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| <b>DOE Hydrogen and Fuel Cells Program Record</b>  |                         |  |
| <b>Record #: 15013</b>   | <b>Date: 9/30/2015</b>  |   |
| <b>Title: Onboard Type IV Compressed Hydrogen Storage System - Cost and Performance Status 2015</b>  |                         |   |
| <b>Update to: Record 13010</b>   |                         |   |
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| <b>Peer reviewed by: Representatives from Ford Motor Co., Hexagon-Lincoln, Pacific Northwest National Laboratory, Argonne National Laboratory, Oak Ridge National Laboratory, and Strategic Analysis, Inc.</b> |                         |   |
| <b>Approved by: Ned Stetson and Sunita Satyapal</b>  | <b>Date: 11/25/2015</b> |   |

**Item**

The projected cost and capacities (gravimetric and volumetric) of the 700 bar Type IV compressed hydrogen storage system have been updated to reflect the status in 2015 (see table 1) as follows:

- System Cost
  - \$14.8/kWh [-\$0.8/kWh, +1.7/kWh] at manufacturing volumes of 500,000 systems/year,
  - Approximately \$17/kWh at manufacturing volumes of 100,000 systems/year
- Gravimetric Energy Density: 1.40±0.04 kWh/kg system, and
- Volumetric Energy Density: 0.81±0.01 kWh/L.

**Summary**

This record summarizes the status in FY 2015 of the projected capacities and manufacturing costs of 700 bar Type IV compressed hydrogen storage systems, storing 5.6 kg of usable hydrogen, for onboard light-duty automotive applications when manufactured at a volume of 500,000 systems per year. The current projected performance and cost of these systems are presented in Table 1 against the DOE Hydrogen Storage System targets [1]. These analyses were performed in support of the Hydrogen Storage Program of the DOE Fuel Cell Technologies Office (FCTO) within the Office of Energy Efficiency and Renewable Energy. This Record was peer reviewed by representatives of industrial stakeholders, national laboratories and DOE representatives including: Ford Motor Co., Hexagon-Lincoln, Strategic Analysis, Inc. (SA), Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL). Industry stakeholder participants voluntarily furnished relevant confidential commercial information to the government in support of the analysis represented in the Record. This confidential commercial information is not publicly available and is customarily held in confidence.

**Table 1: Projected cost and performance of 700 bar Type IV compressed hydrogen storage systems compared to Department of Energy technical targets.**

|                                   | Units         | 2020 Target [1] | Ultimate Target [1] | 2013 Status [2] | 2015 Status                    |
|-----------------------------------|---------------|-----------------|---------------------|-----------------|--------------------------------|
| <b>Gravimetric Capacity</b>       | kWh/kg system | 1.8             | 2.5                 | 1.5             | 1.40±0.04 <sup>a</sup>         |
| <b>Volumetric Capacity</b>        | kWh/L system  | 1.3             | 2.3                 | 0.8             | 0.81±0.01 <sup>a</sup>         |
| <b>Cost at 500,000 units/year</b> | 2007\$/kWh    | 10              | 8                   | 16.8            | 14.8 [-0.8, +1.7] <sup>b</sup> |

<sup>a</sup> Uncertainty in capacity represents the 90% confidence interval. The uncertainty is based on the range of tank masses measured by PNNL and an estimated 10% mass uncertainty in the balance of plant (BOP) components as described further in the Uncertainty Analysis Section.

<sup>b</sup> Uncertainty in cost is calculated using Monte Carlo analysis and represents the 90% confidence interval. The ranges of uncertainties and the values varied for the Monte Carlo analysis are summarized in Table 6.

### **Assumptions and Rationale**

In FY 2015, ANL and SA conducted analyses to project updated system performance (finite element analysis) and costs (Design for Manufacturing and Assembly<sup>®</sup>) for 700 bar Type IV<sup>1</sup> compressed hydrogen storage systems based on technology and tank manufacturing improvements, and design knowledge gained in the past two years. This update reflects the following changes in materials and tank design compared to the 2013 DOE Record design.

- Part reductions in the balance of plant (BOP) through component integration (integrated BOP)
- Carbon fiber composite mass reduction through use of a lower cost resin that also has a low-density (low-cost resin)
- Carbon fiber cost reductions due to a lower cost carbon fiber based on a high volume textile precursor fiber process (low-cost precursor fiber)
- Composite mass increase due to replacement of the previously used carbon fiber dome reinforcements (doilies<sup>2</sup>) with additional helical windings as per current industrial practice to
  - minimize risk of single-point failure
  - reduce manufacturing complexity

Results from the analyses were presented by ANL and SA at the 2015 DOE Hydrogen and Fuel Cell Program Annual Merit Review and Peer Review Evaluation meeting [3, 4]. All system capacities are reported as net usable capacity able to be delivered to the fuel cell, and costs are reported in 2007\$ to remove inflation from year-to-year comparisons. The storage system includes the interface with the station fueling dispenser (i.e. receptacle and communication hardware for refueling), the storage vessel itself, and balance of plant components (BOP). The BOP includes safety devices, regulators, electronic controllers and sensors, all onboard conditioning equipment necessary to store the hydrogen (e.g. filters), as well as mounting hardware and gas lines to connect the storage system components. Figure 1

<sup>1</sup> Type IV refers to pressure vessels with a polymer liner wrapped completely with a composite of fiber and resin.

