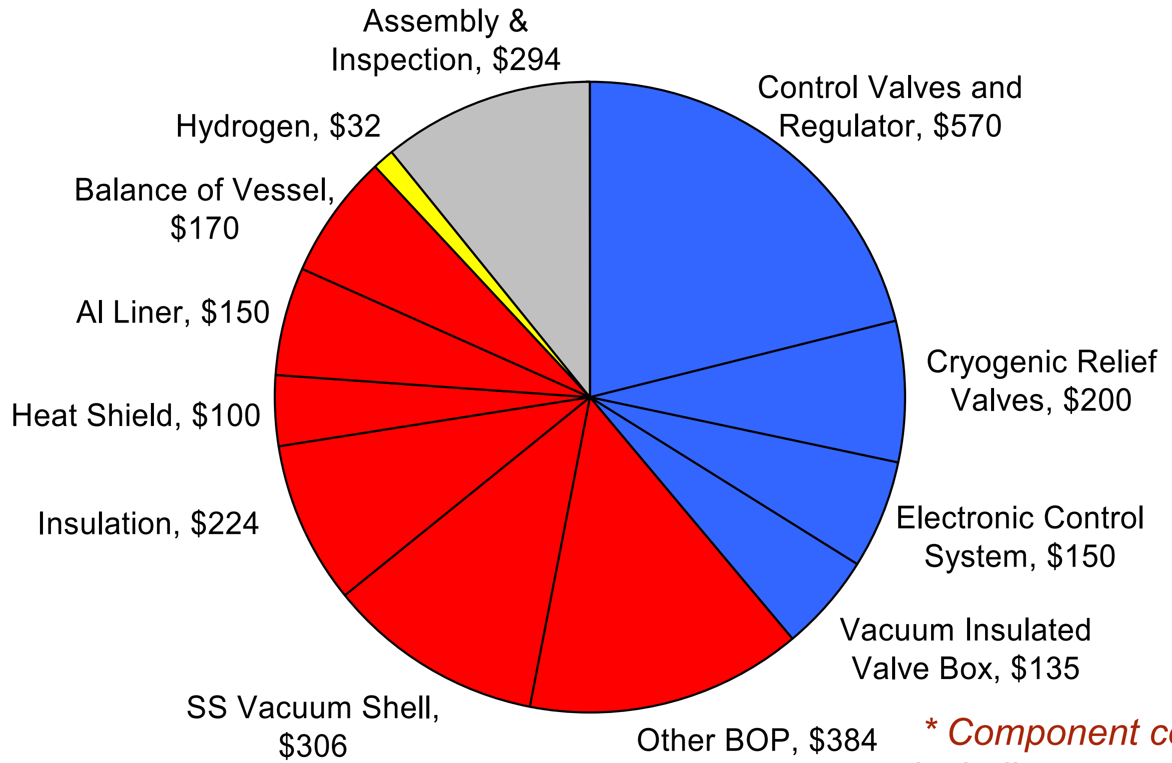


Liquid Hydrogen Tank Specifications
• 151 L (38 gal, 10.7 kg) LH_2 • -253 ^{o}C min temp • 3 mm (0.118") thick Al inner tank • 40 mm (1.57") vacuum gap w/ 40 layer of MLVI, 10-5 torr, ~1 W HT rate • 3 mm (0.118") thick SS304 outer shell • 10% tank ullage requirement

Modifications were made based on literature and developer feedback.

Control and relief valves account for a combined 30% of the total cost, but costs are relatively evenly distributed among major components.

Preliminary Liquid System Cost, 10.7 kg LH_2 Capacity (10.1 kg Usable[a]) = \$2,715 (\$8.1/kWh)[b]



