Hydrogen Storage Cost Analysis, Preliminary Results

STRATEGIC ANALYSIS INC

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Project ID ST100

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Overview

Timeline

- Project start date: 9/30/11
- Project end date:
  - 11/30/12, Budget Period 1
  - 9/29/16, all 5 Budget Periods
- Percent complete:
  - 25% of Budget Period 1

Budget

- Total project funding
  - $2M for all 5 years
  - Cost Share: 0% (not req. for analysis projects)
- Funding Received in FY11:
  - $125k (new project)
- Funding for FY12:
  - $255K total
    - $165K SA
    - $60k ANL
    - $30k NREL

Barriers

- System Cost:
  - Realistic, process-based system costs
  - Need for realistic values for current and future cost targets
- Demonstrates impact of technical targets & barriers on system cost:
  - Balance of plant components
  - Materials of construction
  - System size and capacity (weight and volume)
- System Life-Cycle Assessment

Partners

- Argonne National Laboratory
- National Renewable Energy Laboratory

Relevance: Objectives

- Overall goal of project:
  - Process-based cost analysis of current & future H_2 storage technologies.
  - To be used to gauge and guide DOE R&D efforts.
  - Validate cost analysis methodology so there is confidence when methods are applied to novel systems
- Sensitivity studies
  - Determine the cost impact of specific components on the overall system.
- Five-year project, annually renewed
  - Analyze systems of interest identified by DOE.
  - Allows researchers cost impact updates throughout year and feedback on technical advances or proposed strategies
- Identify most fruitful research paths to cost reduction
  - System technology and design parameters
  - System size and capacity
  - Balance of plant components
  - Materials of construction

Relevance: Systems of Interest

- First analysis is of pressure vessel systems
  - These results will be presented today
  - Results to be vetted against proprietary industry numbers for similar systems in order to validate costing methodology
- Second & third cost analyses focus on off-board recycle costs
  - Recycle process for spent fuel from Alane and Ammonia Borane on-board storage systems
- Additional storage technologies for cost analysis will be selected by DOE in the future
- As needed, past analyses will be updated to reflect altered performance/assumptions/design

Approach: SA's DFMA® - Style Costing Methodology

What is DFMA?

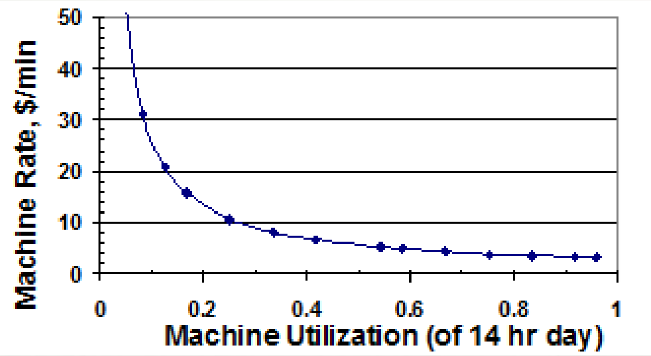
- DFMA® (Design for Manufacturing & Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Co. design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA®, industry standards and practices,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

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

Approach: Cost Factors Included in Estimates

Not Included in Cost Analysis

- Markup for primary manufacturer/assembler (G&A, scrap, R&D, profit)
- Non-recurring RD&E costs
- Warranty
- Advertising
- Taxes

Profit

One-Time Costs

General Expenses

→ Cost Excluded from SA Analysis

Included in Cost Analysis

Fixed Costs

- Equipment depreciation
- Tooling amortization
- Utilities
- Maintenance

Variable Costs

- Direct Materials used in manufacturing
- Direct Materials purchased from suppliers
- Manufacturing scrap
- Manufacturing labor
- Assembly labor

Factory Expenses

Direct Materials

Direct Labor

→ Cost Included in SA Analysis

OEM Price

Approach: Basic Cost Modeling Work Flow

1. Obtain or create system design for technology of interest
   - ANL/HSECoE (typically) provides key parameters, system diagram
2. Develop physical embodiment of system design
   - Materials, scaling, dimensions, design embodiment
   - ANL/HSECoE/other may provide design details
3. Investigate & conceptually model the manufacturing process train for system production
   - Manufacturing methods based on SA experience, industry input, analogy to similar products
4. Vary key parameters to obtain sensitivity data for modeled technology
5. Share results with ANL, NREL, DOE, HSECoE, and Industry to obtain feedback/improvements
6. Modify cost analysis as needed

HSECoE = Hydrogen Storage Engineering Center of Excellence

Accomplishments: Pressure Vessel Cost Analysis

- Estimate cost of H_2 Pressure Vessels to provide validation of cost analysis methodology
  - Baseline system (Complete):
    - 5.6 kg H_2 (usable) at 700bar
    - Carbon Fiber, Type 4 pressure vessel
    - Single tank system design
    - Include Balance of Plant components
    - List all assumptions and analysis steps
- Conduct sensitivity analysis of key parameters
  - Sensitivity Analysis (Complete):
    - Explore cost of systems holding 4-8 kgH_2
    - Examine five annual system production rates:
      - 10k, 30k, 80k, 130k, and 500k
  - Sensitivity Analysis (In Progress):
    - Compare to 350 bar systems
    - Consider system designs with 2 and 3 tanks

First Task is to validate cost analysis methodology on a well-understood system: compressed H_2 pressure vessels.

