Question and Answer

- Please type your question into the question box.
Onboard Type IV Compressed Hydrogen Storage System Cost Analysis
Funded by the U.S. Department of Energy’s Fuel Cell Technologies Office

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1/26/2016
Overview

• Cost methodology—DFMA® primer
• System diagram
• System cost status comparison between 2013 and 2015
• Cost reductions
  – Balance of Plant
  – Resin with lower density and cost
  – Carbon fiber from high volume process
• Cost increases
  – Doily removal
  – Manufacturing variations
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:
- Capital Cost
  - Installation
  - Initial Expenses
- Operating Expenses
  - Maintenance/Spare Parts
  - Utilities
  - Miscellaneous
- Used to calculate annual capital recovery factor based on:
  - Equipment Life
  - Interest Rate
  - Corporate Tax Rate

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

Production Volume Range of Analysis:
10,000 to 500,000 H₂ storage systems per year
System Diagram

• System cost based on a single tank configuration
• Balance of tank includes:
  • Integrated in-tank valve
  • Integrated pressure regulator block

Type 4 carbon fiber composite vessel with plastic liner

1 Manual Override
2 Filter
3 Check Valve
4 Pressure Transducer
5 Temperature Transducer
6 Thermally Activated Pressure Relief Device (TPRD)
7 Excess Flow Valve
8 Auto Solenoid Valve
9 Pressure Regulator
10 Manual Defuel Valve & Defueling Receptacle
11 Automated Shutoff Valve
12 Temperature Sensor
Process Flow Schematic
(Black indicates processes @500k systems/year)

- **Tank Boss**
- **Liner Formation (RotoMold)**
  - Cost/Line: $400k
  - Cycle Time: 130 min (5)
  - Laborers/Line: 0.6
- **Visual Inspection**
- **Liner Formation (Blow Mold)**
  - Cost/Line: $690k
  - Cycle Time: 1 min
  - Laborers/Line: 0.6
- **Visual Inspection**
- **Liner Annealing (Manual QC)**
  - Cost/Line: $440k
  - Cycle Time: 120 min (10)
  - Laborers/Line: 0.9
  - Laborers/Line: 2.5
- **Liner Bore Inspection**
- **Liner Annealing (Auto QC)**
  - Cost/Line: $560k
  - Cycle Time: 210 min (10)
  - Laborers/Line: 2
- **Liner Bore Inspection**
- **Liner Bore Inspection**
  - Laborers/Line: 2.25
- **B-Stage Curing (Continuous)**
  - Cost/Line: $315k
  - Cycle Time: 150 min (30)
  - Laborers/Line: 0.35
- **B-Stage Curing (Batch)**
  - Cost/Line: $60k
  - Cycle Time: 150 min (20)
  - Laborers/Line: 2.25
- **Full Cure (Pressurized)**
  - Cost/Line: $600k
  - Cycle Time: 480 min (192)
  - Laborers/Line: 2
- **Hydro Test**
  - Cost/Line: $270k
  - Cycle Time: 4 min
  - Laborers/Line: 2
- **Gaseous Leak Test**
  - Cost/Line: $2M
  - Cycle Time: 12 min
  - Laborers/Line: 1
- **BOP & System Assembly**
- **Visual Inspection**
- **Tank Shoulder Foam**
  - Cost/Line: $400k
  - Cycle Time: 310 min (2)
  - Laborers/Line: 0.75
- **Fiber Winding**
  - Cost/Line: $400k
  - Cycle Time: 1 min
  - Laborers/Line: 0.6
Storage System Cost Reduced by 12%

*Cost at 500,000 systems per year
**Integrated BOP**

Integration of functionality reduces system cost

**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 update | $4.37/kWh
2015 | Integrated pressure regulator block will reduce number of fittings (translates to other H₂ storage systems) | $3.64/kWh

(projected 9% system cost savings)
Lower-Cost, Low-Density Resin (as replacement for epoxy resin in pressure vessel)

PNNL, Hexagon Lincoln, and Ford Collaboration

- Alternative lower-cost and lower-density vinyl ester resin
- Used alternate fiber sizing