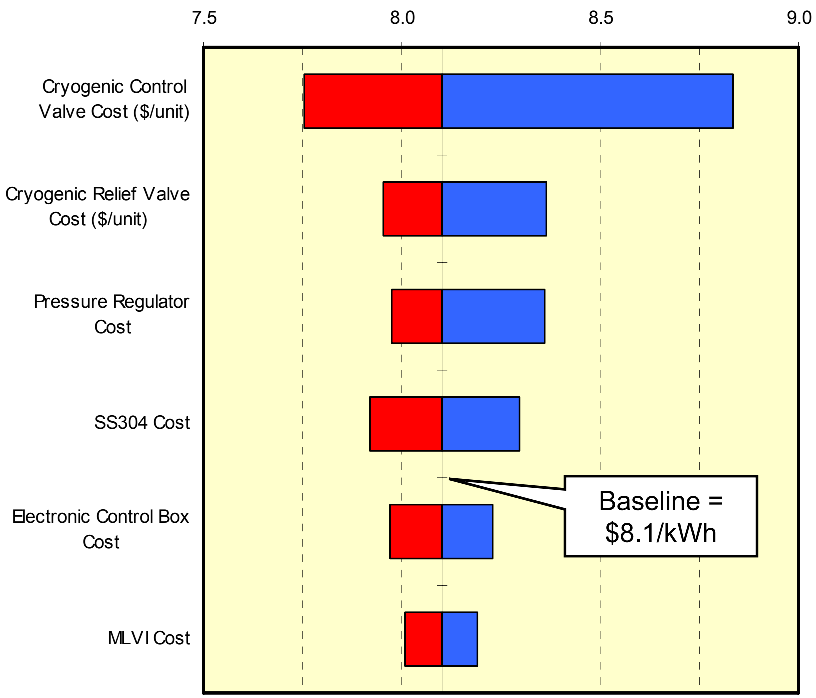
** Component costs including processing*

[a] Costs per kWh are based on a projected 10.1 kg (336 kWh) "usable" hydrogen assuming 94% drive cycle utilization (ANL 2006) for cryo-compressed drive cycle efficiency. Utilization needs to be updated for LH_2.

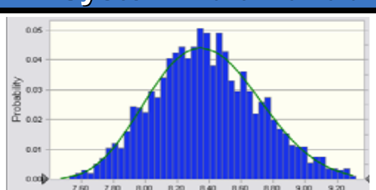
[b] The total system cost could be reduced by ~8% by using an aluminum shell rather than stainless steel.

Variability in the cryogenic valve costs can significantly affect the overall cost of the liquid system.

Preliminary Liquid Hydrogen System Factory Cost, $/kWh (10.7 kg LH_2 Capacity)



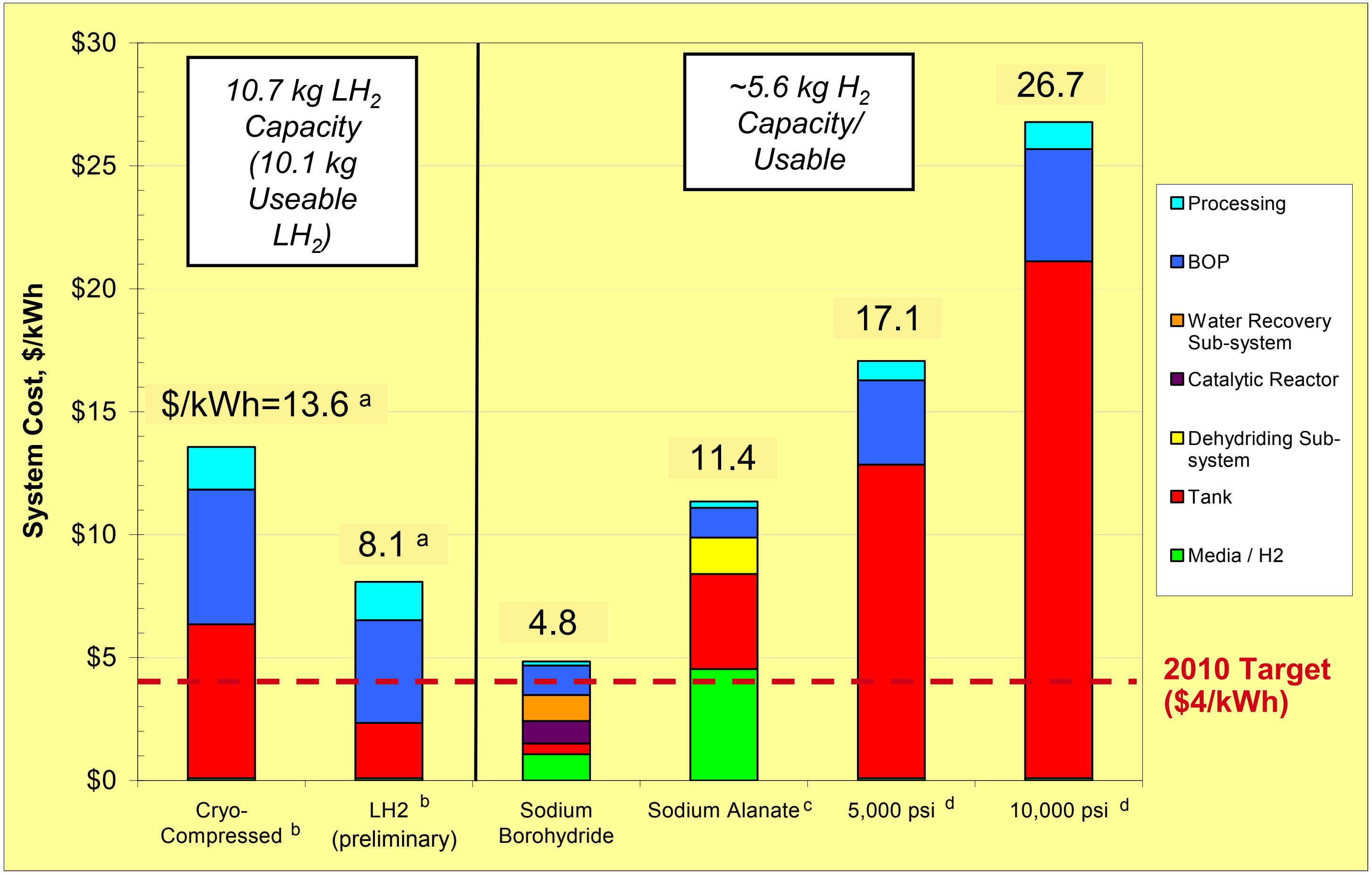
System Multi-variable Sensitivity Analysis