Accomplishments: Define Baseline System Assumptions

Baseline Physical Assumptions

- H_2 Stored (usable): 5.6kg
- H_2 Stored (total): 5.77kg
- Rated Pressure: 700 bar (10kpsi)
- Single tank
- Type 4 Pressure Vessel (HDPE liner)
- Liner thickness: 5mm
- Foam energy-absorbing end-caps
- Boss: 316SS
- Water volume (interior): 149 Liters
- Vessel External Diameter: 572mm
- Vessel External Length: 900mm

- T-700S carbon fiber
  - Tensile Strength: 4.9 GPa (711kpsi)
  - Modulus: 230 GPa (33.4 Mpsi)
- Safety Factor: 2.25
- Translation Efficiency: 80%
- Fiber Strength Rating: 100%

Ongoing validation with Tank Manufacturers to ensure an accurate physical basis for cost modeling.

Accomplishments: Processing Steps for Pressure Vessel Cost Analysis

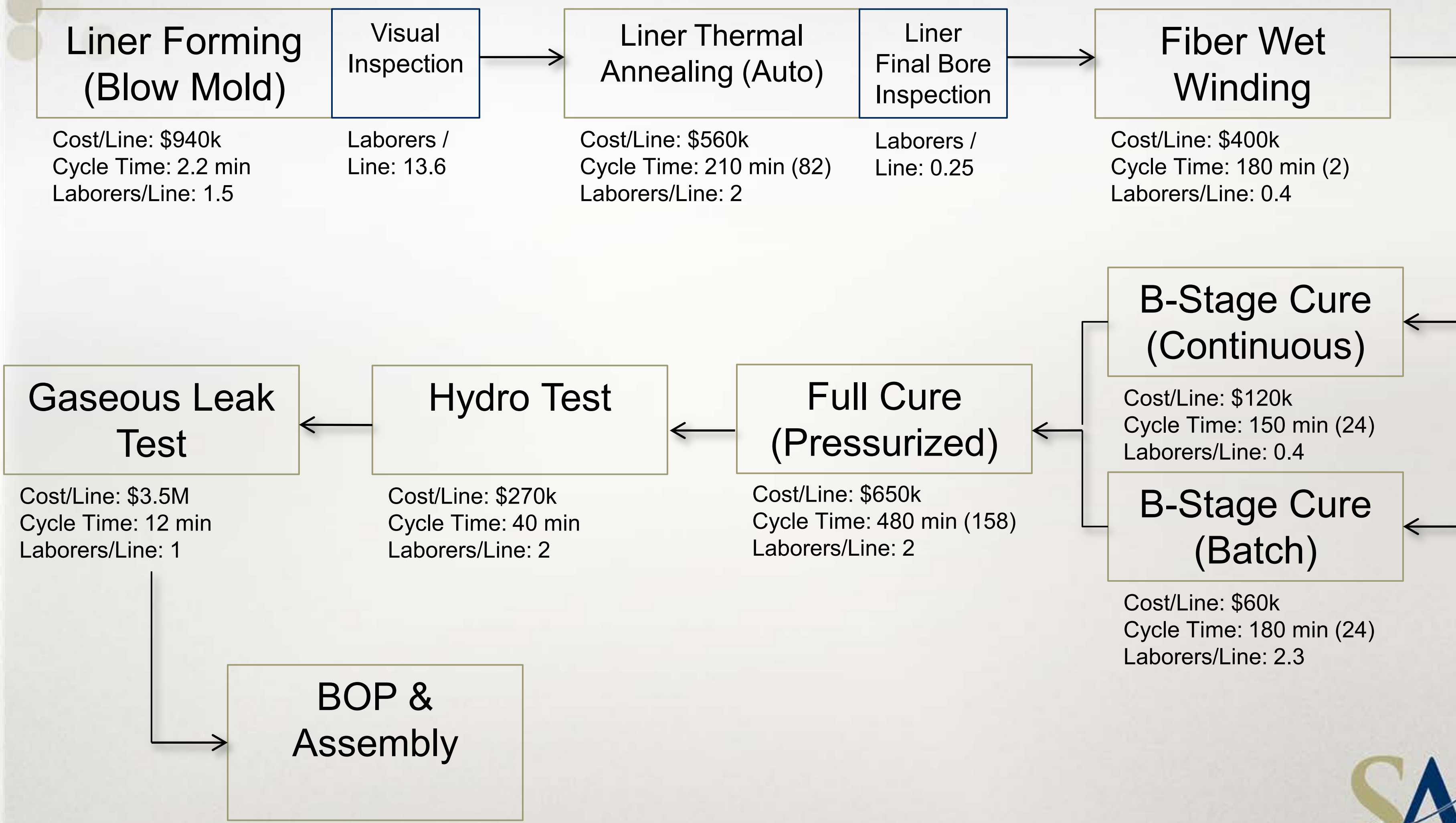
- Step 1: Liner Formation- Blow Mold — Rotomolding also cost modeled but was found to be higher cost than blow molding.
  - Step 2: Visual Inspection
- Step 3: Liner Thermal Annealing
  - Step 4: Liner Final Bore Inspection
- Step 5: Fiber Wet Winding Operation — Pre-preg winding also cost modeled.
- Step 6: B-stage Cure
- Step 7: Full-cure
- Step 8: Hydro Test
- Step 9: Gaseous Leak test
- Step 10: BOP Assembly

