Ongoing Analysis of H_2 Storage System Costs

Project ID: ST100

STRATEGIC ANALYSIS INC

2014 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Strategic Analysis Inc.

Brian D. James (PI)

Jennie M. Moton

Whitney G. Colella

17 June 2014

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Project start date: 9/30/11
- Project end date: 9/29/16
- Percent complete:
  - ~50% (in Year 3 of 5)

Barriers

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

Budget

- Total Funding Spent
  - $641k (total)
    - $459k SA
    - $ 59k NREL
    - $123k ANL
- Total DOE Project Value
  - $2M for all 5 years (includes FFRDC)
- Cost Share: 0% (not req. for analysis projects)

Partners

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

Relevance: Overall Project Objectives

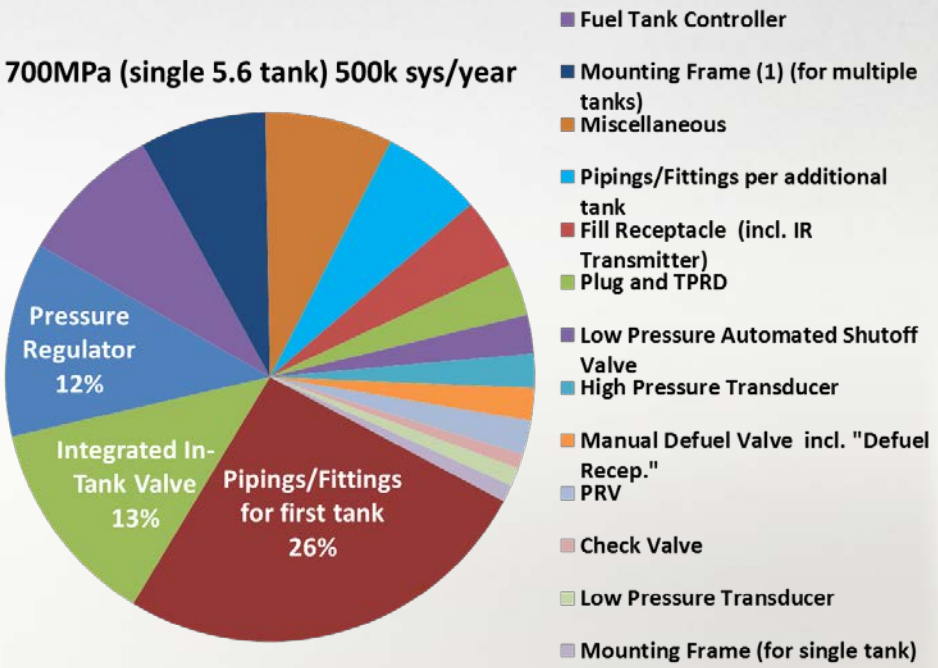
- **Overall goal of project:**
  - Process-based cost analysis of current & future H_2 storage technologies
  - Gauge and guide DOE research and development (R&D) efforts
  - Validate cost analysis methodology so there is confidence when methods are applied to novel systems
- **Sensitivity studies**
  - 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

2014 Approach Overview

- **Continue investigation of Balance of Plant (BOP) Components** (for H_2 Compressed Gas Systems)
  - BOP cost drivers
    - Fittings, integrated solenoid valve, and pressure regulator
  - Comparison of CNG & H_2 System BOP components
- **Validation of low manufacturing volume compressed tank cost through comparison with current CNG tank costs**
  - Review of tank manufacturers: Hexagon Lincoln, 3M, and Quantum Technologies
  - DFMA of CNG tank for cost comparison
- **Initiate Cost Analysis of PNNL Compressed Cold Gas System**
  - Discussed in Backup Slides (due to slide number constraint)

BOP Components Overview

- **Concentrate on highest cost BOP components**
  - Fittings
  - Integrated Solenoid Valve
  - Pressure Regulator

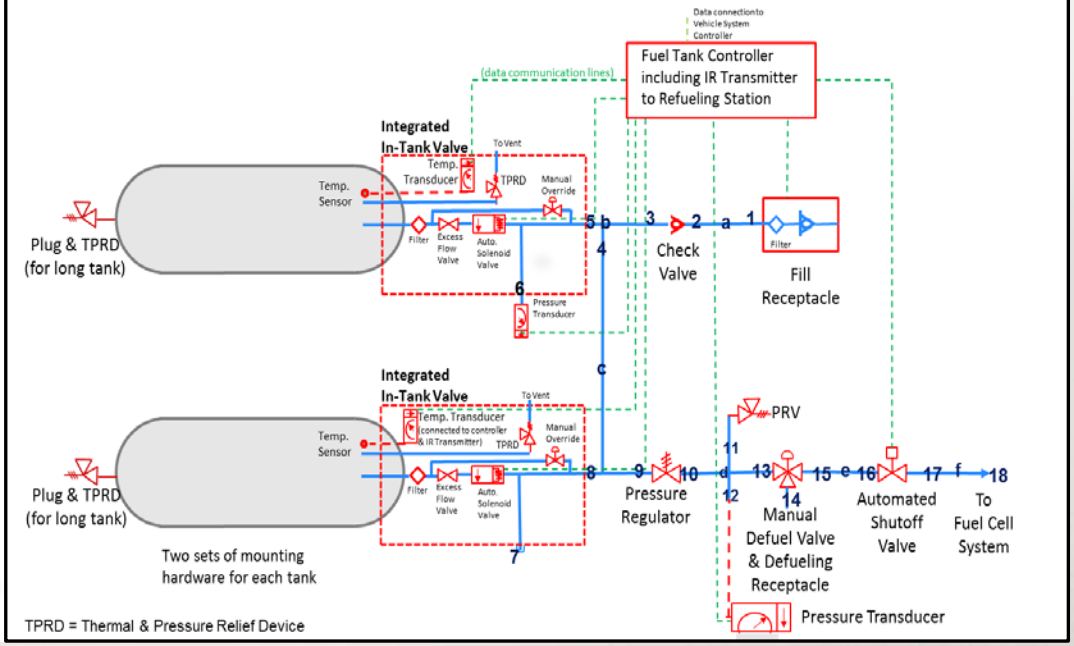


- **Compare to CNG components where feasible**
- **Apply DFMA cost methodology where feasible**
- **Consider how future improvements might be made**
- **Unless otherwise specified, all costs displayed in 2013$**

Fittings and Piping Runs Re-examined

- **High pressure vs low pressure**
  - High pressure: >12kpsi rating, ¼" SS lines prior to press. regulator
  - Low pressure: <400psi rating, ½" SS lines after press. regulator
- **Each connection considered**
  - 6 high pressure connections
  - 8 low pressure connections
- **Lengths of lines computed**
  - 1.5m high pressure line
  - 1m low pressure line
  - Bends, welds, ties added
- **Fittings**
  - Details next page

Storage system schematic used to enumerate components, fittings, and lines



Current BOP diagram is a baseline design.
Future cost optimization potentially achieved by component integration.

