STRATEGIC ANALYSIS INC

2018 DOE Hydrogen and Fuel Cells Program Review

Hydrogen Storage Cost Analysis

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Project ID# ST100

Overview

Timeline

- Project Start Date: 9/30/16
- Project End Date: 9/29/21
- % complete: 30% (in year 2 of 5)

Barriers

- A: System Weight and Volume
- B: System Cost
- K: System Life-Cycle Assessment

Budget

- Total Project Budget: $1,500,000
  - Total DOE Funds Spent*: $368,000
- *Through March 2018

Partners

- Pacific Northwest National Laboratory (PNNL)
- Argonne National Lab (ANL)

Relevance

- **Objective**
  - Conduct rigorous, independent, and transparent, bottoms-up techno-economic analysis of H_2 storage systems.
- **DFMA® Methodology**
  - Process-based, bottoms-up cost analysis methodology which projects material and manufacturing cost of the complete system by modeling specific manufacturing steps.
  - Predicts the actual cost of components or systems based on a hypothesized design and set of manufacturing & assembly steps
  - Determines the lowest cost design and manufacturing processes through repeated application of the DFMA® methodology on multiple design/manufacturing potential pathways.
- **Results and Impact**
  - DFMA® analysis can be used to predict costs based on both mature and nascent components and manufacturing processes depending on what manufacturing processes and materials are hypothesized.
  - Identify the cost impact of material and manufacturing advances and to identify areas of R&D interest.
  - Provide insight into which components are critical to reducing the costs of onboard H_2 storage and to meeting DOE cost targets

Approach/Activities In Past year

- **Light-Duty Vehicle (LDV) Analysis**
  - Updates to the baseline 700 bar Type 4 system cost
    - Hoop-intensive winding pattern analyses
    - Modified gas temperature and regulator pressure drop assumptions
  - Hybrid reversible metal hydride analysis
    - Reverse engineering analysis based on ANL proposed hybrid 350 bar system
- **Fuel Cell Electric Bus (FCEB) Analysis**
  - 500 bar (60-80K) cryo-compressed H_2 (CcH_2) for bus applications
    - Super-Critical H_2
    - Based on performance analysis by ANL and system design from LLNL
    - Completed cost analysis of CcH_2 for bus applications (40 kg usable H_2)
  - 350 bar Type 3 cH_2
- **Type IV CNG Analysis**
  - 3600 psi natural gas storage system in support of the Institute for Advanced Composites Manufacturing Innovation (IACMI) and the Advanced Manufacturing Office (AMO)
  - Modeled advanced thermoplastic tape placement system to compare with baseline costs

Metal Hydride Reverse Engineering

Minimum Material & System Requirements

Variables	Related Variables	Reference Values	Constraints
UMH Intrinsic Capacity		5.6% H capacity	4.3 wt% gravimetric
Fill Ratio	Bulk Density Thermal Conductivity	81.4% bed porosity 263 kg/m^3 UMH bulk density 5 W/m.K bed conductivity	24.6 g/L volumetric
Desorption Kinetics	X_{min} = 10%	τ_d = 6.1 min	1.6 g/s min full flow
Sorption Kinetics	X_{max} = 98.8%	τ_c = 6.4 min	X_{min} to X_{max} in 3.7 min
HX Tube Spacing	Number of HX Tubes	r_2/r_1 = 4.3 66 U tubes	1.5 kg/min refueling
Refueling Pressure	Storage Pressure	400 atm	350 atm design pressure 25% overpressure limit
Mass of UMH	Mass of Expanded Natural Graphite	45.9 kg UMH 4.6 kg EG	5.6 kg usable H_2 3.4 kg as cH_2 2.3 kg H_2 in UMH

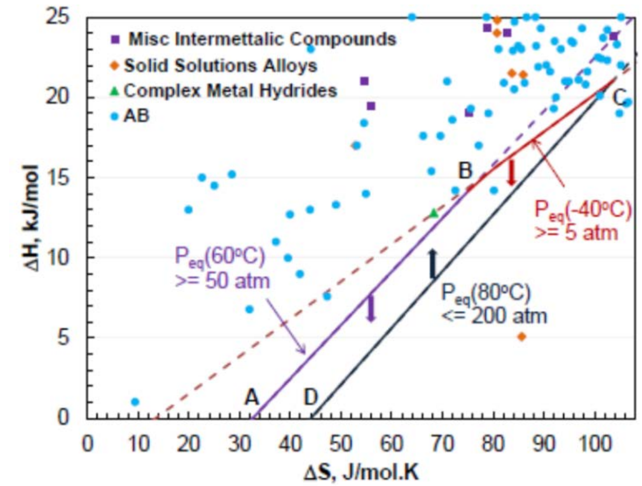
- This work builds on metal hydride reverse engineering analysis from Argonne reported in
  - Presentation to the HSTT (2016)
  - Ahluwalia et al IJHE 39 (2014)
- ANL system performance model outputs are a set of system parameters—composite mass, metal hydride mass, heat transfer tube spacing—for a hybrid 350 bar Type 4 metal hydride storage system meeting a set of vehicle constraints:
  - Discharges to empty using stack coolant
  - Equilibrium pressure > 5 atm at -40°C
  - Refuel at 350 bar in < 3 min without exceeding 80°C

SA Cost Analysis Goal: identify system parameters that can be optimized to achieve cost targets for different regions of the enthalpy-entropy chart

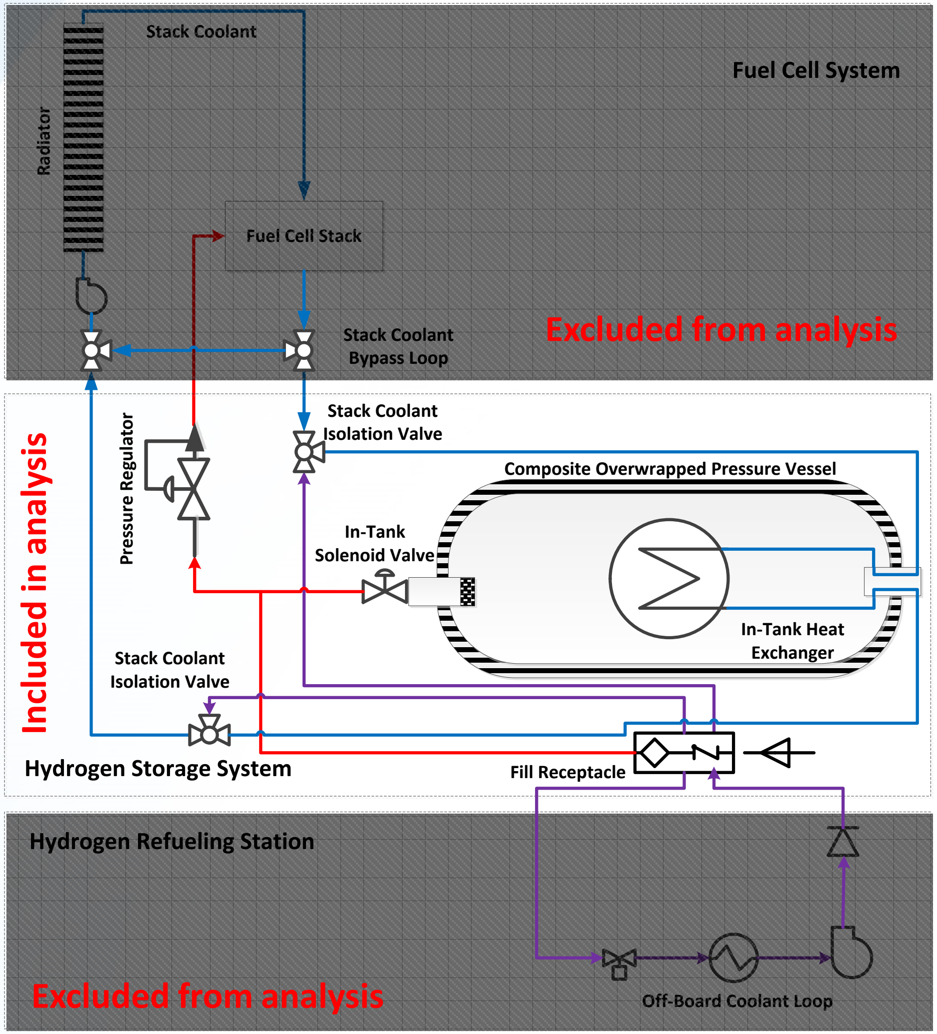
Vehicle Operation and Refueling Constraints

