Hydrogen Storage Cost Analysis

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:
  - 11/30/13, Budget Period 2
  - 9/29/16, all 5 Budget Periods
- Percent complete:
  - 25% of Budget Period 2

Barriers

- A: system weight and volume
- B: system cost
- K: system lifecycle assessment

Budget

- Total project funding
  - $2M for all 5 years
  - Cost Share: 0% (not req. for analysis projects)
- Funding Received in FY12:
  - $410k (total SA/NREL/ANL)
- Funding for FY13:
  - $350K total
    - $290k SA
    - $60k ANL

Partners

- Argonne National Laboratory (ANL)
- National Renewable Energy Laboratory (NREL)

Relevance: Objectives

- Overall goal of project:
  - Process-based cost analysis of current & future hydrogen (H_2) storage technologies.
  - Gauge and guide DOE research and development (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: Cost Analyses of Systems

- Pressure vessel systems for vehicles
  - 35 and 70 Megapascals (MPa) / 5,000 and 10,000 pounds per square inch (psi)
  - At varying annual production levels
- Off-board recycle costs
  - Recycle of Alane chemical hydride spent fuel
  - Recycle of Ammonia Borane (AB) spent fuel
- Additional storage technologies for cost analysis will be selected by DOE in the future

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Approach: SA's Design for Manufacturing and Assembly (DFMA)® - Style Costing Methodology

What is DFMA®?

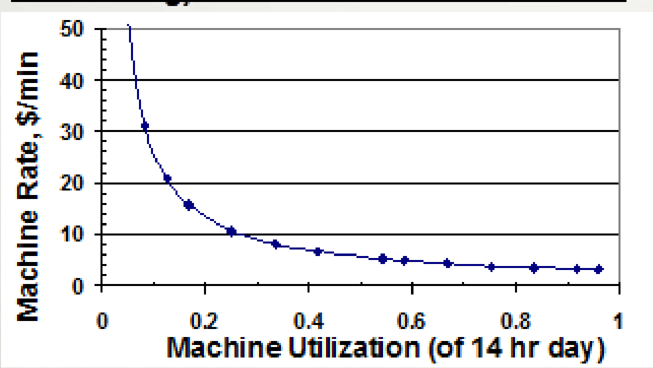
- DFMA® (Design for Manufacturing & Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Company (Ford) design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA®, industry standards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

Original Equipment Manufacturer (OEM) Price

Approach: Basic Cost Modeling Work Flow

1. Obtain or create system design for technology of interest
   - ANL/HSECoE/other 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, technology developers, and Industry to obtain feedback/improvements
6. Modify cost analysis as needed

Accomplishments: Updated Pressure Vessel Cost Analysis

- Revised pressure vessel mass estimates
  - Application of ANL ABAQUS models
  - Resulted in mass increase of 35%
- Improved manufacturing process parameters
  - Parameter adjustment after discussion with Ford, Pacific Northwest National Laboratory (PNNL), & Lincoln Composites
- Improved Balance of Plant (BOP) cost estimates
  - Updated system schematic from OEM input
  - Revised cost estimates
- Updated and Expanded Sensitivity Analysis
  - System size variation (4-8 kilograms (kg) H_2)
  - Multiple storage pressure (350 bar and 700 bar)
  - Multiple tanks (1,2 and 3 vessels per system)

Last year's analysis updated to reflect additional input from ANL modeling and OEMs.

Accomplishments: Completed Initial Cost Model & Methodology Validation

Baseline Physical Assumptions

- H_2 Stored (usable): 5.6 kg
- H_2 Stored (total): 5.77 kg
- Single tank
- Rated Pressure: 700 bar (10 kpsi)
- Type 4 Pressure Vessel (HDPE liner)
- Liner thickness: 5 millimeter (mm)
- Boss: 316 stainless steel (SS)
- Water volume (interior): 149 Liters
- Vessel External Diameter: 572 mm
- Vessel External Length: 900 mm
- T-700S carbon fiber
  - Tensile Strength: 4.9 Gigapascals (Gpa) (711 kpsi)

- Safety Factor: 2.25
- Effective Translation Efficiency: 69.6%
  - 87% composite efficiency
  - 80% winding efficiency
- Fiber Strength Variability De-rating: 90%

Key Cost Input Assumptions (at 500ksys/yr)

- \$28.67/kg carbon fiber (dry), in 2007\$
- \$8.25/kg_{net}, in 2012\$ (includes allowance for resin wastage in winding process)
- \$2.06/kg liner material, in 2012\$
- Costs are consensus values with HSECoE/PNNL

Continue 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
  - Step 2: Visual Inspection
- Step 3: Liner Thermal Annealing
  - Step 4: Liner Final Bore Inspection
- Step 5: Fiber Wet Winding Operation
- Step 6: B-stage Cure
- Step 7: Full-cure
- Step 8: Hydro Test
- Step 9: Gaseous Leak test
- Step 10: BOP Assembly

Rotomolding also cost modeled but was found to be higher cost than blow molding. (Step 1)

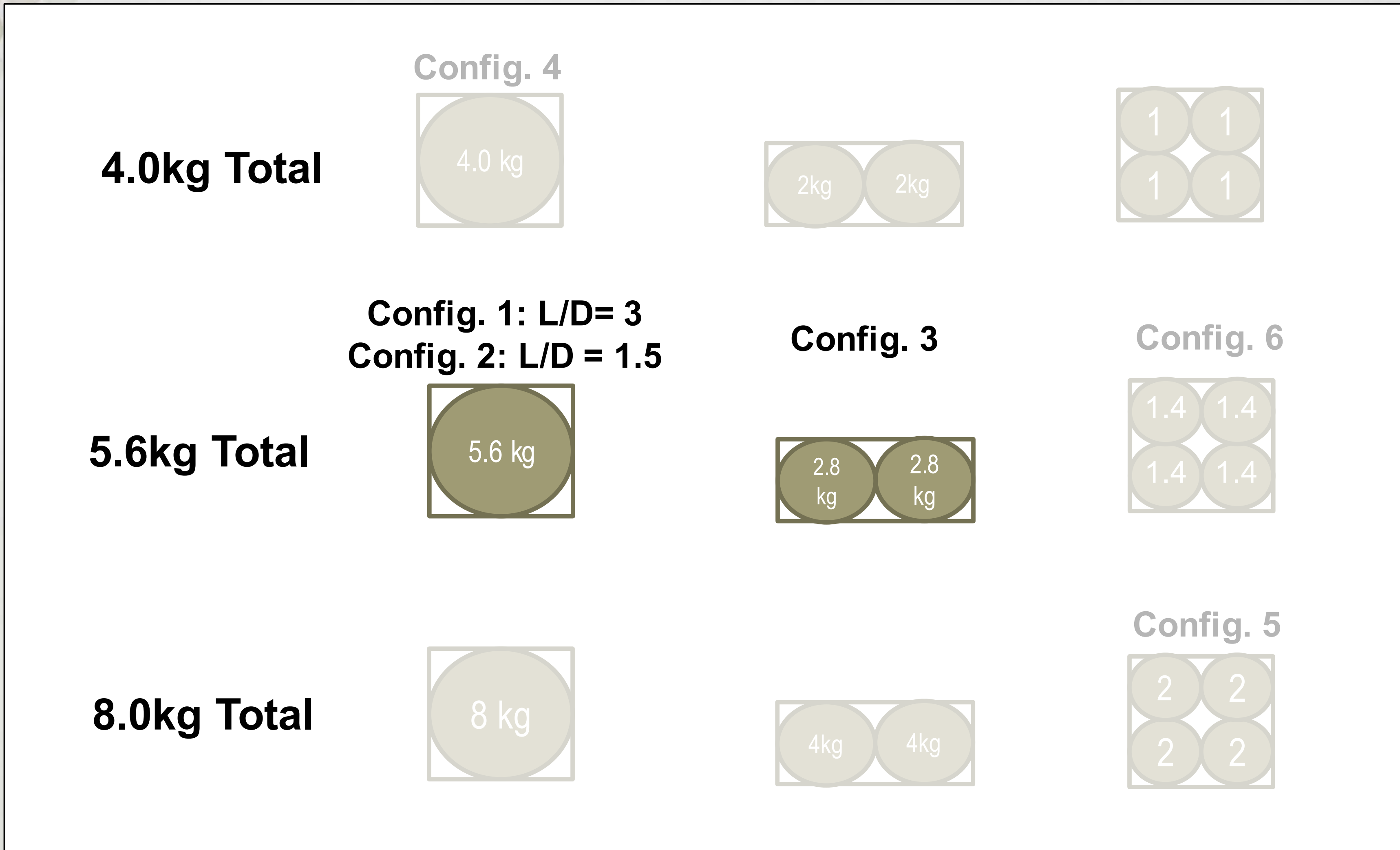
Pre-preg winding also cost modeled. (Step 5)

