Cost Analysis of Hydrogen Storage Systems

DOE and FreedomCAR & Fuel Partnership Delivery and On-Board Storage Analysis Workshop

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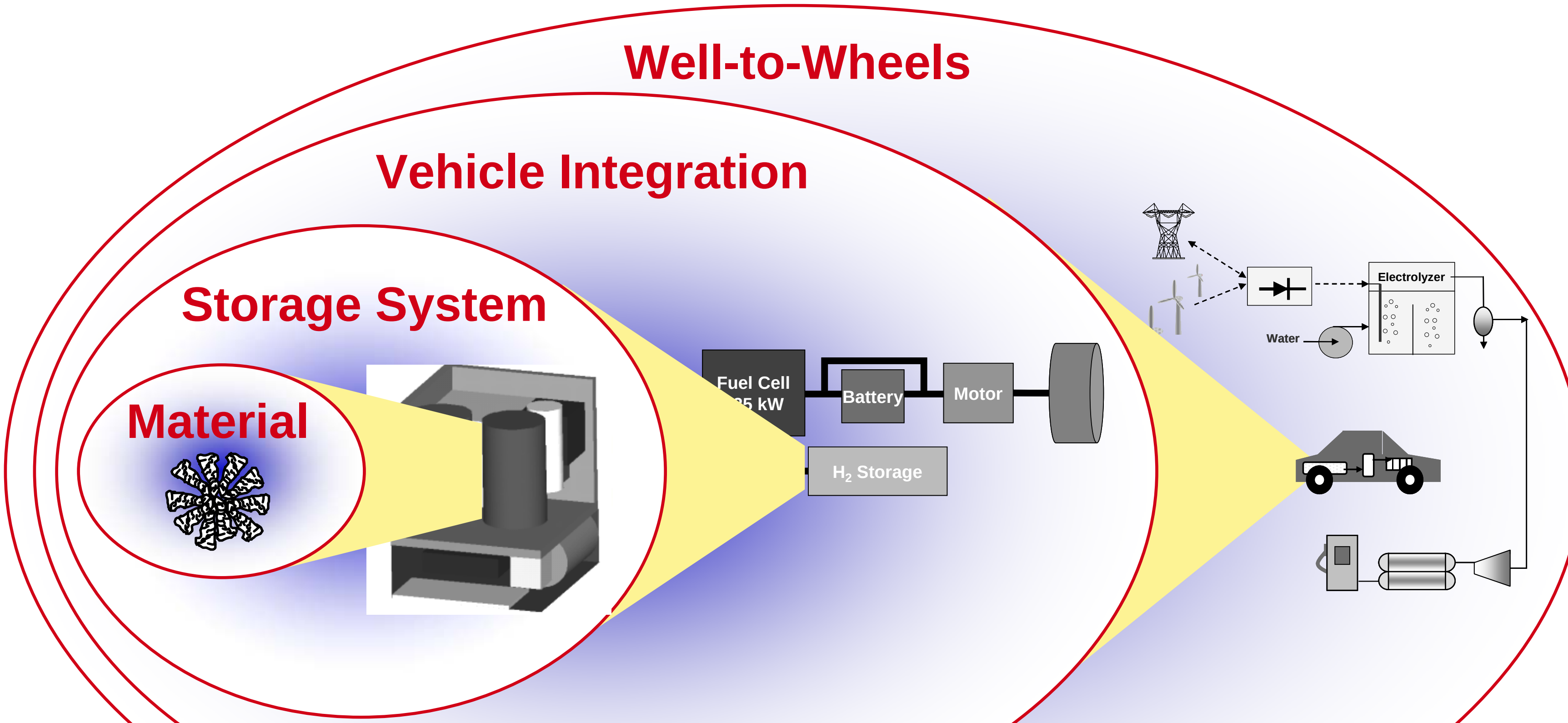
Reference: D0268

In 2004, DOE has selected TIAX to evaluate the lifecycle cost and WTW energy use and GHG emissions of various hydrogen storage options.



- Material wt %
- P, T requirement
- Thermo, kinetics

- BOP requirements
- System size, cost
- System issues

- Power unit and thermal integration
- Vehicle cost, weight
- Fuel economy

- Fuel chain requirement
- Ownership cost
- WTW energy use, GHG

We are in the process of completing the on-board assessment of the initial cases for reversible on-board and regenerable off-board categories.

Category	Initial Cases	Tech Status[1]	Storage State	H_2 Release	Refueling Type
Compressed and Liquid Hydrogen	5,000 & 10,000 psi	Pre-commercial	Gas	Pressure regulator	cH_2 gas
Reversible On-board: Metal Hydrides and Alanates	Sodium Alanate (UTRC)	Proof of Concept	Solid	Endothermic desorption	cH_2 gas and HTF loop
Regenerable Off-board: Chemical Hydrides	Sodium Borohydride (MCell)	Early Prototype	Aqueous solution	Exothermic hydrolysis	Aqueous solution in/out
High Surface Area Sorbents: Carbon	TBD	R&D	Solid (low T?)	Endothermic desorption	cH_2 gas (low T?)

[1] For discussion purposes only. Developer claims may vary.

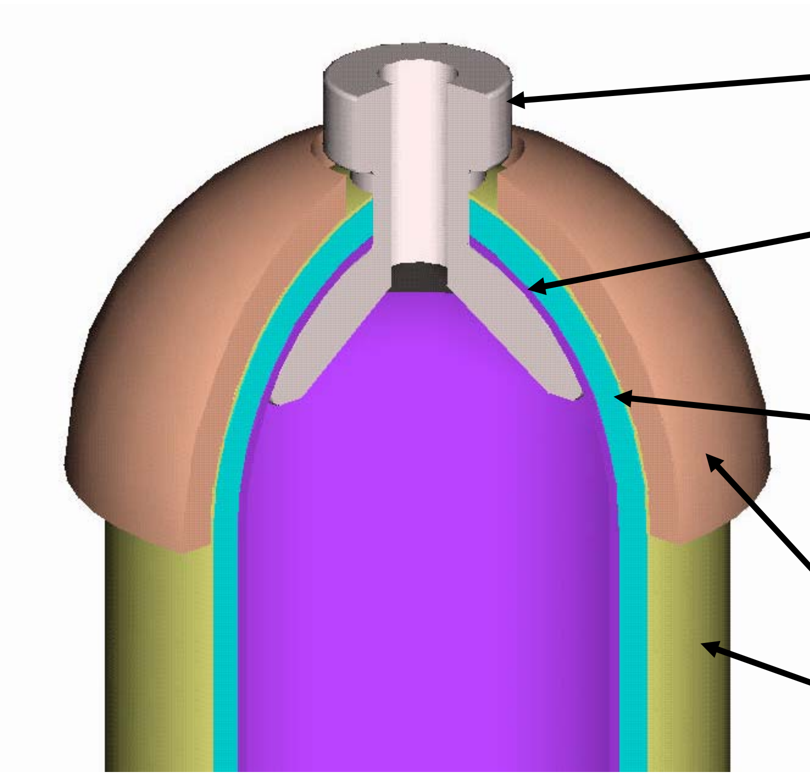
As we finalize the sodium alanate and sodium borohydride cases, our findings show they will not meet the 2007 weight and volume targets.

Storage Parameter	Units	2007 Target	Sodium Alanate	Sodium Borohydride
Specific energy (mass)	kWh/kg (kg H_2/kg)	1.5 (0.045)	0.53 (0.016)	1.1 (0.033)
Energy density (volume)[1]	kWh/L (kg H_2/L)	1.2 (0.036)	0.61 (0.018)	0.96 (0.029)
Storage system cost	$/kWh ($/kg H_2)	6 (200)	11 (370)	4.7 (160)
Fuel cost	$/gge	3	TBD	TBD
Refueling rate	kg H_2/min	0.5	0.3	N/A
Min full-flow rate	(g/s)/ kW	0.02	0.004	0.02

Note: Targets must be met simultaneously. Results are not accurate to the number of significant figures shown.
[1] Volume results do not include void spaces between components (i.e., no packing factor was applied).

