2015 DOE Hydrogen and Fuel Cells Program Review

Hydrogen Storage Cost Analysis

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Strategic Analysis Inc.

9 June 2015

Project ID# ST100

Overview

Timeline

- Project Start Date: 9/30/11
- Project End Date: 9/29/16
- % complete: 70% (in year 4 of 5)

Barriers

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

Budget

- Total Project Budget: $1,239,997
  - Total DOE Funds Spent*: $950,924
    - SA: $630,924
    - ANL: $200,000
    - NREL: $120,000
- *As of 31 Mar 2015

Partners

- Project Lead: Strategic Analysis Inc.
- National Renewable Energy Laboratory (NREL)
- Argonne National Lab (ANL)

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Argonne NATIONAL LABORATORY

Objective/Relevance

- Conduct independent DFMA® cost analysis for multiple on-board hydrogen storage systems
  - 700 bar pressure vessel system
  - Adsorbent systems (Hexcell and MATI concepts)
  - Chemical systems (alane and ammonia-borane (AB))
  - Metal Hydride for forklift applications (Hawaii Hydrogen Carriers)
- Assess/evaluate cost reduction strategies
- Target:
  - Identify pathways to reduce the cost of on-board hydrogen storage systems by 15% compared to DOE's 2013 record.
  - DOE 2020 target of $10/kWh for onboard hydrogen storage for light-duty fuel cell vehicles.

Approach: H_2 Storage System Cost Status

On-board Storage Systems examined by SA

Apply new technological advances and designs of hydrogen storage systems into techno-economic models

Project	Timeline	Cost Analysis Project Status	Estimated Cost Status
700 Bar Carbon Fiber Automotive Pressure Vessel System	Ongoing -PNNL testing to be completed May 2015	-Updated with ORNL's PAN/MA textile precursor fiber - Updated BOP integration and DFMA® costs -Updated based on PNNL Low Cost Carbon Fiber tank innovations	\$12.99/kWh (2007\$) (500k sys/yr)
HSCOE Adsorbent System: HexCell	--	Completed March 2015	\$12.79/kWh (2007\$) (500k Sys/yr)
HSCOE Adsorbent System: MATI	--	Completed March 2015	\$13.34/kWh (2007\$) (500k Sys/yr)
Hawaii H_2 Carriers Forklift System	Projected to be complete Summer 2015	Preliminary bill of materials (BOM) and manufacturing process list made.	NA
HSCOE Chemical Storage System: Alane	Projected to be complete May/June 2015	Preliminary BOM and manufacturing process list made. Initial cost estimates on major components.	NA
HSCOE Chemical Storage System: AB	Projected to be complete June/July 2015	Will begin after Alane system cost analysis complete.	NA

Accomplishments and Progress:
ORNL Low Cost PAN MA Fiber

- **ORNL (Dave Warren) project to develop lower cost carbon fiber precursor.**
- **SA expanded ORNL CF cost estimates to project high-volume CF price & system cost.**
- **Change in carbon fiber price results in a ~10% cost reduction from 2013 ($15.04/kWh).**

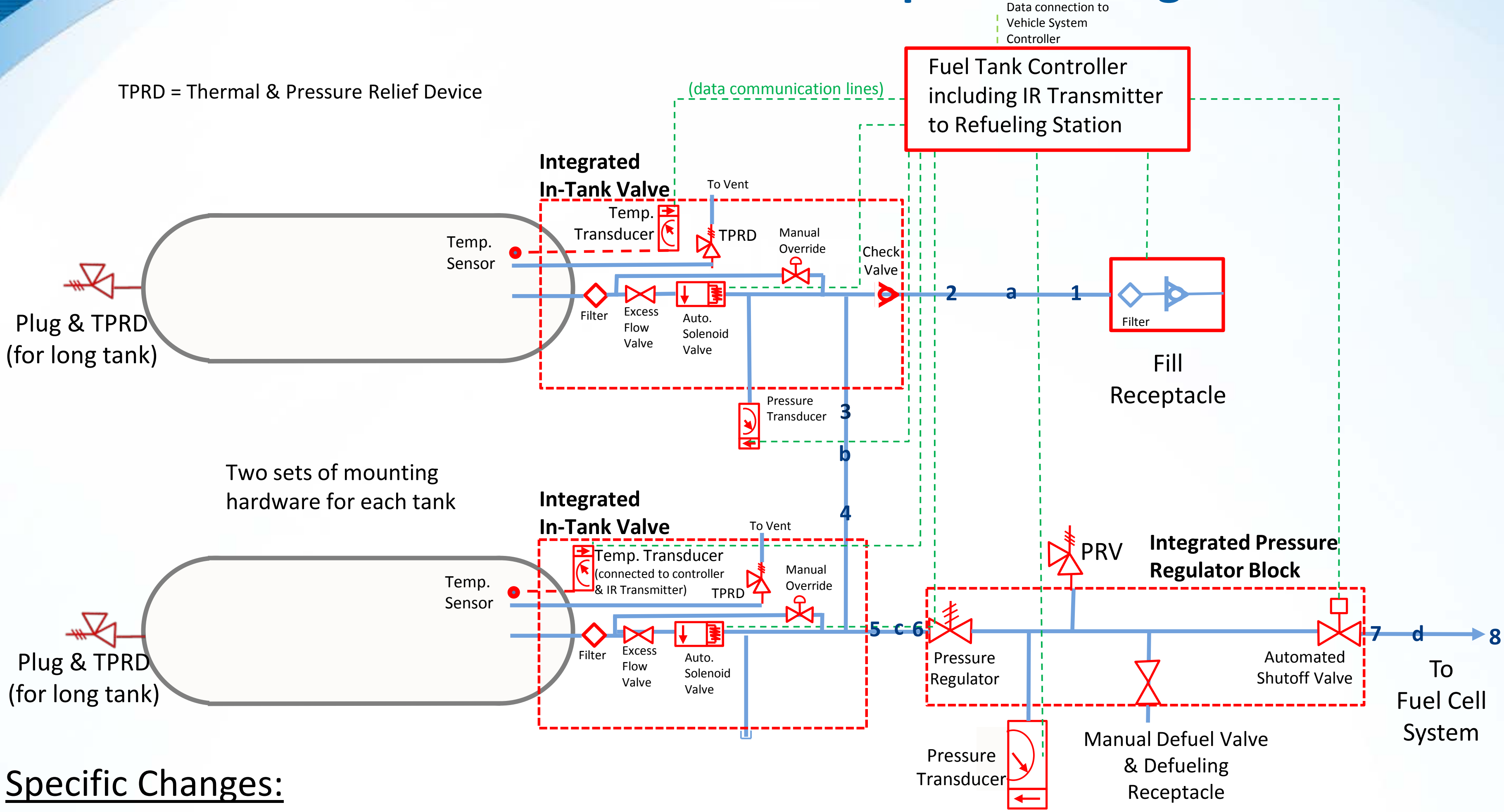
Parameter	2013 Baseline System (T-700S)	Reported ORNL Textile PAN MA CF	Textile PAN MA CF as used in SA's System Cost Model
Ultimate Tensile Strength	711 KSI	577 KSI (in 2014 AMR[1]) 655 to 750+ KSI (ORNL[2])	711 KSI
Modulus	33 MSI	39.8 MSI (2014 AMR)	NA
TOW	24k	24K	24K
Filament diameter	7 micron	7 micron	7 micron
CF Density (dry)	1.8 g/cc	1.78-1.81 g/cc	1.8 g/cc
CF Price (2007$)	$13/lb (at 25,000 tonnes/year)	Price NA (2014$ cost as reference: $9.49/lb, at 25,000 tonnes/year)	**$10.63/lb** (at 25,000 tonnes/year)
System Cost (5.6kg H2 usable, single tank, 500ksys/year, 2007$)	$16.76/kWh	NA	**$15.04/kWh** (10% reduction) (Based only on change in CF price)

18.3% CF cost reduction

10% system cost reduction

[1] "Development of Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)", C. David (Dave) Warren, Oak Ridge National Laboratory, presentation at 2014 DOE Hydrogen and Fuel Cells Program Annual Merit Review Meeting, Washington, D.C., June 2014.
[2] Personal communication with Dave Warren, ORNL, 19 September 2014. Results not yet published.