System Cost	$/kWh
Mean	$8.4
Std. Dev.	$0.3
Baseline	$8.1

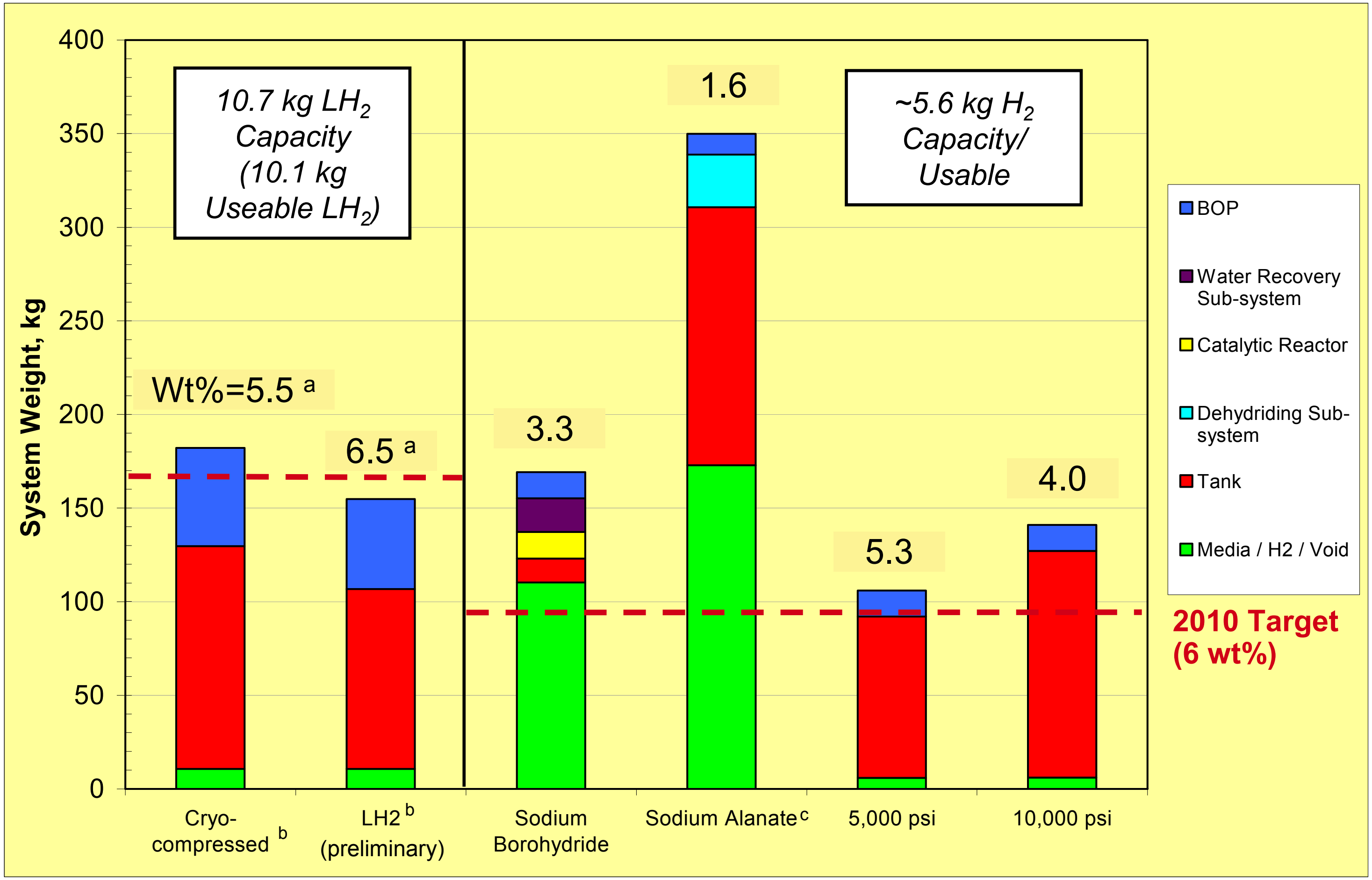
Key Sensitivity Parameters	Liquid Hydrogen System			
	Base -line	Min	Max	Comments/Source
Cryogenic Control Valve Cost ($/unit)	105	70	175	◆ Discussions with Circle Seal (2007), Valcor (2007), and tank developers (2007)
Cryogenic Relief Valve Cost ($/unit)	50	35	75	◆ Discussions with Circle Seal (2007) and Swagelock (2007) venders
Pressure Regulator Cost ($/unit)	150	100	250	◆ Discussions with Circle Seal (2007), Valcor (2007), and tank developers (2007)
SS 304 Cost ($/kg)	4.7	3.7	5.8	◆ Baseline, Min, and Max are the average, min, and max monthly costs, respectively, from Sep '06 – Aug '07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Electronic Control Box Cost ($/unit)	150	100	200	◆ Estimate based on interviews with technology experts (includes microcontroller, valve relays, analog inputs, and power regulator)
MLVI Cost ($/kg)	50	35	65	◆ Estimates based on discussions with MPI (2007)