Two Main Types of H_2 High Pressure Fittings Designs Considered

Metal-on-Metal Cone/Thread Sealing

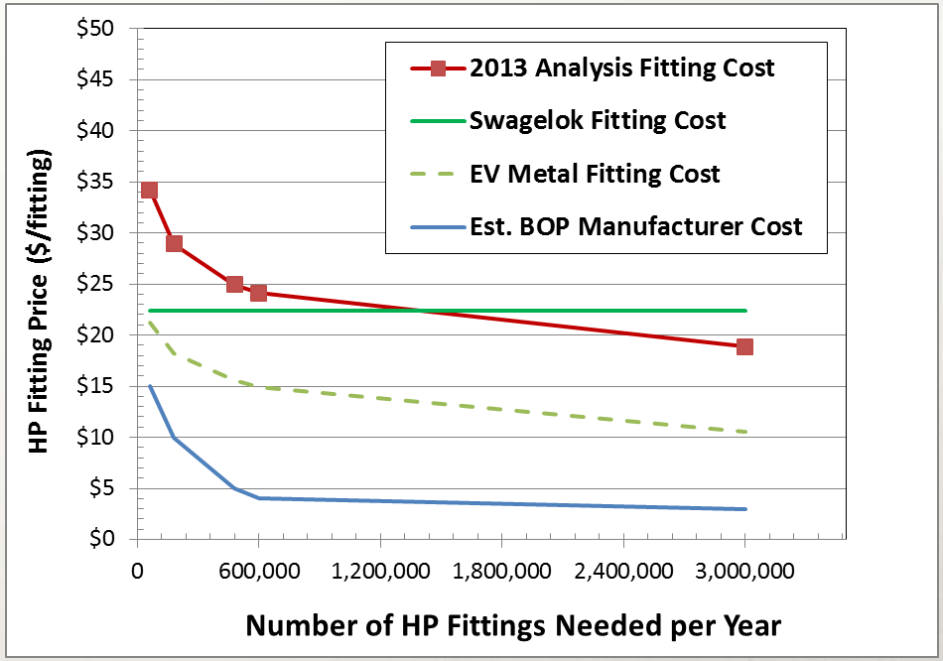
- Cajon/Swagelok
- EV Metals

O-ring sealing

- Parker Hannifin Corporation Seal-Lok™
- In-house design (BOP manufacturer)

Fittings Quotes Show Wide Variation

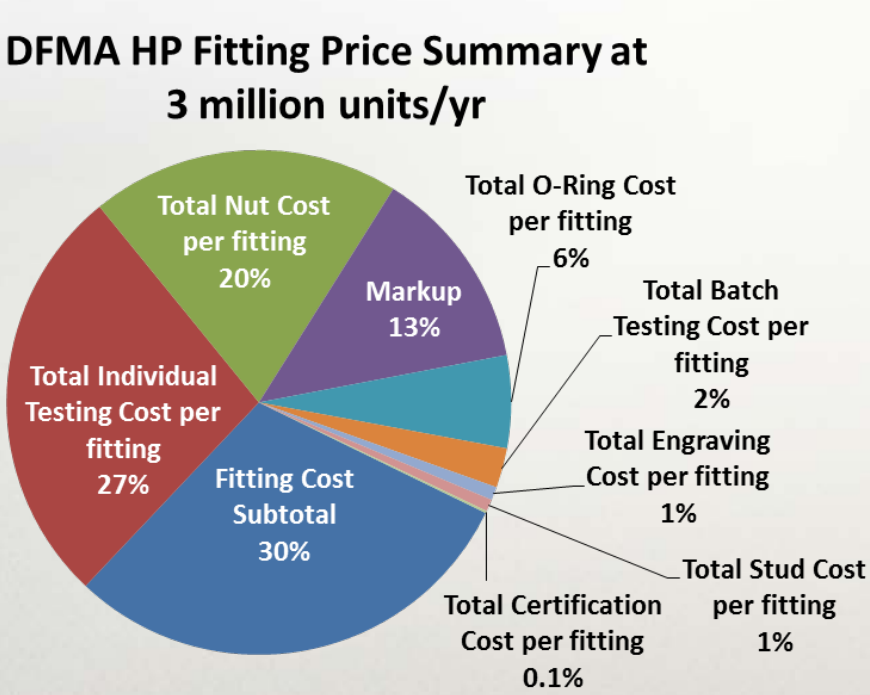
- Parker fitting price extremely high with no reduction at high volumes (~$100 - $200/fitting).
- Swagelok also constant price with no reduction at high volumes (~$20-$40/fitting).
- BOP manufacturer produces fittings in-house
  - Competitors viewed as expensive
  - In-house manufacturer claims drastically lower price

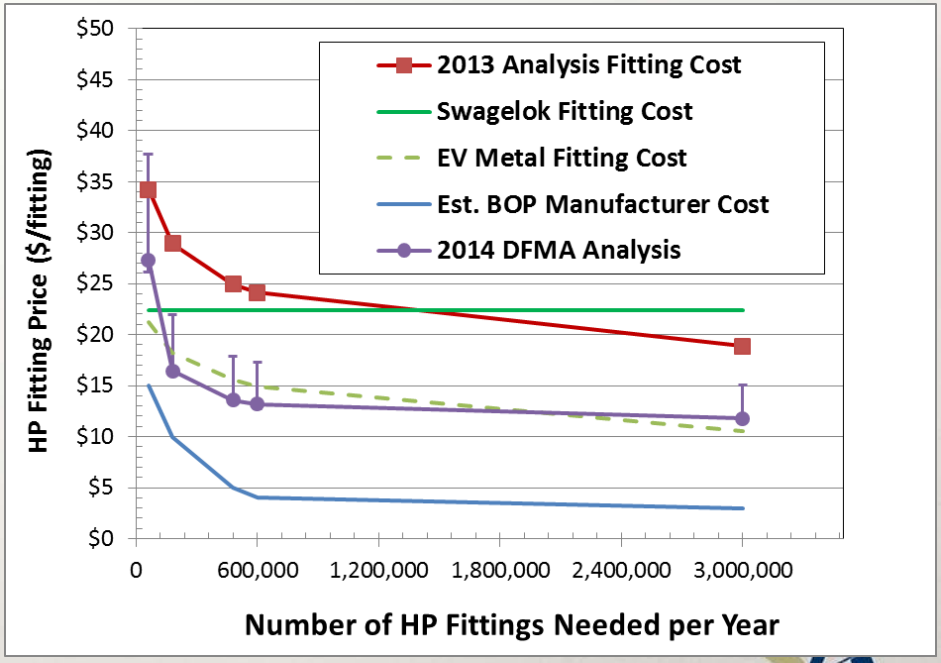


*EV Metal quotes obtained up to 50,000 units, however a 0.935 learning curve factor applied to extrapolate out to 3 million units.