Sub-scale experimental burst test results used to calibrate finite element model

- Vinyl ester resin reduced composite mass by 6.6%
- Vinyl ester resin + alt sizing reduced composite mass by 9.0%
- Lower density resin and lower volume fraction largely responsible
- But some reduction in CF due to higher translation efficiency

<table>
<thead>
<tr>
<th>Weight (kg)</th>
<th>Hoop</th>
<th>Helical</th>
<th>Doilies</th>
<th>Total</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013 Baseline (with doilies)</td>
<td>40.2</td>
<td>48.0</td>
<td>2.8</td>
<td>91.0</td>
<td>$16.76/kWh</td>
</tr>
<tr>
<td>Calibrated Performance Model (no doilies)</td>
<td>34.3</td>
<td>72.3</td>
<td>N/A</td>
<td>106.6</td>
<td>$16.17/kWh</td>
</tr>
<tr>
<td>Calibrated Model + Low-Cost Resin</td>
<td>31.4</td>
<td>68.2</td>
<td>N/A</td>
<td>99.6</td>
<td></td>
</tr>
<tr>
<td>Calibrated Model + Low-Cost Resin + Alternate Sizing</td>
<td>30.3</td>
<td>66.7</td>
<td>N/A</td>
<td>97.0</td>
<td></td>
</tr>
</tbody>
</table>

(projected 4% system cost savings)
ORNL Low Cost Fiber

Textile precursor process projected to reduce cost of CF by enabling higher volume CF manufacturing

Approach to applying CF cost reduction to total system cost

- Established baseline of T700S CF cost (not price) from ORNL’s report
  - Increased CF production volume
  - Baseline established: $11.61/lb<sub>CF</sub>

- Switch to ORNL PAN MA CF
  - Reduced CF processing cost
  - Cost reduced to $11.16/lb<sub>CF</sub>

- Switch to higher precursor production volumes (41k tonnes/yr)
  - Reduced precursor processing cost
  - Cost reduced to $9.49/lb<sub>CF</sub>
  - (Total cost reduction of 18.3%)

- Applied cost ratio to 2013 DOE record price (assuming same markup for price)
  - New price of CF: $10.63/lb<sub>CF</sub> (2007$)

- Inserted new price into DFMA model to get total system cost
  - $15.04/kWh (2007$)

All costs in current year dollars, unless otherwise specified
### ORNL Low Cost Fiber

ORNL CF has similar tensile strength to conventional T700S but is less expensive to produce due to economies of scale.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2013 Baseline System (T-700S)</th>
<th>Reported ORNL Textile PAN MA CF</th>
<th>Textile PAN MA CF as used in SA’s System Cost Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultimate Tensile Strength</strong></td>
<td>711 KSI</td>
<td>577 KSI (in 2014 AMR(^1)) 655 to 750+ KSI (ORNL(^2))</td>
<td>711 KSI</td>
</tr>
<tr>
<td><strong>Modulus</strong></td>
<td>33 MSI</td>
<td>39.8 MSI (2014 AMR)</td>
<td>NA</td>
</tr>
<tr>
<td><strong>TOW</strong></td>
<td>24k</td>
<td>24K</td>
<td>24K</td>
</tr>
<tr>
<td><strong>Filament diameter</strong></td>
<td>7 micron</td>
<td>7 micron</td>
<td>7 micron</td>
</tr>
<tr>
<td><strong>CF Density (dry)</strong></td>
<td>1.8 g/cc</td>
<td>1.78-1.81 g/cc</td>
<td>1.8 g/cc</td>
</tr>
<tr>
<td><strong>CF Price (2007$)</strong></td>
<td>$13/lb (at 25,000 tonnes/year)</td>
<td>Price NA</td>
<td>$10.63/lb (at 25,000 tonnes/year)</td>
</tr>
<tr>
<td><strong>System Cost</strong></td>
<td>$16.76/kWh</td>
<td>NA</td>
<td>$15.04/kWh</td>
</tr>
</tbody>
</table>