Detailed cost, weight, and volume results and comparisons are presented in the preliminary results section.

Under a previous DOE contract, we evaluated the cost of compressed H_2 tank systems designed to accommodate 5,000 and 10,000 psi pressures.



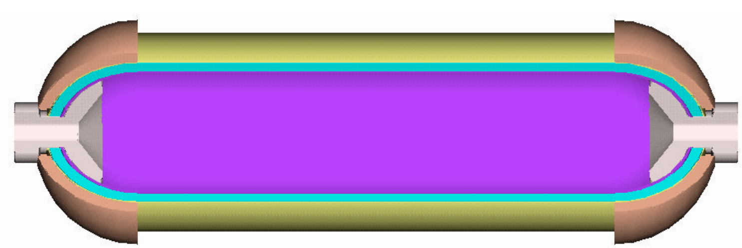
Metal Boss (aluminum) for Tank Access (some constructions may also use a plug on the other end)

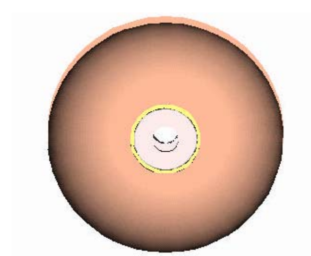
Liner (polymer, metal, laminate)
HDPE 6.3 mm thick
Al 2.3 mm thick

Wound Carbon Fiber Structural Layer with Resin Impregnation
(V_f CF:Epoxy 0.6:0.4; W_f 68/32)

Impact Resistant Foam End Dome

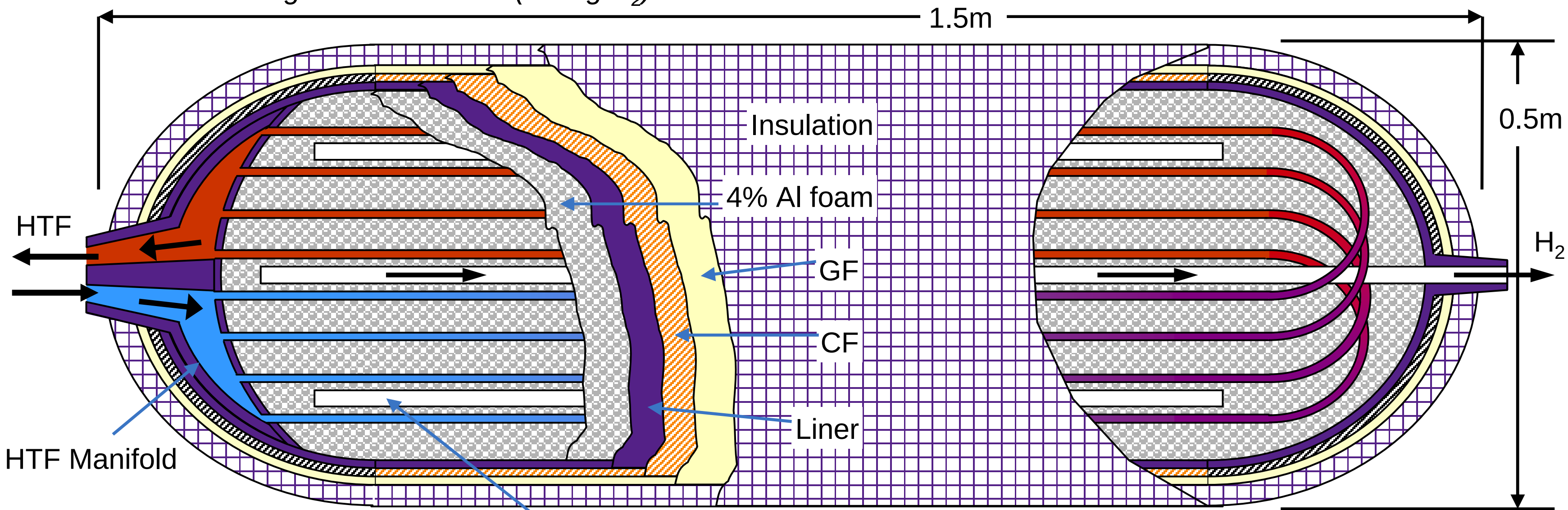
Damage Resistant Outer Layer (typically glass fiber wound)

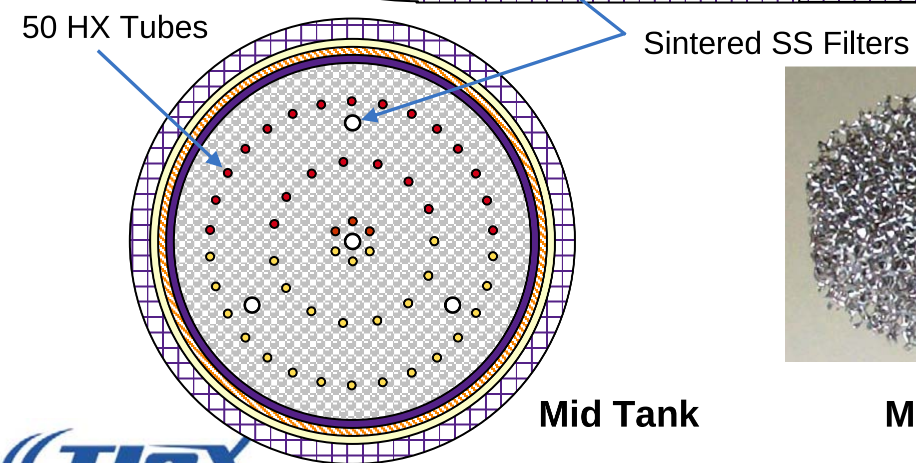




Our sodium alanate ($NaAlH_4$) tank design is based on the 2004 literature, particularly UTRC's published prototype and scaled-up concepts.

TIAX Base Case Design with Insulation (5.6 kg H_2):