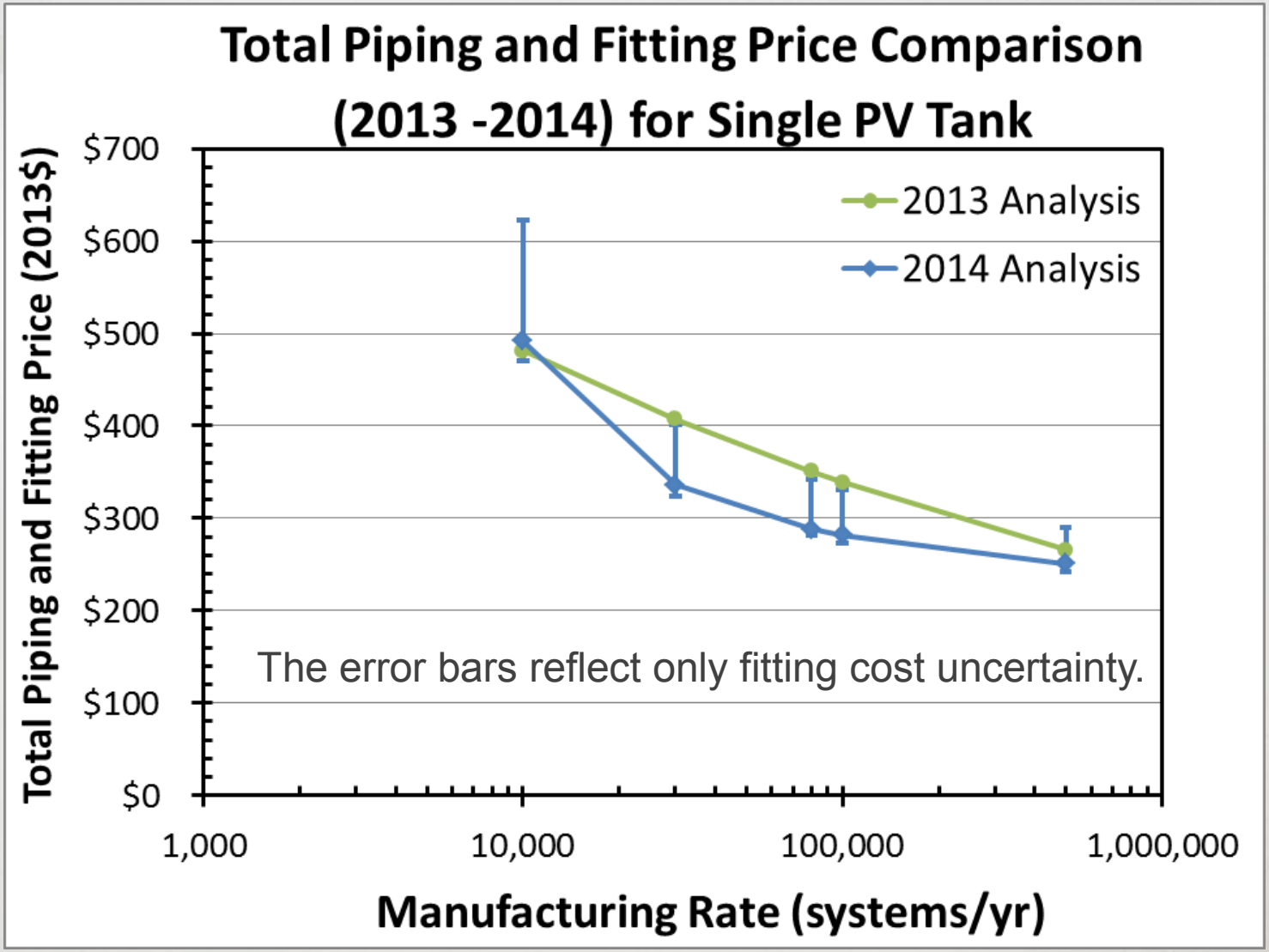
2014 DFMA Cost Estimation Suggests a Low Fitting Price (~$11-$27/fitting)

- Assume dimensions of Parker fitting 4 F57OLO-SS H2U
- Process machining using CNC lathe with tolerances ± 0.004”
- Assume individual water pressure testing at 1.5 x max pressure and underwater leak (bubble) test at 1.1 x max pressure
- Monte Carlo multi-variable sensitivity used to project possible range in fitting cost
  - Variables: capital cost, processing time & testing times, material cost, markup rate
  - Cost range for middle 90% probability shown in error bars