System Target	Approach	Material Requirement
Refuel at 350 atm (P_c)	Limit the temperature to 80°C (Type 4 liner)	For reasonable charge kinetics, desirable to have $\Delta P(P_c-P_{eq})$ > 150 atm.
		The equilibrium pressure, P_{eq}(80°C) should be less than 200 atm
Ability to start FC at -40°C	Maintain gaseous H_2 in tank at -40°C	Equilibrium pressure should be above the minimum delivery pressure at all temperatures.
		P_{eq}(-40°C) > 5 atm
Discharge MH using stack coolant as the heat source	Stack coolant operating temperature varies between 60 and 90°C	MH should discharge at the lowest operating coolant temperature
		For reasonable discharge kinetics, desirable to have $\Delta P(P_{eq}-P_d)$ > 50 atm.
		P_{eq}(60°C) > 50 atm

Desirable Metal Hydride Thermodynamics

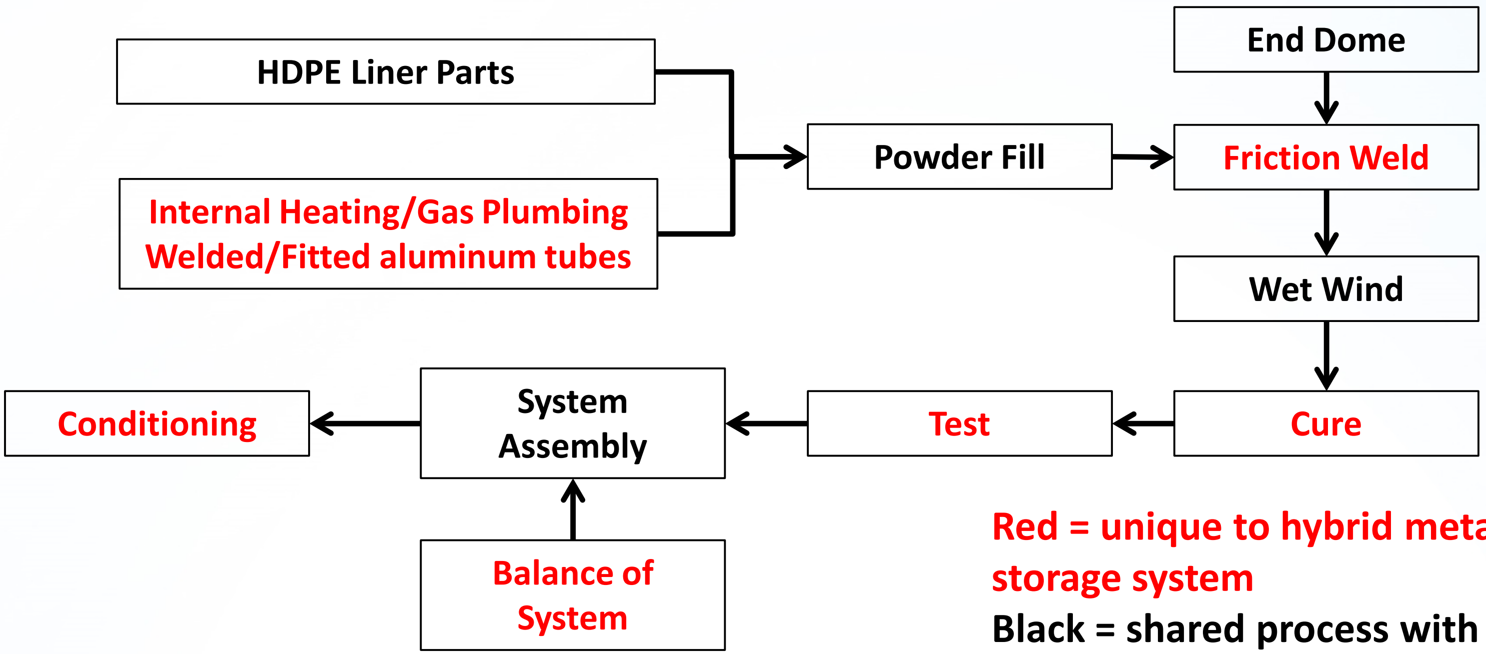


Hybrid Reversible Metal Hydride System Configuration



- System configuration with the fuel cell stack and refueling station is shown highlighting:
  - Interface between the stack coolant loop and the metal hydride bed
  - Off-board cooling loop requirement for rejecting heat during refueling

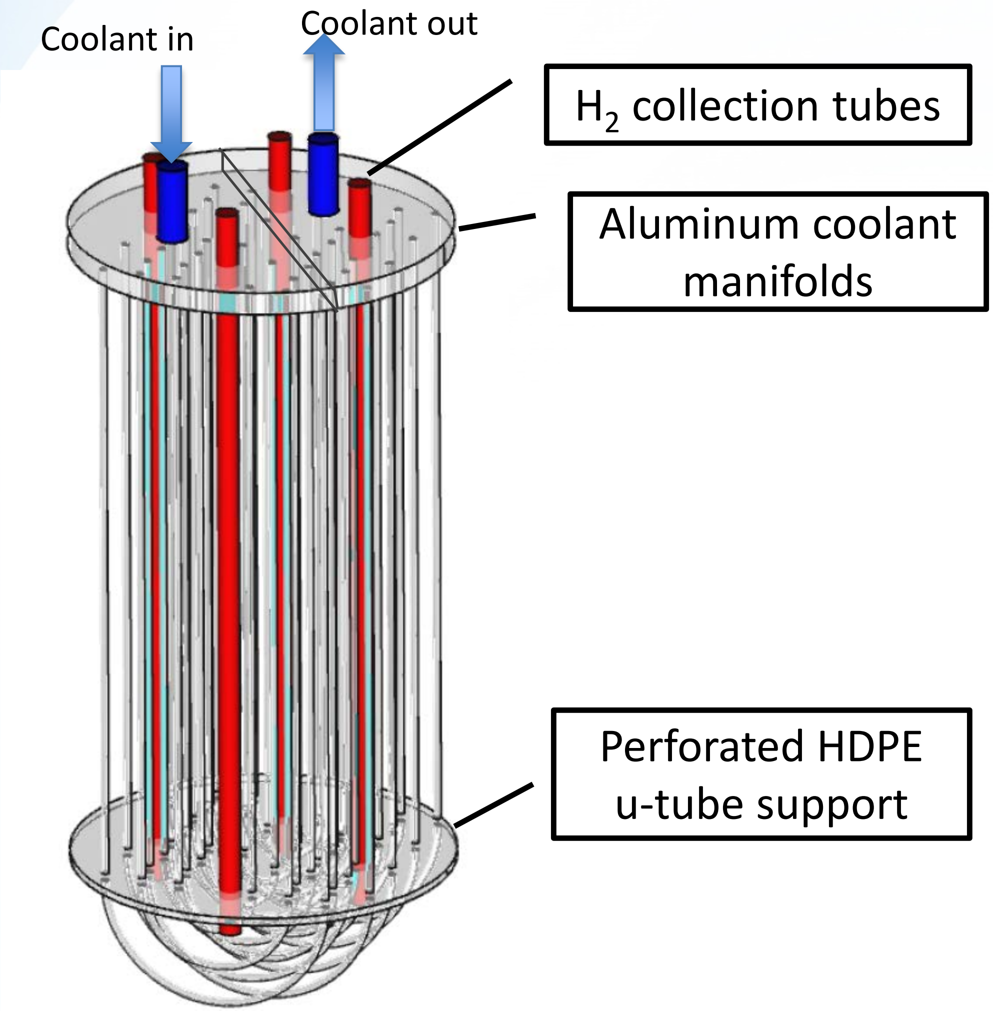
General Manufacturing Process Flow for Metal Hydride Reverse Engineering