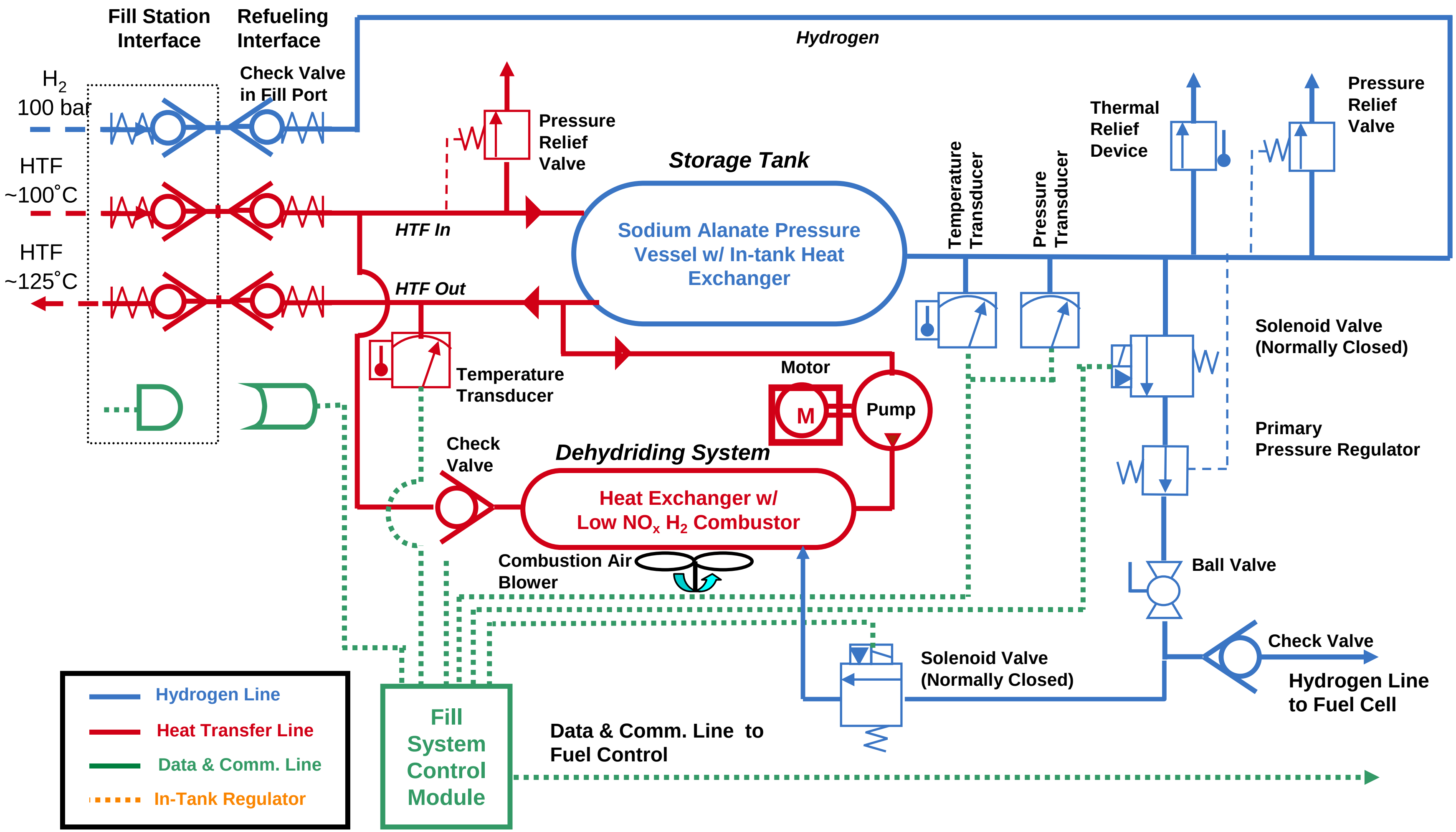
Mid Tank

Metal Foam

Legend

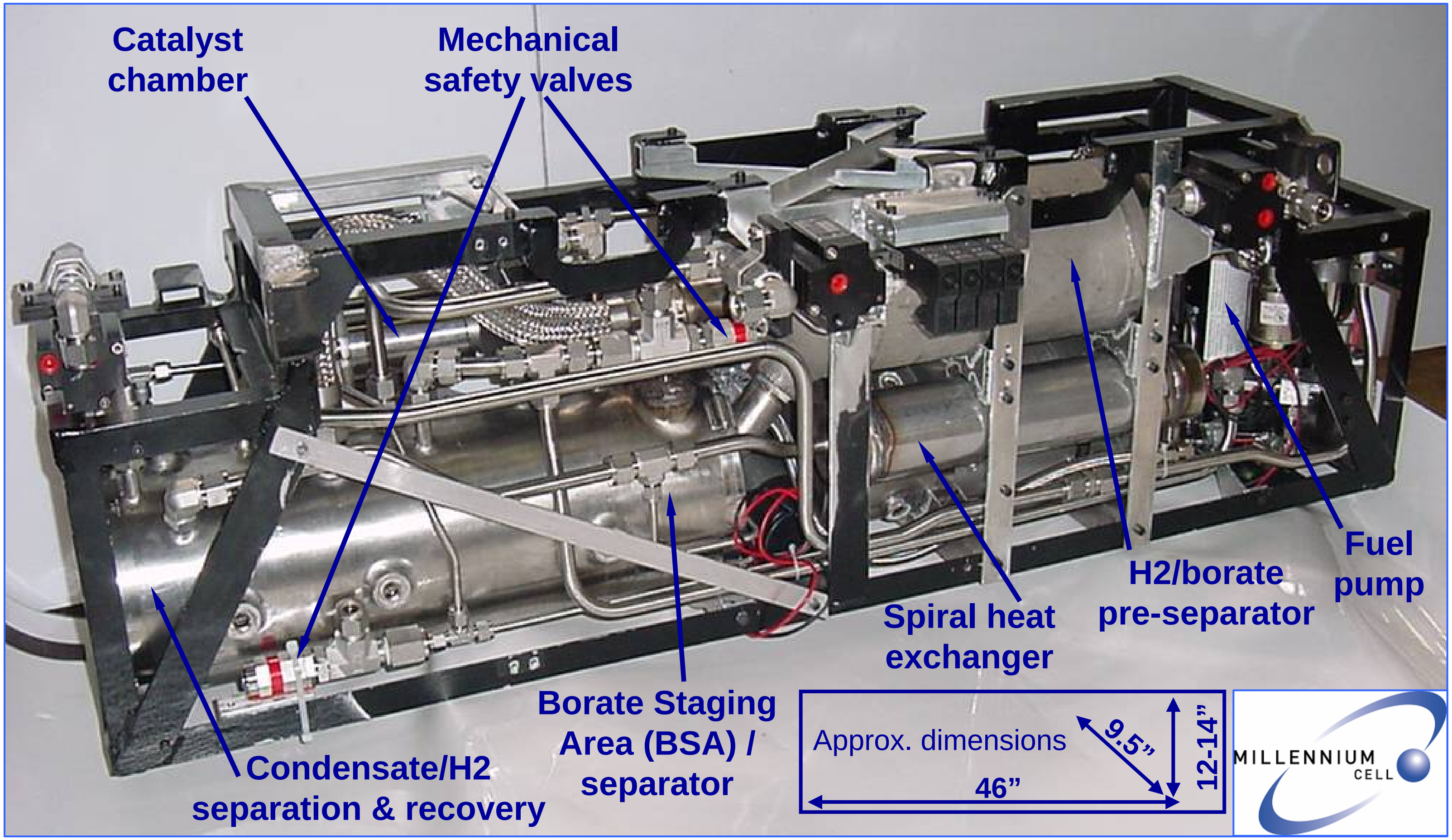
- Al = Aluminum
- GF = Glass Fiber
- CF = Carbon Fiber
- HTF = Heat Transfer Fluid
- HX = Heat Exchanger
- SS = Stainless Steel

A sodium alanate storage system would be complex relative to a conventional compressed hydrogen (cH_2) storage system.



*Note: Schematic is representative only. Additional safety and start-up components may be required.

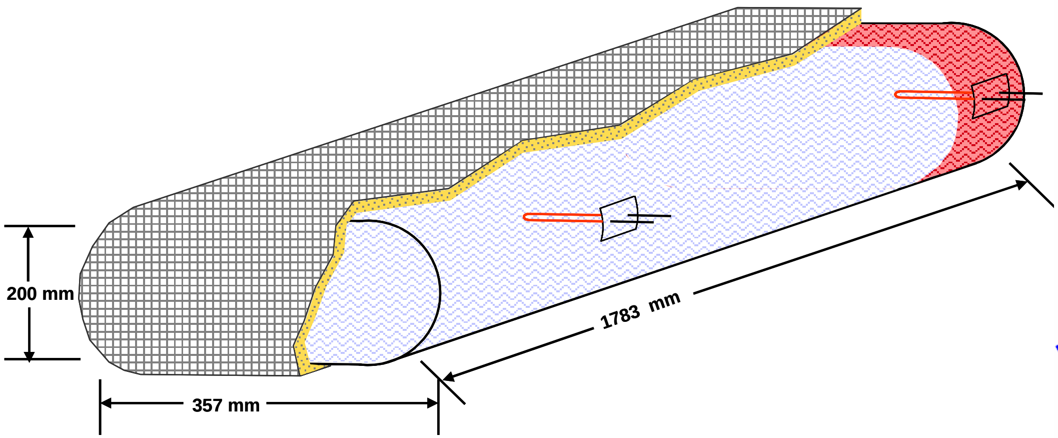
Likewise, the sodium borohydride system as demonstrated by MCell consists of several process vessels with greater complexity than cH_2.