Not cost modeled: (deemed unnecessary)

- Tank sanding
- Tank washing
- Overwrap with fiberglass layer
- Tank gel coating/painting
- Water submersion test
- Burst test

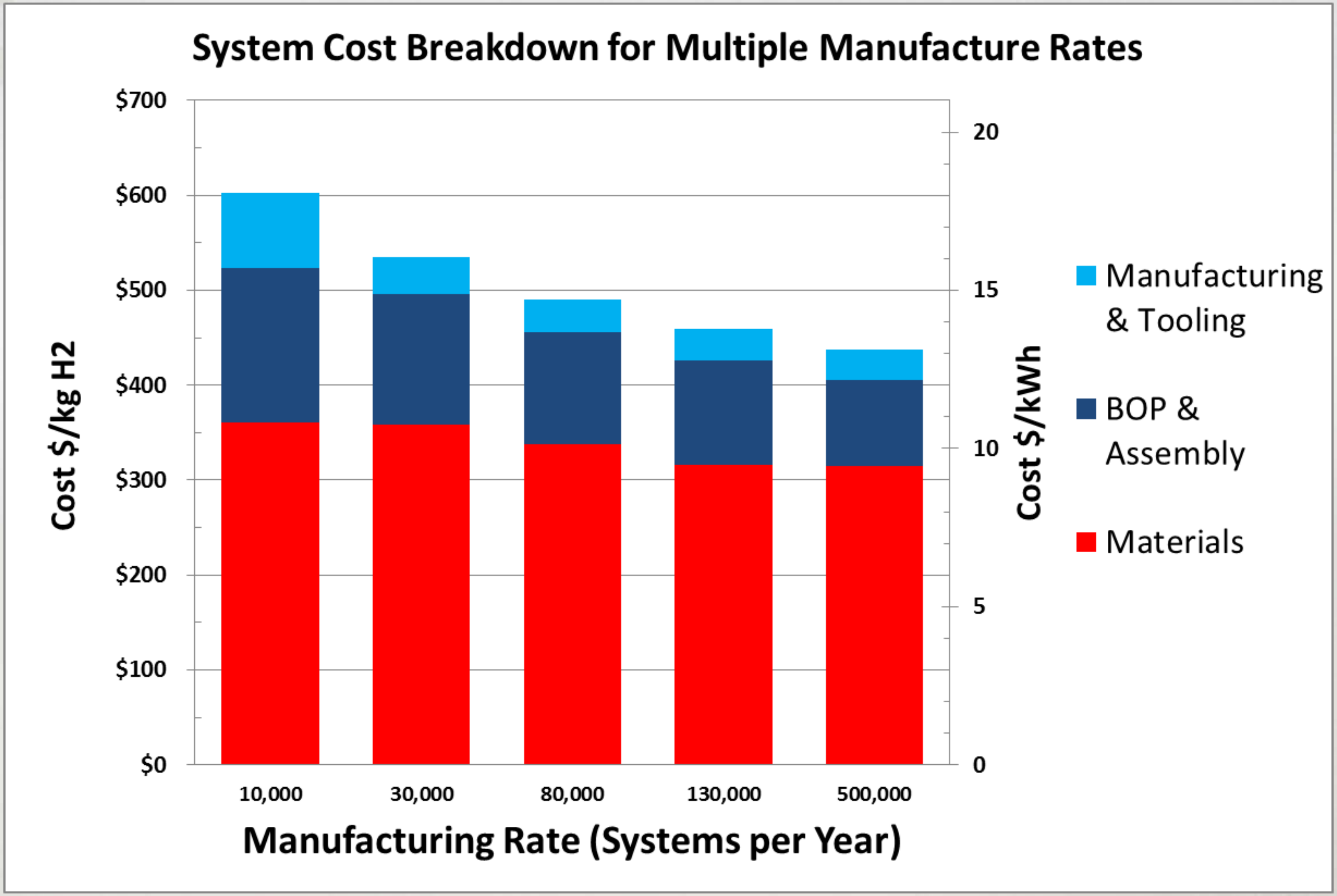
Each step of the pressure vessel manufacturing process was defined in sufficient detail to allow cost analysis.