Red = unique to hybrid metal hydride storage system
Black = shared process with type 4 compressed storage system

- Process flow reflects similarity to type 4 compressed gas storage system assembly and unique challenge of assembling tank around internal heat exchanger
- Many processes steps are shared with type 4 COPV
- A general internal heat and gas exchange design that captures the cost impactful features based on ANL heat transfer analysis was selected

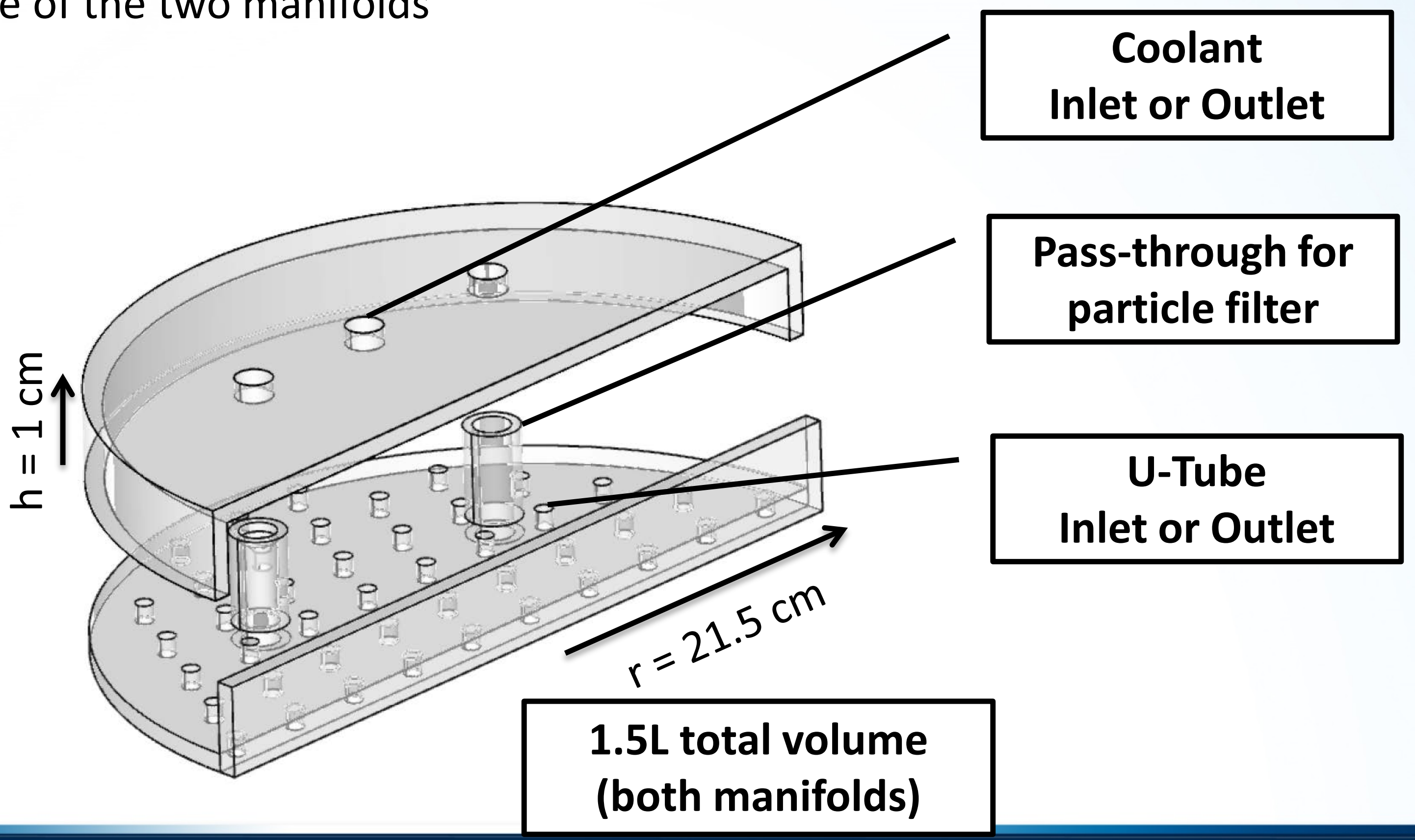
Internal Heat Exchanger Design



- Coolant is distributed by the coolant manifolds
  - Inlet manifold and outlet manifold (shown in next slide)
- ANL performance model results estimate 58 pairs of coolant tubes
- Four H_2 collection tubes are included to reduce the diffusion path to the valve and to provide a diffusion path through the full length of the tank
- HDPE support is perforated to allow fill of metal hydride powder

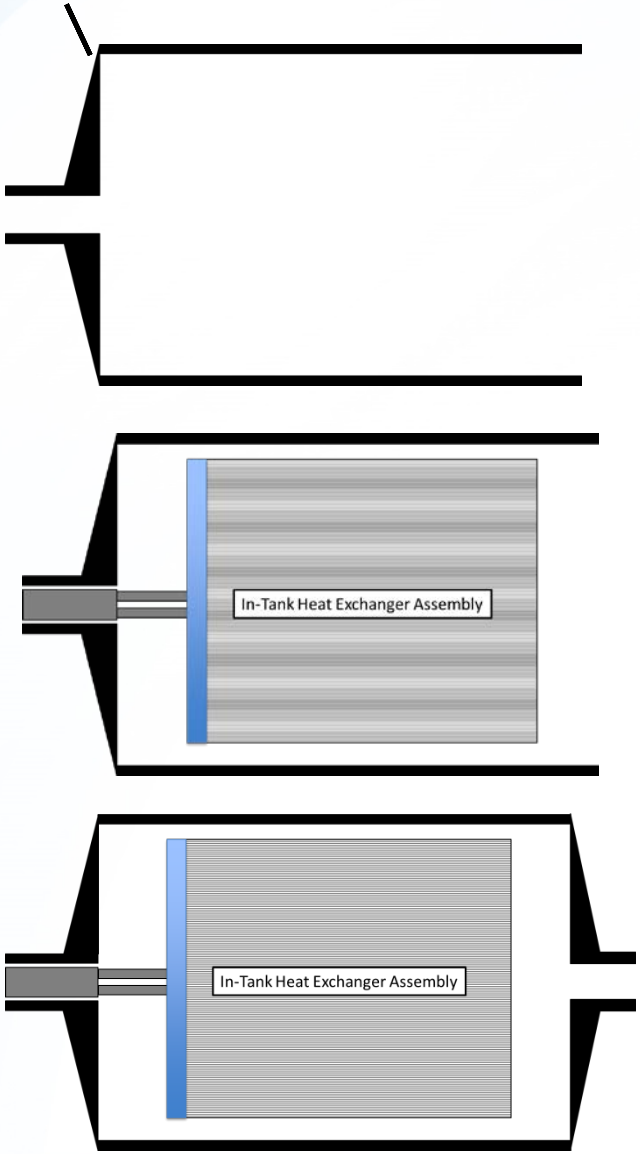
Internal Heat Exchanger Coolant Manifold Design

- Two separate coolant manifolds will be modeled, an inlet to distribute coolant and an outlet to collect the coolant and return it to the radiator
- Each manifold is a two-piece construction (shown as a blow-up below)
- Figure shows one of the two manifolds



In-Tank Heat Exchanger Assembly Scheme

Coolant-Side Boss, Shoulder, and Liner



1. Assemble coolant-side dome and cylindrical section of tank liner
2. Insert pre-assembled heat exchanger and coolant port through the boss throat
3. Friction weld valve-side dome onto cylinder section of the liner