Not cost modeled: (deemed unnecessary)

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

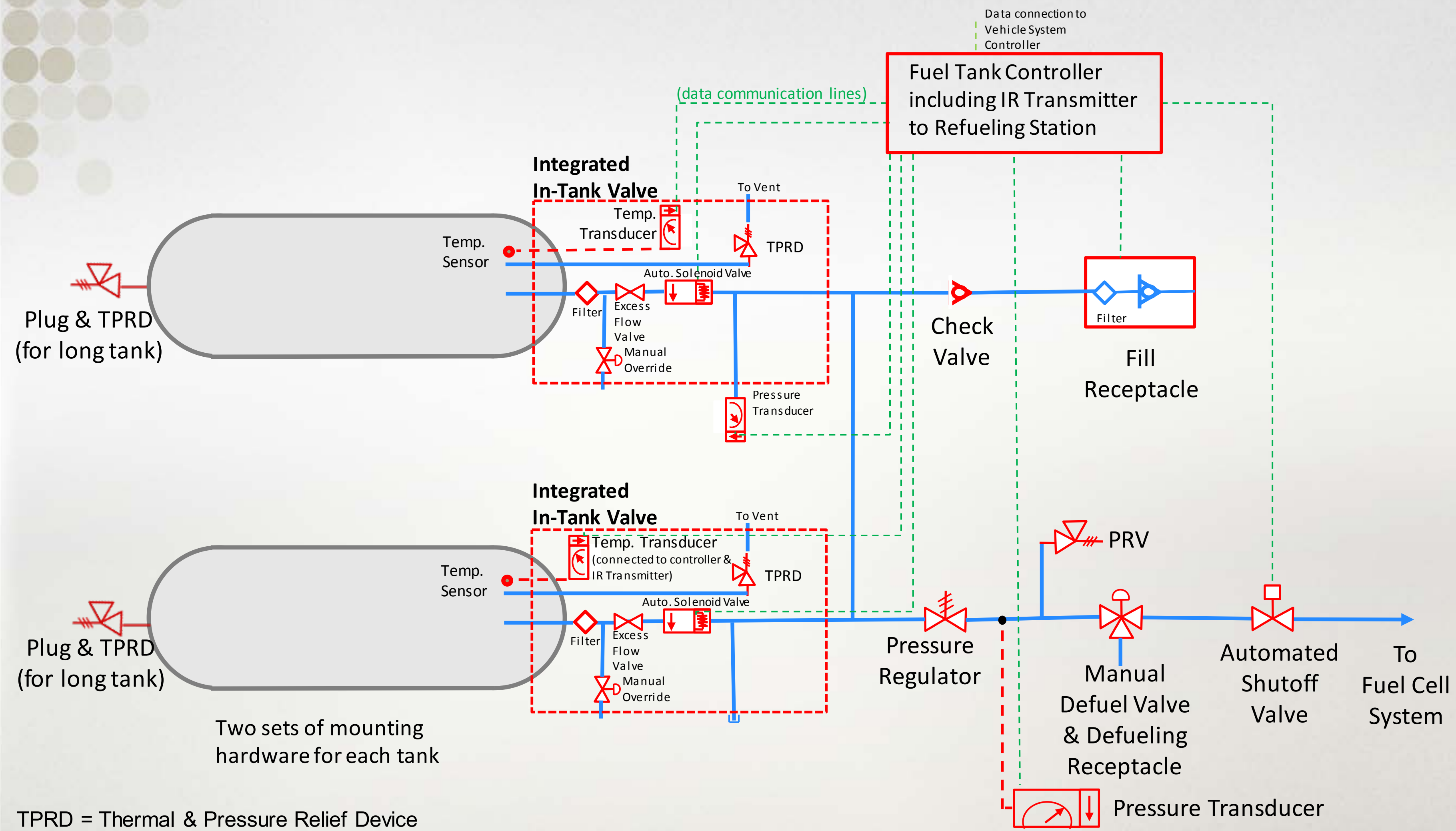
Each step of the pressure vessel manufacturing process was defined in sufficient detail to allow cost analysis.

Pressure Vessel Configurations (70 MPa) Selected to Represent Range of Expected Vehicle Configurations



Five main configurations selected representing 3 total H_2 storage amounts and 1, 2, or 4 tanks per system.

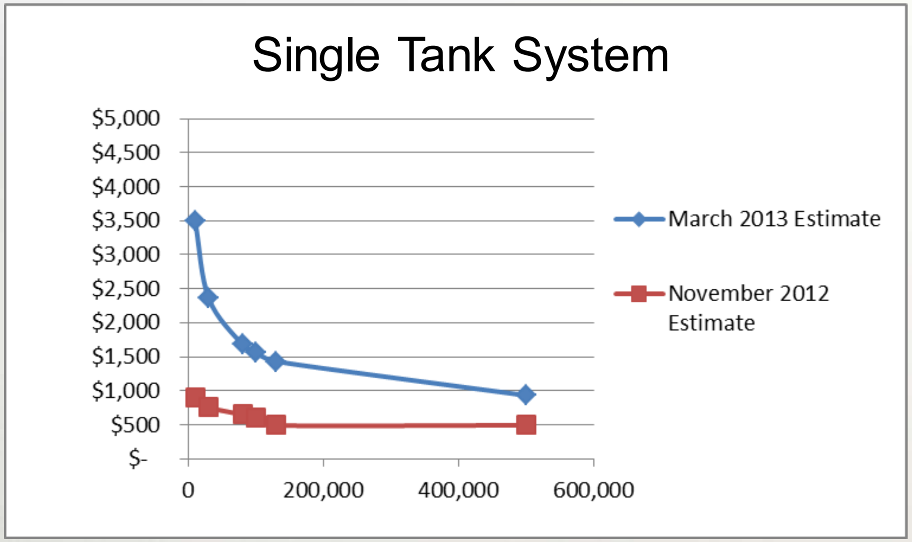
Revised System Layout Based on OEM Input

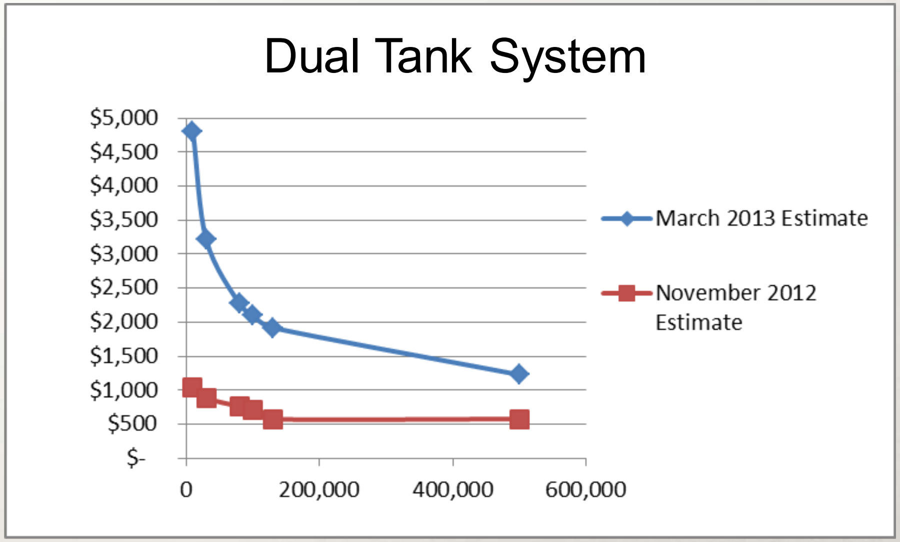


Some new components were added compared to the previous 2010 ANL baseline layout (particularly for multiple tank systems).