Accomplishments and Progress:
Pressure Vessel BOP Component Integration



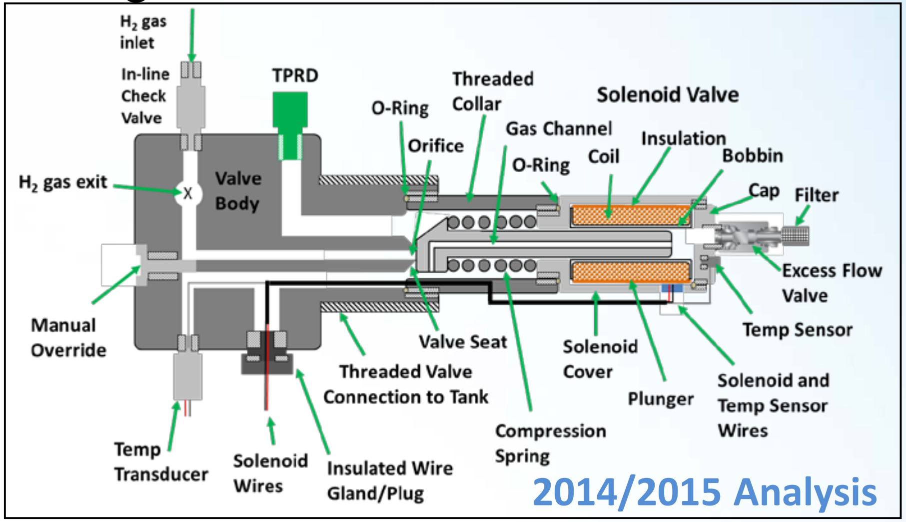
Specific Changes:

- Pulled check valve and bends into the integrated in-tank valves
- Combined the bottom 5 right components into one module
- Assumption: all components attached to a valve body have a custom fitting machined into the part and the valve body has a machined port for attachment to those components

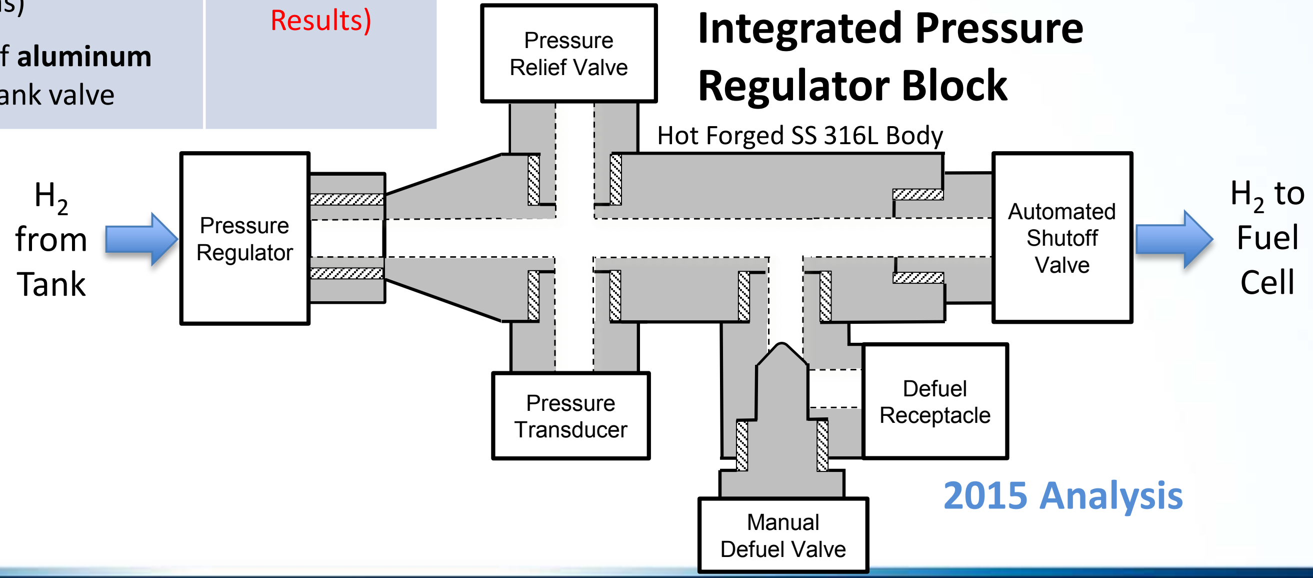
Accomplishments and Progress:
Pressure Vessel BOP Component Integration

Analysis Year	BOP Assumptions/Changes	BOP Cost (2007$/kWh)
2013 (DOE Record)	Majority of vendor quotations, **limited by product availability**	$4.98/kWh
2014	**DFMA® analysis of integrated in-tank valve** and pressure regulator quotation	$4.37/kWh
2015	• Integrated pressure regulator block will **reduce number of fittings** (translates to other H_2 storage systems) • Investigation of **aluminum** integrated in-tank valve	$3.64/kWh (Preliminary Results)

Integrated In-Tank Valve



Integrated Pressure Regulator Block



Accomplishments and Progress:
PNNL Low Cost Carbon Fiber Tanks

- Collaboration of PNNL, Hexagon Lincoln, and Ford to reduce the cost of the 700 bar carbon fiber tanks. Concepts explored:
  - Using optimized winding patterns (to reduce fiber mass)
  - Use of graded fiber strengths (to reduce fiber cost)