Accomplishments: Processing Steps for Pressure Vessel Cost Analysis, Details



Accomplishments: Summary of Preliminary System Costs

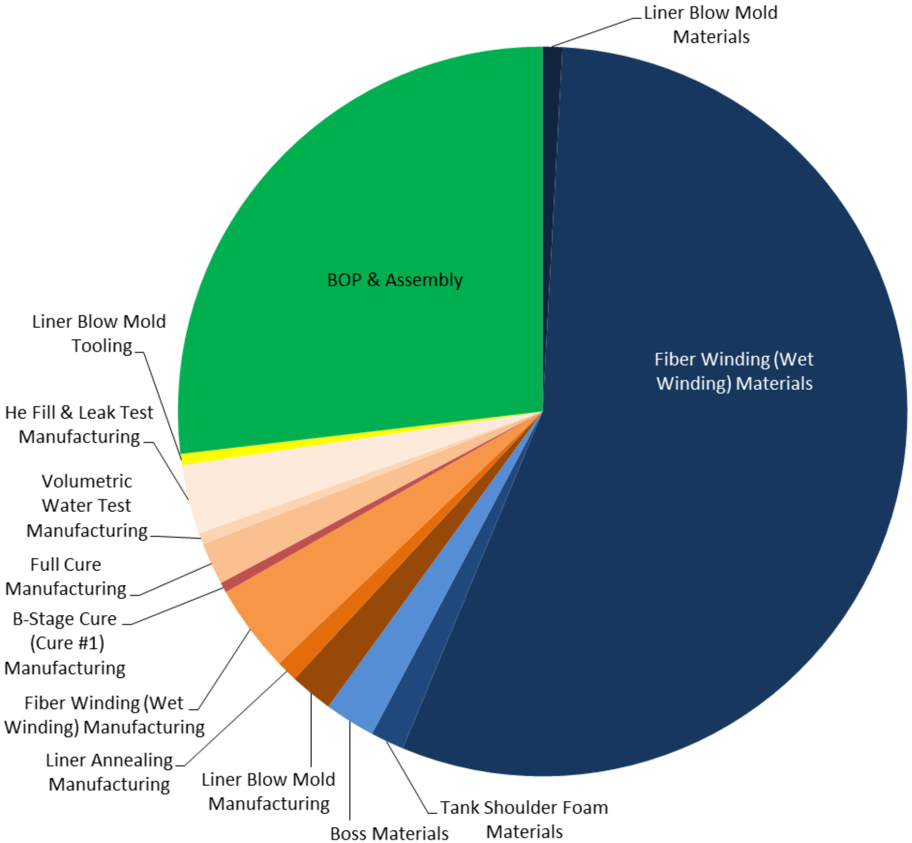
5.6kg H_2 (usable) Single Tank System

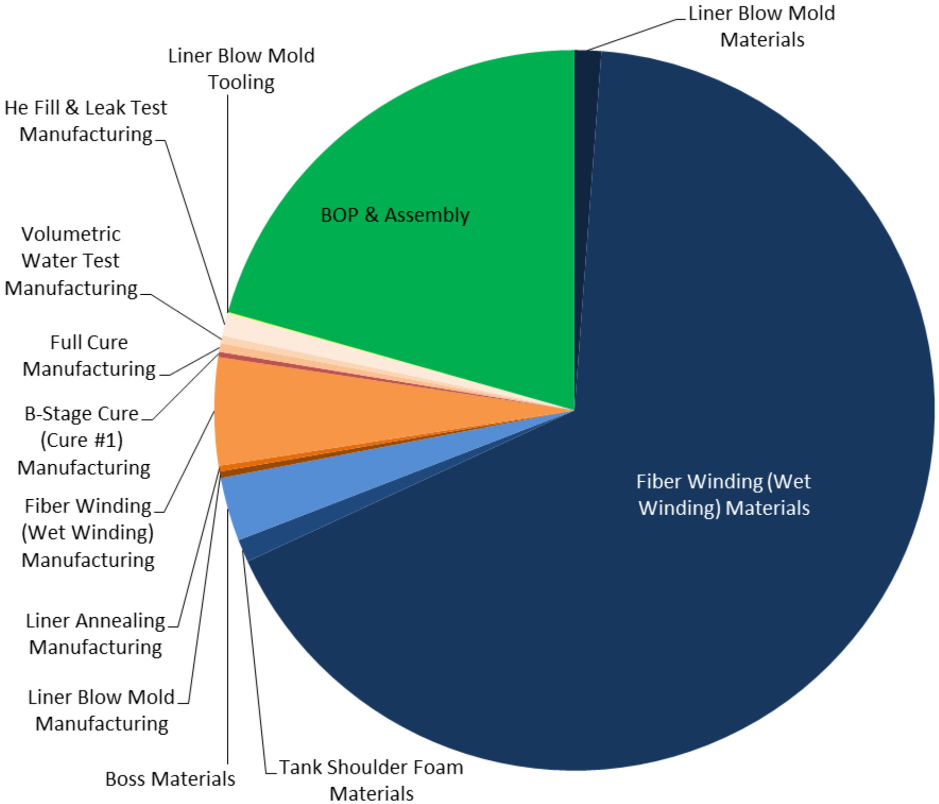


Material cost, driven by carbon fiber cost, dominates at all annual production rates.