The cryo-compressed and liquid hydrogen on-board systems are projected to be cheaper than pressurized-only options.



[a] Normalizing the cryo-compressed and liquid systems for 5.6 kg of usable hydrogen storage results in system costs of approximately $20/kWh and $14/kWh, respectively.
[b] An aluminum shell (rather than SS) offers approximately 5% and 8% costs savings for the cryo-compressed and liquid systems, respectively.
[c] The sodium alanate system requires high temp waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.
[d] Includes updated carbon fiber cost estimate, 2007.

The liquid system meets the 2010 weight target, and the cryo-compressed system would also meet the target with an aluminum shell[a].

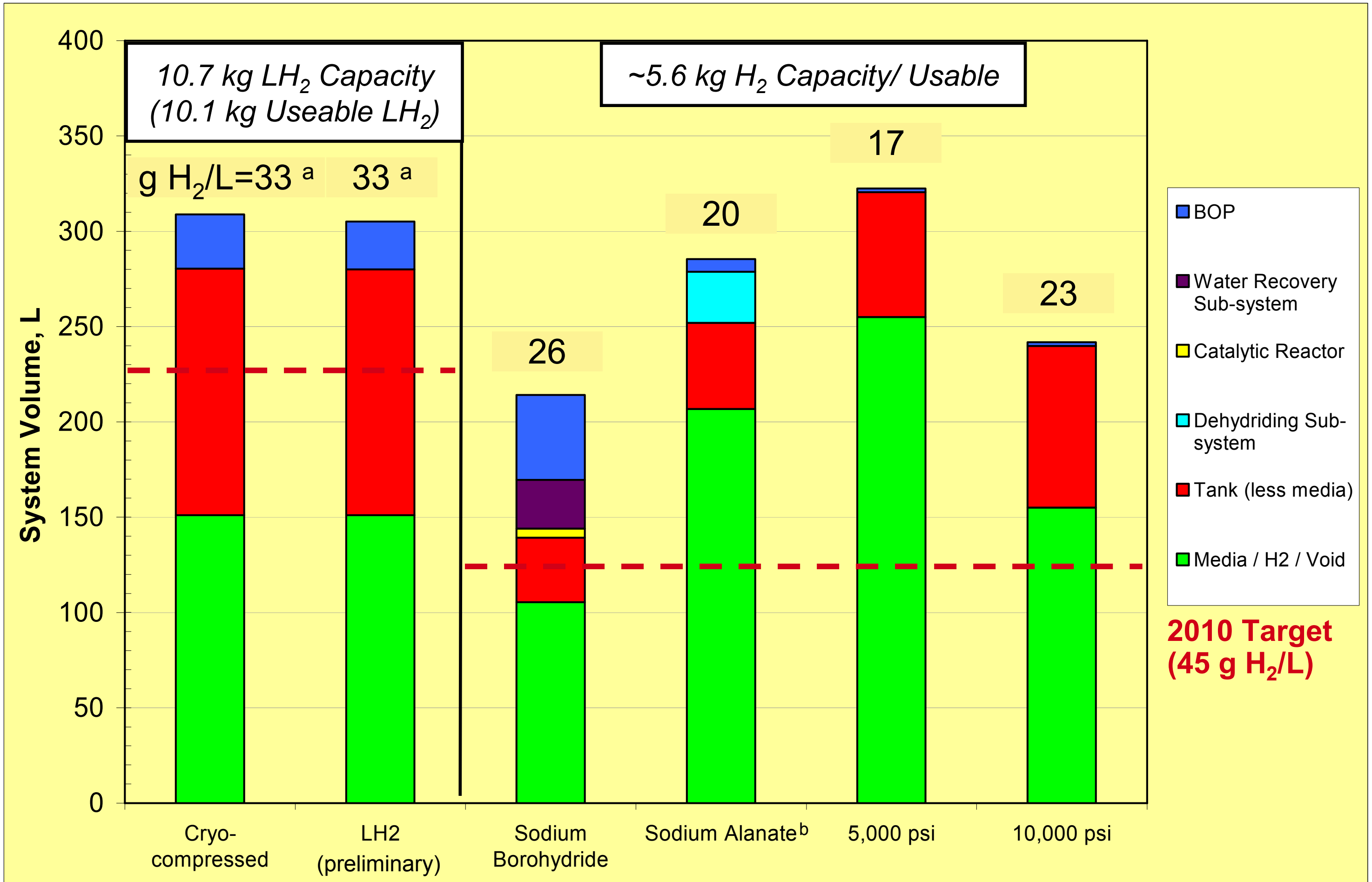


[a] Normalizing the cryo-compressed and liquid systems for 5.6 kg of usable hydrogen storage results in system gravimetric capacities of approximately 4.0 wt% and 4.4 wt%, respectively.

[b] An aluminum shell (rather than SS) increases gravimetric capacities to 7wt% and 9 wt% for the cryo-compressed and liquid systems, respectively.

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

None of the on-board storage systems evaluated to date meet the 2010 volume target given our base case assumptions.



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

[a] Normalizing the cryo-compressed and liquid systems for 5.6 kg of usable hydrogen storage results in system volumetric capacities of approximately 28 g/L each.

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

We will focus on the liquid hydrocarbon- (HC) and ammonia borane-based hydrogen storage systems for the remainder of FY08.