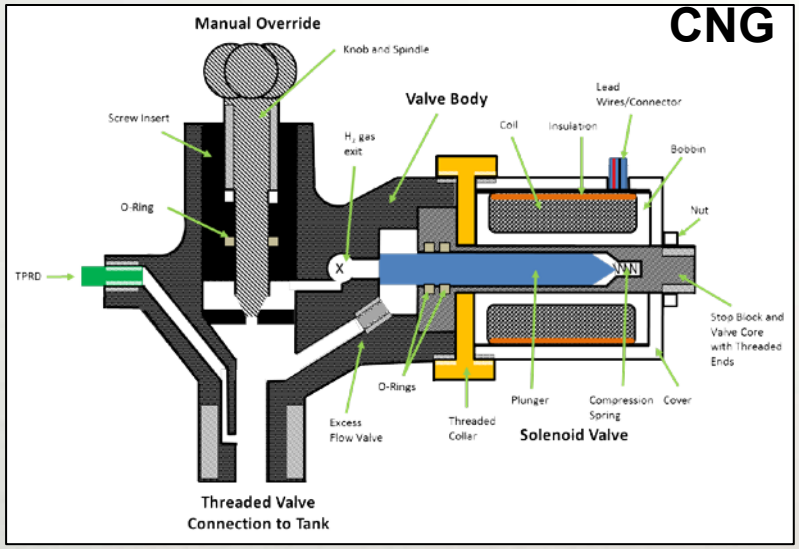


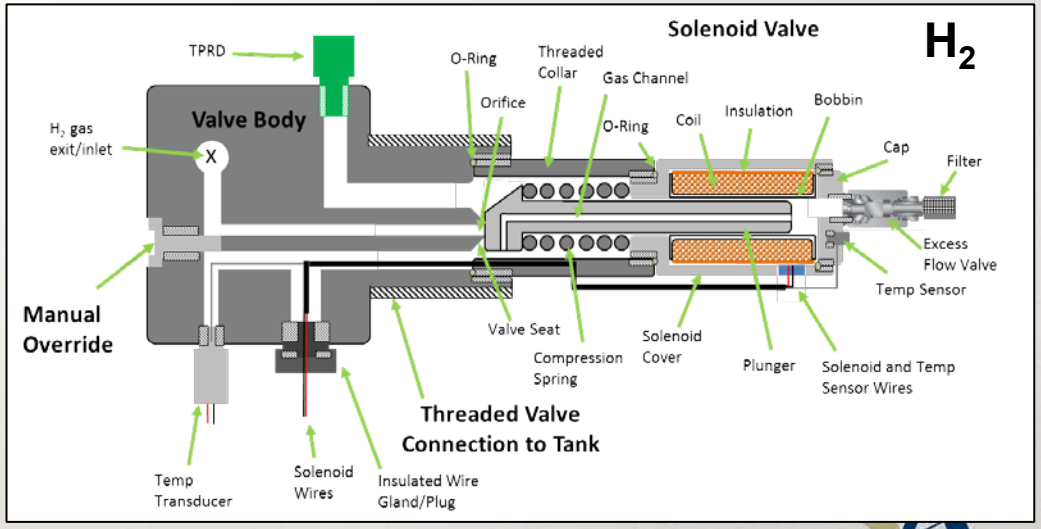
More Detailed Piping and Fitting System Analysis Results in Lower Price for 2014



DFMA Analysis Applied to CNG and H_2 Integrated Valves

- **H_2 tank integrated solenoid valves are not produced in high quantities**
  - Investigated CNG tank "automatic solenoid valves" (~10,000 valves/yr)
- **Acquired quotations for CNG and H_2 integrated valves**
  - CNG automatic solenoid valves : $130 @ 17,000 valves
  - H_2 solenoid integrated valve: $2,000/valve (future target of $675/valve)
- **DFMA of CNG integrated valve conducted & compared to quotation**
  - DFMA design based on patent[1] with dimensions from an OMB Saleri Lyra CV valve
- **DFMA of H_2 integrated valve conducted & compared to quotation**
  - DFMA design based on in-tank solenoid valve (similar to Quantum Technologies design)



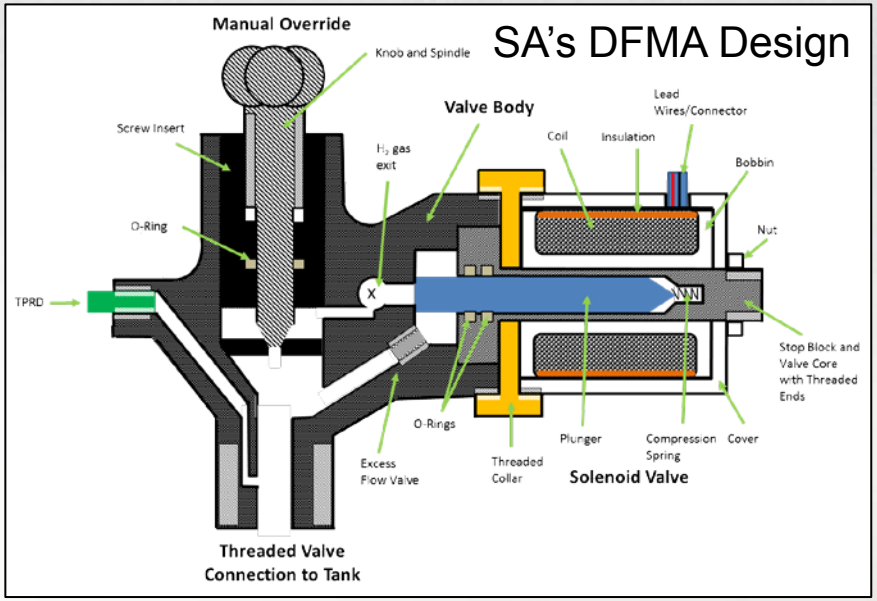


[1] European Patent (EP 0805295 B1) to GFI Control Systems Inc.

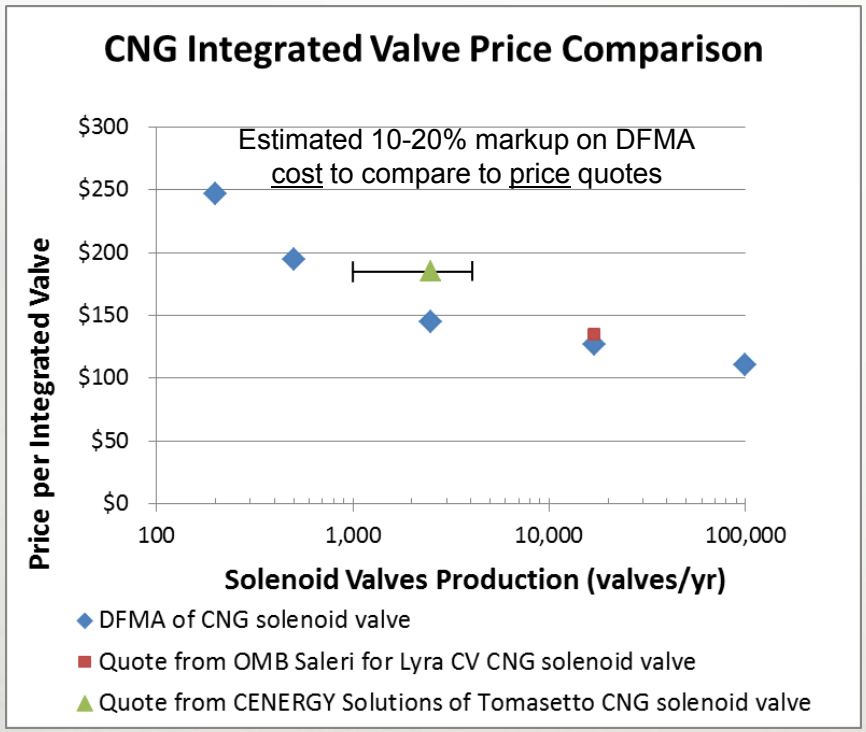
DFMA Cost of CNG Integrated Valves

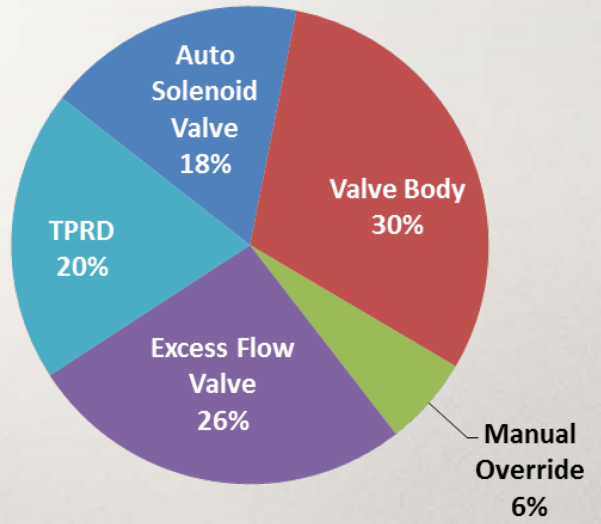
- DFMA "price" of CNG integrated valve aligns with OMB Saleri Lyra CV valve quote at 17,000 valves per year.