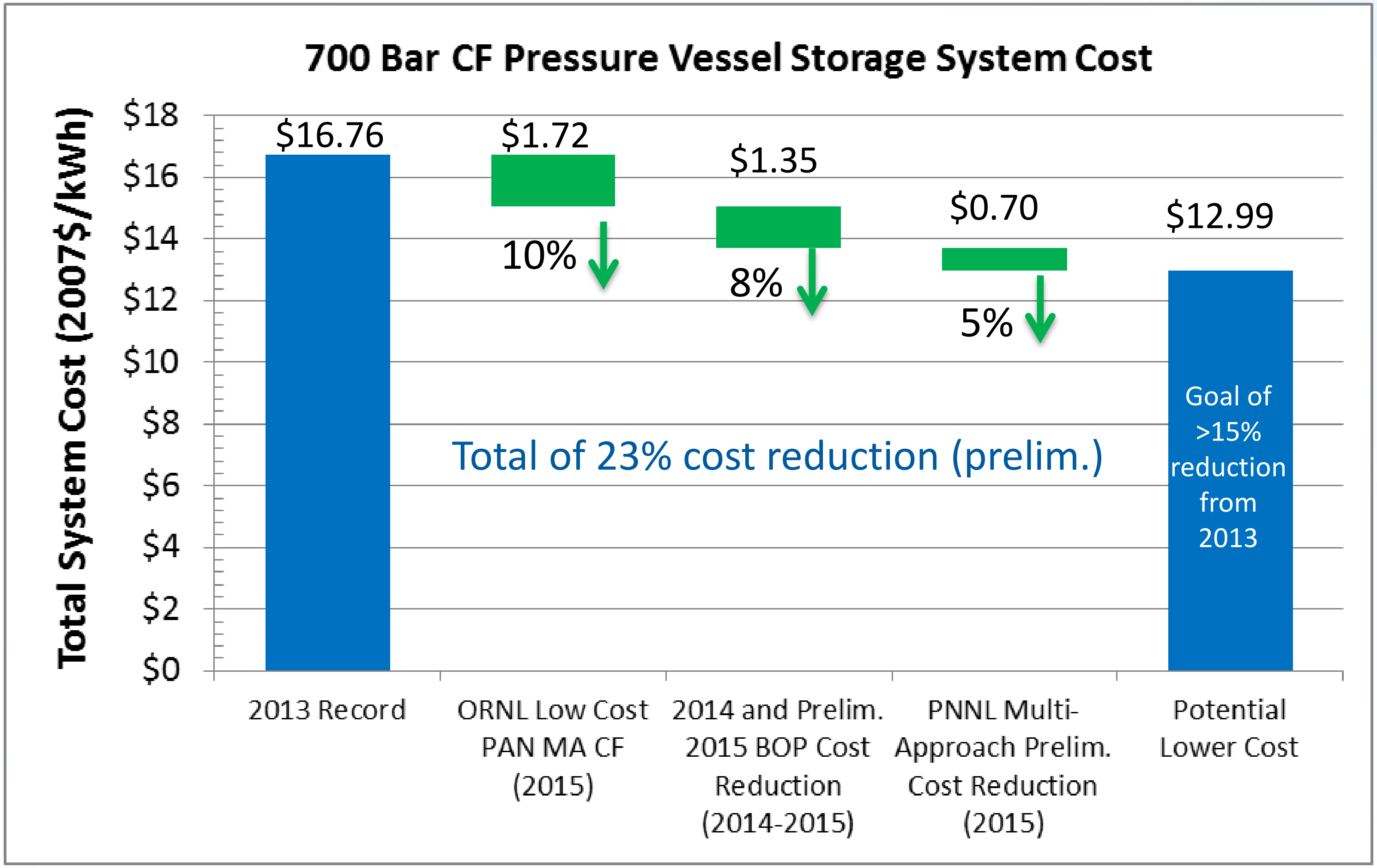
  No cost reduction

  - Using alternative lower-cost resins (reduce resin cost) ← **Promising Route**
  - Using carbon fiber nano-additives to resin (reduce mass & cost) ← **In-Process**
- Pressure vessel fabrication and burst testing by Hexagon

SA's Role:

- Monthly conference call with PNNL project team to discuss progress and results
- Based on **burst test results**, project cost of advanced storage system on apples-to-apples basis with DOE baseline cost projections

Accomplishments and Progress:
Working to Determine Potential Cost Reduction from R&D Efforts



- PNNL burst testing to determine carbon fiber (CF) mass reduction through increased translational strength, low cost resins, nano-additives, and other optimization techniques.

Accomplishments and Progress:
Adsorbent System Analysis Approach

- Adsorbent H_2 storage project originated from HSECOE working group
- SA has conducted DFMA® cost analysis for the HexCell and MATI adsorption systems at multiple manufacturing rates.
- Created BOM based on HSECOE's Hexcell and MATI system designs
  - Independent, yet influenced, by PNNL/SRNL analysis work
- Leveraged past work
  - Past SA DFMA® work for ARPA-E on metal organic framework (MOF) materials
  - PNNL/SRNL system analysis work
  - Past SA Balance-of-Plant (BOP) component work for 700 bar pressure vessels
- Vetted results with HSECOE working group and made iterative changes
- Although SA's system design may be similar and based on HSECOE's design, SA ensured identical system function, but not identical system components

HSECOE = Hydrogen Storage Engineering Center of Excellence
DFMA® = Design for Manufacturing and Assembly cost methodology
Hexcell = refers to hexagonal heat transfer fins/partitions within bed
MATI = Modular Adsorption Tank Insert (heat transfer concept within bed)

Accomplishments and Progress:
MOF Cost Assumptions

- **<u>MOF price: DFMA® Analysis completed for MOF-5 Production</u>**
- Cost developed from DFMA® cost analysis on MOF processing under an ARPA-E contract for natural gas adsorbent system at lower volumes than H2 storage systems (2.5kMT/yr)
- Using this model, SA projected the cost of MOF-5 at high volumes, assuming modern processing techniques are used for synthesis
- Applied markup of 30% results in a MOF price of $8.49/kg (2007$) at 500k sys/yr
- Sensitivity analysis of MOF cost completed and used in adsorbent system tornado chart

6.224kg H_2 stored (full tank)

– 5.6kg useable H_2 (full tank)

= 0.62kg H_2 (left in tank or consumed for electrical heating)

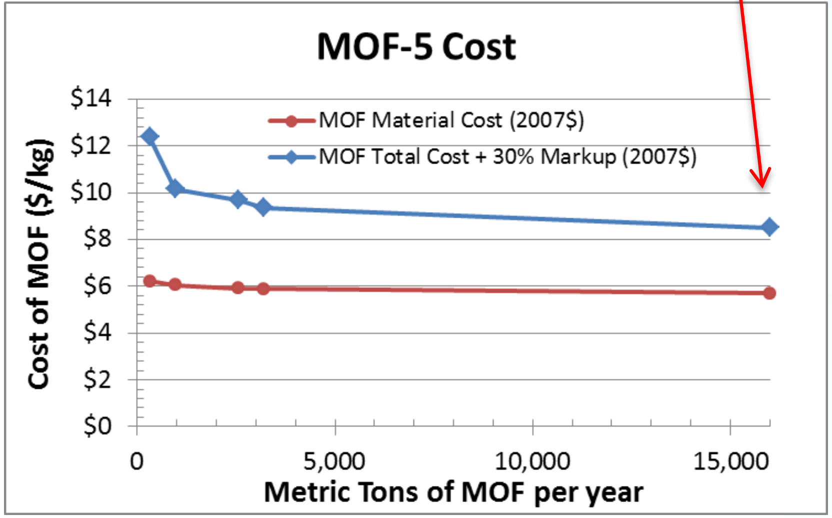
Required MOF for Systems:

32kg MOF5 for Hexcell System => 16k MT/yr

41kg MOF5 for MATI System => 20.5k MT/yr

(at 500,000 storage systems per year)