Wet-Winding Operation

Valve-Side Boss and Liner

Preliminary Metal Hydride Reverse Engineering Analysis

	Est. @500k	Notes
Type 4 pressure vessel (boss, liner, composite)	$6/kWh	51 kg CF composite Aluminum bosses HDPE liner (blow mold only; cost for friction welding not included)
Fill Receptacle	$0.30/kWh	Based on high volume quote for 350 bar compressed gas receptacle. Cost for off-board heat transfer fluid not yet included
Integrated regulator block	$1.75/kWh	Complete
In-tank valve	$0.89/kWh	Complete
In-Tank HX	>$1/kWh	based on high volume tube quotes with a single bend, but does not yet include assembly or the coolant manifolds
MH/EG	Parameter	ANL assumed 5.6% MH hydrogen capacity and 45.9 kg MH with 4.6 kg EG. Goal of this analysis is to set cost-driven targets on this parameter
Other BOP	TBD	Additional costs for storage-side coolant pump, valve and plumbing
Total	>$10/kWh	

Preliminary results suggest thermodynamic constraints predicted by ANL are not stringent enough to achieve cost targets; additional constraints to intrinsic hydrogen capacity may be required

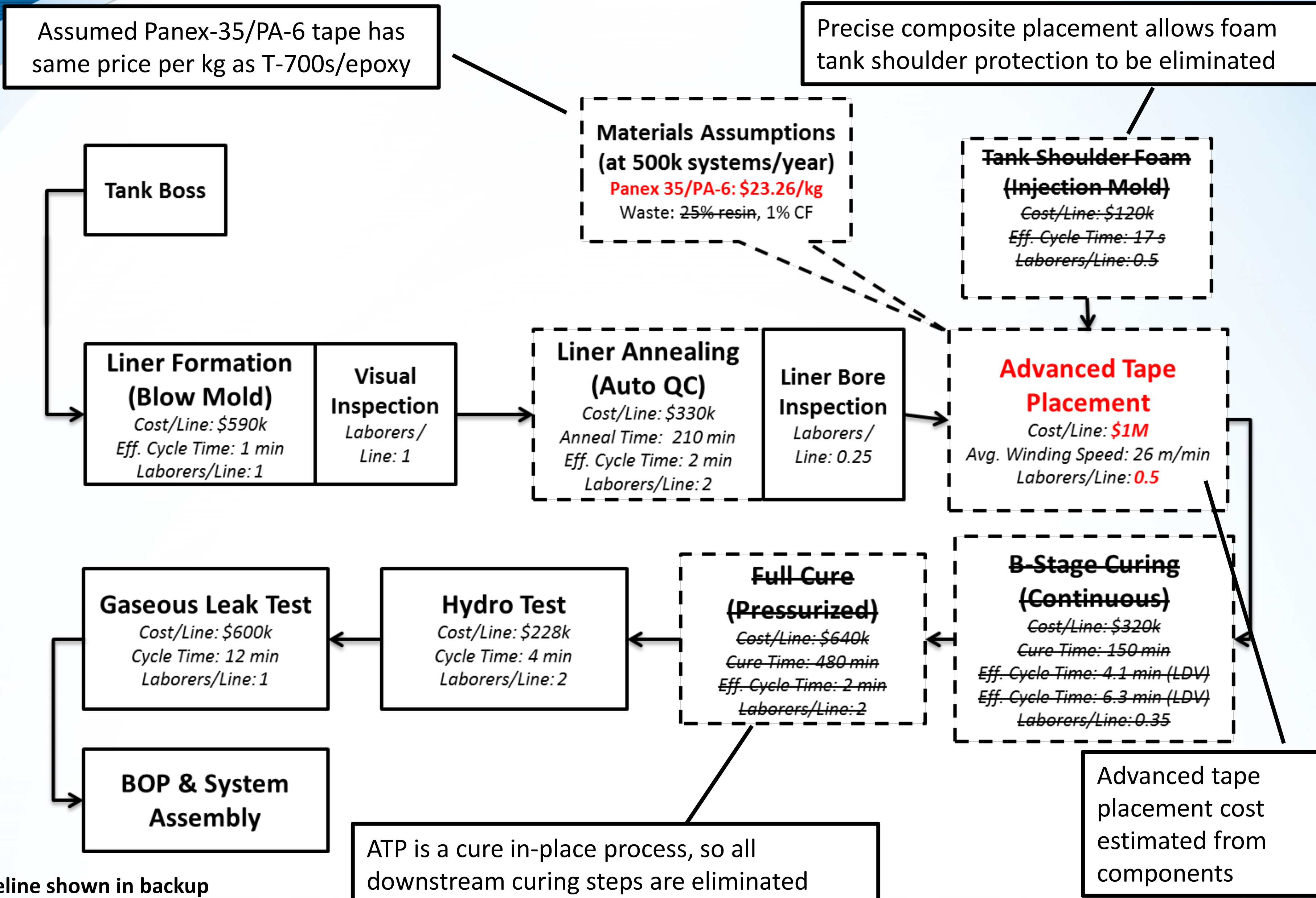
DuPont/Steelhead Composite Collaboration Under IACMI

- **Baseline CNG storage system analysis (in support of IACMI)**
  - Traditional wet fiber layup
  - Toray T-700s/Epoxy resin
  - 64.4 L and 538 L Type 4 pressure vessels
  - 3,600 psi rated pressure

- **Alternative approach developed by DuPont/Steelhead**
  - Advanced tape placement (ATP)
  - Panex-35/PA-6 Resin thermoplastic tape
  - Both type 3 (aluminum liner) and Type 4 liners modeled
  - Compared at intermediate production volumes (up to 10k tanks/year)
  - 3,600 psi rated pressure

- **The focus of this analysis is on the manufacturing approach**
  - Quantify cost differences between wet layup and Advanced Tape Placement
  - Help define thermoplastic tape cost targets

Alternate* Type 4 CNG Process Flow



*baseline shown in backup

Tank Costs Comparison

Comparison is for 64.4L Type 4 Tank

Baseline

Production Rate	Tanks/year	1,000	10,000	30,000	80,000	100,000	500,000
Liner Blow Mold	$/system	*$146*	*$34*	*$26*	*$17*	*$16*	*$15*
Liner Annealing	$/system	*$30*	*$20*	*$12*	*$6*	*$5*	*$5*
Fiber Winding (Wet Winding)	$/system	*$619*	*$487*	*$481*	*$454*	*$436*	*$427*
B-Stage Cure (Cure #1)	$/system	*$30*	*$8*	*$6*	*$4*	*$5*	*$4*
Tank Shoulder Foam	$/system	*$57*	*$7*	*$3*	*$2*	*$2*	*$1*
Full Cure	$/system	*$148*	*$28*	*$13*	*$6*	*$5*	*$4*
Boss	$/system	*$54*	*$36*	*$29*	*$26*	*$26*	*$25*
Hydro Test	$/system	*$113*	*$16*	*$9*	*$8*	*$8*	*$8*
He Fill & Leak Test	$/system	*$23*	*$21*	*$11*	*$9*	*$9*	*$9*
System Cost	**$/system**	**$1,221**	**$657**	**$589**	**$533**	**$512**	**$497**

Costs affected by manufacturing changes

Advanced Thermoset Tape Placement

Production Rate	Tanks/yr	1,000	10,000	30,000	80,000	100,000	500,000
Liner Blow Mold	$/system	*$146*	*$34*	*$26*	*$17*	*$16*	*$15*
Liner Annealing	$/system	*$30*	*$20*	*$12*	*$6*	*$5*	*$5*
Advanced Fiber Placement (Type 4)	$/system	*$921*	*$630*	*$630*	*$601*	*$579*	*$568*
Boss	$/system	*$54*	*$36*	*$29*	*$26*	*$26*	*$25*
Hydro Test	$/system	*$113*	*$16*	*$9*	*$8*	*$8*	*$8*
He Fill & Leak Test	$/system	*$23*	*$21*	*$11*	*$9*	*$9*	*$9*
System Cost	**$/system**	***$1,289***	***$758***	***$717***	***$668***	***$643***	***$629***
Difference	**$/system**	***$68***	***$101***	***$128***	***$135***	***$131***	***$132***