- Tomasetto valve quote
  - may contain distributor markup
  - unknown valve production



SA's DFMA design derived from combination of patent[1] and OMB Lyra Valve[2] dimensions.





[1] European Patent (EP 0805295 B1) to GFI Control Systems Inc.
[2] OMB Saleri Lyra Valve most widely used valve on CNG vehicle tanks

Differences Identified between CNG & H_2 Integrated Valves

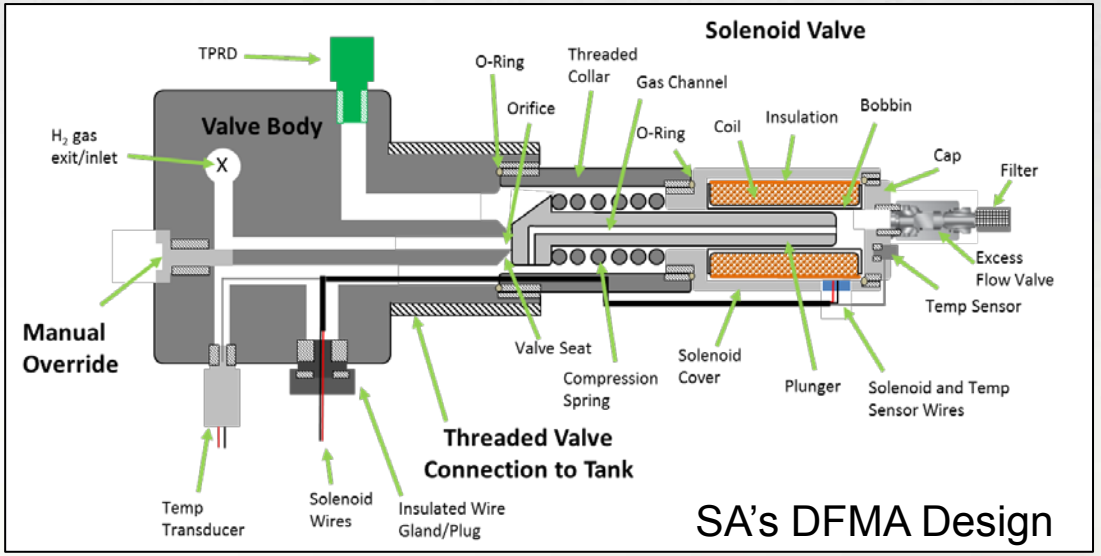
Component Difference	CNG Integrated Valve	Hydrogen Integrated Valve
Pressure Rating	3,600psi	10,000 psi
Solenoid Valve	External of Tank	Internal to Tank
Temperature Transducer	Not Included	Included
Filters	Not Included	Included
Material of Construction	SS or Aluminum/Brass	Stainless Steel
Neck Opening (diameter)	Usually 2 inches	Usually 1.5 inches
Common Components/Functions	solenoid, manual override, temperature/pressure relief device (TPRD), excess flow valve	

Details of H_2 Integrated Valve appear in the Backup Slides.

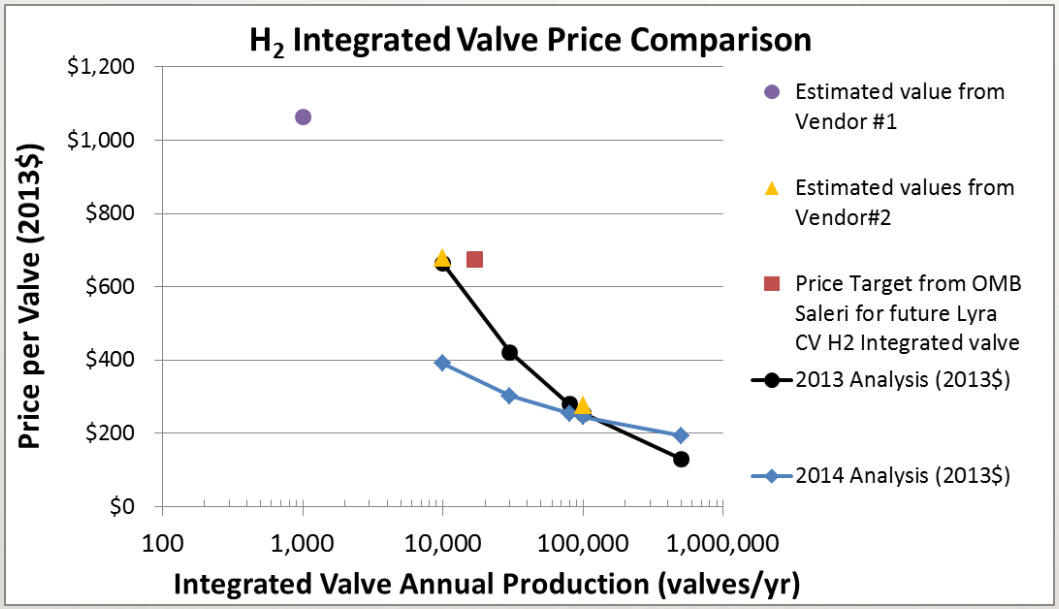
12

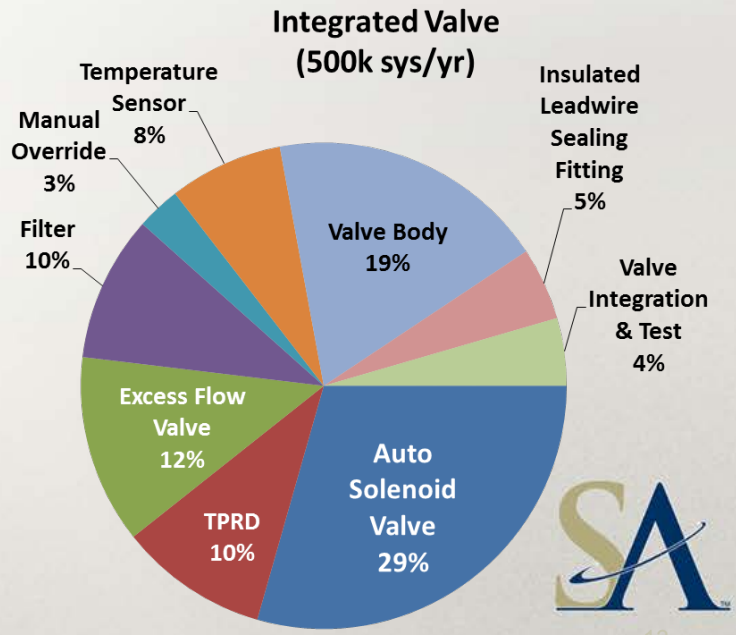
DFMA Cost of H_2 Integrated Valves

- DFMA "price" of H_2 integrated valve aligns with 2013 estimates at 100k valves/year.
- DFMA analysis suggests a shallower learning curve than used in 2013.
- Bulk of integrated valve costs from auto solenoid and valve body.