- Complete on-board assessments of APCI liquid HC system and begin assessment of ammonia borane system
  - Solicit feedback from developers and coordinate with ANL on final system requirements and design assumptions
  - Specify manufacturing processes and equipment and determine material and processing costs
  - Use sensitivity analysis to account for uncertainties and potential future technology developments
- Conduct off-board analyses for the liquid HC and ammonia borane systems
  - Finalize designs and cost inputs for the complete fuel chain
  - Estimate refueling cost and Well-to-Tank energy use and GHG emissions for the fuel chain
- Continue to work with DOE, H2A, other analysis projects, developers, National Labs, and Tech Teams to revise and improve past system models
  - Including finalize liquid hydrogen storage system results based on developer (e.g., Air Liquide) and stakeholder feedback

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

Analysis To Date		cH_2	Alanate	MgH_2	SBH	Cryo-comp	LH_2	AC	Liquid HC
On-Board	Review developer estimates	√	√		√	√	√	√	√
	Develop process flow diagrams and system energy balances	√	√		√	√	√		WIP
	Independent performance assessment (wt, vol)	√	√		√	√	√ *		WIP
	Independent cost assessment	√	√		√	√	√ *	WIP	WIP
Off-Board	Review developer estimates	√		√	√		√		√
	Develop process flow diagrams and system energy balances	√		√	√		√		√
	Independent performance assessment (energy, GHG)	√			√		√		WIP
	Independent cost assessment	√			√		√		WIP
Overall	WTT analysis tool[a]	√							
	Solicit input on TIAX analysis	√	√		√	√	√ *	WIP	WIP

* Preliminary results under review.

[a] Working with ANL and H2A participants on separate WTT analysis tools.

(grey box) = Not part of current SOW

WIP = Work in progress