Significant Increase in BOP Price Due to Revised Components and Improved Price Data

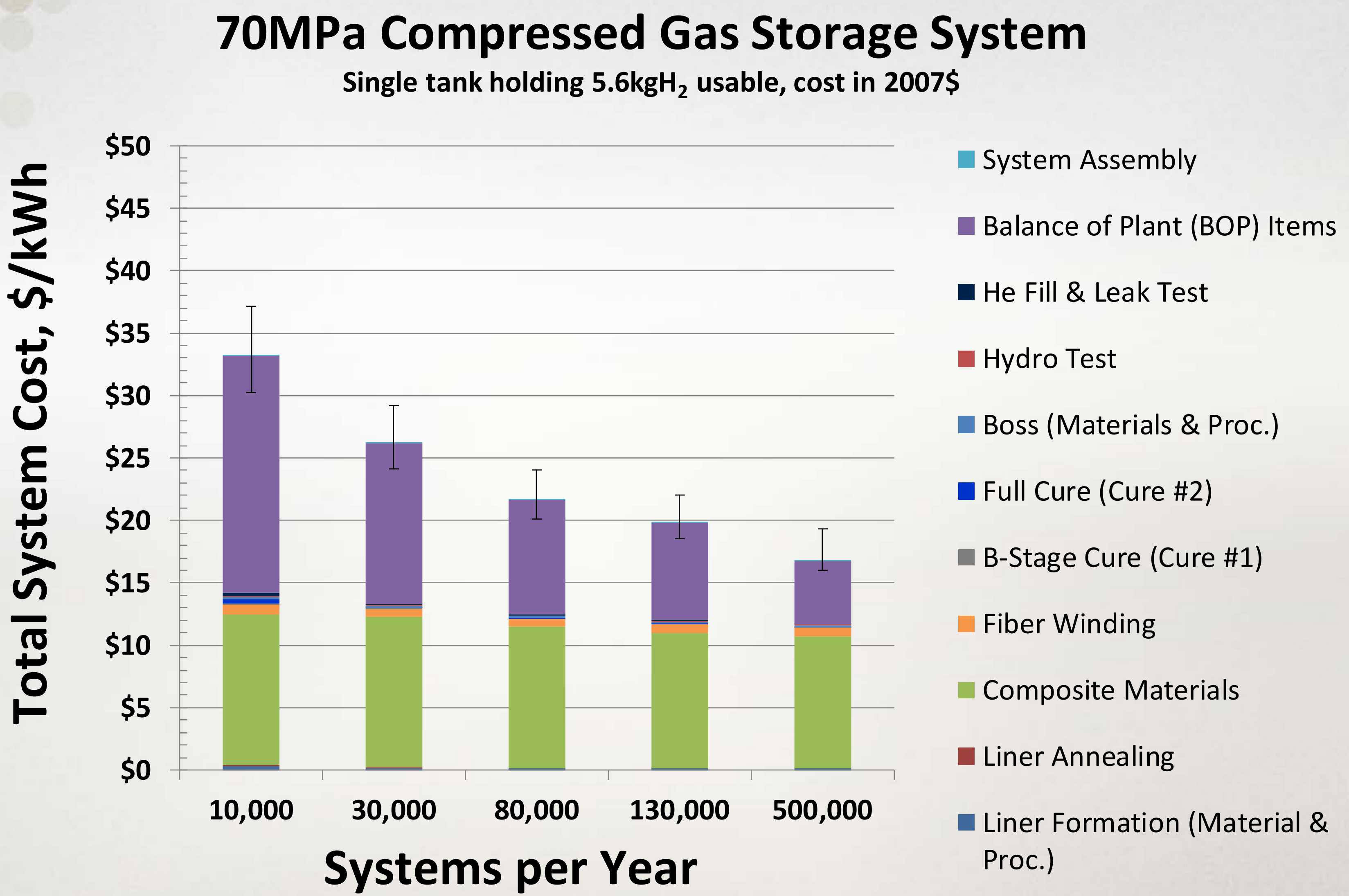
- Dramatic increase in BOP subsystem cost caused primarily by:
  - Updated system schematic (based on OEM feedback)
  - Component cost increase at low manufacturing rates
    - Better OEM data obtained
    - Cost validated at 10k & 100k rates
    - Costs follow 0.75 Learning Curve (rather than previous 0.9 curve)
  - Increase in number of BOP components required "per tank" rather than "per system"





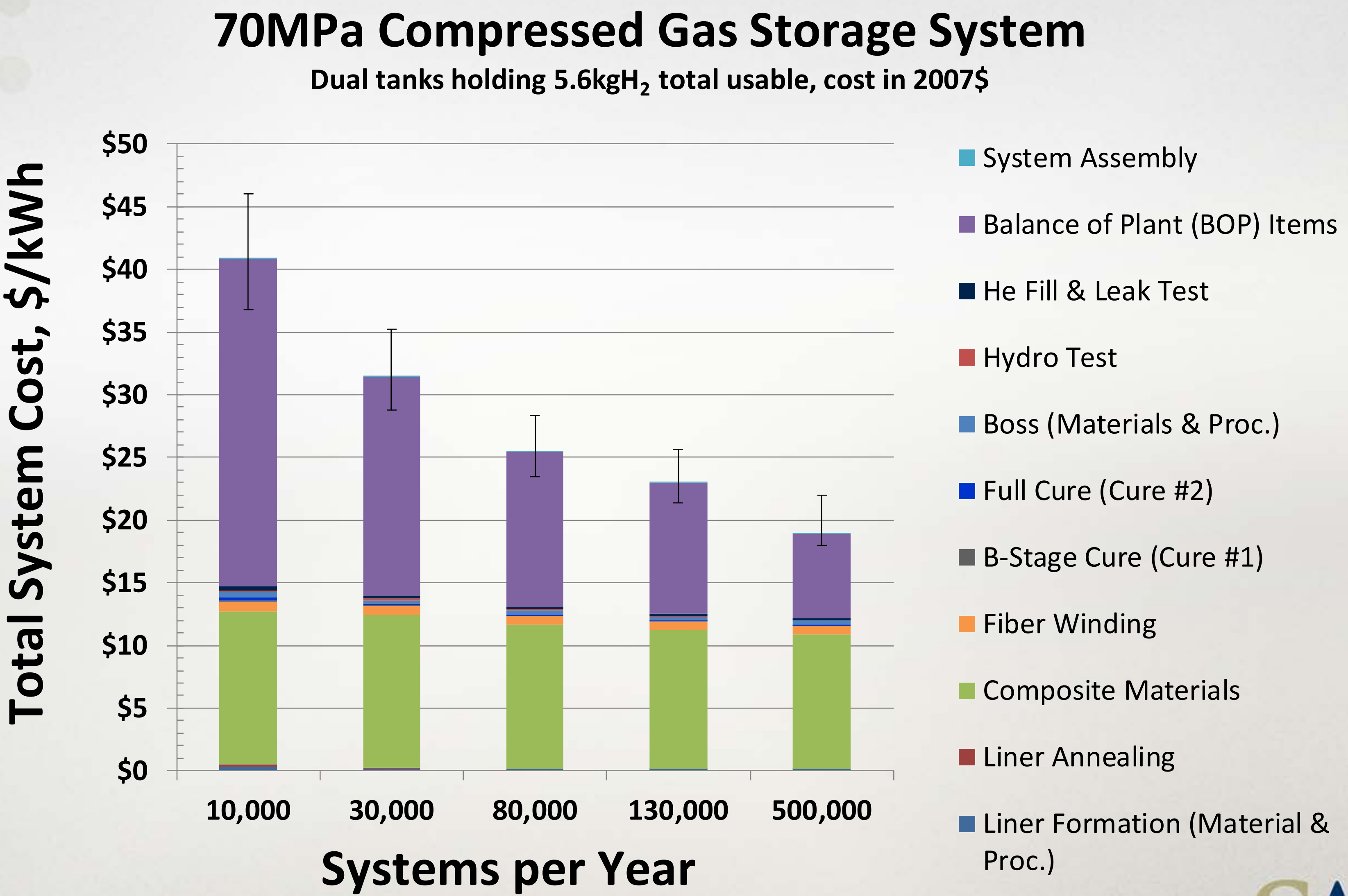
- Change in curvature of graphs reflects change in assumed learning factor.