Primary Differences between ATP and Wet Layup

	Baseline	Alternative	Notes
Composite Layup	Wet Winding	Advance Tape Placement	Analysis assumption
Capital Cost (Uninstalled)	$343k	$1M	Baseline capital cost from supplier quote for 2-spindle winder Alternative capital cost estimated by SA from components (w/o 40% installation cost)
Winding Speed (average)	26 m/min	26 m/min	Analysis assumption based on conventional average composite winding speeds
Composite Cost ○ 10k tanks/year ○ 500k tanks/year	 $26.31/kg $23.26/kg	 $26.31/kg $23.26/kg	Price based on T-700s/epoxy with 25% resin wastage, 1% composite wastage, and 3.3% COV for manufacturing and fiber **Preliminary analysis of thermoplastic tape suggests material costs could be as low as 20% lower for Panex 35/PA-6**
Composite Mass (64.4L Type 4 tanks)	16.3 kg	19 kg	Baseline estimated by SA from PNNL reported performance factor. Alternative mass reported to SA by Steelhead Composites. Difference likely lies in lower strength Panex-35 as discussed later.
Materials Cost ○ 10k tanks/year ○ 500k tanks/year	 $429/tank $379/tank	 $500/tank $442/tank	For 64.4L Type 4 tank
Manufacturing Cost ○ 10k tanks/year ○ 500k tanks/year	 $58/tank $48/tank	 $131/tank $126/tank	
Curing and Dome Protection Cost ○ 10k tanks/year ○ 500k tanks/year	 $43/tank $9/tank	 $0/tank $0/tank	

Updates to the 700 bar baseline system

Accomplishments & Progress

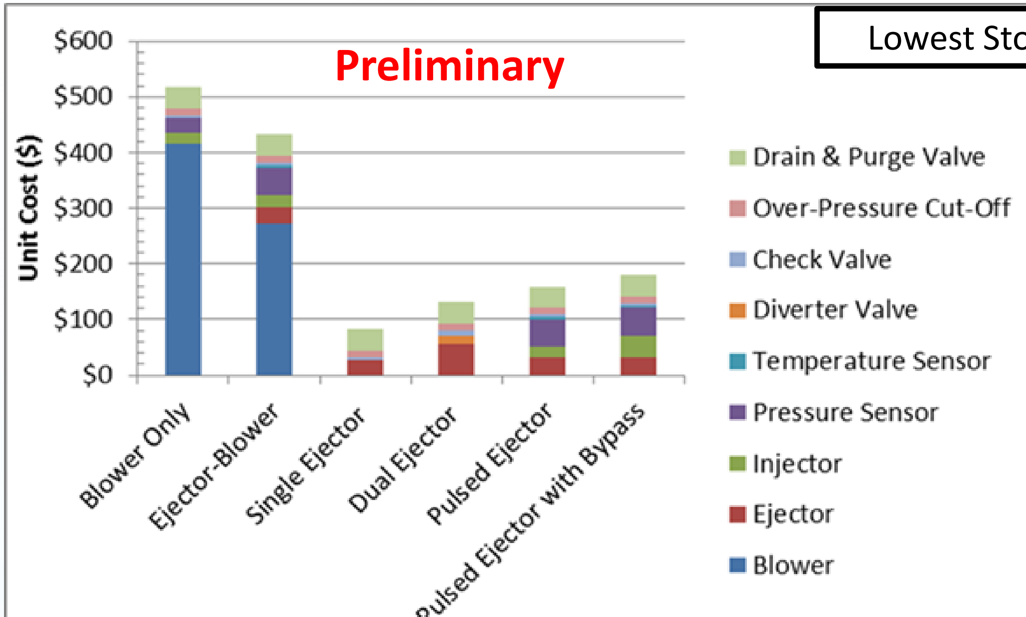
Item	Cost (Cumulative Change)	Composite Mass (kg)	Basis
2015 Baseline	$14.75/kWh	97	https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf.
Aluminum BOP components	$14.57/kWh (-$0.18/kWh)	97	Replaced 316L integrated regulator and valve assembly bodies with aluminum
Lowering gas temp (from 20°C to 15°C)	$14.45/kWh (-$0.30/kWh)	95.9	Updated assumptions to be consistent with J2601
Hoop-intensive winding pattern	$13.94/kWh (-$0.81/kWh)	91.2	Hua, Roh, and Ahluwalia. "Performance Assessment of 700-Bar Compressed Hydrogen Storage for Light Duty Fuel Cell Vehicles." IIJHE 42 (2017) 25121. https://doi.org/10.1016/j.ijhydene.2017.08.123.
Reduction in regulator pressure drop (from 15 bar to 10 bar) to deliver 5 bar to stack	**$13.84/kWh (-$0.91/kWh)**	**90.3**	Reduced regulator hysteresis and droop reported in Yamashita et al. "Development of High-Pressure Hydrogen Storage System for the Toyota 'Mirai.'" SAE Technical Papers, (2015). https://doi.org/10.4271/2015-01-1169.
Lower storage system costs are possible with relaxed fuel cell system requirements and flow rates			
Design for full fuel utilization (Option 1: 10 bar H_2 outlet)	$13.74/kWh (-$1.01/kWh)	89.3	Allow for reduced flow rate at low tank pressure to deliver 10 bar (with passive FC stack H_2 recirculation)
Design for full fuel utilization (Option 2: 5 bar H_2 outlet)	$13.64/kWh (-$1.11/kWh)	88.4	Allow for reduced flow rate at low tank pressure to deliver 5 bar (with active FC stack H_2 recirculation) and per MYRDD https://www.energy.gov/sites/prod/files/2015/05/f22/fcto_myrdd_storage.pdf

Updates to the 700 bar baseline system

	Storage System				Fuel Cell System		
Storage System	**Minimum Empty Pressure (bar)**	**Internal Tank Volume (L)**	**Composite Mass (kg)**	**Storage Cost ($/system)**	**Required FCS Recirculation System Pressure (bar)**	**FCS H2 Recirculation System Cost ($/System)**	**Net Cost ($/system)**
2015 storage baseline	20	147.1	97	$2,753	--	$520	Ref. Case
Hoop-Intensive Winding	15	142.4	89.3	$2,584	--	$520	-$169
Pulsed Ejector w/Bypass	10	140.9	88.4	$2,565	10	$180	-$528
Blower Only	5	140.9	88.4	$2,546	5	$520	-$207

Lowest Storage System Cost

Lowest Vehicle Cost

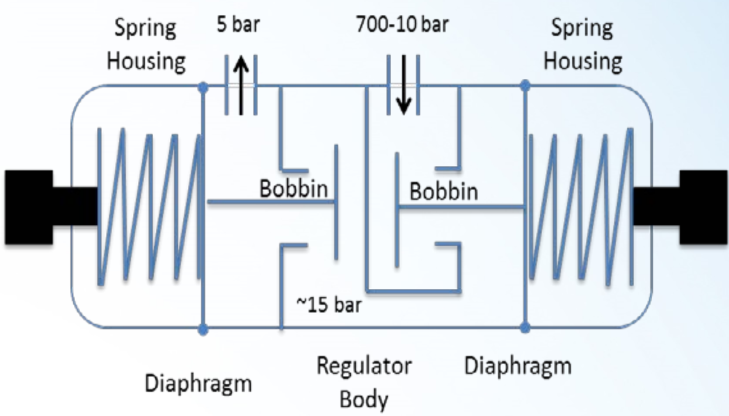


James, Houya-Kouadio, Houchins, DeSantis, "Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2017 Update"

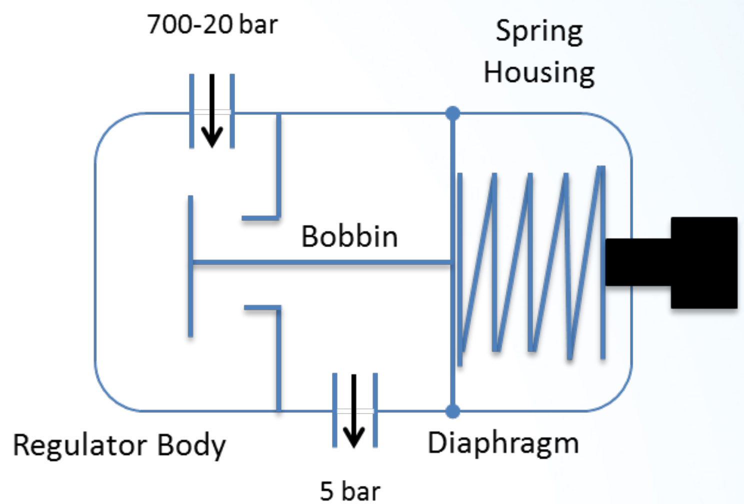
- 10-15 bar pressure differential between regulator inlet and outlet currently assumed
- In 'full fuel utilization' scenario the vehicle can operate at part power with low flow from the regulator
- An ejector fuel recirculation with higher minimum inlet pressure is less expensive (by $321) than a blower recirculation with lower inlet pressure.