Accomplishments: Summary of System Costs

5.6kg H_2 (usable) Single Tank System



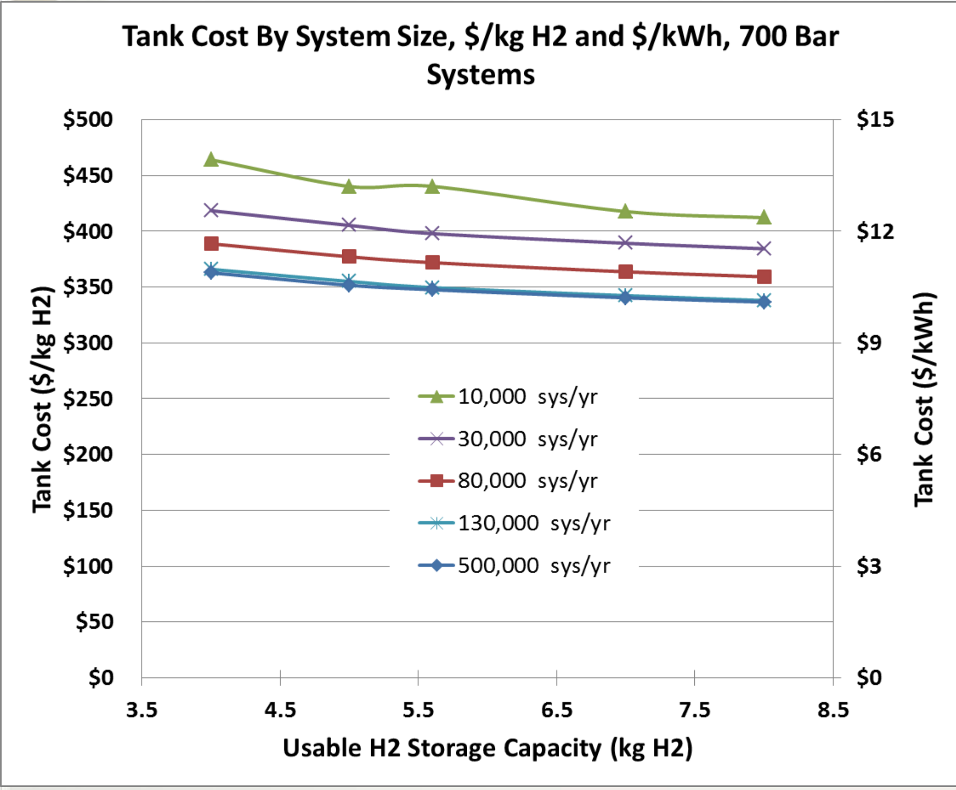


10k Systems per Year
System Cost: \$3371
\$602/kgH_2
\$18/kWh

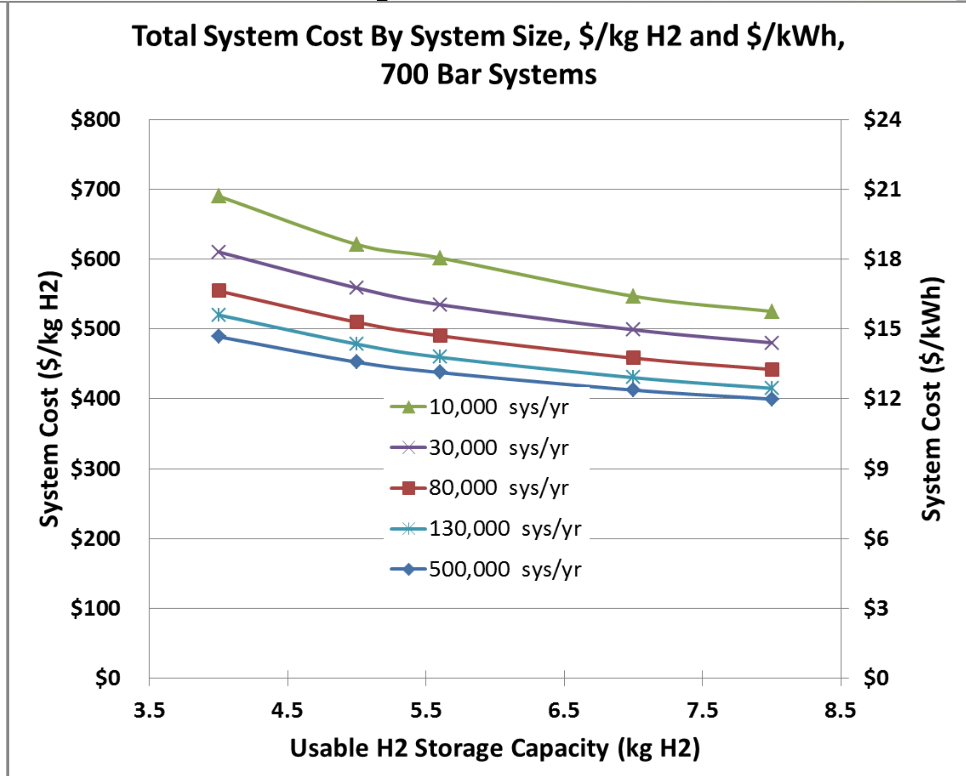
500k System per Year
System Cost: \$2452
\$438/kgH_2
\$13/kWh

Accomplishments: Sensitivity to Usable H_2 Storage Capacity

Tank Cost



System Cost



- Nearly linear variation of tank and system cost with H_2 storage capacity over range examined.