<sup>2</sup> Doilies refer to discrete strips of carbon fiber composite that are applied to reinforce the endcap. The doilies are held in place by overwrapping with continuous carbon fiber and become a cohesive part of the load bearing composite structure.

shows a schematic of the system diagram used in performance and cost analyses. This update also reflects significant changes made to the cost and performance models. The cost models were updated to explicitly account for tank performance uncertainty due to statistical manufacturing variations which result in increased carbon fiber composite mass usage to ensure that tanks pass required certification/quality control tests. The performance model was modified to account for removal of the doilies.

### **System Performance Properties**

The ANL tank performance model was updated for the 2015 analysis. The updated model uses the finite element code ABAQUS calibrated against sub-scale experimental 35-L burst-tested tanks [5] to obtain the translation efficiency for the fiber winding process. The composite overwrap was modeled with 33 hoop layers and 20 helical layers based on tank weight and burst pressure experimental results from PNNL. This resulted in an 11.22 mm thick hoop layer and a 13.6 mm helical thickness corresponding to 8.97 kg composite in the hoop windings and 17.15 kg of composite in the helical windings. The modeled composite mass was found to be in good agreement with the experimental tanks, within 1% of the average composite mass. Furthermore, the ABAQUS model results showed that the highest composite strain occurred in the innermost hoop layer which is consistent with the failure pattern observed in the test tanks. Using the test tank dimensions, burst pressure, and mass of carbon fiber composite, the finite element analysis predicted that the composite failure strain occurred at 1.44%, or about 85% of the tensile strain specified in Toray's technical data sheet for T700 composite [6]. Tanks in these analyses are designed with a 2.25 safety in reference to FMVSS 304 (49 CFR 571.304).<sup>3</sup> The tanks in the test program that generated burst test data used to calibrate the model have an additional amount of composite to account for variations in carbon fiber and manufacturing effectively increasing the safety factor above 2.25. The amount of additional composite used to account for fiber and manufacturing variation is unique to each manufacturer. However, as described below, separate cost modeling parameters representing coefficients of variation for fiber and manufacturing variations ( $COV_{\text{Fiber}}$  and  $COV_{\text{Manufacturing}}$ ) have been added to numerically represent these statistical variations and to allow the system cost impact to be assessed.

The calibrated ABAQUS model described above was used to project the performance of a full-sized 147 L tank with 5.6 kg net usable  $H_2$ .<sup>4</sup> Table 2 summarizes analysis results for cases considered for 2015 as well as the 2013 tank for comparison. The 2013 tank was projected to have a composite mass of 91.0 kg. A tank with the same design as the 2013 tank analyzed with the 2015 calibrated model was projected to have a composite mass of 91.7 kg thereby showing close agreement between the previous and updated models. Note that the tank analyzed in the 2013 record [2] included doilies for local reinforcement of the dome. The addition of doilies was projected to reduce the number of helical windings which must be wound through the cylinder section resulting in a reduction of the total composite mass. However, doilies were eliminated from the 2015 tank design based on tank manufacturer experience with

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<sup>3</sup> The 2.25 safety factor requires that a 700 bar pressure vessel be designed to burst at a pressure no less than 1,575 bar when tested.

<sup>4</sup> The total tank capacity is 5.9 kg  $H_2$ .

manufacturability. Doilies may still represent an opportunity to reduce the carbon fiber composite, but further work is required to demonstrate and validate their manufacturability at high volume. In the 2015 updated tank design, the composite overwrap was modeled with 46 hoop layers, 32 helical layers reflecting failure modes from the PNNL project tank burst results, and no doilies. The hoop and helical thicknesses were projected to be 15.64 mm and 21.76 mm, respectively, and the total composite weight was projected to be 106.6 kg for the 2015 tank, requiring an additional 15.6 kg composite as a result of removing the doilies and adding more helical layers.<sup>5</sup>

In addition, two other variations of the 2015 tank design were also considered: one design incorporated the vinyl ester low-cost resin, and a second design incorporated the vinyl ester resin with alternate sizing.<sup>6</sup> These different material substitutions studied in PNNL’s low-cost tank project reflect variations in the resin density, carbon fiber (CF) volume fraction, and total composite mass [5]. The very small percentage reduction in the CF weight for the two alternate designs projected by the updated model was in good agreement with PNNL’s test results. While there is a meaningful reduction in the composite weight (from 106.6 kg for the 2015 tank) for each of the two variations (99.6 and 97 kg), the reduction is primarily due to a reduction in the density of the resin (1.14g/cc vs. epoxy at 1.25g/cc) and lower resin volume fraction due to increased squeeze-out with the lower viscosity vinyl ester resin. The contribution to the total weight from hoop, helical, and doilies windings are summarized in Table 3.