Accomplishments: System Cost Results (70Mpa, Single Tank)

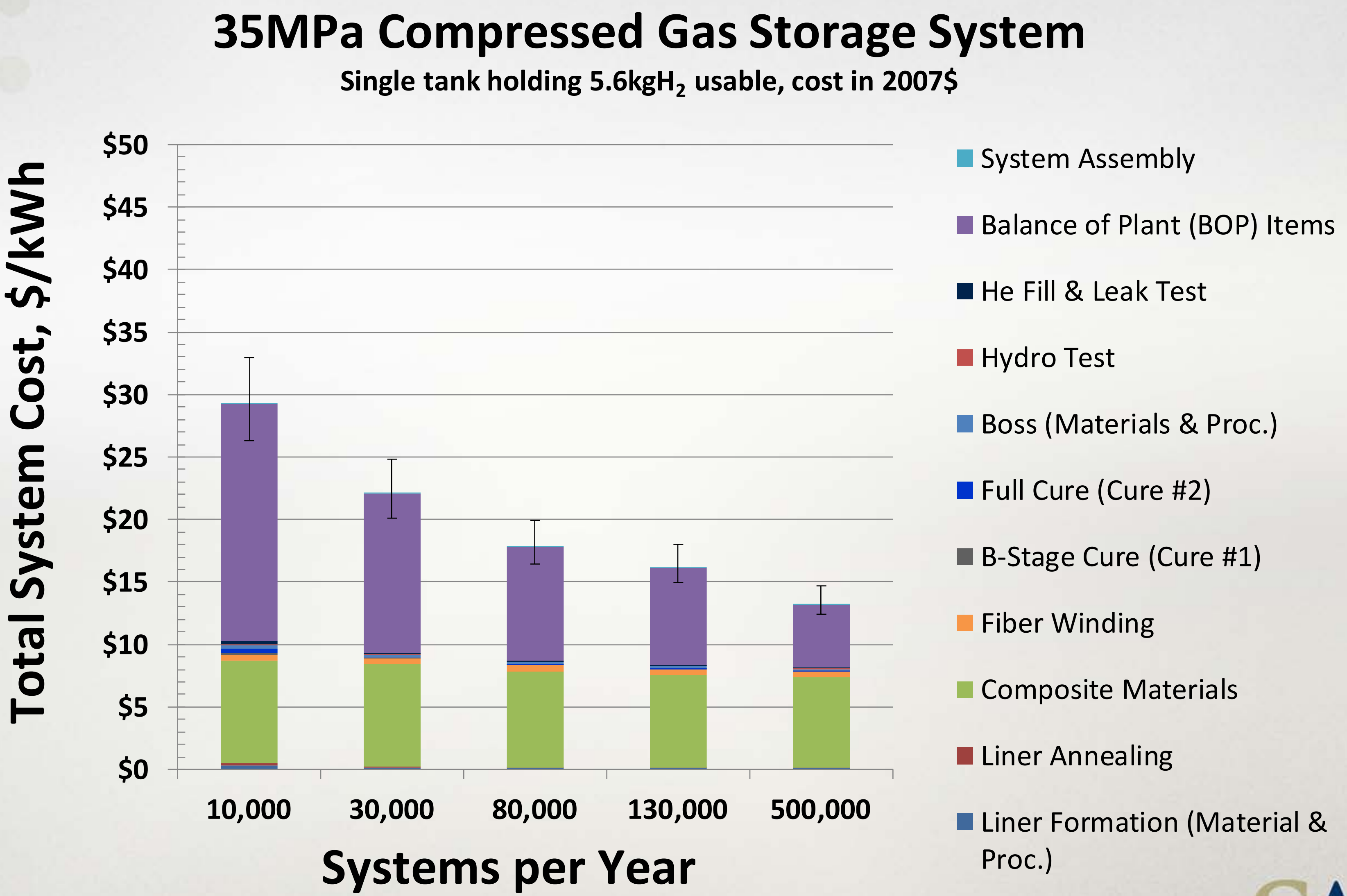


Material cost, driven by carbon fiber cost, and BOP costs dominate at all annual production rates.

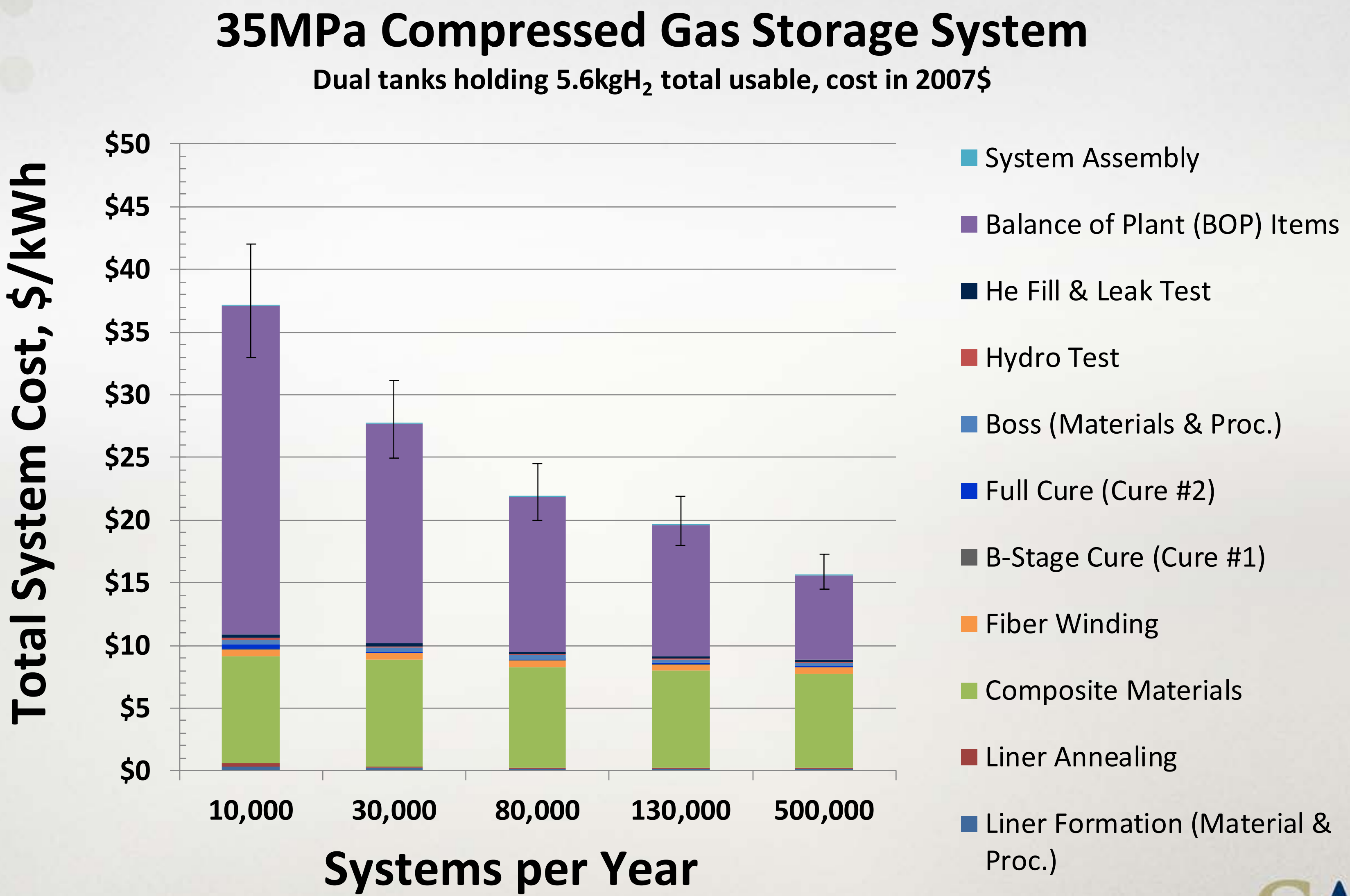
Accomplishments: System Cost Results (70Mpa, Dual Tank)



Accomplishments: System Cost Results (35Mpa, Single Tank)