Accomplishments: Top Areas for Further Analysis

- After preliminary cost analysis, six areas are identified for additional work and scrutiny in carbon fiber pressure vessels:
  - Validate carbon fiber composite mass required
  - Pre-preg fiber cost and comparison with wet-winding
  - Average Winding speed
  - BOP cost (particularly at low manufacturing rates)
  - Complete assembly analysis
  - Sensitivity Studies: 350 bar, multiple vessels

15

Accomplishments: Off-Board Recycle Cost Analysis

- Two on-board systems previously considered by HSECoE:
  - Alane:

    $AlH_3 \rightarrow Al + 1.5\ H_2$ (onboard H_2 gen. reaction)

  - Ammonia Borane (AB):

    $NH_3BH_3 \rightarrow BNH_x + nH_2$ (onboard H_2 gen. reaction)

- Our task is to examine the cost of the **off-board recycle system** for each storage system

- Alane Recycle
  - ANL has previously examined multiple recycle pathways
  - Previously experimentally demonstrated at Brookhaven Nat Lab.
  - Selected 3-step organometallic process for cost analysis
    - Step 1: $Al + 1.5\ H_2 + N(CH_3)_3 \rightarrow AlH_3\ N(CH_3)_3$ Amination
    - Step 2: $AlH_3\ N(CH_3)_3 + N(C_2H_5)_3 \rightarrow AlH_3\ N(C_2H_5)_3 + N(C_2H_5)_3$ Transamination
    - Step 3: $AlH_3\ N(C_2H_5)_3 \rightarrow AlH_3 + N(C_2H_5)_3$ Decomposition
    - Net: $Al + 1.5\ H_2 \rightarrow AlH_3$ Net recycle reaction

Task initiated. Results not yet available.

Accomplishments: Off-Board Recycle Cost Analysis

- Ammonia Borane Recycle
  - Multiple recycle pathways have been proposed
  - LANL one-pot process using hydrazine selected for cost analysis
    - $BNH_2 + N_2H_4 \xrightarrow{NH_3} BH_3NH_3 + N_2$
  - ANL previously conducted life-cycle, energy, & GHG emission analysis
  - DOW Chemical previously did detailed analysis of several pathways
    - Estimated resulting H_2 at \$45/kg due to hydrazine cost contribution
    - H_2 cost at zero hydrazine price drops to \$2/kgH_2.
    - Clearly, a low cost hydrazine pathway is a necessity
  - SA updating/revisiting DOW cost analysis
    - Based on alternative, low cost hydrazine production pathway
    - Updating assumptions to be consistent with storage/delivery teams

Task initiated. Results not yet available.

Collaborations

- Argonne National Labs
  - System design & modeling support (pressure vessels, Alane, AB)
  - Specification of key system parameters & range of sensitivity studies (pressure vessels)
  - Validation/Cross-checking of SA calculations. Point designs verified against ANL modeling. (pressure vessels)
- National Renewable Energy Laboratory
  - System design & modeling support (pressure vessels, Alane, AB)
  - Validation/Cross-checking of SA calculations. (pressure vessels)
- Industry Interactions
  - Consultation/Phone-Interviews with variety of industry players
    - Quantum, TIAX, Lincoln Composites, McClean-Anderson, Robotworx, Toray, Entek/Zoltek
  - Vet results and provide manufacturing process insight

18

Proposed Future Work

- Remainder of FY 12
  - Pressure Vessels Cost Analysis
    - Complete sensitivity analyses
    - Vet results with industry and HSECoE
    - Complete report on results, assumptions, and methodology
  - Off-board Recycle Cost Analysis
    - Complete cost analysis of Alane and Amonia Borane recycle systems
    - Vet results with industry and HSECoE
    - Complete report on results, assumptions, and methodology
  - Cost Analysis of On-Board H_2 Storage System
    - System to be selected by DOE
    - Cost analysis, vetting, and report
    - Will begin analysis in FY12 and conclude in FY13
- FY13 Activities
  - Continuation of Storage System Cost Analysis

Summary

- Overview
  - In year 1 of 5 year project
  - Cost analysis H_2 storage systems
  - Examining a sequence of storage systems concepts
- Relevance
  - Cost analysis used to assess practicality of proposed storage system, determine key cost drivers, and provide insight for direction of R&D priorities
- Approach
  - Process based cost analysis methodologies (e.g. DFMA)
- Accomplishments
  - Initial focus has been on high pressure composite pressure vessels
  - Serves to confirm cost analysis methodology
  - Initial examination of Alane and Ammonia Borane off-board recycle costs
- Collaborations
  - ANL and NREL under contract to provide cooperative analysis and vetting of assumptions/results
- Future Work
  - Conclude vetting of pressure vessel cost analysis
  - Conclude analysis of Alane and AB recycle costs
  - Initiate cost analysis of next on-board storage systems