**Table 2: ABAQUS results for Type IV, 700-bar, 147-L tanks.**

|  | Doilies | Density (g/cc) |       |           | Fiber vol.% | Weight (kg) |       |       |
|--|---------|----------------|-------|-----------|-------------|-------------|-------|-------|
|  |         | Fiber          | Resin | Composite |             | Fiber       | Resin | Total |
| 2013 Baseline [2]                                    | Yes     | 1.8            | 1.25  | 1.58      | 60.0        | 62.2        | 28.8  | 91.0  |
| <b>2015 Updates</b>                                  |         |                |       |           |             |             |       |       |
| Calibrated Performance Model                         | No      | 1.8            | 1.25  | 1.58      | 60.0        | 72.9        | 33.8  | 106.6 |
| Calibrated Model + Low-Cost Resin                    | No      | 1.8            | 1.14  | 1.55      | 62.2        | 72.0        | 27.6  | 99.6  |
| Calibrated Model + Low-Cost Resin + Alternate Sizing | No      | 1.8            | 1.14  | 1.57      | 64.7        | 72.0        | 25.0  | 97.0  |

<sup>5</sup> Previous analysis by ANL of the 2013 baseline system showed that removing the doilies increased the mass of carbon fiber composite in the tank from 91 kg to 102 kg, representing a decrease of ~7% in the gravimetric capacity of the system.

<sup>6</sup> Sizing is a proprietary coating that is applied to the carbon fiber, protecting the carbon fiber during handling and processing (e.g., weaving). Sizing also holds filaments together in individual tows to reduce fuzz, improve processability and increase interfacial shear strength between the fiber and matrix resin.

<http://www.compositesworld.com/articles/the-making-of-carbon-fiber>

**Table 3: Composite weight for tanks with and without doilies.**

|  | Doilies | Weight (kg) |         |         | Total |
|--|---------|-------------|---------|---------|-------|
|  |         | Hoop        | Helical | Doilies |       |
| 2013 Baseline [2]                                    | Yes     | 40.2        | 48.0    | 2.8     | 91.0  |
| Calibrated Performance Model                         | No      | 34.3        | 72.3    | N/A     | 106.6 |
| Calibrated Model + Low-Cost Resin                    | No      | 31.4        | 68.2    | N/A     | 99.6  |
| Calibrated Model + Low-Cost Resin + Alternate Sizing | No      | 30.3        | 66.7    | N/A     | 97.0  |

Results from the ANL system performance model were used by SA to project the high volume manufacturing cost of 700 bar Type IV compressed hydrogen storage systems. In particular, cost analysis is based on the CF composite projected by ANL for the Calibrated Model + Low-Cost Resin + Alternate Sizing shown in Table 2 and Table 3 (97 kg composite with 64.7% by volume CF).

### **System Cost Analysis**

Cost analyses were updated for 700-bar compressed hydrogen storage systems to project the cost impact of design and material changes since the 2013 baseline system was reported [2]. SA applied a Design-for-Manufacture and Assembly® (DFMA®) cost methodology to project the high volume cost to manufacture compressed hydrogen storage systems. DFMA® is a process-based cost analysis methodology which projects material and manufacturing cost of the complete system by modeling specific manufacturing steps. The cost analysis results reported are the cost to manufacture storage systems, not the price. The system cost results do not include mark-up for profit, one-time costs such as non-recurring engineering costs, and general expenses; however, some components for the system (e.g. valves, gas lines, etc.) are purchased and include vendor markup. System costs are reported in 2007 dollars and were deflated where appropriate using the Producer Price Index: Finished Goods (PPIFG) [7]. Key material cost, capital cost, and processing assumptions are summarized in Table 4. Material costs were selected based on discussions with suppliers and coordinated with tank and automotive OEMs for secondary verification. A summary of the modeled fabrication, assembly, and testing steps used to manufacture 700 bar pressure vessels is presented in Table 5. Prices for CF and resin changed from the 2013 prices due to improvements as discussed below. The analysis is based on T-700S fiber for tow sizes of either 12k or 24k, which are similar in performance and cost. The aluminum base year price was adjusted from 2007\$ to 2012\$ based on feedback from the DOE Hydrogen Storage Tech Team, which lead to a negligible \$0.01/kWh reduction in system cost. Other changes in material and capital costs reflect adjustments to the PPIFG.

**Table 4: Comparison of key cost and processing assumptions used in 2013 and 2015 for bulk 700 bar Type IV compressed hydrogen storage system.**

| Key Cost Assumptions <sup>a</sup>        | Units  | 2013 Values | 2015 Values | Notes                    |
|--|--------|-------------|-------------|--------------------------|
| System Production Volume                 | #/year | 500,000     | 500,000     |                          |
| Carbon Fiber                             | USD/kg | 28.67       | 23.43       | Low-cost precursor fiber |
| Resin for Carbon Fiber                   | USD/kg | 7.09        | 4.52        | Low-cost resin           |
| High Density Polyethylene (HDPE) (Liner) | USD/kg | 1.77        | 1.77        |                          |
| Aluminum (Boss)                          | USD/kg | 4.75        | 4.10        | Footnote b               |
| Blow Molding Capital Cost                | \$     | 592,916     | 591,940     | Footnote c               |
| Wet Winding Capital Cost                 | \$     | 343,719     | 343,154     | Footnote c               |
| Average Fiber Laydown Rate               | m/min  | 26          | 26          |                          |
| Curing Oven Capital Cost                 | \$/ft  | 2,008       | 2,008       |                          |
| B-Stage Dwell Time                       | hrs    | 2.5         | 2.5         |                          |
| Full Cure Dwell Time                     | hrs    | 8           | 8           |                          |
| Helium Pressure Test Rig Capital Cost    | \$     | 1,671,267   | 1,673,747   | Footnote c               |

<sup>a</sup> All costs are reported in 2007\$.