SA's DFMA design derived from combination of patent[1] & Quantum Technologies design.





[1] U.S. Patent (005197710A)

Integrated Valve Cost Comparison with 2013

Integrated In-Tank Valve Costs Per Tank						
		Annual Manufacturing Rate				
	Year	10,000	30,000	80,000	100,000	500,000
Auto Solenoid Valve	2013	$405.82	$257.22	$171.20	$156.06	$80.02
	2014	$124.34	$91.03	$75.34	$72.80	$57.14
TPRD	2013	$118.49	$75.10	$49.99	$45.56	$23.36
	2014	$36.64	$31.46	$27.04	$26.01	$19.27
Excess Flow Valve	2013	$46.36	$29.39	$19.56	$17.83	$9.14
	2014	$47.06	$37.94	$32.69	$31.40	$24.38
Filter	2013	$26.79	$16.98	$11.30	$10.30	$5.28
	2014	$31.61	$26.42	$23.51	$22.75	$18.85
Manual Override	2013	$51.52	$32.65	$21.73	$19.81	$10.16
	2014	$6.80	$6.23	$5.99	$5.91	$5.67
Temperature Sensor	2013	$14.74	$9.34	$6.22	$5.67	$2.91
	2014	$51.17	$33.96	$24.98	$23.21	$14.72
Valve Body	2013	$0.00	$0.00	$0.00	$0.00	$0.00
	2014	$47.45	$41.27	$39.00	$38.34	$36.07
Insulated Leadwire Sealing Fitting	2013	$0.00	$0.00	$0.00	$0.00	$0.00
	2014	$34.54	$23.84	$17.17	$15.91	$9.39
Valve Integration & Test	2013	$0.00	$0.00	$0.00	$0.00	$0.00
	2014	$10.91	$9.82	$9.38	$9.24	$8.73
Total	2013	$663.71	$420.68	$280.00	$255.24	$130.87
	2014	$390.51	$301.98	$255.10	$245.58	$194.24

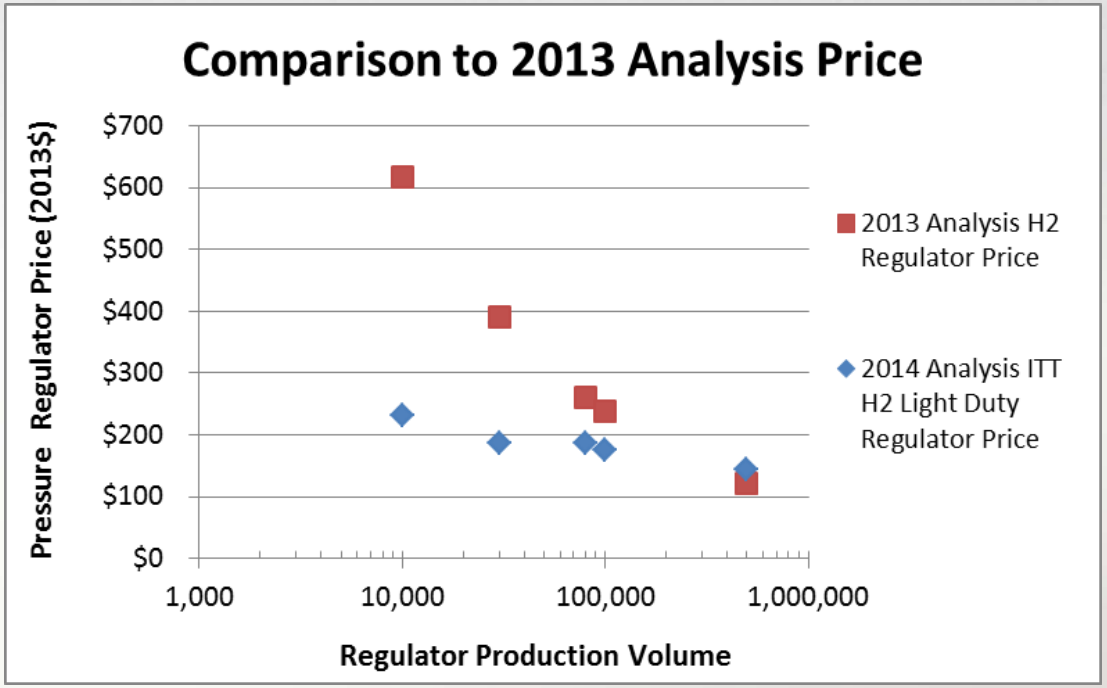
Added components for 2014 analysis

(All Values in 2013$)

Improved analysis suggests a modest change in valve cost at 80k and 100k sys/yr. However, percentage differences are substantial: -41% to +48%.

Pressure Regulator Cost Updated based on Vendor Quotes

2013 Analysis:
0.75 learning factor used for pressure regulator
($600 @10,000 regulators)



(All Values in 2013$)

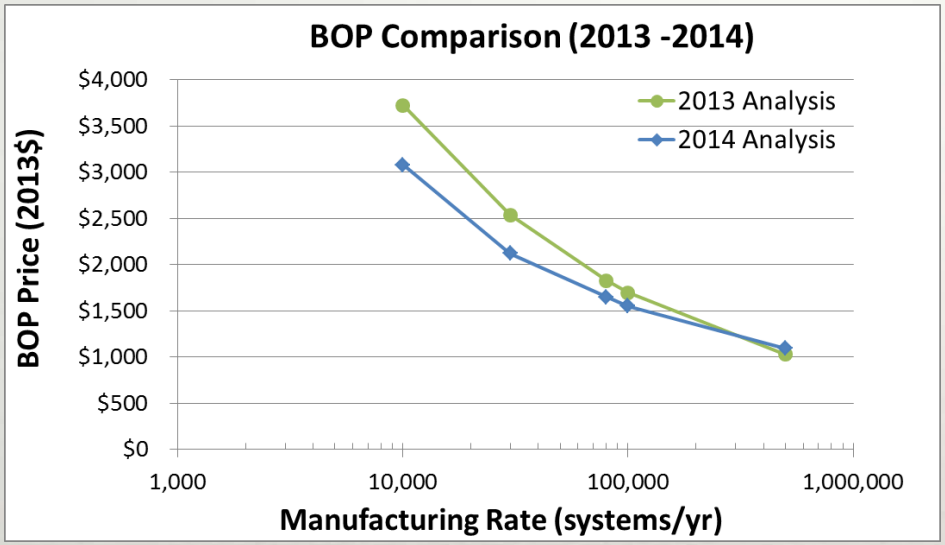
Annual Prod. Volume of Pressure Regulators	10k	30k	80k	100k	500k
ITT Price Quotes					
ITT CNG Light Duty Regulator	$155	$125	$125	$115	$115
ITT H2 Light Duty Regulator	$232	$187	$187	$175	$145
2013 Analysis H2 Regulator Price	$618	$392	$261	$238	$122