18.3% cost reduction from $13/lb projected 11% system cost savings


\(^2\) Personal communication with Dave Warren, ORNL, 19 September 2014. Results not yet published.
Vessel/Manufacturing Design Change—Doily Removal

- Doilies are strips of CF applied to the dome to provide local reinforcement
  - Reduce number of helical windings
  - Transfers load to hoop windings
  - Reduces composite materials which reduces total cost

- Doilies introduce High Vol. Prod. challenges
  - Increases manufacturing complexity
  - Creates possibility for single-point failures

- Doilies removed from 2015 design after input from vessel manufacturers resulting in $1.36/kWh increase
  - May still be useful in reducing composite mass in the future but R&D needed

Projected 9% system cost increase
Addition of Explicit Manufacturing Variation COV (COV = Coefficient of Variation)

Pressure vessels are designed to withstand pressures with a safety factor 2.25 greater than the nominal fill pressure.
Addition of Explicit Manufacturing Variation COV (COV = Coefficient of Variation)

In high volume manufacturing, tank burst pressures are normally distributed (shown in red) due to statistical variations in carbon strength fiber and manufacturing process.

Nominal Fill Pressure

Safety Factor (2.25)
Addition of Explicit Manufacturing Variation COV (COV = Coefficient of Variation)

To ensure tanks are designed to meet the 2.25 safety factor, manufacturers design tanks with additional carbon fiber to meet $3\sigma$ quality standards.

Extra margin results in 99.7300204% of tanks won’t rupture below 22,500 psi.
## Uncertainty Analysis

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Low</th>
<th>Most Probable</th>
<th>High</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CF Composite Mass</strong></td>
<td>kg</td>
<td>92</td>
<td>97</td>
<td>102</td>
<td>Based on the difference of 5 kg between the 2013 PNNL/Ford and ANL analyses. The distribution was assumed to be symmetric with a range of ±5 kg.</td>
</tr>
<tr>
<td><strong>Polymer Base Price</strong></td>
<td>$/kg</td>
<td>1.34</td>
<td>1.79</td>
<td>2.69</td>
<td>Assumed -10% to +20%. Baseline is SA projection of CF fiber using ORNL low-cost precursor.</td>
</tr>
<tr>
<td><strong>Carbon Fiber Base Price</strong></td>
<td>$/kg</td>
<td>21.08</td>
<td>23.43</td>
<td>28.11</td>
<td>Assumed +25%. Baseline is approximate commodity pricing.</td>
</tr>
<tr>
<td><strong>Blow Molding Capital Cost</strong></td>
<td>$</td>
<td>443,955</td>
<td>591,940</td>
<td>739,925</td>
<td>Assumed ±25%. Baseline is approximate equipment cost.</td>
</tr>
<tr>
<td><strong>Blow Molding Cycle Time</strong></td>
<td></td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>Assumed -50% to +100%. Range based on our level of uncertainty in cycle time.</td>
</tr>
<tr>
<td><strong>Wet Winding Capital Cost</strong></td>
<td>$</td>
<td>274,523</td>
<td>343,154</td>
<td>600,519</td>
<td>Assumed ±50% to +100%. Baseline is average of several vendor price quotes.</td>
</tr>
<tr>
<td><strong>Average Fiber Laydown Rate</strong></td>
<td>m/min</td>
<td>18</td>
<td>26</td>
<td>32</td>
<td>Assumed -8 m/min to +6 m/min. Range and average taken from informal survey of winding literature and discussions with PNNL regarding winding times.</td>
</tr>
<tr>
<td><strong>Curing Oven Capital Cost</strong></td>
<td>$/ft</td>
<td>1,506</td>
<td>2,008</td>
<td>2,511</td>
<td>Assumed ±25%. Baseline is based on vendor quotation.</td>
</tr>
<tr>
<td><strong>Conveyor Capital Cost</strong></td>
<td></td>
<td>0.20</td>
<td>1.00</td>
<td>1.50</td>
<td>Assumed -80% to +50%. Range is deliberately wide as conveyor costs are relatively low and thus % uncertainty is high.</td>
</tr>
<tr>
<td><strong>B-Stage Dwell Time</strong></td>
<td>hrs</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>Assumed ±0.5 hrs. Baseline from vendor input. Range based on eng. judgement.</td>
</tr>
<tr>
<td><strong>Full Cure Dwell Time</strong></td>
<td>hrs</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>Assumed ±50%. Baseline from vendor input. Range based on eng. judgement.</td>
</tr>
<tr>
<td><strong>Compr. System Capital Cost</strong></td>
<td>$</td>
<td>834,258</td>
<td>1,668,518</td>
<td>3,337,036</td>
<td>Assumed -50% to +100%. Baseline from vendor input. Range based on eng. judgement.</td>
</tr>
<tr>
<td><strong>BOP Cost Factor</strong></td>
<td></td>
<td>0.75</td>
<td>1.00</td>
<td>1.25</td>
<td>Assumed ±25%. Range based on eng. judgement.</td>
</tr>
<tr>
<td><strong>Resin Cost</strong></td>
<td>$/kg</td>
<td>1.58</td>
<td>4.52</td>
<td>7.69</td>
<td>Assumed -65% to +70%. Range based on same ±% used in 2013 DOE Record. Baseline based on vendor quote of PNNL low-cost resin at high production quantity, inclusive of 25% overage for winding wastage.</td>
</tr>
<tr>
<td><strong>Foam Dome Protection</strong></td>
<td>$/kg</td>
<td>1.25</td>
<td>2.50</td>
<td>5.00</td>
<td>Baseline from online pricing for polyurethane foam. Assumed -50% and +100% based on ranges in price and eng. judgement.</td>
</tr>
</tbody>
</table>
Sensitivity Study