LDV regulator analysis

- Argonne analysis suggests that a two-stage regulator is required to deliver full-flow below 20 bar inlet pressure due to the supply pressure effect; however, OEMs are currently using single-stage regulators
- Cost analysis conducted to explore cost differences between single and two-stage regulators
- Our preliminary analysis results in a high-volume cost about 25% lower than quoted for a single stage regulator ($145/unit). We are seeking input from two regulator vendors to vet our assumptions.



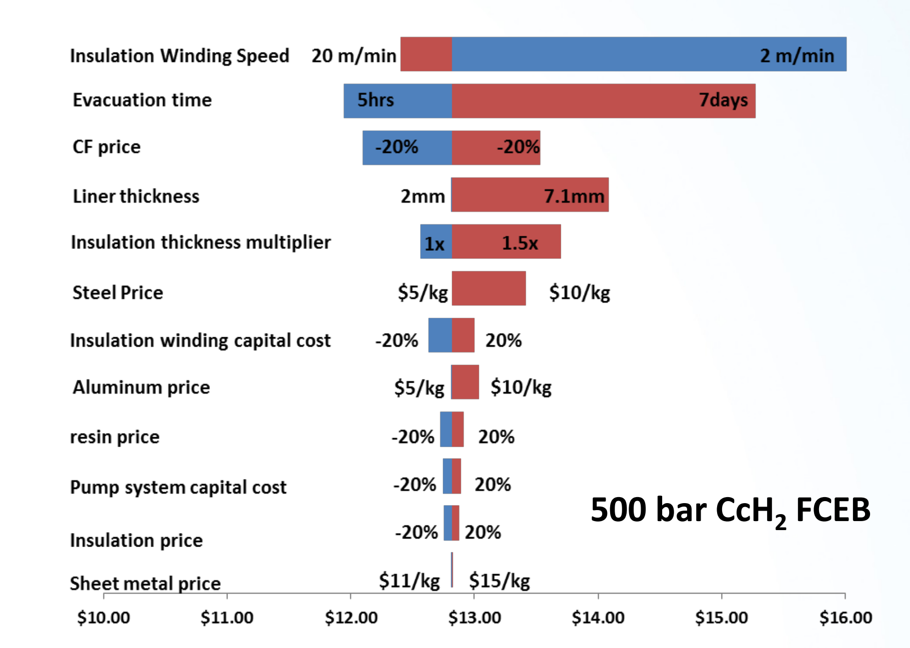
Preliminary	Material	Make/Buy	Cost Basis	One-Stage #/unit	One-Stage Cost/unit	Two-Stage #/unit	Two-Stage Cost/unit
Regulator Body	Aluminum	Make	BDI	1	$19.97	1	$20.44
Regulator Spring Housing	Aluminum	Make	BDI	1	$10.39	2	$20.78
Bobbin	Aluminum	Make	BDI	1	$0.57	2	$1.14
Spring	316L	Buy	Quote	1	$4.67	2	$9.33
Diaphragm	316L	Make	BDI	1	$2.01	2	$4.01
Seat	PEEK	Make	BDI	1	$0.43	2	$0.86
O-Rings	PEEK	Buy	BDI	4	$9.20	4	$18.40
Anodization Coating			SA/DFMA		$5.63		$11.25
Polishing			SA/DFMA		$3.92		$7.67
Assembly			SA/DFMA		$1.11		$2.21
Testing (Outlet Pressure & Leak)			SA/DFMA		$24.03		$24.03
Markup (18%)					$14.75		$21.62
Contingency (15%)					$14.50		$21.26
Total at 500k units per year					**$111**		**$163**
Est. Regulator Envelope Volume (L)					**0.4**		**0.5**
Est. Regulator Mass (kg)					**1.1**		**1.5**



Analyzed FCEB Storage Options

		Cryo-Compressed			cH_2
Storage Pressure	Bar	350	500	700	350
Storage Temperature	K	64	70	79	288
Liner		2mm 316L	2mm 316L	2mm 316L	7.1mm 6061
Number of Tanks		4	4	4	8
Internal Volume	L/tank	150	140	131	208
Composite Mass	kg/tank	36	53	81	50
Insulation Thickness	mm	9	9	8	--
Gravimetric Capacity	wt.%	9.6	8.4	6.9	4.4
Volumetric Capacity	g/L	46.1	50.1	50.3	18.5
System Cost	**$/kWh**	**$11**	**$13**	**$15**	**$14**

- 500 bar CcH_2 balances cost with improvements in capacity over 350 bar cH_2
- Cryo-Compressed (CcH_2) and 350 Type results reported in a paper with ANL submitted to IJHE



Accomplishments and Progress:
Responses to Previous Year's Reviewers' Comments

Reviewer's Comments	Response to Reviewer's Comment
An improvement in the approach could be to include additional verification of the results based on supplier cost estimates or confirmation. The weakness is that there is no way to validate how closely it will represent the real cost.	We actively engage with vendors to provide feedback and validation of our manufacturing assumptions. Typically through vendor validation of component costs and tech community validation of design concepts and completeness.
This project appears to have heavy collaboration with national laboratories, and it should expand to collaborate with industry to confirm its cost results.	We attempt to vet all our model assumptions and results with manufacturers as well as with the labs. See Collaborators page for list of companies.
The reverse engineering of material cost should be emphasized as a key item in the future work plan.	The metal hydride reverse engineering was begun this year and we plan to extend this approach to the MOF storage system.

Collaborations

Partner	Project Role
Pacific Northwest National Laboratory (PNNL) (sub on project)	Contributor to metal hydride, cryo-compressed, bus storage, and 700 bar compressed cost analyses
Argonne National Laboratory (ANL) (sub on project)	Performed system analyses. Contributor to metal hydride, cryo-compressed, bus storage, and 700 bar compressed cost analyses
Lawrence Livermore National Laboratory (LNNL)	Review and feedback on cryo-compressed analysis
DuPont/Steelhead Composites	Input and feedback on advanced thermoplastic tape placement analysis
Industry Partners	We actively seek out input from manufacturing experts, including: Ford, Westport Innovations, Lydall, Westinghouse, BMW, Automated Dynamics, Lincoln Electric Wayne Trail, and Hexagon

Proposed Future Work

- **Light-Duty Vehicle (LDV)**
  - 700 bar Type 4 baseline system
    - Resolve minimum regulator inlet and outlet pressure between storage and fuel cell system cost and performance models (requires coordination between multiple groups)
    - Document updates in a 2018 system design report to DOE
  - Hybrid reversible metal hydride reverse engineering analysis
    - Complete internal heat exchanger analysis
    - Sensitivity analysis to identify material properties needed to meet cost targets
  - Metal organic framework reverse engineering analysis
    - Begin analysis of MOF storage system to identify cost-bound material targets
    - Complementary work to recent analysis reported by ANL
- **Fuel Cell Electric Bus (FCEB)**
  - Finalize Monte Carlo sensitivity analysis
- **Type 4 CNG Analysis**
  - Investigate thermoplastic tape costs
  - Investigate potential cost savings for recycled thermoplastic tape composite