<sup>b</sup> The aluminum base year price was adjusted from 2007\$ to 2012\$.

<sup>c</sup> Small differences in capital equipment costs between 2013 and 2015 are due to updates to the CPI reported by the U.S. Department of Labor. For example, the Blow Molding Capital Cost in both 2013 and 2015 is based on the same quoted cost of \$690,000 in 2012. The difference of 0.2% reflects updates to the price index made between the 2013 and 2015 analyses.

**Table 5: Fabrication, assembly, and testing processes for 700 bar Type IV pressure vessel.**

| Step Number | Function  |
|-------------|---|
| 1           | HDPE liner formation via blow molding                           |
| 2           | Visual inspection of the liner                                  |
| 3           | Liner thermal annealing   |
| 4           | Liner final bore inspection                                     |
| 5           | Fiber wet winding operation                                     |
| 6           | B-stage cure of the composite fiber                             |
| 7           | Full-cure of the composite fiber                                |
| 8           | Hydro (water) test in accordance with CGA C-1 protocols         |
| 9           | Gaseous helium leak test in accordance with ANSI NGV2 protocols |

Since the last update in 2013 [2], a number of design changes and material advances have been incorporated into the cost model. Material changes made since the 2013 baseline include the low-cost, low-density resin identified by PNNL and a low-cost CF from a polyacrylonitrile/methyl acrylate comonomer precursor based on a high volume textile fiber process developed by ORNL. Design changes from the previous baseline include further integration of the BOP, removal of doilies, and explicit accounting for manufacturing variations. A single variable sensitivity analysis was performed to project the approximate cost impact for each of these five changes compared to the 2013 baseline. The relative impact of each component change computed versus the 2013 baseline is presented in the waterfall chart in Figure 2. Note that the 2015 status is a result of the cumulative impact of the five changes applied together, thus the sum of the individual cost reductions due to the single variable sensitivity

analyses cannot be simply added together to achieve the same end result. The waterfall chart shown in Figure 2 qualitatively illustrates how each change contributed to reducing the manufacturing cost from 2013 baseline to the 2015 status by 12%.

A discussion of each of the five changes to design and materials is presented in the following paragraphs. While Monte Carlo error analysis of the system cost projection (discussed in the Uncertainty Analysis section) predicts an uncertainty of \$2.48/kWh at the 90% confidence interval, the costs reported below to the \$0.01/kWh suggest a level of cost discernment that exceeds the precision of the analysis. This is done to facilitate comparisons between individual changes and is consistent with standard practice to maintain high precision of intermediate calculations within the model to avoid introducing rounding errors.

Discussions with the U.S. DRIVE<sup>7</sup> Hydrogen Storage Tech Team prompted a review of the number of fittings required in the BOP leading to component integration and part reduction for the low-pressure components. The system configuration used in the 2015 cost analysis is shown in Figure 1. In the current system, a DFMA<sup>®</sup> analysis was conducted on a forged stainless steel (SS316) integrated pressure regulator block with high tolerance machining and O-rings to provide a proper seal for coupling components. Figure 3 shows a diagram of the integrated pressure regulator block, bringing together six low-pressure components (downstream of the pressure regulator). By combining the components into one unit, the integrated pressure regulator block body adds a component to the BOP list but reduces overall cost by eliminating piping and fittings. The combined cost reduction of the fitting component costs and the integrated pressure regulator block for a single tank system is \$1.34/kWh from the 2013 tank at 500,000 systems per year.

PNNL identified a low-cost, lower density (vinyl ester) resin to replace the epoxy resin in the carbon composite. The new resin reduced the total composite cost by lowering both the total mass of resin required as well as using a less expensive resin. The cost impact of using this alternative resin was modeled by adjusting four key parameters: 1) a reduction in composite mass required to meet the designed burst pressure, 2) a reduction in the resin density, 3) an increase in the CF volume fraction, and 4) a reduction in the resin price. The total mass of composite required to meet the design burst pressure was reduced by ~10% as measured by burst testing while the material cost of the resin was reduced by ~36% as measured by price quotation. These changes result in a reduction of \$0.59/kWh over the 2013 baseline at 500k systems per year.

Compressed hydrogen storage system cost reduction was also achieved through use of a lower cost CF developed at ORNL. The ORNL-developed CF is a replacement for the baseline Toray T-700S CF and is based on a polyacrylonitrile with methyl acrylate (PAN-MA) comonomer precursor that is produced

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<sup>7</sup> U.S. DRIVE, which stands for United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability, is a government-industry partnership among the U.S. Department of Energy; USCAR, representing FCA US LLC, Ford Motor Company and General Motors; five energy companies – BP America, Chevron Corporation, ExxonMobil Corporation, Phillips 66 Company, and Shell Oil Products US; Tesla Motors; two utilities – Southern California Edison and Michigan-based DTE Energy; and the Electric Power Research Institute (EPRI).  
[www.usdrive.org](http://www.usdrive.org)

through a high volume textile processing technique. PAN-MA made using textile processing results in a 26% reduction in precursor cost (from \$2.91/lb to \$2.15/lb), primarily as a result of increasing the precursor manufacturing plant capacity from 7,500 tonnes per year to 41,000 tonnes per year. In addition to cost savings in the precursor, a reduction of 25% in the cost of CF processing due to high volume CF manufacturing (from 1,500 tonnes per year to 25,000 tonnes per year) are projected based on results from the Kline report [8]. CF from PAN-MA precursor (produced at higher volume than the PAN precursor used in the baseline T-700S fiber) results in a projected total material cost savings of 18.3% for PAN-MA CF over Toray T-700S CF.