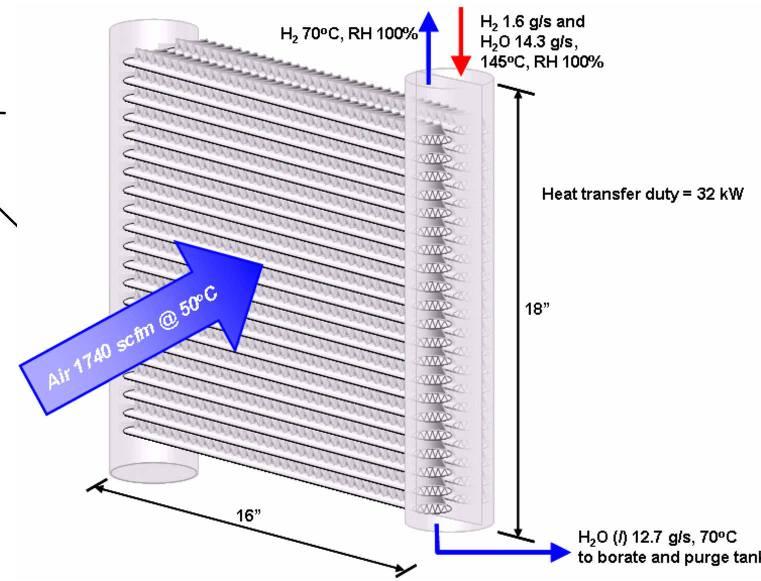
Source: Ying Wu. Director R&D, Millennium Cell – 65 kW Hydrogen on Demand System hardware

System-level design assumptions were used to develop individual component specifications and designs for each storage technology.

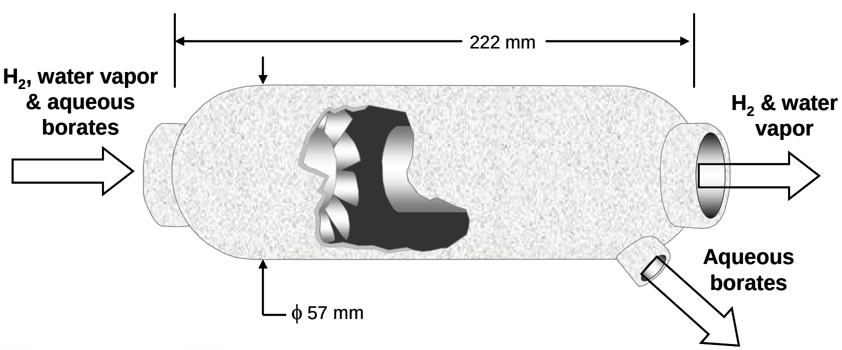
Storage Tank



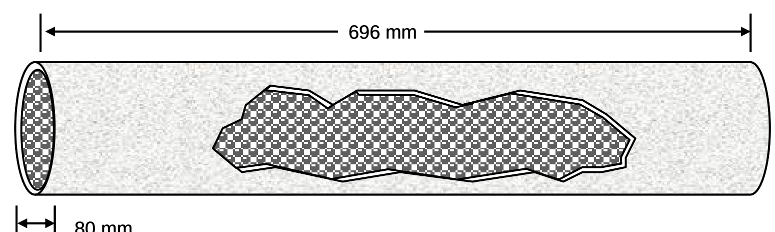
Condenser



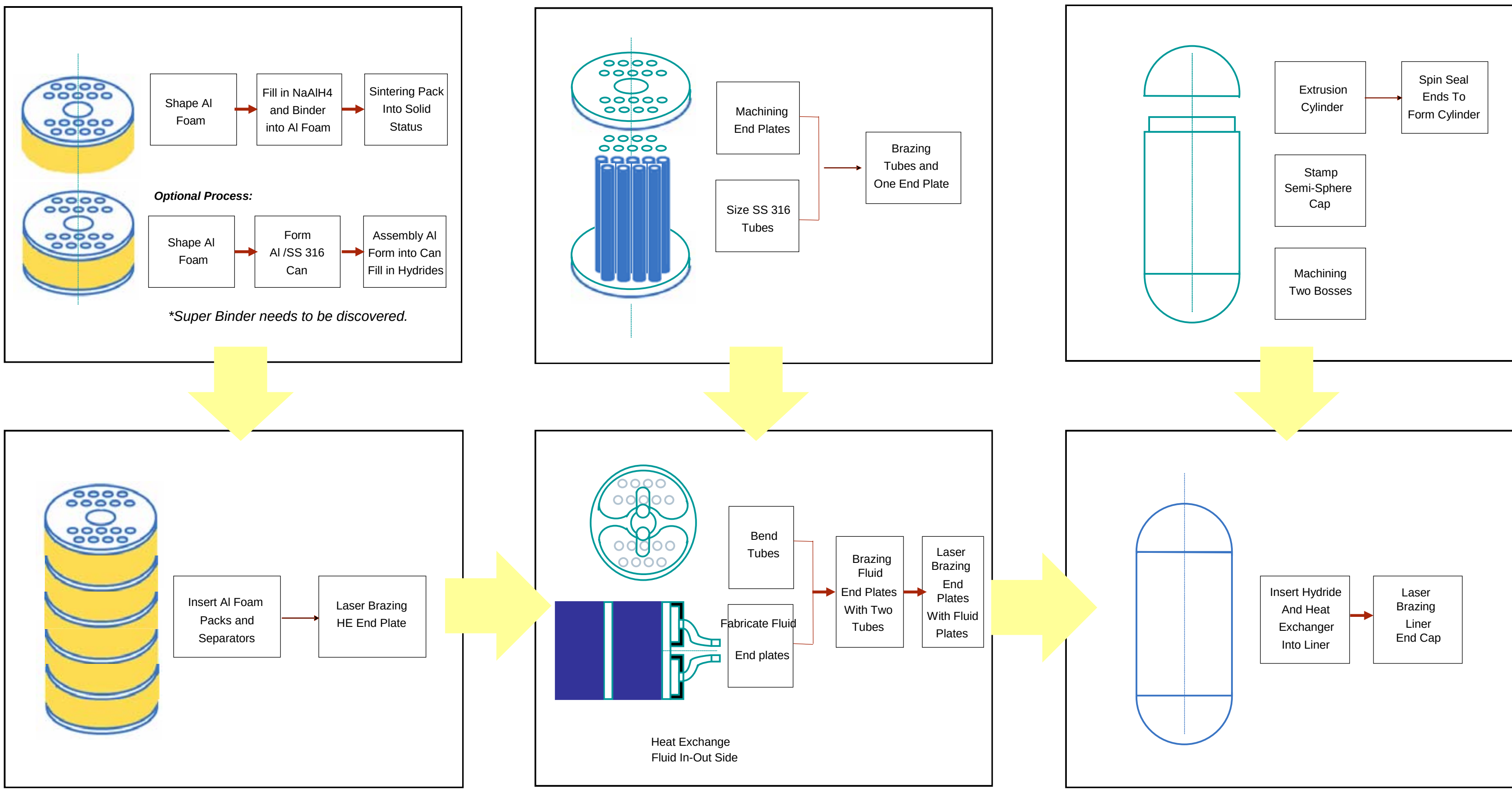
Liquid Separator



Reactor



Processing costs are estimated based on manufacturing steps that could be scaled-up to high volume.



DFMA® software is used to estimate balance of plant (BOP) component costs based on material, machining and assembly costs.