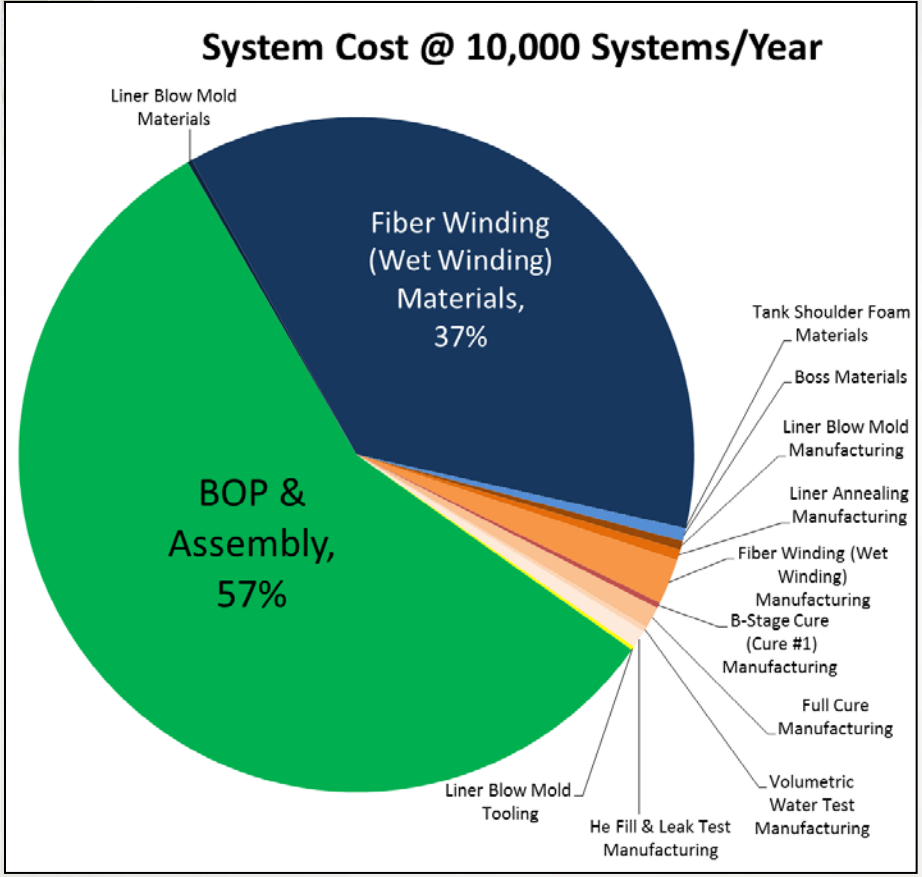


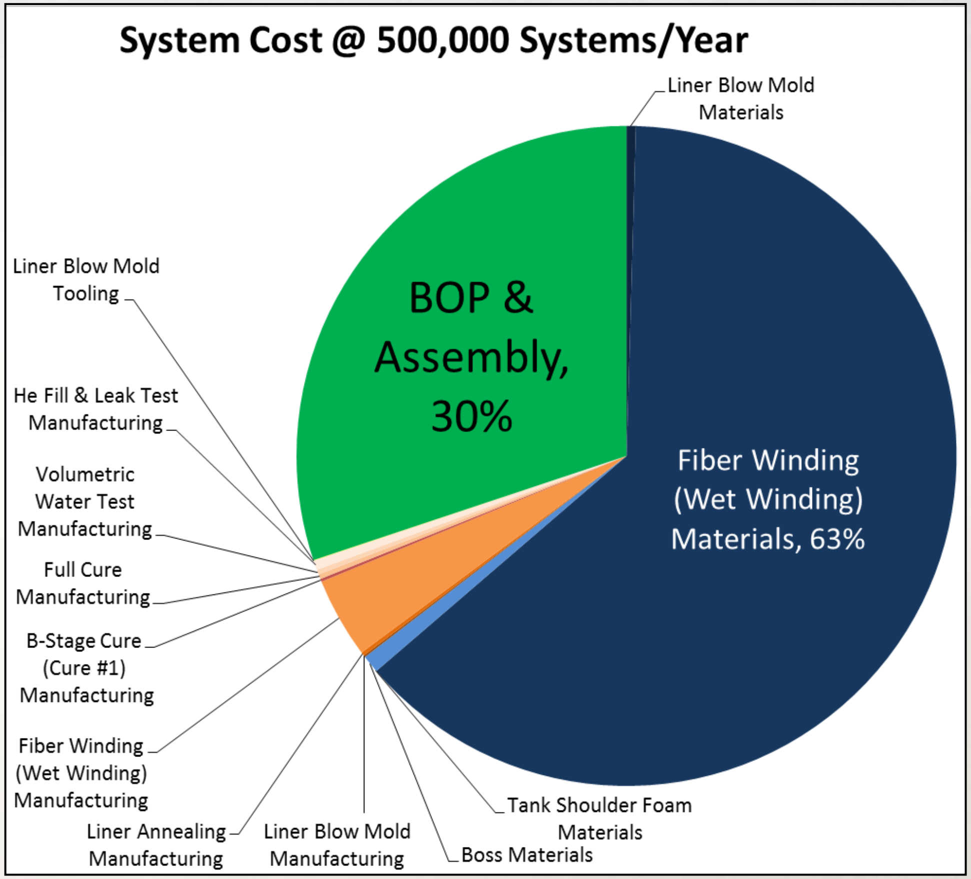
Accomplishments: System Cost Results (35Mpa, Dual Tank)



Accomplishments: Summary of System Costs

5.6kg H_2 (usable) 70MPa Single Tank System



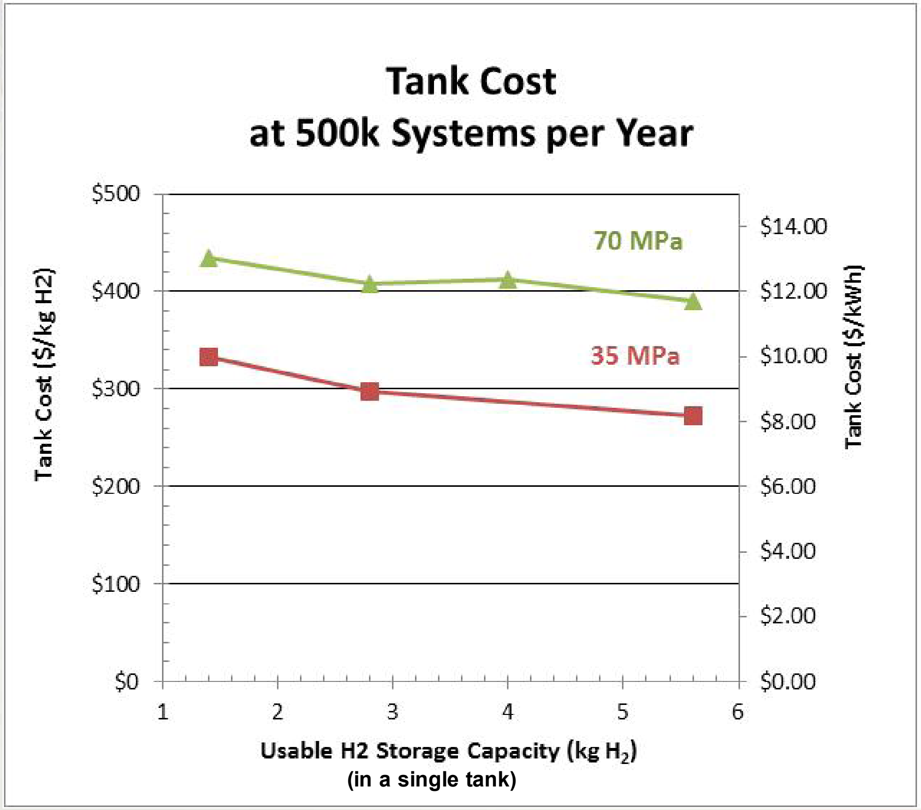


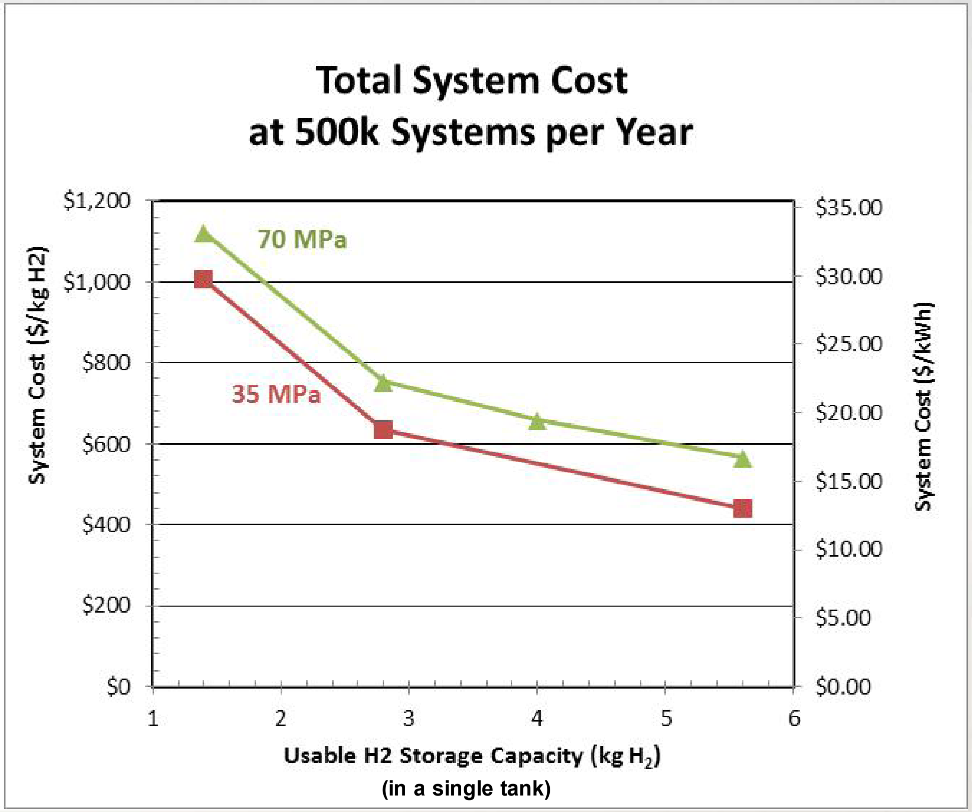
10k Systems per Year
System Cost: $6,158
$1,100/kgH$_2$
$33/kWh