Price at 500,000 Hexcell systems per year



Accomplishments and Progress:
Adsorption Systems Parameter Summary

Design Considerations

- H_2 Storage
  - Total H_2 stored: 6.22kg
  - Useable H_2 stored: 5.6kg

6.22 kg H_2 stored (full tank)
– 5.6 kg useable H_2 (full tank)
= 0.62 kg H_2 (left in tank or consumed for electrical heating)

- Dual Wall Pressure Vessel
  - 6061 Grade Al
  - 100 bar design oper. pressure
  - 2.25 safety factor
  - Hexcell ~64kg vessel (inner + outer)
  - MATI ~61kg vessel (inner + outer)

- LN_2 required for charging
  - Cryogenic insulation included
    - 20 cm multi-layer insulation (MLI)
  - LN_2 supplied by station
  - LN_2 purged after H_2 charge
- H_2 Heating
  - Hexcell: Al heat honeycomb coil (0.38cm cell, 50µm thick foil) with electric heater inside vessel
  - MATI: MOF pucks stacked between Modular Adsorption Tank Inserts
  - Exiting H_2 further heated in external radiator prior to fuel cell
- MOF Storage
  - Hexcell: 32kg on board storage
  - MATI: 41kg on board storage
  - Welded tank: NO access to MOF

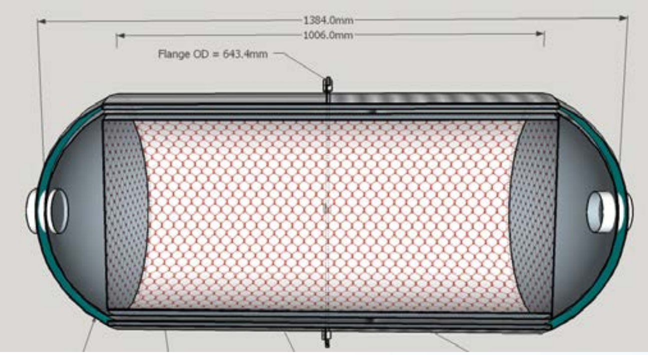
Accomplishments and Progress: Pressure Vessel Concept Welded Internal Vessel for Adsorption Systems

Four Vessel Construction Concepts Considered

Concept	Main Features
1) Welded (used in baseline cost estimate)	• Inner tank halves joined by welding • Outer tank joined by welding • No easy access to adsorbent after welding
2) Retaining Ring	• Inner & Outer tanks each in two pieces, joined by retaining ring. • HSECOE lab testing concept • Access to adsorbent
3) Flanged	• Tank halves joined by flanges/bolts • Access to adsorbent
4) Hot Swaged	• Inner tank halves joined by hot swaging. • No easy access to adsorbent after welding

Hexcell Vessel Layer Dimensions

External Al Shell (2mm)
Vacuum Layer (25.4mm)
LN2 Channel (6.8mm)
Internal Al Shell (10mm)

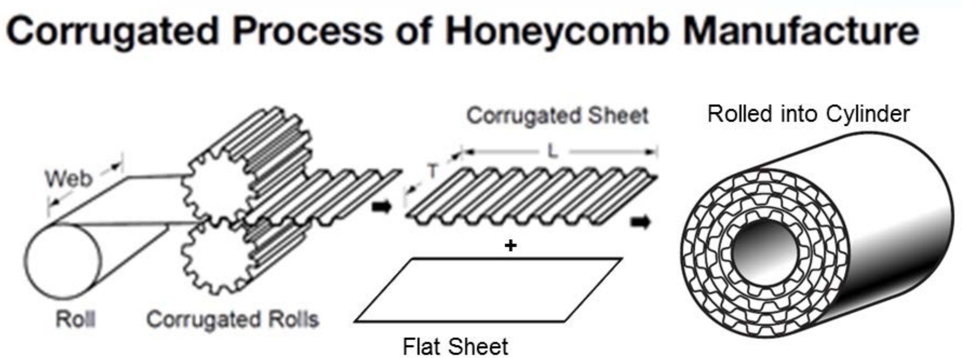


- Welded internal vessel handles high pressures. A tank safety factor of 2.25 was recommended by field experts
- Full Pen weld both internal and external vessels
- No access to internal HexCell or MOF
- MOF is poured into vessel/MATI Pucks placed in vessel
- The tank boss is a hot forged metal threaded plug with a threaded interior for the isolated solenoid valve attachment

Process	Hot Forged
Aluminum 6061 Cost	$5.071/kg In BDI
Machinery (machine rate)	150 ton Billet Shearing Press ($45/hr) 5,000 lb Power Hammer ($90/hr) 75 ton Mechanical Trimmer ($90/hr) CNC Machine ($20/hr)
Tooling Cost	$8.27/tank (at 500,000 sys/yr)

Accomplishments and Progress: Hexcell Design Assumptions

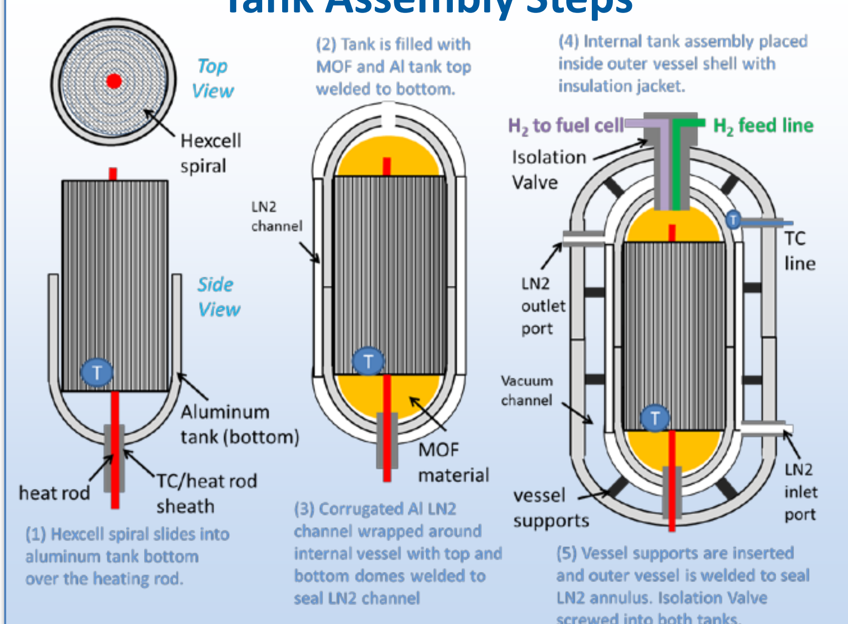
Corrugated aluminum bonded to a flat aluminum sheet and rolled into Hexcell cylinder



Adapted figures from:
http://www.hexcel.com/Resources/DataSheets/Brochure-Data-Sheets/Honeycomb_Attributes_and_Properties.pdf

Process	Corrugated Aluminum sheeting
Aluminum 6061 Cost	\$5.51/kg for 51microns thick (\$0.76/m^2)
Cell Width/Height	0.38cm/0.38 cm
Machinery	Unwind Stand with Tensioner Corrugation Machine Bonding Machine Rolling Stand, with web shear & Tensioner
Capital Cost of Machinery	\$237,300
Roll Width	120cm
Line Rate	15m/min
Effec. Unit Processing Time	37 parts/hr
Machine Rate	\$1.30/min (at 500k sys/yr)
Tooling Cost (for cutting blades)	\$0.50/tank (at 500k sys/yr)
Adhesive Cost	\$3.52/kg (\$0.08/tank)