20

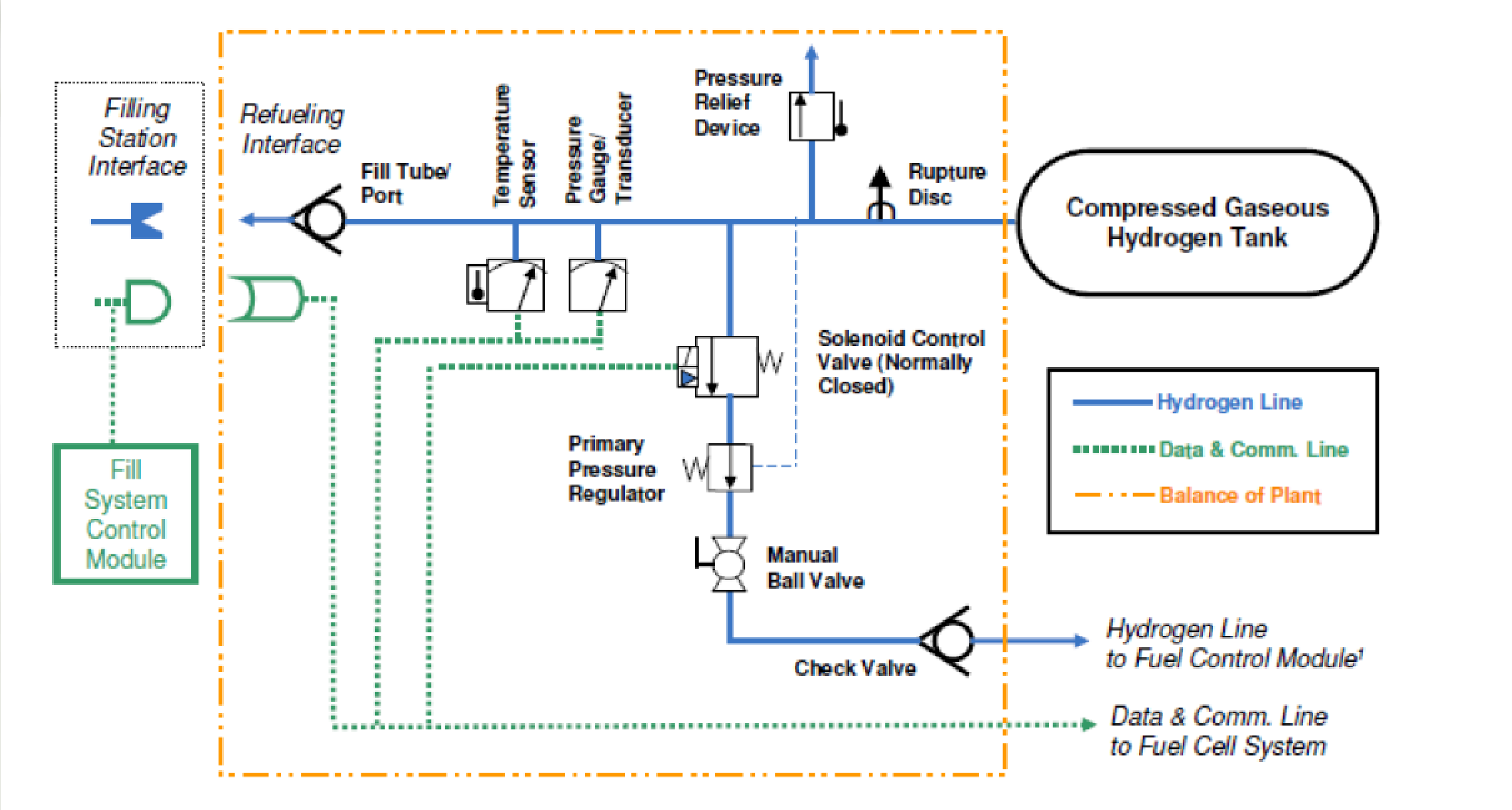
Technical Backup Slides

Materials & System Cost Assumptions

Material	SA Cost
Liner Polymer	$4 / kg
Pre-Preg Carbon Fiber (initial values used for comparison with wet winding analysis)	$42 / kg @ 10k sys / year $42 / kg @ 30k sys / year $39.2 / kg @ 80k sys / year $36.4 / kg @ 130k sys / year $36.4 / kg @ 500k sys / year
Raw Carbon Fiber (used in cost analysis)	$15 / lb @ 10k sys / year $15 / lb @ 30k sys / year $14 / lb @ 80k sys / year $13 / lb @ 130k sys / year $13 / lb @ 500k sys / year
Foam Shoulder Caps	$25 / cap - $12.5 / cap

Parameter	SA Value
Nominal Pressure	700 bar
Number of Tanks	1
Tank Liner Type	Type 4
Useable H_2 Capacity	5.6 kg
Total Interior Volume	149 L
Tank Length	0.9 m
Tank Diameter	0.572 m
Fiber & Resin Weight	75.9 kg
Tank L/D Ratio (external dimensions)	1.6
Safety Factor	2.25

System Diagram



* Schematic based on the requirements defined in the draft European regulation "Hydrogen Vehicles: On-board Storage Systems" and US Patent 6,041,762.
[1] Secondary Pressure Regulator located in Fuel Control Module of the Fuel Cell System.

Components listed in 2010 TIAX system update (for dual tank system):

- Two Extra Solenoid Control Valves
- Extra Check Valve
- Extra Manual Valve
- Extra Pressure Relief Device
- Extra Rupture Disc