Technology Transfer Activities

Not Applicable to SA's Cost Analysis

Technical Backup Slides

Approach:
SA's DFMA® - Style Costing Methodology

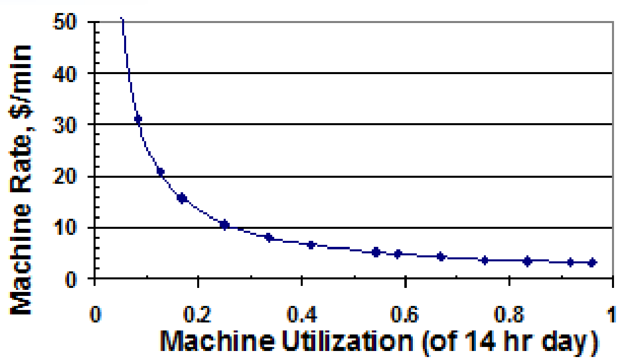
- DFMA® (Design for Manufacture & Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Co. design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA®, industry standards and practices, DFMA® software, innovation, and practicality

Estimated Cost = (Material Cost + Processing Cost + Assembly Cost) x Markup Factor

Manufacturing Cost Factors:

1. Material Costs
2. Manufacturing Method
3. Machine Rate
4. Tooling Amortization

Methodology reflects cost of under-utilization:



Methodology Reflects Cost of Under-utilization:

Capital Cost
Installation
} **Initial Expenses** → **Used to calculate annual capital recovery factor based on:**

- Equipment Life
- Interest Rate
- Corporate Tax Rate

Maintenance/Spare Parts Utilities
Miscellaneous
} **Operating Expenses**

$$\frac{\text{Annual Capital Repayment} + \text{Annual Operating Payments}}{\text{Annual Minutes of Equipment Operation}} = \text{Machine Rate (\$/min)}$$

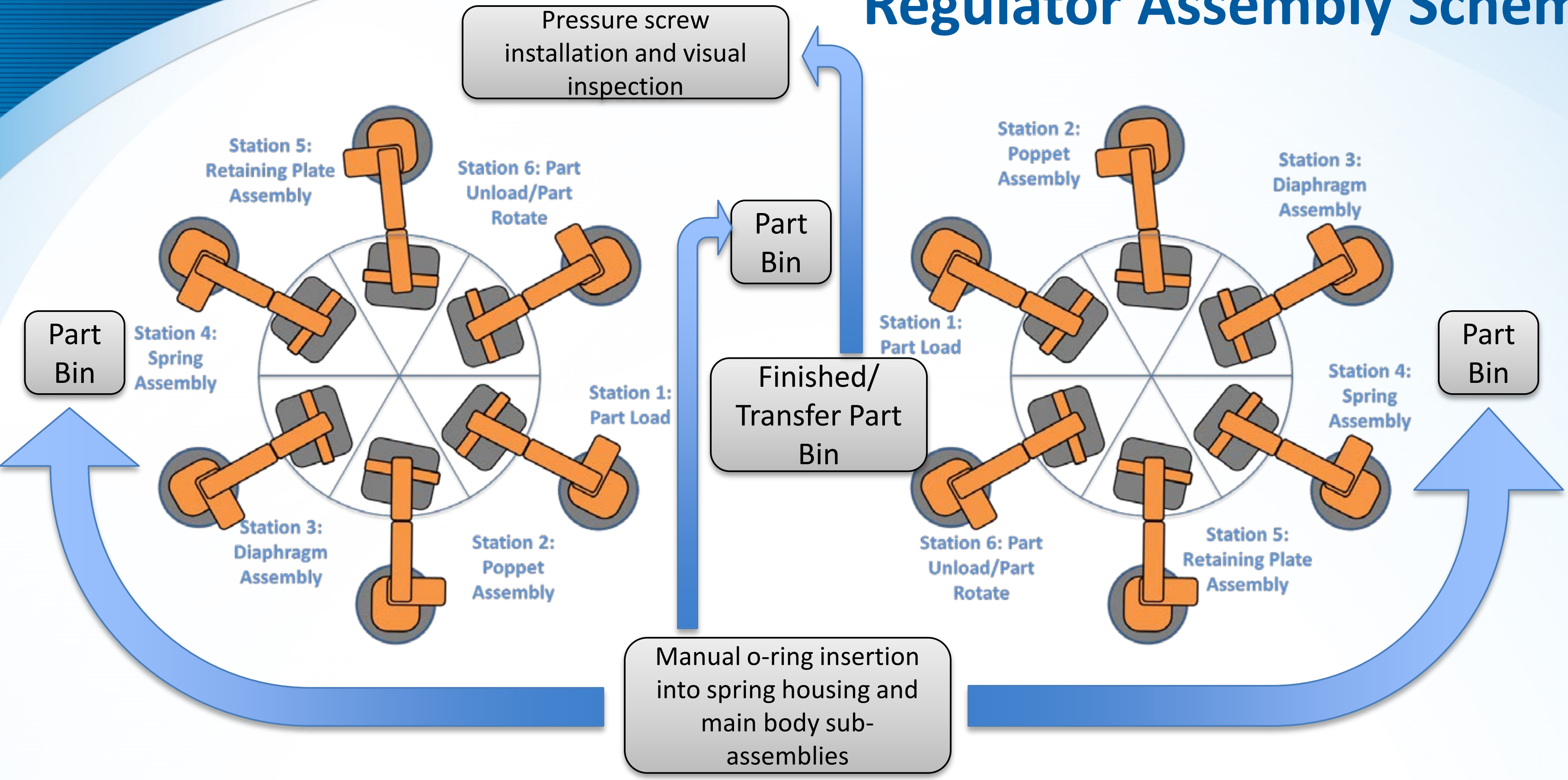
Production Volume Range of Analysis:

10,000 to 500,000 H_2 storage systems per year

Hybrid Metal Hydride System Design Assumptions

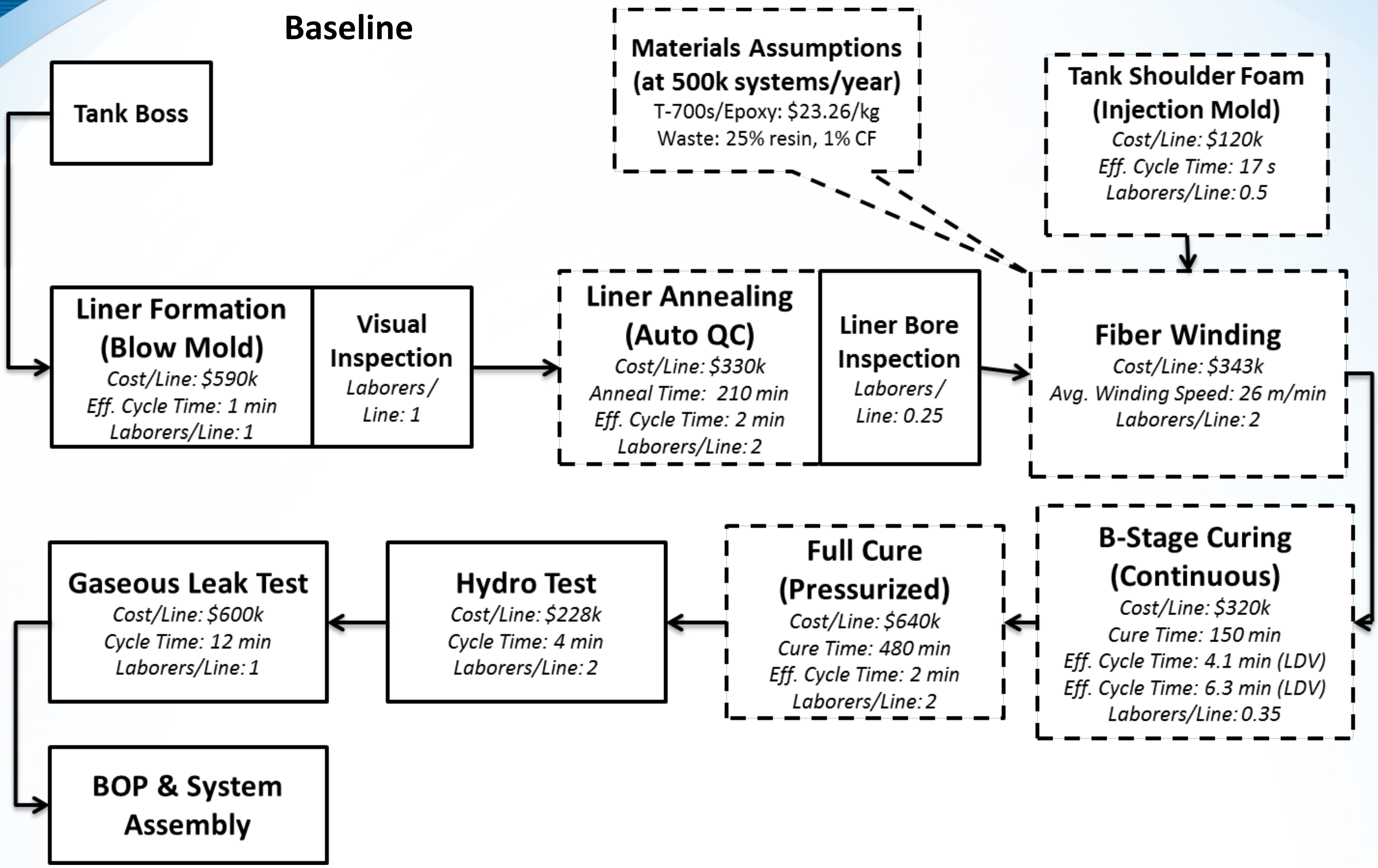
Design Parameter	SA Value	ANL Value	Notes
Rated Pressure	350 bar	350 bar	Design parameter
Burst Pressure	898 bar	898 bar	Includes $3\sigma=14\%$ with $\sigma_{fiber}=\sigma_{mfg}=3.3\%$
Minimum Empty Pressure	**20 bar (under reconsideration)**	**20 bar (SA estimate)**	Current design parameter based on one-stage regulator. Two-stage regulator being considered.
Stack Coolant Temperature	NA	60-80°C	ANL model parameter
Number of Coolant U-Tubes	58	58	ANL model results
Coolant Tube External Radius	4.75 mm	4.75 mm	ANL model results
Coolant Tube Wall Thickness	0.9 mm	0.9 mm	ANL model results
Coolant Tube (center-to-center) Spacing	42.8 mm	42.8 mm	ANL model results
Usable H_2	5.6 kg	5.6 kg	DOE design parameter
Internal Volume	**256L**	**254L (SA estimate)**	SA includes HX manifold volume
Aspect Ratio (L/D)	3	3	Design parameter
Composite Mass	**51.4 kg**	**51 kg**	Additional composite needed for larger internal volume estimated by SA
Fiber Volume Fraction	60%	60%	ANL model parameter
Carbon Fiber	T-700s	T-700s	ANL model parameter
Resin	Epoxy	Epoxy	ANL model parameter
Liner	HDPE	HDPE	Type 4 pressure vessel
Metal Hydride Intrinsic Capacity	5.6%	5.6%	ANL model parameter
MH Bed Porosity	81.5%	81.5%	ANL model parameter
MH Mass	45.9 kg	45.9 kg	ANL model result
ENG Mass	4.6 kg	4.6 kg	ANL model result

Regulator Assembly Scheme



- Automated assembly assumptions based loosely on Rotarex
  - Estimated automated assembly station cost is $725 ($125k rotary indexed table + $480k for robots + $120k fine control placement heads)
  - Second stage assembly is a duplicate of first stage
  - 10s index time
  - 2 laborers (for sub-assembly, pressure screw installation, and visual inspection) per station
- Low-volume assembly assumptions
  - Manual assembly with costs for labor only estimated at ~20 and 40 minutes for one and two-stage regulators, respectively

Type 4 CNG Process Flow



Basic ATP/AFP System Layout

Examples of ATP systems used in SA interpretation of capital cost

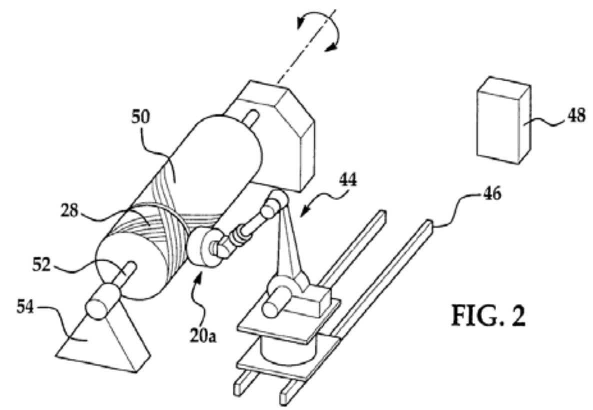
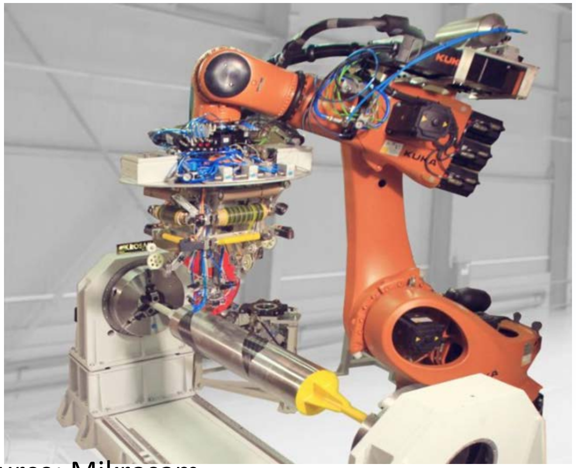
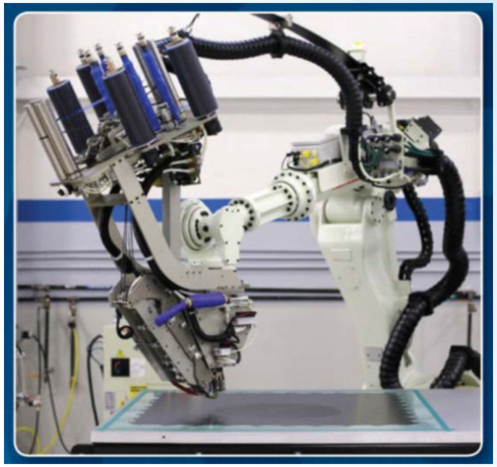


FIG. 2

Source: 2013 Boeing Patent https://patents.google.com/patent/US8557074B2/en?oq=7063118.



Source: Mikrosam https://www.compositespress.com/insights/mikrosam-expands-market-reach-north-america/



Source: Automated Dynamics Inc. http://www.automateddynamics.com/wp-content/uploads/2016/09/ADC-Composite-Manufacturing-Equipment.pdf

Element	Cost	Note/Cost Basis
Robot (for Fiber Placement)	$93k-$143k	Six-axis robotic placement arm with optional large tank (>2m) 1-axis translation base
ATP Head	$220k	Multi-spool processing head with integrated 1.5kW continuous wave fiber laser
Head base price	*$80k*	*Rough estimate for custom head, mounts, fiber guide*
Fiber laser	*$120k*	*Quote for 1.5 kW fiber laser system including optics and chiller*
Tape carriage	*$20k*	*Estimate based on analogous wet layup creel system*
Spindle	$140	Single-tank spindle based on quote (spindle and frame, motor, motor control)
System controls	$60k	Computer aided control system (includes digital interfaces, computer, software license)
Safety	$80k	50 lin. ft. industrial (class 4) laser system enclosure, human detection system and safety interlock
Custom Engineering	$8k	10 FTE days at $100/hour
Company Markup	$418	Assumes 40% gross margin.
Installation & Training	$417k	Standard SA 40% (on $1.2M) of capital equip. cost assumption. Note PFDs show uninstalled capital cost.
Estimated Total (Installed)	**$1.5M**	**Markup, installation, and total are based on the mid-point of the robot cost.**