Tank Assembly Steps

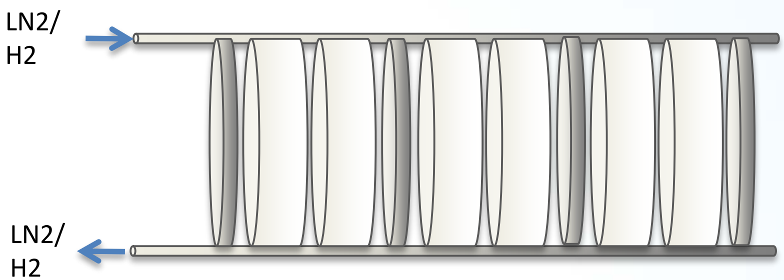


Accomplishments and Progress: MATI Heat Transfer Plates

- Metal is electro-chemically etched to create flow properties
- Plates can then be stamped from the etched metal
- Plates are welded together to create a single heat transfer disc
- Heat transfer discs can then be welded to the LN2 tubing inside the MATI vessel

MATI Disc Costs	2007$/system
Etched plate cost	$32
Non-etched plate cost	$21
LN2 tubing (within tank) cost	2.5m x $3/m = $7
MATI assembly cost (grouped with tank assembly)	$2.68/min*5min = $13
Total	**$73**

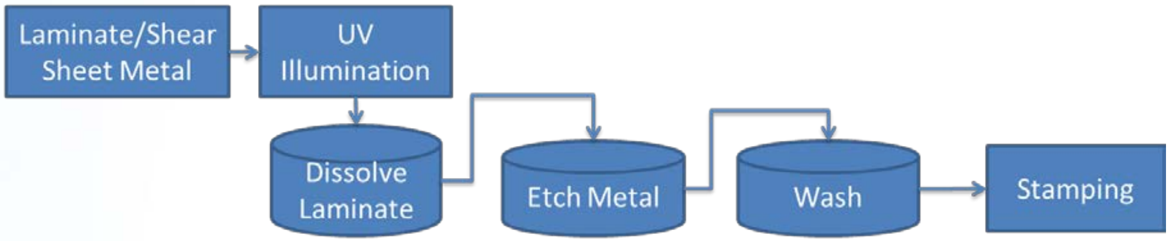
- 11 MATI discs per Vessel
- Discs cost approximately $4.80 each at 500,000 vessels per year