Cost analysis for the PAN-MA CF is based on a tensile strength of 711 KSI chosen to match the T-700S specification based on discussions with ORNL researchers and preliminary tensile strength measurements. The PAN-MA CF is therefore assumed to be a one-to-one replacement for T-700S. Another critical assumption made in estimating the cost impact of the PAN-MA CF is that a large enough market exists to support building a large precursor manufacturing plant and to realize the projected economies of scale.<sup>8</sup> System cost using the ORNL PAN-MA CF is projected to be \$15.03/kWh using a CF price of \$23.43/kg vs. \$16.76/kWh for the 2013 system using T-700S CF at a price of \$28.67/kg. This is a system cost reduction of \$1.73/kWh.

Discussions with vessel manufacturers and ANL led to removal of the doilies previously used in the 2013 tank design for this update because of concerns about manufacturability as discussed above. This design change increases composite mass to meet the same burst pressure without doilies, resulting in an increase of \$1.36/kWh from the 2013 tank.

High volume manufacturing of composite pressure vessels with fiber and manufacturing variability requires some level of overdesign to ensure batch differences will always meet or exceed the certification requirements. Consequently, vessels are designed with increased wall-thickness/burst-pressure to account for these variations. Current design practice is based on a 3 standard deviation ( $\sigma$ ) overdesign, which enables high product yields with reasonable (<1%) destructive<sup>9</sup> testing. Based on conversations with tank manufacturers, typical coefficients of variation (COV) for manufacturing and fiber variation are around 3% each. In the 2013 analysis, a 10% increase in composite mass was included to account for variations in fiber strength: this was approximately equivalent to a  $3\sigma$  overdesign and a  $COV_{Fiber}$  of 3.3%. In order to explicitly account for manufacturing variability and to be consistent with current manufacturing practices, a  $COV_{Manufacturing}$  of 3.3% was assumed for the 2015 tank. This results in a combined fiber and manufacturing overdesign<sup>10</sup> of 14%, reflected in the effective safety factor as a 14% increase over the standard 2.25 safety factor. The cost impact relative to the 2013 tank for including a 3.3% manufacturing variation is \$0.42/kWh. Finally, injection molded foam pieces were added for tank shoulder protection (\$0.06/kWh). When all changes are applied to the model (the ORNL

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<sup>8</sup> One 41,000 tonne per year precursor plant supplies enough precursor to produce CF for about 300,000 compressed hydrogen storage systems per year.

<sup>9</sup> [https://en.wikipedia.org/wiki/68%E2%80%939395%E2%80%9399.7\\_rule](https://en.wikipedia.org/wiki/68%E2%80%939395%E2%80%9399.7_rule)

<sup>10</sup>  $3\sigma = 3\sqrt{COV_{Manufacturing}^2 + COV_{Fiber}^2}$



low-cost CF, PNNL low-cost resin, integrated BOP, design change, and manufacturing variation) the 2015 tank cost is \$14.75/kWh or a reduction of \$2.01/kWh from the 2013 tank.

The cost analyses presented thus far were performed at production rates of 500,000 systems per year in order to project the impact of improvements in technology and manufacturing for a mature market. However, the fuel cell vehicle market is currently far from mature. To better understand costing trends for the nascent market, system cost has also been projected at 100,000 systems per year. Except for the CF price, all other parameters shown in Table 4 remain the same but at a production rate of 100,000 systems per year. The CF price curve for Toray T-700S used in the cost analysis is shown in Figure 4 along with a projected price curve for the PAN-MA CF. It should be acknowledged that the T-700S prices were selected for this cost analysis based on the average of historical pricing trends observed from various sources and will vary based on market factors and raw materials prices. To estimate the PAN-MA price at 100,000 systems per year, the price curve shown in Figure 4 price was shifted down by the price difference between T-700S and PAN-MA at 500,000 systems per year, a difference of \$5.23/kg. Between 100,000 systems per year and 500,000 systems per year, the Toray T-700S price curve is relatively flat; in fact, the knee of the price curve starts just below 100,000 systems per year. This simplistic price adjustment approach is expected to be less accurate for lower production rates where the price curve is more sensitive to volume. This approach also assumes that a large CF market exists outside the automotive industry so that economies of scale in the CF precursor can be realized. Based on the approach described above, the estimated price of compressed hydrogen storage system is \$16.64/kWh at a manufacturing rate of 100,000 systems per year using the PAN-MA CF.

### **Uncertainty Analysis**

Variation in tank CF composite mass among tank manufacturers is due to differences in vessel winding patterns and tank design. These differences are reflected in vessel mass estimates from different computational models. The 2013 baseline vessel mass is based on the ANL ABAQUS model which was calibrated against burst test results of sub-scale tanks without doilies [2]. ANL extended their analysis to include doilies which provided the CF mass used in the 2013 cost analysis [9, 10]. In comparison, Ford Motor Co. evaluated the CF mass based on a regression analysis of tank data from a larger database of proprietary tanks [10]. The Ford regression analysis predicts a composite mass 5 kg lighter than the ANL analysis for tanks without doilies. Work continues to better understand these differences and the performance variations between the model assumptions and manufactured tanks.