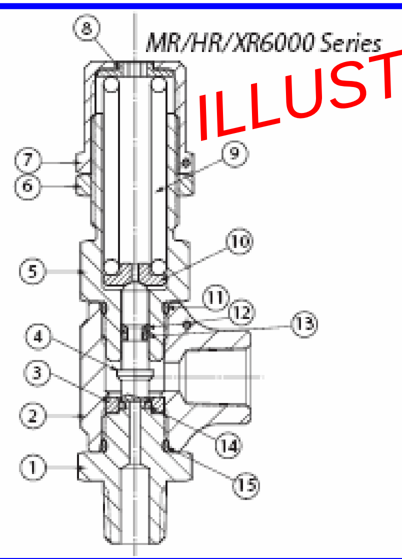
Example: Pressure Relief Valve

Material = $5.80

Assembly = $2.20

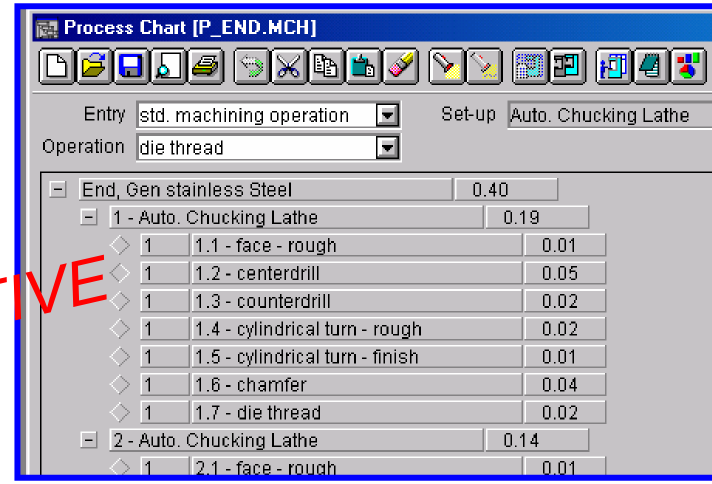
Total = $8.00

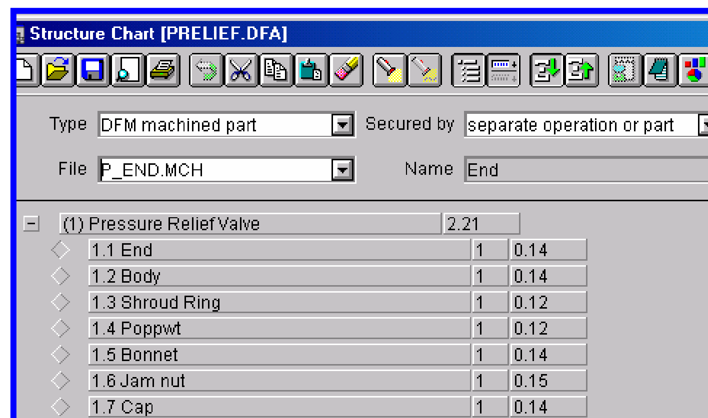
	MR/HR/XR
1	End
2	Body
3	Shroud ring
4	Poppet
5	Bonnet
6	Jam nut
7	Cap
8	Spring holder
9	Spring
10	Spring equalizer
11	O-ring
12	Delta ring
13	O-ring
14	Seat o-ring
15	O-ring



R6000 series pressure relief valve from Circle seal controls, inc.

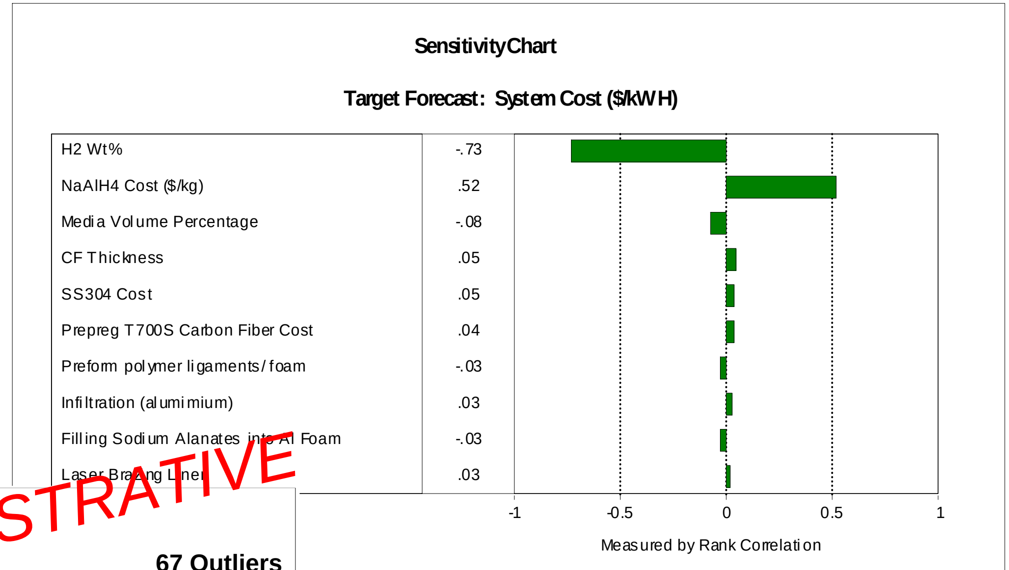
ILLUSTRATIVE

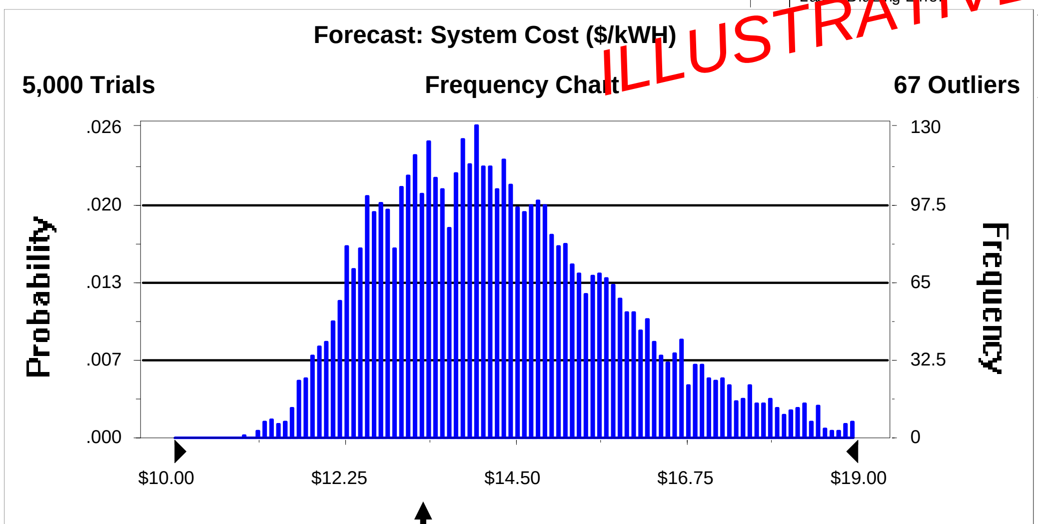




Multivariable sensitivity analysis is used to estimate the dependence and sensitivity of cost on/to the critical cost drivers.