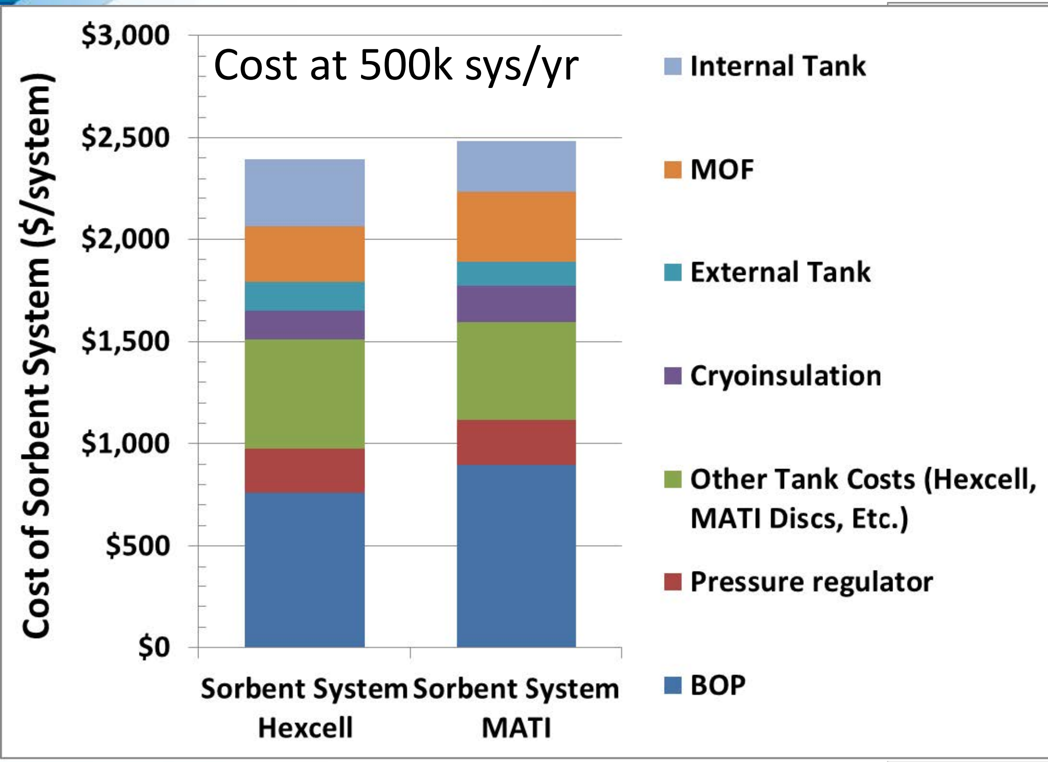
Two MOF pucks between MATI discs

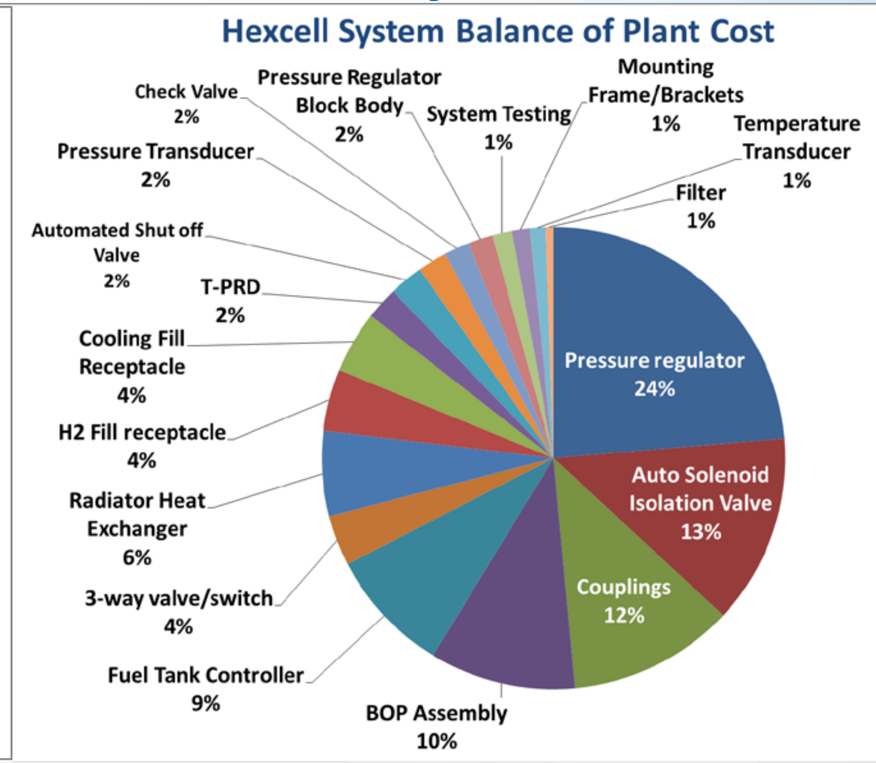
Disc = 1x etched + 1x un-etched plate

Electrochemical Etching Process Steps



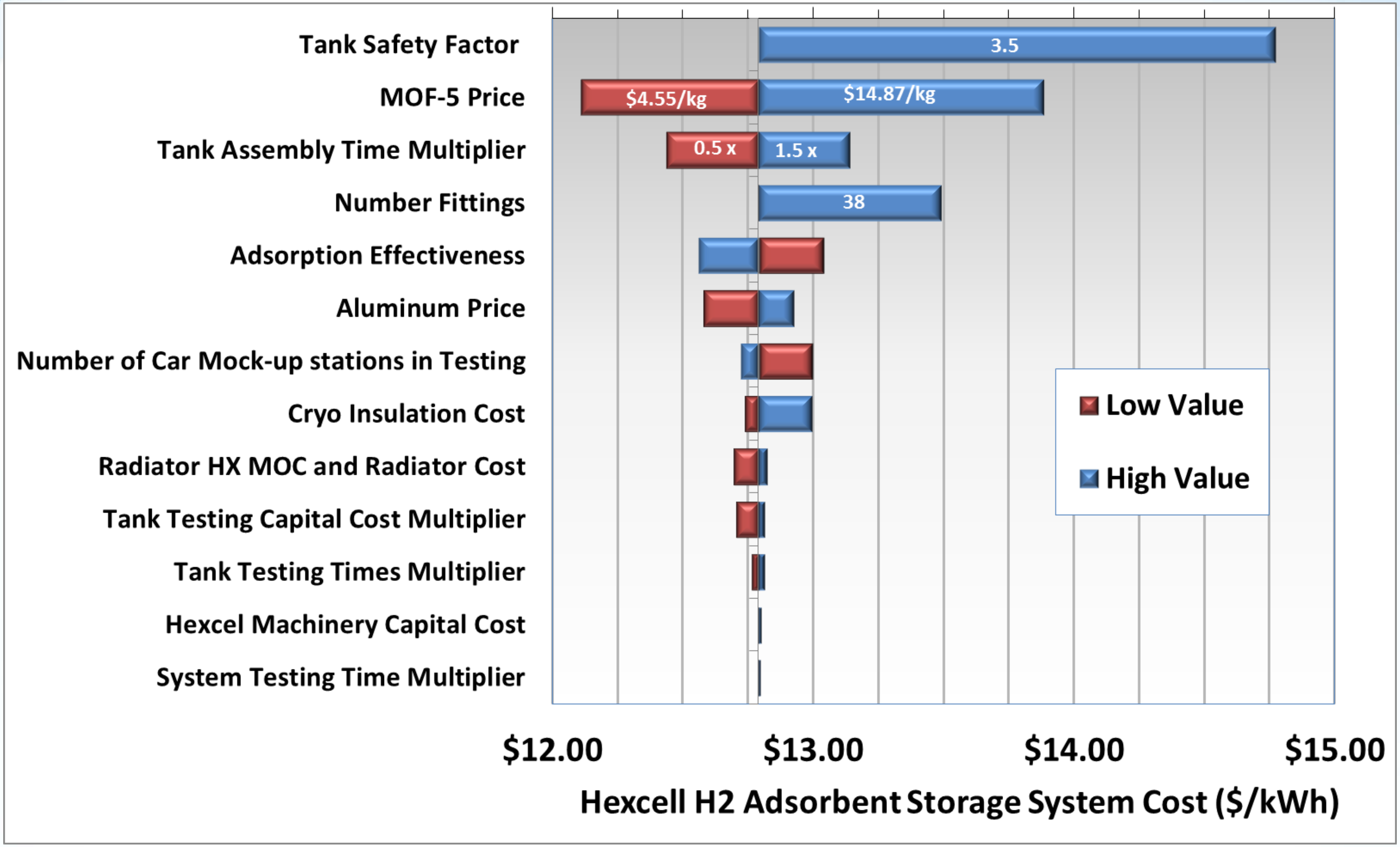
Accomplishments and Progress: Adsorption Systems Cost Summary





- MATI system has a greater BOP cost than the Hexcell system due to greater number of couplings and valves for combined H2 and LN2 manifold.
- Hexcell BOP costs dominated by two pressure regulators, Isolation valve, and couplings (~50% of BOP cost)
- The other 50% of Hexcell BOP cost is composed of 15 components all lower than 10%

Hexcell System Sensitivity Analysis



- The Hexcell system is most sensitive to the tank safety factor (baseline 2.25) due to the thickness of the aluminum required to withstand 2.25-3.5 times the operating pressure.

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

Reviewer's Comments	Response to Reviewer's Comment
Greater emphasis should be placed on reducing the number of components and fittings via higher integration, as well as incorporating the least expensive structural materials (e.g., fibers and resins) and most efficient designs.	For 2015, SA is working toward component integration of low pressure BOP components and reducing the overall number of fittings.
Limits of DFMA® are unclear. When is the DFMA® approach feasible?	The DFMA® cost analysis approach is feasible as long as the key input assumptions are known and can be estimated (eg. geometry, the material cost, processing parameter values, or assembly time, processing technique). Even if values/methods are speculative, there is benefit from the DFMA® results/understanding.
Explain in what ways SA is accounting for close tolerances, interface surfaces for fittings, valves, and minimization of leakage upon integration into the vessel plumbing for long term operations for production volumes >100,000 units/yr.	Extra machining time or alternative machinery is associated with higher tolerances on H2 components. Tolerances are specified for 700 bar H2 fittings (part drawing from Parker). Parker fitting design also includes O-rings to minimize leakage, also included in SA's cost estimates.

Collaborations

Partner	Project Role
National Renewable Energy Laboratory (NREL) (sub on project)	Contributed information on developments within HSECOE, particularly surrounding the adsorbent systems (Hexcell and MATI), and acted as a useful resource in obtaining component updates.
Argonne National Laboratory (ANL) (sub on project)	Conduct system analysis to determine the carbon fiber requirement for compressed gas and cold gas storage for Type-3 and Type-4 tanks. Support SA in cost analysis activities.
PNNL, Hexagon Lincoln, and Ford	Performing testing and advising on project for low cost carbon fiber tanks. Providing SA with burst test results.
Hydrogen Storage Engineering Center of Excellence (HSECoE) SRNL, Ford, PNNL	Vetted adsorption system cost results and clarified system components and functionality.
Oak Ridge National Laboratory (ORNL)	Provided cost and information on current production T-700 CF and projected cost reduction for low cost PAN MA textile precursor.

Remaining Barriers and Challenges

700 bar Pressure Vessel System

- Carbon fiber material remains expensive
- BOP cost is spread over many components
  - High pressure fitting costs are widespread within industry due to high profit margin, testing/certifications, safety inspections, and/or verification/regulations
  - Integrated solenoid valve and pressure regulator

Adsorbent Systems (LN_2 cooling)

- Internal aluminum tank is heavy (~50 kg) and expensive (~$340)
- Welded tank: “ship in a bottle” problem (doesn’t allow access to MOF)
- No current standard for adsorbent welded Type 1 tanks
- Best practice for welded vacuum tanks is to weld on vacuum side of tank (inside the tank)– not practical here.
- (MATI) cooling plates provide partial cooling required, additional external cooling required – two hulled tank
- Heat exchanger required to warm up cold H_2 gas

Hawaii H_2 Carrier

- Complex manifold design is expensive (many fittings and high assembly labor)

Proposed Future Work

Compressed H2 Pressure Vessel System

- Explore further component integration and alternative metal (i.e. aluminum) for in-tank valve material.