To better understand the impact of uncertainty in materials and processing, a Monte Carlo multi-variable sensitivity analysis was performed to estimate the potential variation in system cost. Parameter values varied are presented in Table 6 and the analysis was run over 200,000 iterations to achieve a smooth frequency profile. The tornado plot in Figure 5 shows the single variable cost sensitivity to the parameters studied in the Monte Carlo analysis. The data spread between the ANL and regression analysis CF composite mass predictions (5 kg) described above forms the basis of the Monte Carlo CF mass limits. While large uncertainty in the CF composite mass does have a significant single variable cost impact (\$1.20/kWh), CF material price is the dominant cost driver (\$2.74/kWh) for the ranges studied. The middle 90% confidence range in system cost predicted by Monte Carlo is between \$14.01/kWh and \$16.49/kWh. Results of the Monte Carlo analysis are shown in the histogram in Figure 5.

Data provided by PNNL was used to assess the uncertainty in gravimetric and volumetric capacity for the tank while a 10% mass contingency was assumed for the BOP. Based on the PNNL data, the coefficient of variation in tank masses was found to typically be between 1% and 1.5%. Tank-to-tank manufacturing variation in the CF mass is likely to be very small due to tight manufacturing tolerances. On the other hand, the resin mass may vary measurably given its low-viscosity and the likelihood that resin will drip and be squeezed out from the fibers due to tension/compression during the wet-winding process. BOP mass uncertainty data are not available; consequently a  $\pm 10\%$  BOP mass uncertainty is assumed as a reasonable approximation. Uncertainty in the volumetric capacities was calculated using the mass variations described above and the density of the respective materials. The resulting uncertainty ( $\pm 0.04$  kWh/kg and  $\pm 0.01$  kWh/L) represents the best available estimate given the data available, but may understate the uncertainty. The uncertainty should be revisited as additional and better quality data becomes available.

**Table 6: Parameters used in Monte Carlo analysis.**

|   | <b>Unit</b> | <b>Min</b> | <b>Mid</b> | <b>High</b> |
|---|-------------|------------|------------|-------------|
| <b>CF Mass</b>                              | kg          | 92         | 97         | 102         |
| <b>Polymer Base Price</b>                   | \$/kg       | 1.34       | 1.79       | 2.69        |
| <b>Carbon Fiber Base Price</b>              | \$/kg       | 21.08      | 23.43      | 28.11       |
| <b>Blow Molding Capital Cost</b>            | \$          | 443,955    | 591,940    | 739,925     |
| <b>Blow Molding Total Cycle Time Factor</b> |             | 0.5        | 1          | 2           |
| <b>Wet Winding Capital Cost</b>             | \$          | 274,523    | 343,154    | 600,519     |
| <b>Average Fiber Laydown Rate</b>           | m/min       | 18         | 26         | 31          |
| <b>Curing Oven Capital Cost</b>             | \$/ft       | 1,506      | 2,008      | 2,511       |
| <b>Curing Conveyor Capital Cost Factor</b>  |             | 0.20       | 1.00       | 1.50        |
| <b>B-Stage Dwell Time</b>                   | hrs         | 2          | 2.5        | 3           |
| <b>Full Cure Dwell Time</b>                 | hrs         | 4          | 8          | 12          |
| <b>Compression System Capital Cost</b>      | \$          | 834,258    | 1,668,518  | 3,337,036   |
| <b>BOP Cost Factor</b>                      |             | 0.75       | 1.00       | 1.25        |
| <b>Resin Cost</b>                           | \$/kg       | 1.58       | 4.52       | 7.69        |
| <b>Foam Dome Protection Material Cost</b>   | \$/kg       | 1.25       | 2.50       | 5.00        |

Figure 1: System diagram showing the single-tank configurations used in the cost and performance models.