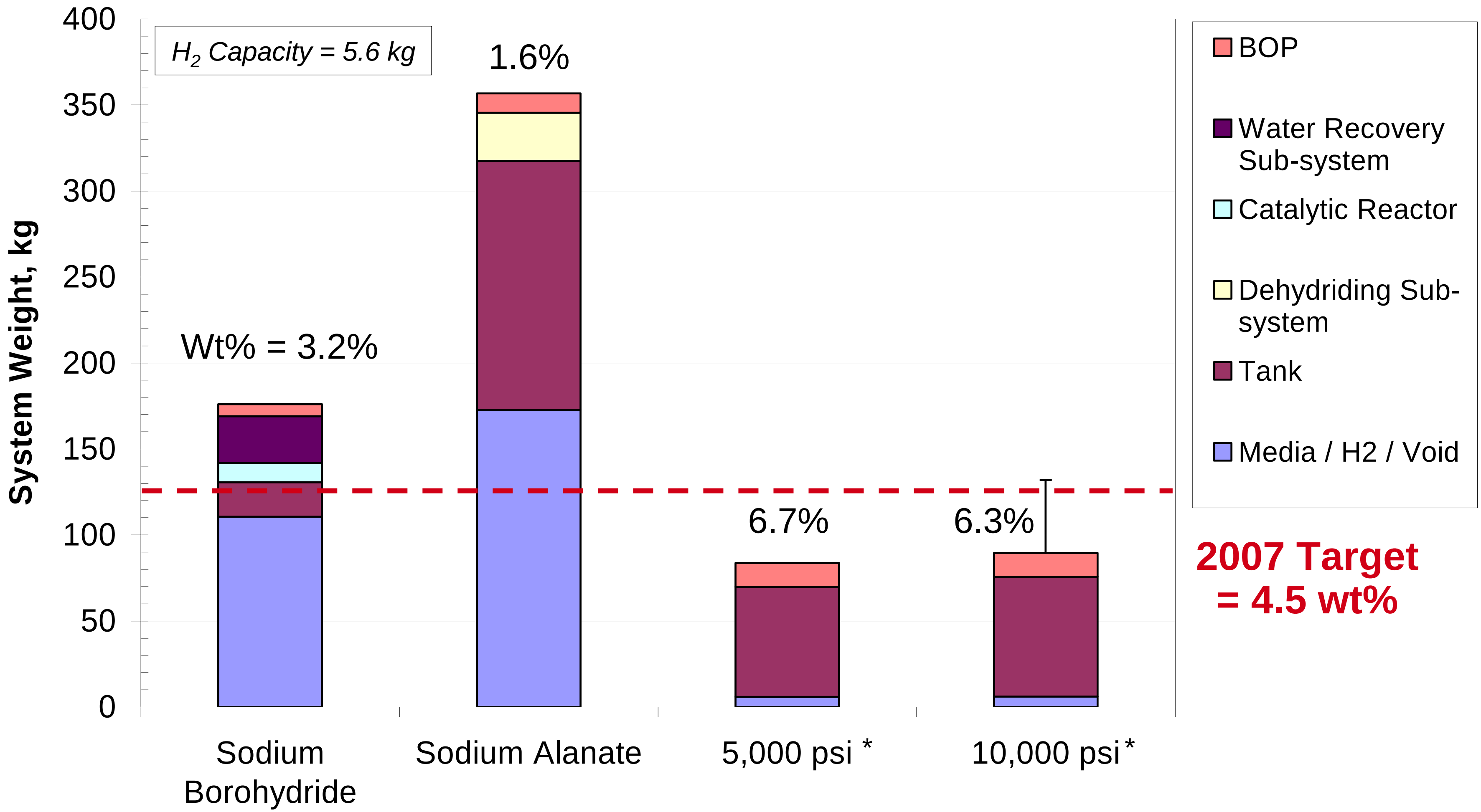
System Cost	$/kWh
Mean	14.40
Std. Dev.	1.67
Base Case	13.15





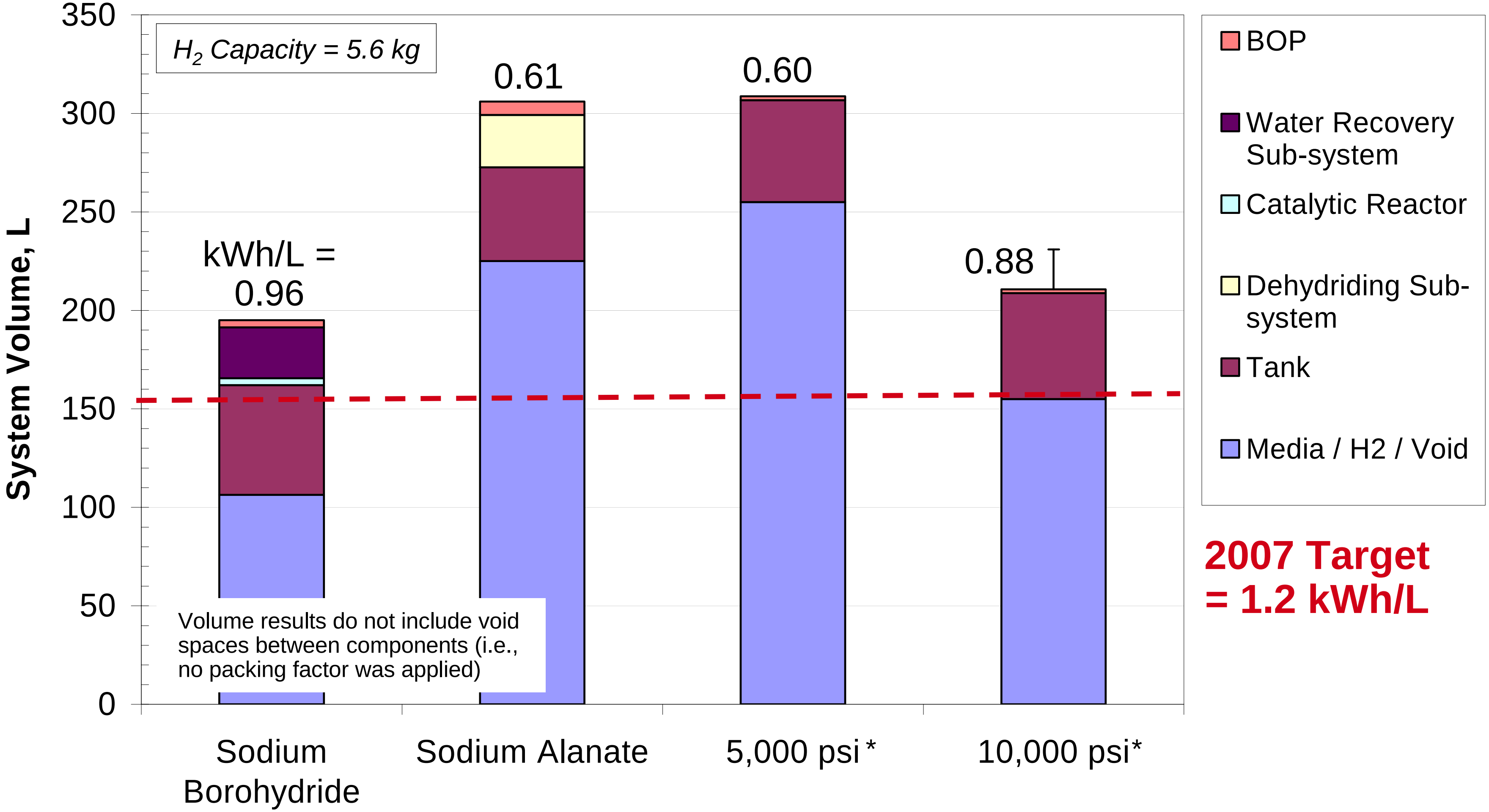
Base Case $13/kWh

The current designs for the sodium alanate and sodium borohydride systems will likely be heavier than compressed hydrogen storage.



* Based on: Carlson, E., et al. (TIAX), "Cost Analyses of Fuel Cell Stacks/Systems", Merit Review, Philadelphia, PA, May 24-27, 2004. Results assume 100% translation of carbon fiber strength. Actual results will likely be higher than show in the chart. Error bar for 10,000 psi is based on a Quantum current design: Geving, B., "Low Cost, High Efficiency, High Pressure Storage", DOE Merit Review, May 2005.