Adsorption Systems

- Vetting of MATI system design by HSECOE

Completion of system design concept and DFMA® analysis

- Chemical Storage Systems
  - Alane – Completion of DFMA® analysis of volume displacement tank, reactor, and phase separator.
  - Ammonia-borane(AB) – Completion of BOM and system design
  - Review preliminary results from both systems with HSECOE
- Metal Hydride Storage System: based on Hawaii Hydrogen Carriers (HHC) LLC design for forklift applications
  - Completion of system design, sharing concerns or ideas with HHC
  - Detailed DFMA® of metal hydride containment tank
  - Vetting of results with HHC

Technology Transfer Activities

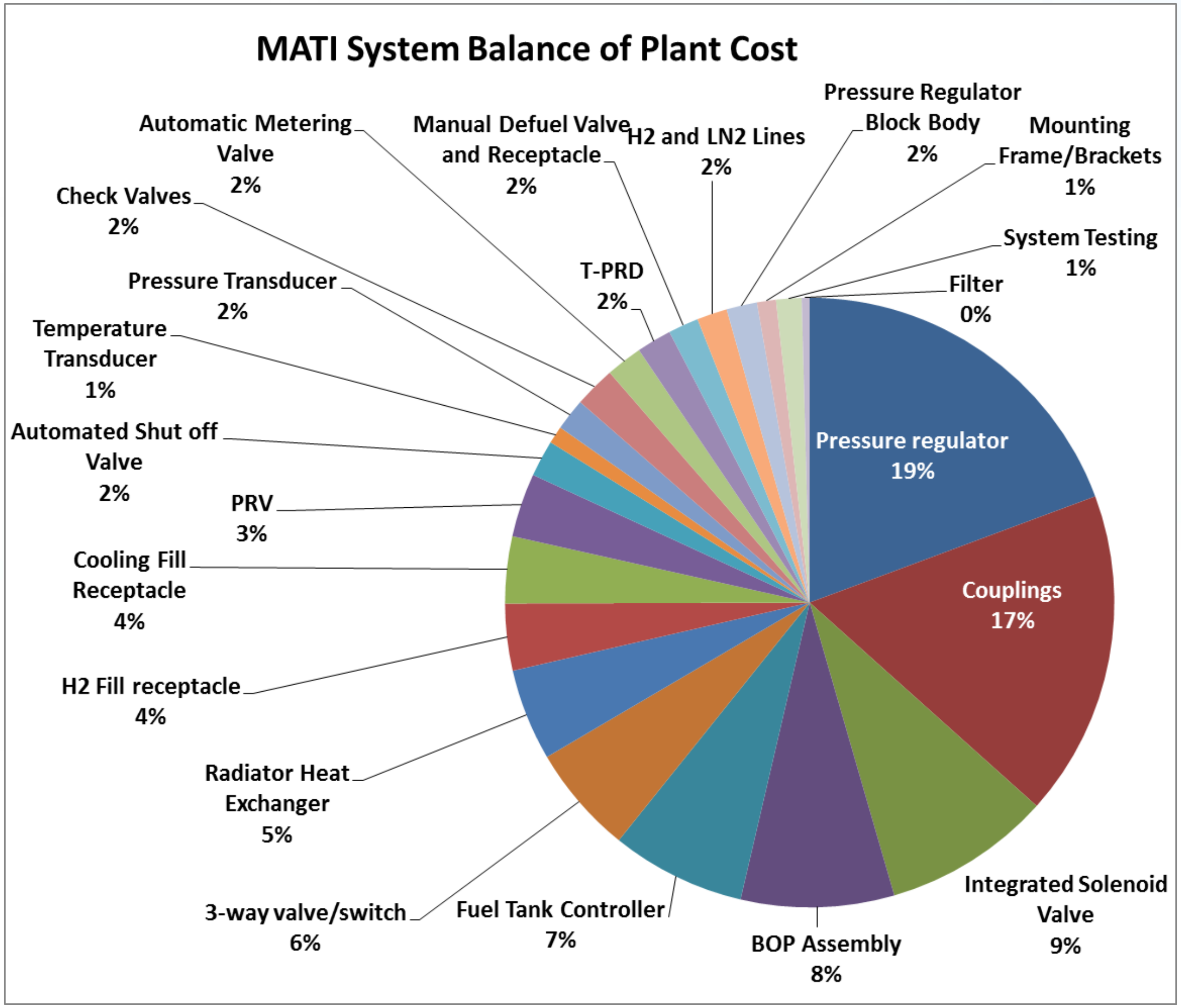
Not Applicable to SA’s Cost Analysis

Summary

- SA has conducted a series of cost analyses to assess the system cost impact of various cost-reduction concepts.
- Cost reduction for the compressed gas storage system for 2014-2015 includes:
  - Switching to a PAN MA precursor carbon fiber ($1.72/kWh reduction)
  - Re-evaluation/Integration of BOP components ($0.62/kWh reduction)
  - Use of a low-cost resin with nano-additives (cost reduction TBD)
- 2015 700 bar System (at 500ksys/year): $12.99/kWh (23% from 2013 baseline)
- Completed DFMA® analysis of both Hexcell and MATI adsorbent systems and vetted results with HSECOE and the H2 Storage Technical Team
- MATI adsorbent system is higher cost than Hexcell
  - Greater mass of MOF required
  - MATI cooling/heating plates are expensive to assemble
- Greatest cost contributors within adsorbent tanks are:
  - MOF and aluminum inner vessel

Technical Backup Slides

MATI BOP Breakdown



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Tornado Chart Bounds

Hexcell H2 Adsorbent Storage System (500k Sys/yr)				
Parameter	**Units**	**Low Value**	**Base Value**	**High Value**
Tank Safety Factor		2.25	2.25	3.5
MOF-5 Price	\$/kg	\$4.55	\$8.49	\$14.87
Tank Assembly Time Multiplier		0.5	1	1.5
Number Fittings		17	17	38
Adosrption Effectiveness	kg H_2/kg MOF	0.18	0.19	0.21
Aluminum Price	\$/kg	\$4.40	\$5.07	\$5.51
Number of Car Mock-up stations in Testing		5	10	15
Cryo Insulation Cost	\$/m^2	\$59.50	\$63.53	\$79.34
Radiator HX MOC and Radiator Cost	Material \$/radiator	Mild Steel \$37.36	SS304 \$54.81	SS316 \$61.80
Tank Testing Capital Cost Multiplier		0.5	1	1.5
Tank Testing Times Multiplier		0.75	1	1.25
Hexcel Machinery Capital Cost	\$	\$104,403	\$208,807	\$417,614
System Testing Time Multiplier		0.75	1.00	1.25
Hexcel H2 Adsorbent Storage System Cost (\$/kWh)			**\$12.79**	