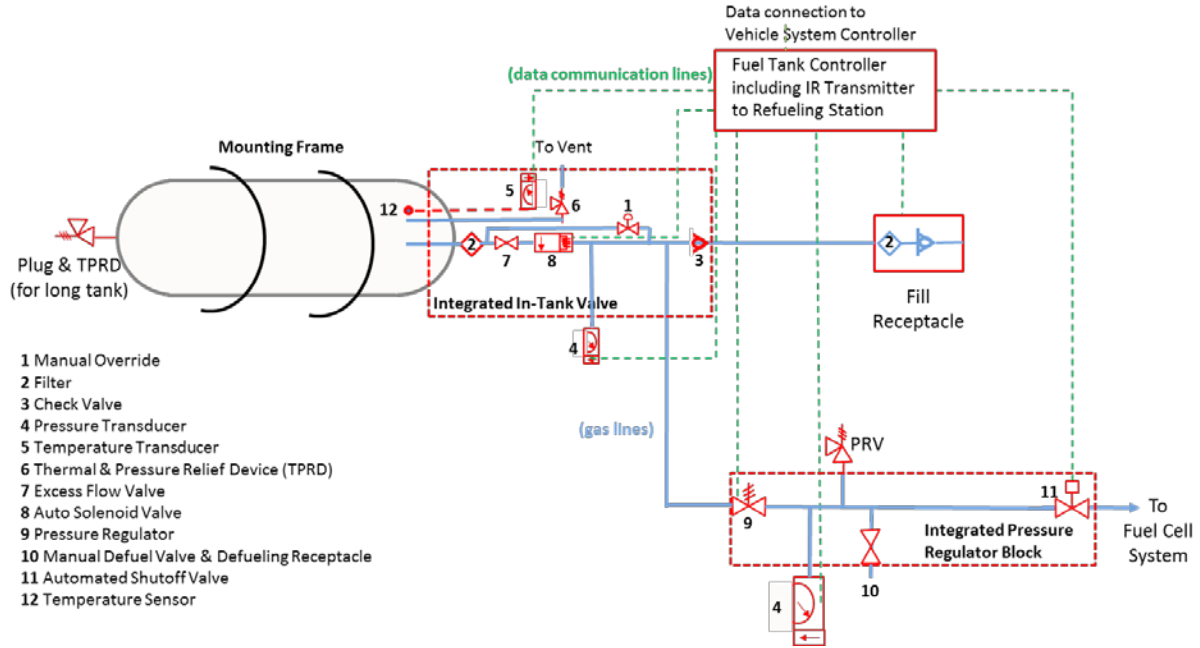


Figure 2: 700 bar type IV pressure vessel storage system cost update for 2015 showing approximate cost impact of multiple simultaneous changes since 2013.

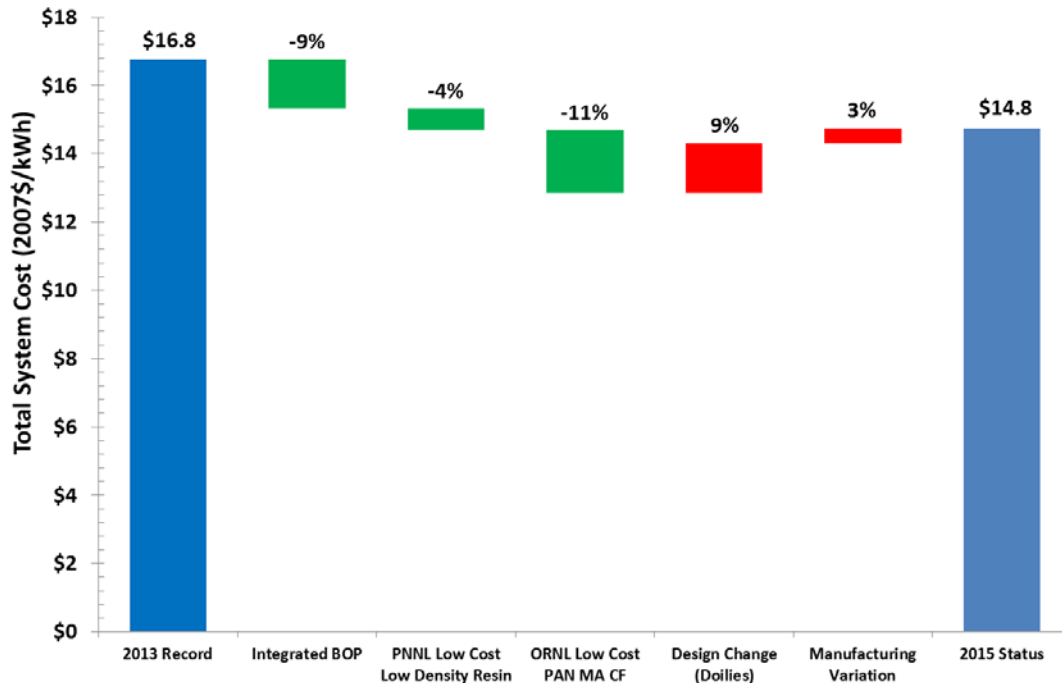


Figure 3: Cross-section of integrated pressure regulator block that combines six low-pressure components.