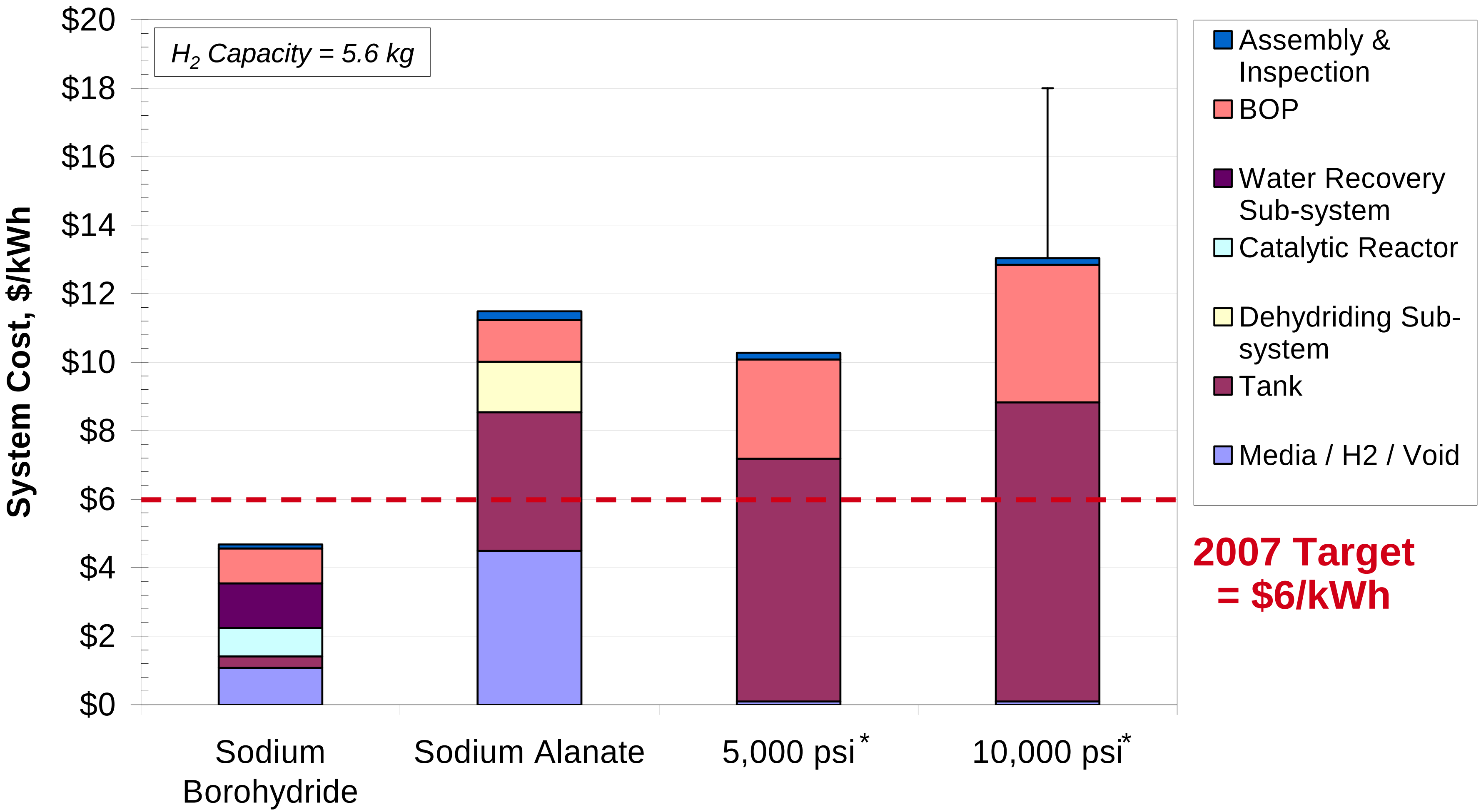
Sodium alanate and sodium borohydride systems will likely be similar in volume to compressed hydrogen storage systems.



2007 Target = 1.2 kWh/L

* Based on: Carlson, E., et al. (TIAX), "Cost Analyses of Fuel Cell Stacks/Systems", Merit Review, Philadelphia, PA, May 24-27, 2004. Results assume 100% translation of carbon fiber strength. Actual results will likely be higher than show in the chart. Error bar for 10,000 psi is based on a Quantum current design: Geving, B., "Low Cost, High Efficiency, High Pressure Storage", DOE Merit Review, May 2005.

Although the factory cost of the $NaBH_4$ system will be much lower than the compressed hydrogen and alanate systems, fuel costs may be higher.



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Next, we will finalize the Alanate and Sodium Borohydride on-board results, conduct a WTW analysis, and begin new technology assessments.

- Finalize results for the on-board Alanate and Sodium Borohydride systems and publish interim report
- Conduct off-board and vehicle integration analyses for Alanate and Sodium Borohydride systems
- Begin assessment of next storage technology - TBD
- Continue to work with DOE, H2A, other analysis projects, developers, National Labs, etc.

A complete Well-to-Wheels (WTW) assessment requires an evaluation of both the on-board and off-board performance and cost.

Analysis Tasks	Tank-to-Wheels (On-board)	Well-to-Tank (Off-board)	Well-to-Wheels (Lifecycle)
Material Performance	✓ Material wt % ✓ P, T requirement ✓ Thermo, kinetics	• Regeneration efficiency and requirements	N/A

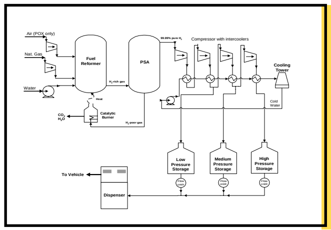
System-level Performance	✓ Storage system weight and volume
	• Vehicle fuel economy (mi/kg H_2)
	  • Powertrain weight
	  • Thermal, power requirements
		• WTT GHG emissions (g/MJ H_2)
		• WTT Primary energy use (MJ/MJ H_2)
			• WTW GHG emissions (g/mile)
			• WTW Primary energy use (MJ/mile)

Cost	✓ Storage system factory cost:
	  ✓ Material
	  ✓ Subsystems
	  ✓ Balance of plant
	  ✓ Process
		• Equivalent H_2 selling price ($/kg)	• Ownership cost ($/mile)

✓ = Completed for sodium alanate and sodium borohydride systems.

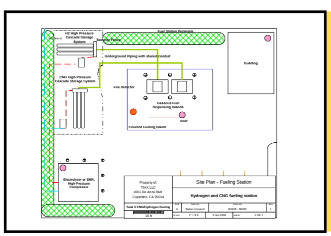
Our WTT analysis will make use of existing (or planned) models to calculate cost and performance for each technology on a consistent basis.

Conceptual Design



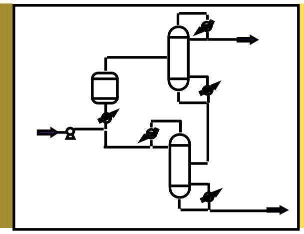
- System layout and equipment requirements

Site Plans



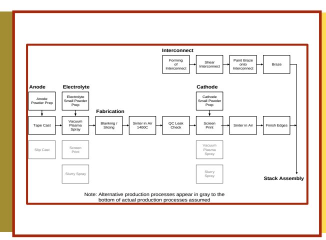
- Safety equipment, site prep, land costs

Process Simulation



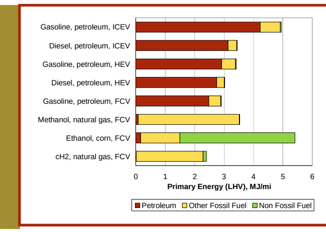
- Energy requirements
- Equipment size/ specs