H_2 pressure regulators (12kpsi) are 25-50% more expensive than CNG lower pressure (3.6kpsi) regulators

2014 BOP Price Compared to 2013 BOP

2013 Analysis		Annual Manufacturing Rate				
		10,000	30,000	80,000	100,000	500,000
BOP						
Integrated In-Tank Valve	**Per Tank**	*$664*	*$421*	*$280*	*$255*	*$131*
TPRD	Per Tank	*$118*	*$75*	*$50*	*$46*	*$23*
Excess Flow Valve	Per Tank	*$46*	*$29*	*$20*	*$18*	*$9*
Filter	Per Tank	*$27*	*$17*	*$11*	*$10*	*$5*
Manual Override	Per Tank	*$52*	*$33*	*$22*	*$20*	*$10*
Temperature Sensor	Per Tank	*$15*	*$9*	*$6*	*$6*	*$3*
Auto Solenoid Valve	Per Tank	*$406*	*$257*	*$171*	*$156*	*$80*
Valve Body	Per Tank	*$0*	*$0*	*$0*	*$0*	*$0*
Insulated Leadwire Sealing Fitting	Per Tank	*$0*	*$0*	*$0*	*$0*	*$0*
Valve Integration and Test	Per Tank	*$0*	*$0*	*$0*	*$0*	*$0*
Check Valve	Per System	*$46*	*$29*	*$20*	*$18*	*$9*
Fuel Tank Controller	Per System	*$163*	*$138*	*$119*	*$115*	*$90*
Pressure Regulator	Per System	*$618*	*$392*	*$261*	*$238*	*$122*
PRV	Per System	*$108*	*$69*	*$46*	*$42*	*$21*
Low Pressure Transducer	Per System	*$59*	*$37*	*$25*	*$23*	*$12*
High Pressure Transducer	Per System	*$108*	*$69*	*$46*	*$42*	*$21*
Manual Defuel Valve incl. "Defuel Recep."	Per System	*$103*	*$65*	*$43*	*$40*	*$20*
Low Pressure Automated Shutoff Valve	Per System	*$124*	*$78*	*$52*	*$48*	*$24*
Pipings/Fittings for first tank	Per System	*$481*	*$407*	*$351*	*$339*	*$265*
Pipings/Fittings per additional tank	per addtl tank	*$114*	*$97*	*$83*	*$81*	*$63*
Plug and TPRD	Per tank	*$165*	*$104*	*$70*	*$63*	*$33*
Fill Receptacle (incl. IR Transmitter)	Per System	*$227*	*$144*	*$96*	*$87*	*$45*
Mounting Frame (for single tank)	Per Tank	*$54*	*$34*	*$23*	*$21*	*$11*
Mounting Frame (1) (for multiple tanks)	Per Tank	*$402*	*$255*	*$170*	*$155*	*$79*
Miscellaneous	Per System	*$292*	*$199*	*$143*	*$133*	*$80*
BOP Subtotal		$3,727	$2,537	$1,825	$1,697	$1,027

2014 Analysis		Annual Manufacturing Rate				
		10,000	30,000	80,000	100,000	500,000
BOP						
Integrated In-Tank Valve	**Per Tank**	*$391*	*$302*	*$255*	*$246*	*$194*
TPRD	Per Tank	*$37*	*$31*	*$27*	*$26*	*$19*
Excess Flow Valve	Per Tank	*$47*	*$38*	*$33*	*$31*	*$24*
Filter	Per Tank	*$32*	*$26*	*$24*	*$23*	*$19*
Manual Override	Per Tank	*$7*	*$6*	*$6*	*$6*	*$6*
Temperature Sensor	Per Tank	*$51*	*$34*	*$25*	*$23*	*$15*
Auto Solenoid Valve	Per Tank	*$124*	*$91*	*$75*	*$73*	*$57*
Valve Body	Per Tank	*$47*	*$41*	*$39*	*$38*	*$36*
Insulated Leadwire Sealing Fitting	Per Tank	*$35*	*$24*	*$17*	*$16*	*$9*
Valve Integration and Test	Per Tank	*$11*	*$10*	*$9*	*$9*	*$9*
Check Valve	Per System	$46	$29	$20	$18	$9
Fuel Tank Controller	Per System	$163	$138	$119	$115	$90
Pressure Regulator	Per System	*$232*	*$187*	*$187*	*$175*	*$145*
PRV	Per System	$108	$69	$46	$42	$21
Low Pressure Transducer	Per System	$59	$37	$25	$23	$12
High Pressure Transducer	Per System	$108	$69	$46	$42	$21
Manual Defuel Valve incl. "Defuel Recep."	Per System	$103	$65	$43	$40	$20
Low Pressure Automated Shutoff Valve	Per System	$124	$78	$52	$48	$24
Pipings/Fittings for first tank	Per System	*$492*	*$336*	*$288*	*$282*	*$251*
Pipings/Fittings per additional tank	per addtl tank	*$115*	*$79*	*$68*	*$66*	*$59*
Plug and TPRD	Per tank	$165	$104	$70	$63	$33
Fill Receptacle (incl. IR Transmitter)	Per System	$227	$144	$96	$87	$45
Mounting Frame (for single tank)	Per Tank	$54	$34	$23	$21	$11
Mounting Frame (1) (for multiple tanks)	Per Tank	$402	$255	$170	$155	$79
Miscellaneous	Per System	$292	$199	$143	$133	$80
BOP Subtotal		$3,079	$2,124	$1,648	$1,553	$1,094



Red text denotes BOP component price change between 2013 & 2014 analyses.

- Close BOP price agreement above 100k systems/yr.
- 2014 estimates are lower than last year at <100k systems/yr.