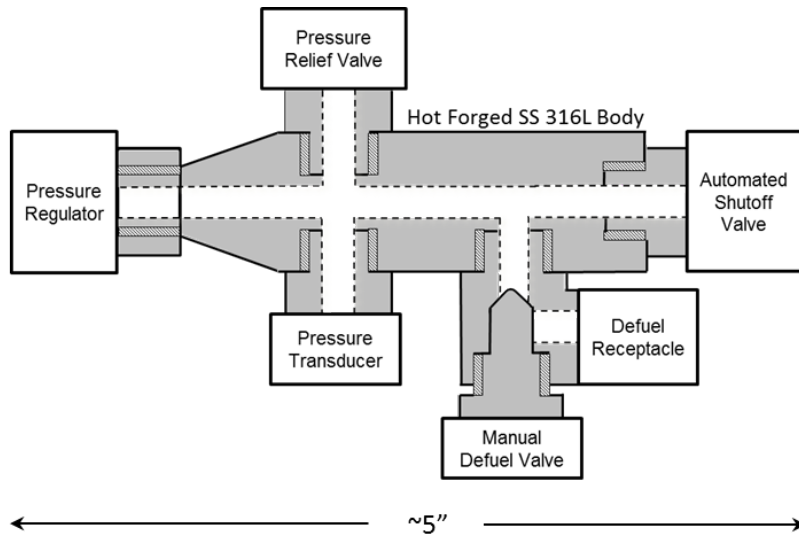
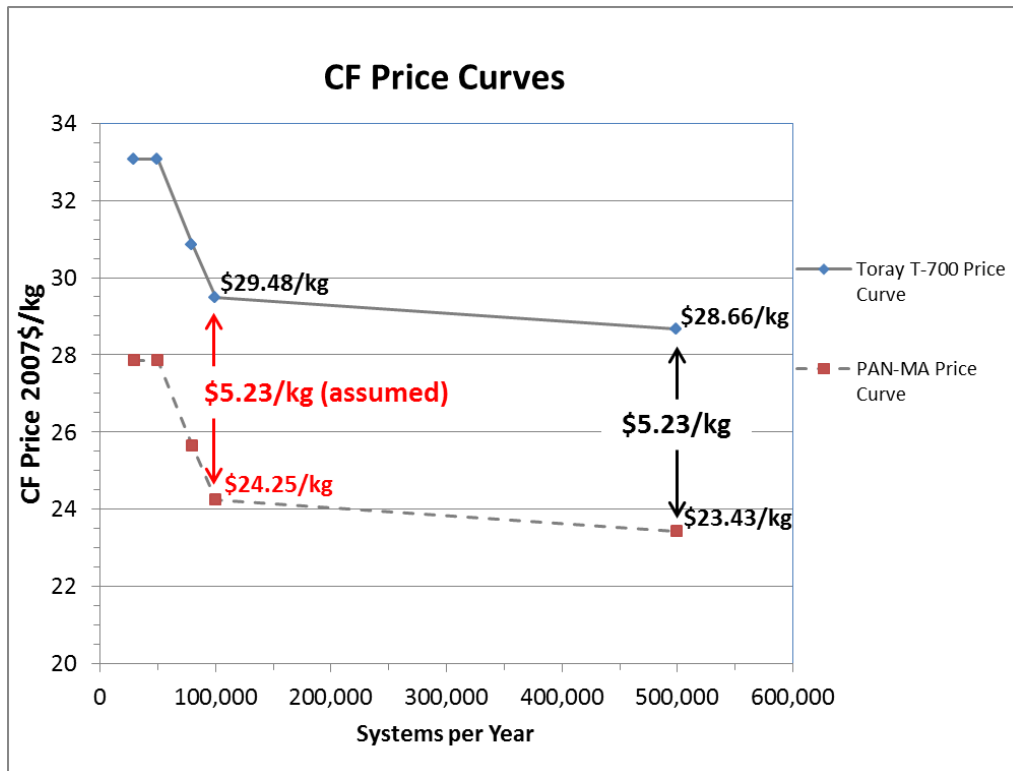
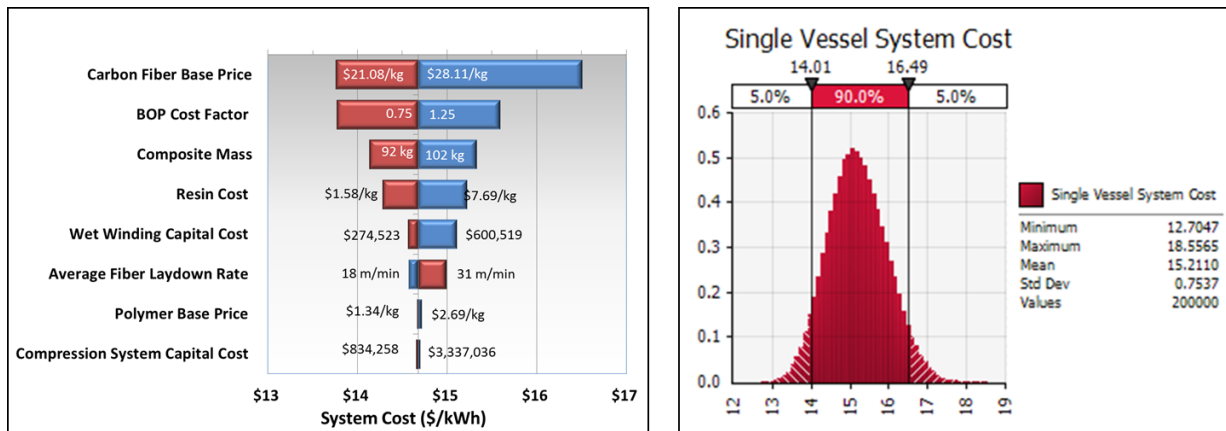


Figure 4: Carbon fiber price curves. The price curve for Toray T-700S was suggested by U.S. DRIVE. The projected ORNL PAN-MA based CF price at 500,000 systems per year was derived from ORNL manufacturing cost analysis and additional reductions based on Kline and Company (Reference 8) analysis. Cost savings for the ORNL CF price at 100,000 systems per year (shown in red) is estimated as the same savings amount as was achieved between the ORNL CF and Toray T-700S CF at 500,000 systems per year. The PAN-MA price curve assumes high volume production of the PAN-MA precursor, even for the lower system production rates where automotive demand alone may not dictate such large scale precursor production.



**Figure 5: Single variable sensitivity (left) and Monte Carlo frequency histogram (right) for cost (at 500,000 systems/year) sensitivity analysis studied using parameters in Table 6. The tornado chart only shows parameters that result in non-zero single variable cost impacts.**



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