Capital Cost Estimates



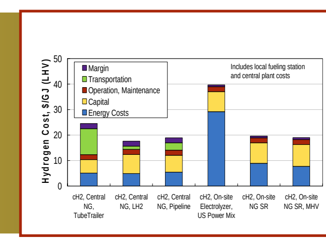
- High and low volume equipment costs

GREET Post Processor



- WTT energy use
- WTT GHG

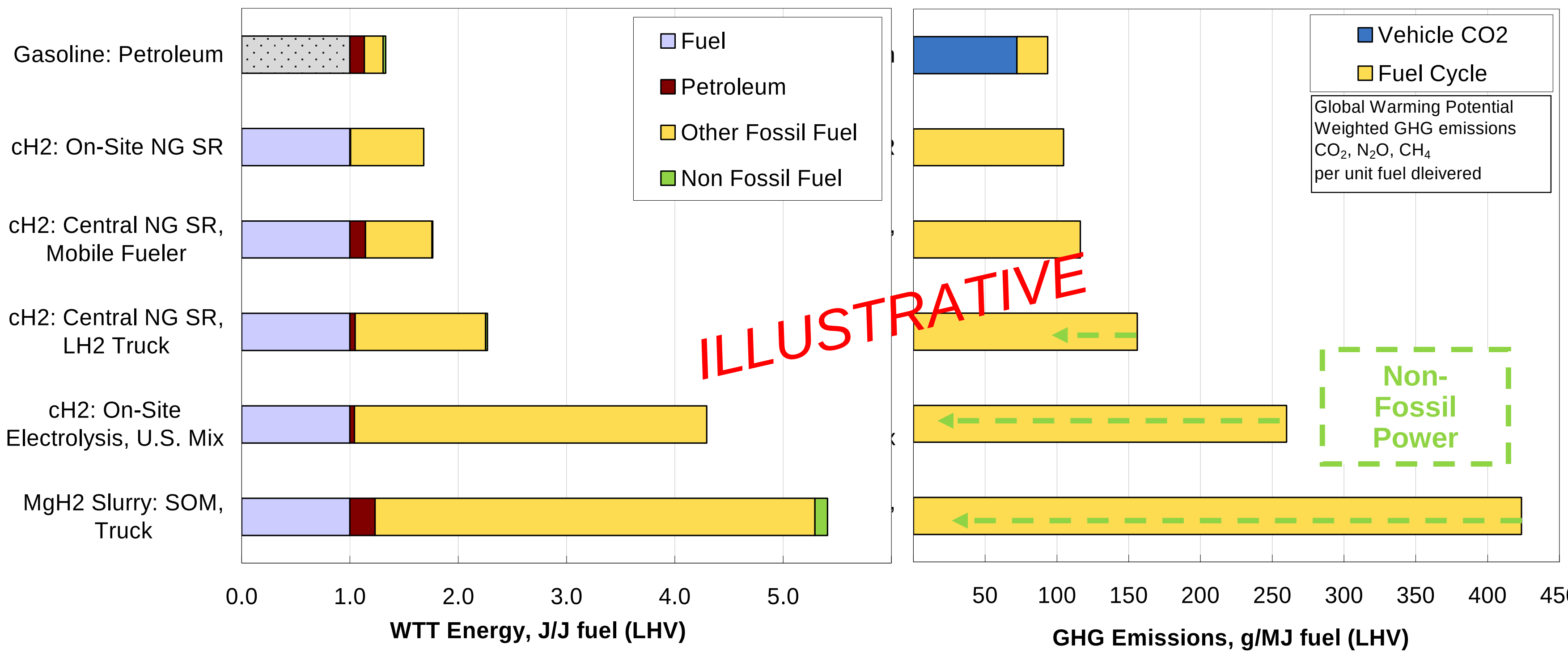
H2A Model



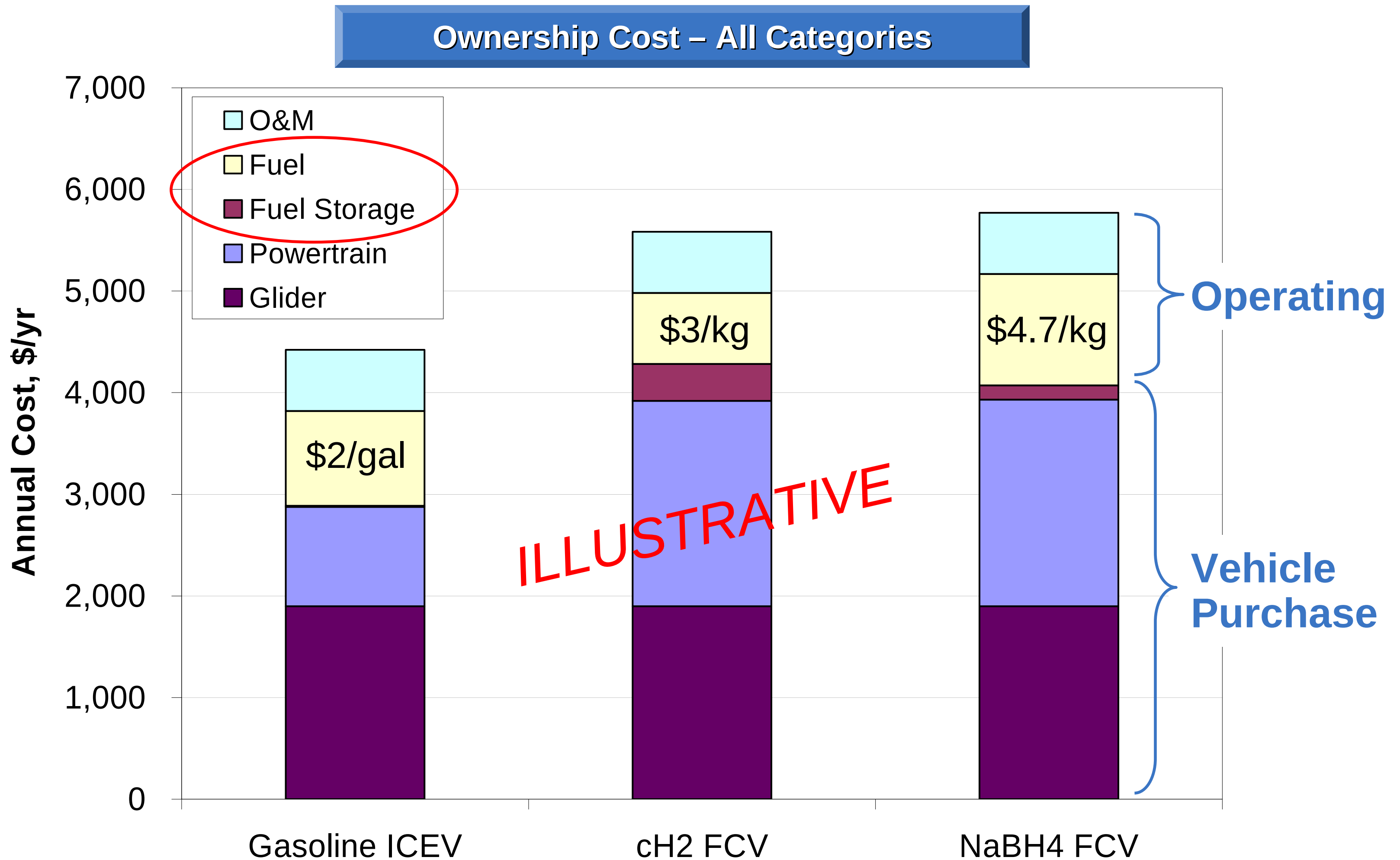
- Hydrogen cost (capital, O&M, etc.)

WTT energy use and GHG emissions will be calculated using the appropriate fuel cycle efficiencies and GHG factors.

WTT GHG Emissions | **WTT Primary Energy**



A complete ownership cost assessment will require that both vehicle purchase cost and operating costs be considered.



Ownership costs results depend on a number of relatively simple assumptions.

ILLUSTRATIVE

Preliminary Ownership Cost Assumptions	Gasoline ICEV	cH_2 FCV	$NaBH_4$ FCV
Annual Discount Factor on Capital	15%	15%	15%
Annual Mileage (mi/yr)	14,000	14,000	14,000
Vehicle Energy Efficiency Ratio	1	2	2
Fuel Economy (mpgge)	30	60	60
H_2 Storage Requirement (kg H_2)	-	5.6	5.6
Fuel Price ($/eq gal)	**2.00**	**3.00**	**4.69**
O&M Cost ($/mi)	0.043	0.043	0.043
H_2 Storage Cost ($/kWh)	**-**	**13**	**5**
Vehicle Retail Price[1] ($/vehicle)	$19,246	$28,547	$27,055

[1] Projected, high-volume price with mark-ups. Includes glider, powertrain, and fuel storage costs.