Summary of System Costs

Technology Type		70MPa Pressure Vessels - System Cost				
System Storage	kgH2/system	5.6kg H2 per system				
Annual System Production Rate	system/yr	10,000	30,000	80,000	130,000	500,000
Liner Rotomold	**$/kWh**	**$0.59**	**$0.53**	**$0.52**	**$0.52**	**$0.52**
Material	$/kWh	*$0.16*	*$0.16*	*$0.16*	*$0.16*	*$0.16*
Manufacturing	$/kWh	*$0.39*	*$0.36*	*$0.35*	*$0.35*	*$0.35*
Tooling	$/kWh	*$0.04*	*$0.01*	*$0.00*	*$0.00*	*$0.00*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Liner Blow Mold	**$/kWh**	**$0.59**	**$0.27**	**$0.21**	**$0.21**	**$0.20**
Material	$/kWh	*$0.16*	*$0.16*	*$0.16*	*$0.16*	*$0.16*
Manufacturing	$/kWh	*$0.34*	*$0.08*	*$0.04*	*$0.05*	*$0.04*
Tooling	$/kWh	*$0.09*	*$0.03*	*$0.01*	*$0.01*	*$0.01*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Method Used	$/kWh	Blow Mold	Blow Mold	Blow Mold	Blow Mold	Blow Mold
Rotomold Liner Annealing	**$/kWh**	**$0.17**	**$0.06**	**$0.05**	**$0.04**	**$0.03**
Material	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Manufacturing	$/kWh	*$0.17*	*$0.06*	*$0.05*	*$0.04*	*$0.03*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Fiber Winding (Pre-Preg)	**$/kWh**	**$17.70**	**$17.67**	**$16.52**	**$15.36**	**$15.36**
Material	$/kWh	*$17.22*	*$17.22*	*$16.07*	*$14.92*	*$14.92*
Manufacturing	$/kWh	*$0.48*	*$0.45*	*$0.45*	*$0.44*	*$0.44*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Fiber Winding (Wet Winding)	**$/kWh**	**$10.69**	**$10.63**	**$10.01**	**$9.41**	**$9.41**
Material	$/kWh	*$9.99*	*$9.99*	*$9.38*	*$8.77*	*$8.77*
Manufacturing	$/kWh	*$0.70*	*$0.64*	*$0.63*	*$0.63*	*$0.63*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Method Used	$/kWh	Wet Winding	Wet Winding	Wet Winding	Wet Winding	Wet Winding
B-Stage Cure (Cure #1)	**$/kWh**	**$0.08**	**$0.03**	**$0.03**	**$0.04**	**$0.03**
Material	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Manufacturing	$/kWh	*$0.08*	*$0.03*	*$0.03*	*$0.04*	*$0.03*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Include in Process?	$/kWh	Include	Include	Include	Include	Include
Tank Shoulder Foam	**$/kWh**	**$0.27**	**$0.21**	**$0.18**	**$0.16**	**$0.13**
Material	$/kWh	*$0.27*	*$0.21*	*$0.18*	*$0.16*	*$0.13*
Manufacturing	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Full Cure	**$/kWh**	**$0.34**	**$0.08**	**$0.06**	**$0.05**	**$0.05**
Material	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Manufacturing	$/kWh	*$0.34*	*$0.08*	*$0.06*	*$0.05*	*$0.05*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Boss	**$/kWh**	**$0.41**	**$0.38**	**$0.38**	**$0.38**	**$0.37**
Material	$/kWh	*$0.41*	*$0.38*	*$0.38*	*$0.38*	*$0.37*
Manufacturing	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Volumetric Water Test	**$/kWh**	**$0.09**	**$0.05**	**$0.05**	**$0.05**	**$0.04**
Material	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Manufacturing	$/kWh	*$0.09*	*$0.05*	*$0.05*	*$0.05*	*$0.04*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
He Fill & Leak Test	**$/kWh**	**$0.55**	**$0.21**	**$0.16**	**$0.15**	**$0.14**
Material	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
Manufacturing	$/kWh	*$0.55*	*$0.21*	*$0.16*	*$0.15*	*$0.14*
Markup	$/kWh	*$0.00*	*$0.00*	*$0.00*	*$0.00*	*$0.00*
BOP Items	**$/kWh**	**$4.78**	**$4.04**	**$3.48**	**$3.24**	**$2.64**
Assembly	$/kWh	*$0.06*	*$0.06*	*$0.06*	*$0.06*	*$0.06*
Total Cost	**$/kWh**	**$18.03**	**$16.03**	**$14.69**	**$13.77**	**$13.11**
Tank Material	$/kWh	$10.82	$10.74	$10.10	$9.47	$9.44
Tank Manufacturing	$/kWh	$2.28	$1.15	$1.03	$1.00	$0.97
Markup	$/kWh	$0.00	$0.00	$0.00	$0.00	$0.00
BOP / Assembly	$/kWh	$4.84	$4.11	$3.55	$3.30	$2.70
Tooling	$/kWh	$0.09	$0.03	$0.01	$0.01	$0.01
Cost per System	$/system	$3,370.97	$2,996.51	$2,746.20	$2,574.80	$2,451.80

Assumptions used in Wet Winding vs. Pre-Preg Cost Comparison*

Assumption Differences

Parameter	Pre-Preg	Wet Winding
Materials Price (@ 500k sys/year)	$36.6/kg of pre-preg material**	$13/lb of carbon fiber $3/lb of resin
Winding Machine Capital Cost	$400k	$400k
Average Winding Speed	40 m/min (1.5x wet winder)	26 m/min
Other Differences Not Currently Modeled		
Overall Tank Scrap Rate	2%	10%
Resin Use as % of Required	100%	102%
Material Storage	Refrigerated	Room Temp
Downtime per shift for resin bath & machine maintenance	0 min	30 min

* Previous TIAX cost analyses were based on pre-preg carbon fiber cost.

** Pre-preg material cost based on Duvall 2001. Additionally, a separate ground-up DFMA analysis of pre-preg fiber pricing will be conducted.