ORNL Low Cost Textile PAN-MA Fiber

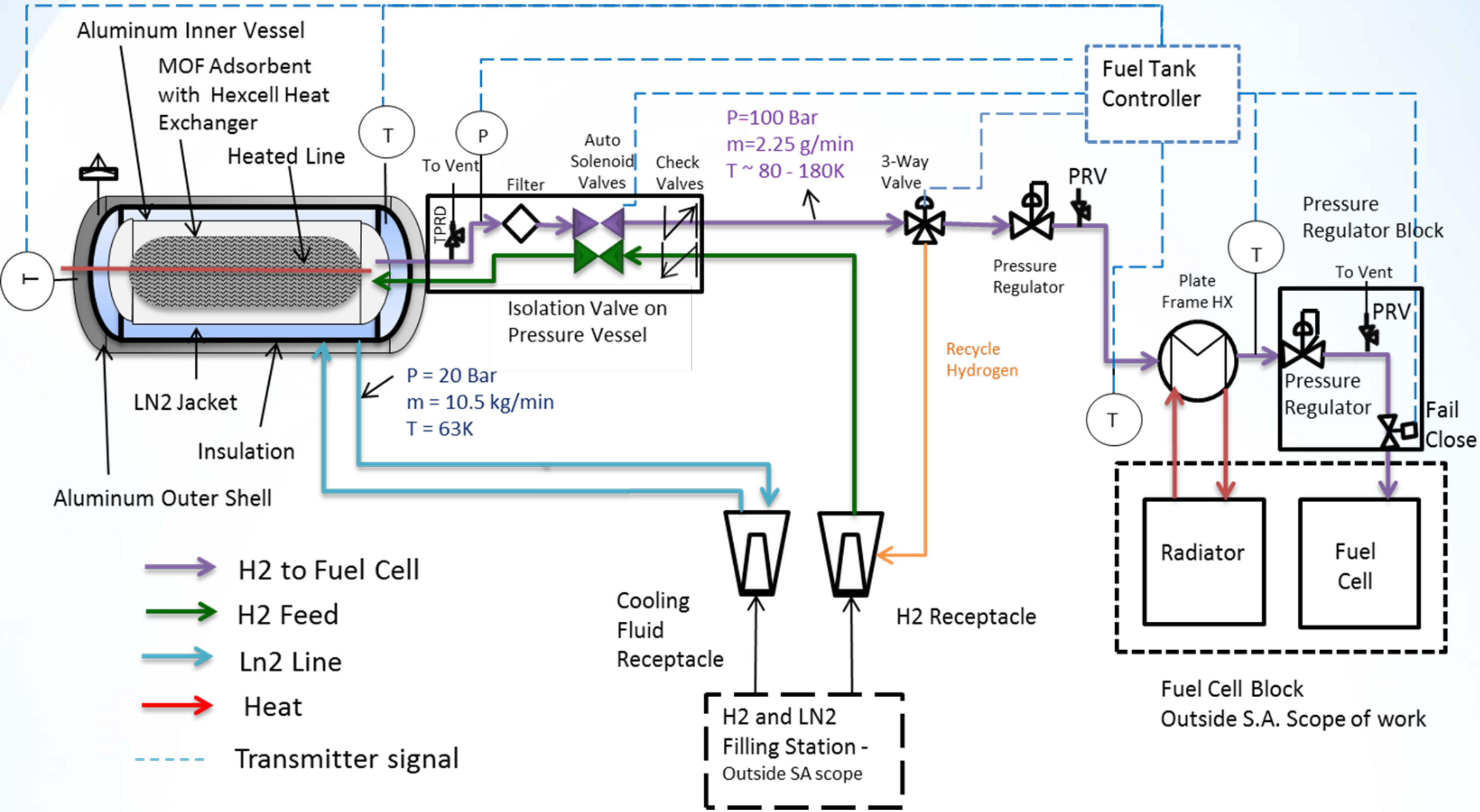
Parameter	Baseline T-700S Carbon Fiber	Baseline T-700S Carbon Fiber	ORNL PAN MA Carbon Fiber	ORNL PAN MA Carbon Fiber
Precursor Assumptions				
(Precursor) Processing Rate	7,500 tonnes/yr		7,500 tonnes/yr	41,000 tonnes/yr
Precursor Material	PAN		"PAN MA" (polyacrylonitrile methacrylate)	
Solution spinning materials	95% acrylonitrile(AN) 5% methacrylate (MA)		95% AN, 4.5% MA 0.5% Itaconic Acid	95% AN, 4.5% MA 0.5% Itaconic Acid
Labor (FTE/shift)	Polymerization: 6 Spinning: 14		Polymerization: 6 Spinning: 14	Polymerization: 4 Spinning: 11
Energy (kWh/kg)	Polymerization: 0.18 Spinning: 8.2		Polymerization: 0.18 Spinning: 8.2	Polymerization: 0.14 Spinning: 5.4
Capital Investment	Polymerization: \$5.5M Spinning: \$58.3M		Polymerization: \$5.5M Spinning: \$58.3M	Polymerization: \$28M Spinning: \$145.2M
Precursor Cost	$\$2.91/\text{lb}_{\text{precursor}}$		$\$2.91/\text{lb}_{\text{precursor}}$	$\$2.15/\text{lb}_{\text{precursor}}$
Carbon Fiber Assumptions				
(CF) Processing Rate	1,500 tonnes/yr	25,000 tonnes/yr	25,000 tonnes/yr	25,000 tonnes/yr
Processing Temp. & Time	Oxidation: 250°C, 100 min. Low Temp.: 700°C, 3 min. High Temp.: 1,600°C, 3 min.		Oxidation: 240°C, 90 min. Low Temp.: 660°C, 3 min. High Temp.:1,350°C, 3 min.	Oxidation: 240°C, 90 min. Low Temp.: 660°C, 3 min. High Temp.:1,350°C, 3 min.
CF Processing Cost (exclusive of precursor cost)	$\$6.95/\text{lb}_{\text{CF}}$	$\$5.21/\text{lb}_{\text{CF}}$ (based on 25% reduction in proc.. cost as shown in Kline Rpt)	$\$4.76/\text{lb}_{\text{CF}}$ (based on 25% reduction in proc.. cost as shown in Kline Rpt)	$\$4.76/\text{lb}_{\text{CF}}$ (based on 25% reduction in proc.. cost as shown in Kline Rpt)
Final CF Cost (before markup)	$\$13.35/\text{lb}_{\text{CF}}$	**$\$11.61/\text{lb}_{\text{CF}}$**	$\$11.16/\text{lb}_{\text{CF}}$	$\$9.49/\text{lb}_{\text{CF}}$
Cost Reduction from T-700 Baseline	**NA**	**0%** **(High Production Baseline)**	**-3.9%**	**-18.3%**

2.2lbs precursor material per lb of CF material

Source: "Hydrogen Storage Tank – High Strength 24K Tow Carbon Fiber Cost Modeling", Sujit Das, Oak Ridge National Laboratory, 12 August 2014.

Accomplishments and Progress: SA's HexCell Adsorption System Diagram

(Majority based on HSECOE system design)



Accomplishments and Progress:
SA's MATI Adsorption System Diagram
(Majority based on HSECOE system design)