All cost results in 2007$

500k System per Year
System Cost: $3,134
$600/kgH$_2$
$17/kWh

Accomplishments: Sensitivity to H_2 Storage Capacity

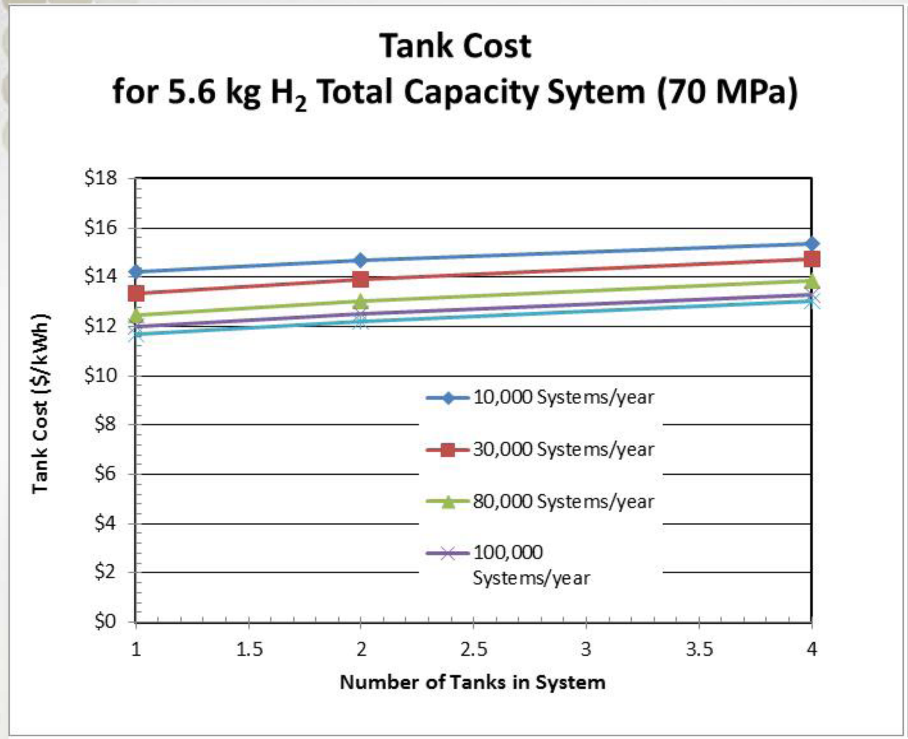


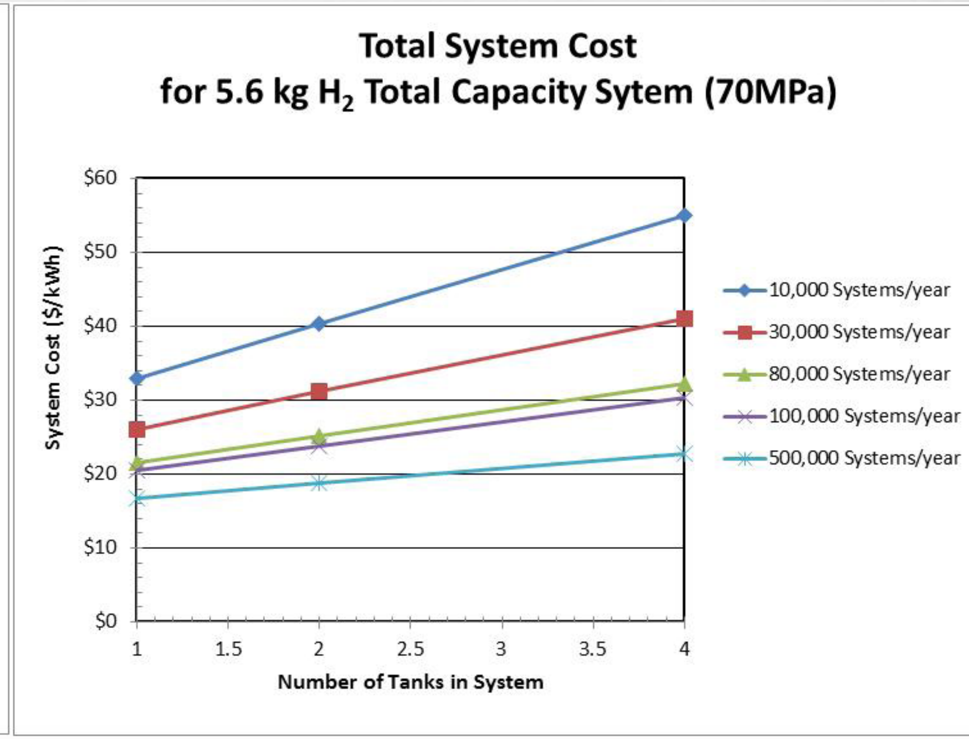


All cost results in 2007$

- Nearly linear variation of tank cost with H_2 storage capacity.
- Curvature in system cost curve is due to scaling of BOP components.
- Better amortization of BOP costs with large capacity systems leads to lower $/kWh cost.

Accomplishments: Sensitivity to Number of Storage Tanks

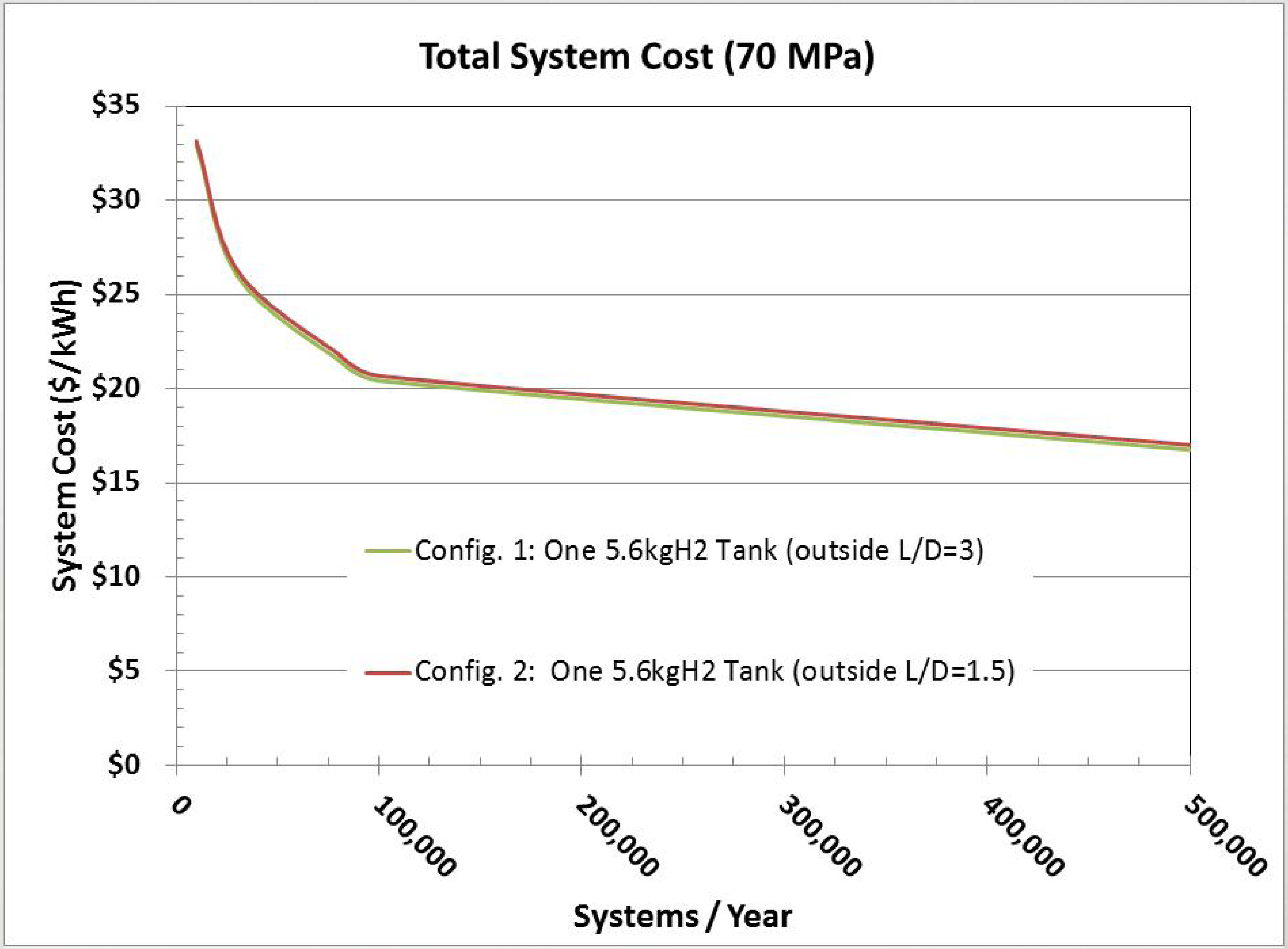




All cost results in 2007$

- Slight tank cost increase with increasing number of tanks in system.
- Significant system cost increase with increase number of tanks in system.