- Carbon Fiber Base Price: $21.08/kg to $28.11/kg
- BOP Cost Factor: 0.75 to 1.25
- Composite Mass: 92 kg to 102 kg
- Resin Cost: $1.58/kg to $7.69/kg
- Wet Winding Capital Cost: $274,523 to $600,519
- Average Fiber Laydown Rate: 31 m/min to 18 m/min
- Polymer Base Price: $1.34/kg to $2.69/kg
- Compression System Capital Cost: $834,258 to $3,337,036

System Cost ($/kWh):
- $13
- $14
- $15
- $16
- $17
Monte Carlo Analysis Results (Stochastic multivariable error analysis)

90% confidence the cost will be between $14.01 and $16.49/kWh.
Conclusions

• Projected storage system costs decreased by a net 12% from 2013 baseline due to technology improvements and design adjustments
  – Cost reductions identified result in a projected decrease in cost of 24%
    • Integrated balance of plant with reduced fittings and part counts
    • Low-density lower-cost vinyl ester resin
    • High volume textile processed carbon fiber precursor
  – Adjustments were made to the tank design that raised cost by a projected 12% but result in improved manufacturability and performance
    • Removed doilies to accommodate high volume manufacturing
    • Increased tank mass to account for manufacturing variation

• CF usage reduction remains key system cost reduction strategy
  – Mirai demonstrates feasibility of reduced CF mass from alternative winding patterns
  – Reduction in manufacturing variations could reduce CF mass and cost
  – Other approaches (e.g. vacuum infiltration of resin) are currently being considered
  – Alternative fibers (e.g. glass)

• Further optimization of BOP components
Acknowledgement

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References

Questions?
Thank You

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Two Tank Configuration

- System cost for two-tank configuration is higher than for single tank
- Two-tank configuration duplicates the integrated in-tank valve
- Overall carbon fiber mass is higher for two-tank configuration

Type 4 carbon fiber composite vessel with plastic liner

- System cost for two-tank configuration is higher than for single tank
- Two-tank configuration duplicates the integrated in-tank valve
- Overall carbon fiber mass is higher for two-tank configuration
Monte Carlo Analysis Results
(Stochastic multivariable error analysis)

Single Vessel: 90% confidence the cost will be between $14.01 and $16.49/kWh
Dual Vessel: 90% confidence the cost will be between $15.56 and $18.29/kWh