Accomplishments: Sensitivity to Length-to-Diameter Ratio



- No cost difference observed between tanks with differing L/D ratio.

Accomplishments: Off-Board Recycle Cost Analysis

- **Two on-board H_2 Storage systems considered by HSECoE:**
  - Alane:

    $AlH_3 \longrightarrow Al + 1.5\ H_2$ (onboard H_2 gen. reaction)
  - Ammonia Borane (AB):

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

- **Total cost of H_2 for a chemical system is composed of:**
  - Transportation to fueling station
  - Dispensing
  - On-board H_2 generation
  - Transportation back to recycle center
  - Spent fuel recycling ← Our Focus is the Off-Board Recycle Cost
  - Generation of source H_2 (to be used in spent fuel recycling)

DOE Target cost for all of above steps: $4/kgH_2$

Alane Off-Board Recycle Cost Analysis Process & Results

- **Modeling of Chemical Plant**
  - Based on dimethylethylamine (DMEA) process from ANL analysis
  - Quantify key mass & energy flows, process unit equipment
- **Capital Cost Estimation**
  - Based on modeled mass flows, energy use, reaction times in literature, etc.
  - Handbook capital cost estimates (not DFMA)
  - Standard installation markups for one-of-a-kind plants
- **Modeled using DOE H2A Models**[1]
  - nominal recycle cost: $4/kg$H_2$
- **Sensitivity Studies**
  - Single variable range: ~$2-$7/kgH_2
  - More potential for cost increase than for cost decrease

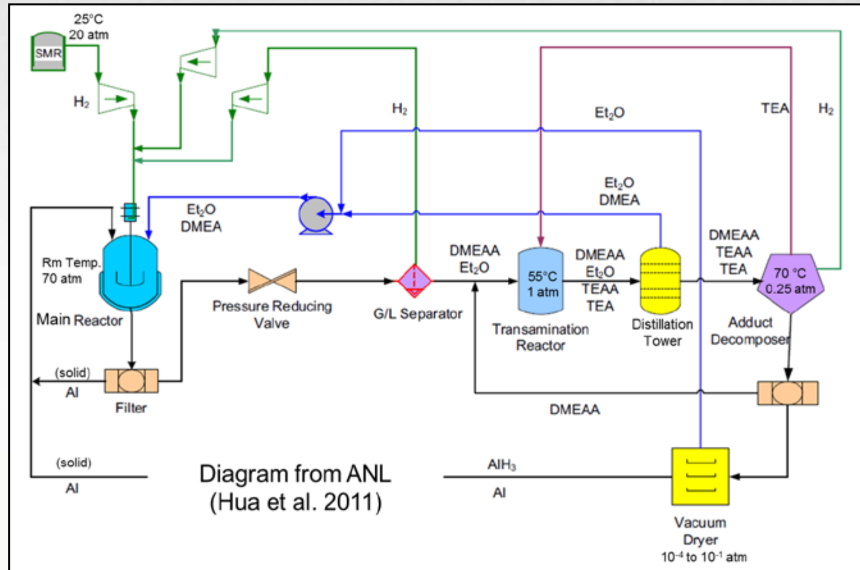
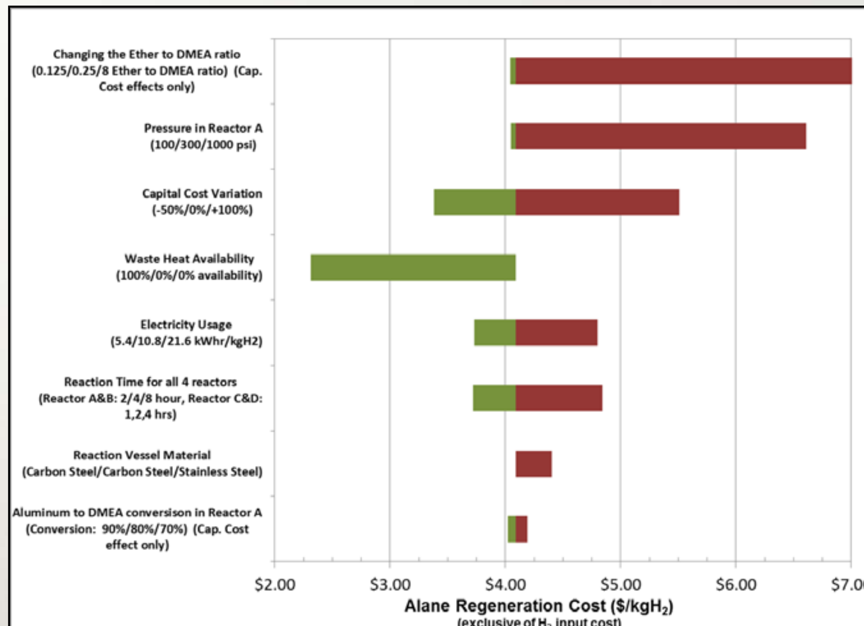


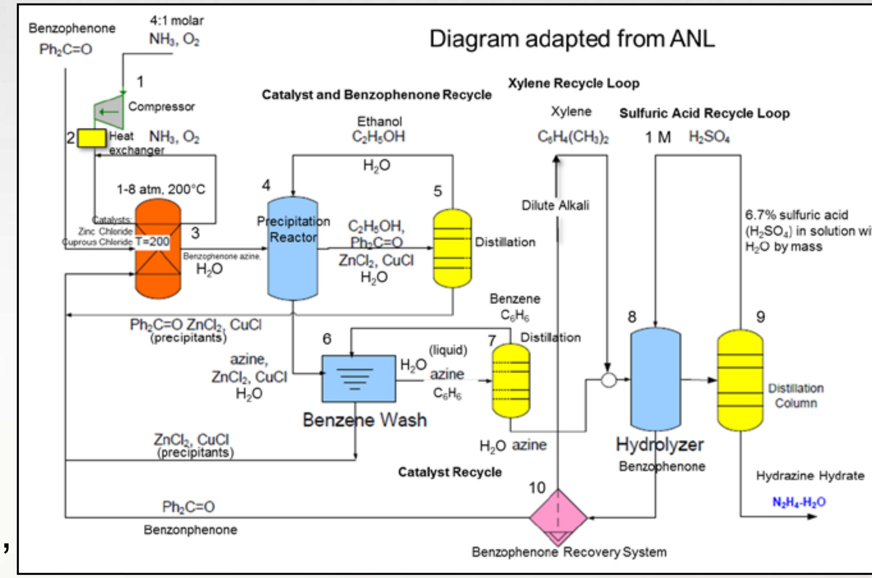
Fig. 3 – Process flowsheet for the regeneration of alane using dimethylethylamine.

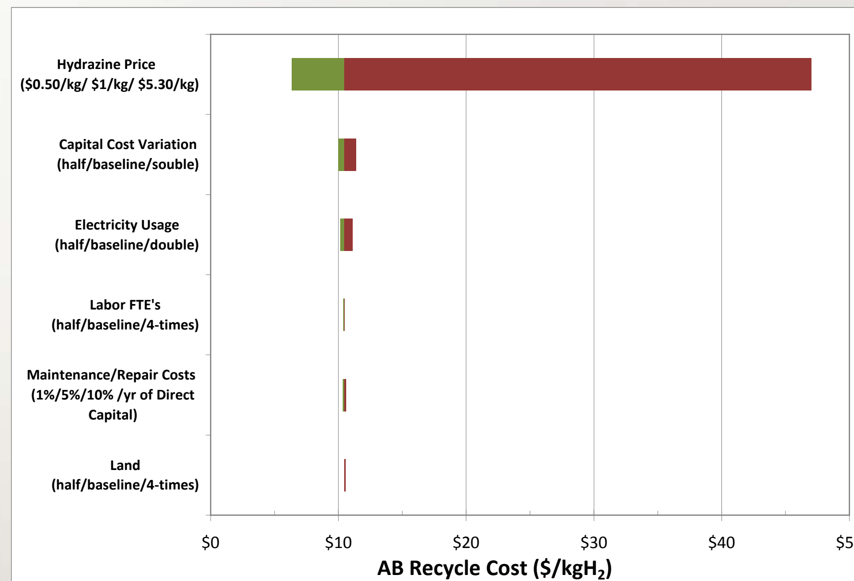


[1]http://www.hydrogen.energy.gov/h2a_analysis.html

Ammonia Borane Off-Board Recycle Cost Analysis Process

- **Modeling of Chemical Plant**
  - Based on LANL one-pot process using hydrazine
  - $BNH_2 + N_2H_4 \Rightarrow BH_3NH_3 + N_2$
  - **<u>Hydrazine quickly determined to be dominant factor in recycle cost</u>**





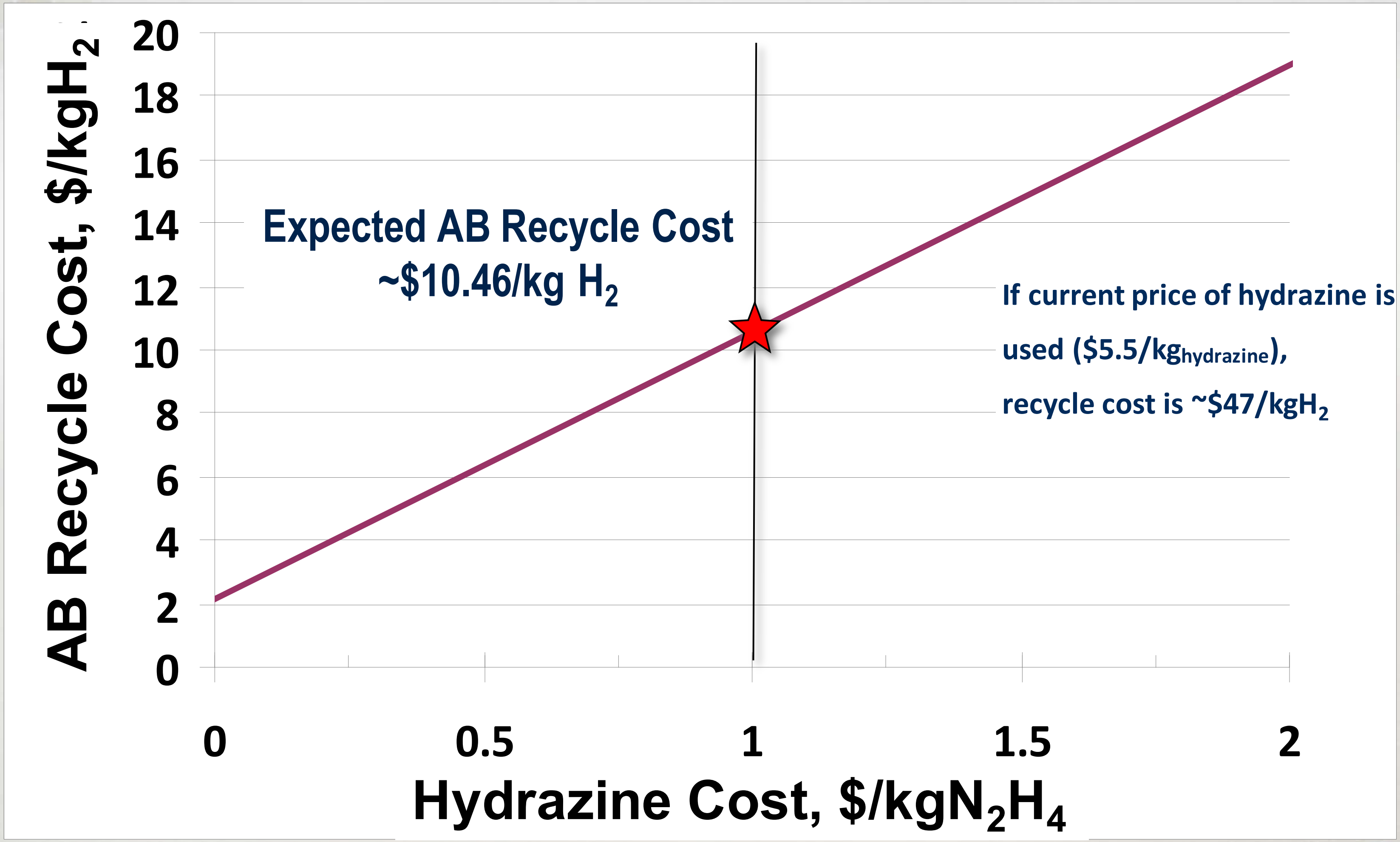
- **Modeling of Hydrazine Plant**
  - Based on Benzophenone process
  - Based on modeled mass flows, energy use, reaction times in literature, etc.

- **Capital Cost Estimation (of both plants)**
  - Sizing of hydrazine plant highly uncertain due to low process maturity

- **Modeled of Hydrazine Cost in H2A**
  - Nominal cost of Hydrazine: ~$1/kg_{Hydrazine}$
  - Current market price: $5.5/kg_{Hydrazine}$
  - This would be a significant breakthrough if achieved.

- **Sensitivity Studies**

Under a 'best case' scenario where hydrazine price is ~1/4th the current market price, H_2 recycle cost is currently ~$10.46/kg H_2 , significantly above DOE H_2 cost goals.



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)
- Hydrogen Storage Engineering Center of Excellence (HSECoE)
  - Pressure vessels assumptions and modeling
- Consultant Mark Paster
  - Chemical hydride parameters
- 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

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Proposed Future Work

- Remainder of FY 13
  - Pressure Vessels Cost Analysis
    - Continue vetting of results with industry and HSECoE
    - Complete report on results, assumptions, and methodology
  - Analyze Pre-preg fiber cost and conduct comparison of wet-winding vs. dry-winding
  - Continue to improve BOP cost estimates (particularly at low manufacturing rates)
  - Cost Analysis of On-Board H_2 Storage System
    - System to be selected by DOE
    - Cost analysis, vetting, and report
    - Will begin analysis in FY13 and conclude into FY14
- FY13 Activities
  - Continuation of Storage System Cost Analysis

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Summary

- Overview
  - In year 2 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
  - Detailed analysis of 35 and 70 MPa composite pressure vessels
  - Preliminary verification of cost analysis methodology
  - Examination of Alane and Ammonia Borane off-board recycle costs
- Collaborations
  - ANL & NREL under contract to provide cooperative analysis & vetting of assumptions/results
  - HSECoE, PNNL, Ford Motor Co., Lincoln Composites, Quantum, McClean-Anderson
- Future Work
  - Conclude vetting of pressure vessel cost analysis
  - Initiate cost analysis of next on-board storage systems

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Publications/Presentations

- James, B. D., Spisak, A. B. Colella, W. G., *Hydrogen Storage Cost Analysis,* annual report for the U.S. DOE EERE FCT program, July 2012.
- James, B. D., Colella, W. G.*, Alane and Ammonia Borane Off-Board Recycle Analysis Status,* presentation to U.S. DOE EERE FCT Headquarters, Forrestal Building, Washington D.C., Sept. 25th, 2012.
- James, B. D., Colella, W. G.*, Analysis of Recycling Alane and Ammonia Borane Off-Board Vehicles,* presentation to U.S. DOE Hydrogen Storage Engineering Center of Excellence (HSECoE), delivered remotely, Arlington, VA, Oct. 11th, 2012.
- James, B. D., Colella, W. G., Paster, M., *Energy, Emissions, and Economic Analysis of Off-board Recycling of Alane and Ammonia Borane for Hydrogen Fuel Cell Vehicles,* presentation to U.S. DOE EERE Fuel Pathways Integration Technical Team (FPITT), delivered remotely, Arlington, VA, Oct. 24th, 2012.
- James, B. D., Spisak, A.B., *Pressure Vessel Cost Analysis*, presentation to Storage Systems Analysis Working Group (SSAWG) & H2 Storage Tech Team, delivered remotely, Arlington, VA, Nov. 14th, 2012.
- James, B. D., Spisak, A.B., *Pressure Vessel Cost Analysis*, presentation to DOE Storage Principal Investigator Meeting, Washington DC (ARPA-E offices), Nov. 28th, 2012.
- James, B. D., Moton, J.M. "Updated Pressure Vessel Balance of Plant and System Costs," update to DOE Storage Team, Arlington, VA, March 12th, 2013.
- Colella, W.G. "Advanced Electrochemical Systems," *California Renewable Energy and Storage Technology Conference*, California State University Northridge, Northridge, CA, May 4th, 2013 (in preparation).
- James, B. D., Moton, J.M., Colella, W. G., "Advanced Hydrogen Compression Systems for Serving a Hydrogen Vehicle Refueling Infrastructure," *American Society of Mechanical Engineers (ASME) 2013 7th International Conference on Energy Sustainability*, Minneapolis, MN, July 14-19th, 2013 (in preparation).