(All Values in 2013$)

Validation of low manufacturing volume compressed tank cost through comparison with current CNG tank costs

- 250 bar CNG Pressure Vessels provide an opportunity to assess the DFMA cost model previously used for 700 bar H_2 vessels
- Review of tank manufacturers: Hexagon Lincoln, 3M, and Quantum Technologies
- DFMA of CNG tank for cost comparison

CNG vs. H_2 Vessel Assumption Differences

	CNG	Hydrogen
Pressure	3,600 psi	10,000 psi
Production Rate	100's to low 1,000's Per year	1k to 500k Per year
Structural Fiber	T-700	T-700
Fiberglass	Outer layer only (could be 25% vol. of structural Fiber)	None
Liner	HDPE (rotomold)	HDPE (blow mold)
Liner thickness	0.4 cm	0.5 cm

17

DFMA Methodology Validation Against CNG Vessel Prices

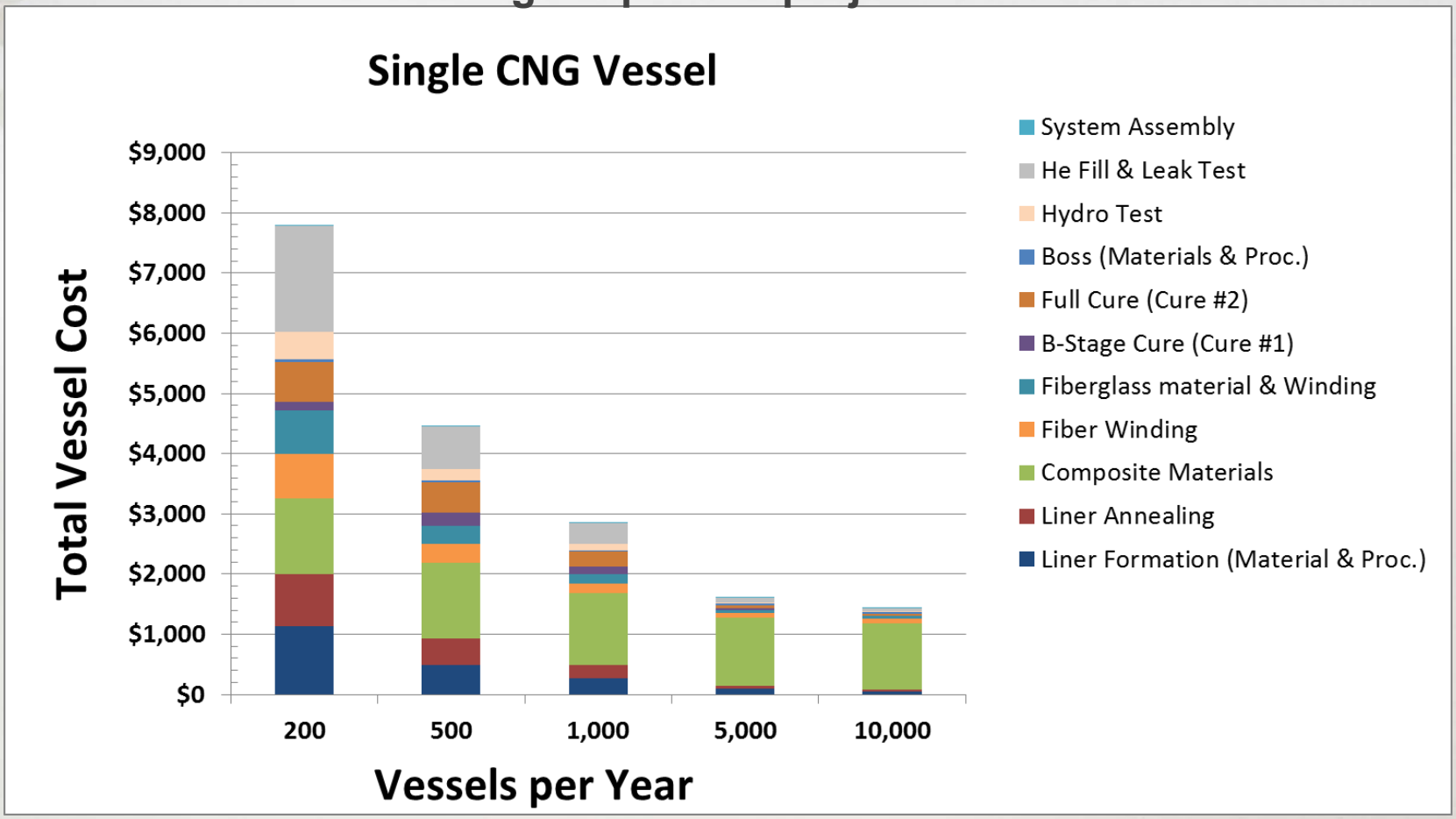
CNG Storage Tank Cost Parameter	Quantum	3M	SA DFMA	Hexagon Lincoln
Annual Purchase Quantity (vessels per year)	Not Spec. (But est. at 1,000)	Not Spec. (But est. at 1,000)	1,000 (prod. Rate)	500
Tank Interior Volume (liters)	274	279	275	251
Tank Mass	60.8	59.4	65.5	92.1
Tank Cost before markup($/tank)	$2,800	$2,260 - $2,730	**$2,852**	$2,420
Tank Manufacturer Markup %	15%	15%	15%	15%
Tank Cost after markup ($/tank)	$3,220	**$2,600 - $3,140**	$3,280	**$2,785**
Authorized Installer Markup %	10%	8-13%	10%	10%
Tank Cost after markup ($/tank)	**$3,500**	**$2,800 - $3,550**	$3,607	$3,030

Red bold indicates vendor quote or DFMA estimate.

- ANL provided data (volume and masses) for the baseline case.
- NREL participated in discussions & introduced an NREL CNG expert to the team.
- 3M confirms having a single layer of fiberglass on outside of tank opposed to Hexagon Lincoln's inclusion of fiberglass both on outside and within tank walls.

Cost Projection Quite Sensitive to Production Rate

Assumption regarding annual production rate can have a large impact on projected vessel cost.



- He Fill & Leak test can be a significant cost.
  - Based on (high) cost of H_2 refueling station.
  - Contributes ~$350 to system (at 1k vessels/year)

19

Summary/Conclusions

- **Balance of plant component costs revisited**
  - Future cost optimization scheme assumed by component integration.
  - DFMA analysis performed on fittings suggests a high manufacturing volume and low cost of $11-$27/fitting.
  - DFMA of integrated valve shows a similar cost at 100k sys/year as in 2013, but +/-45% at other manufacturing rates.
  - New pressure vessel BOP prices suggest a lower slope in cost savings at higher manufacturing rates, but a similar cost at 500k systems per year.
- **Validation of H_2 pressure vessel cost model**
  - Cost of CNG tank using DFMA aligns well with industry quotations specifically at 1,000 systems per year
  - At low production rates (<5k systems/year), vessel cost is highly sensitive to annual production rate
- **Preliminary comparison shows good performance/cost agreement between SA and PNNL projections for the Compressed Cold Gas H_2 storage concept**

20

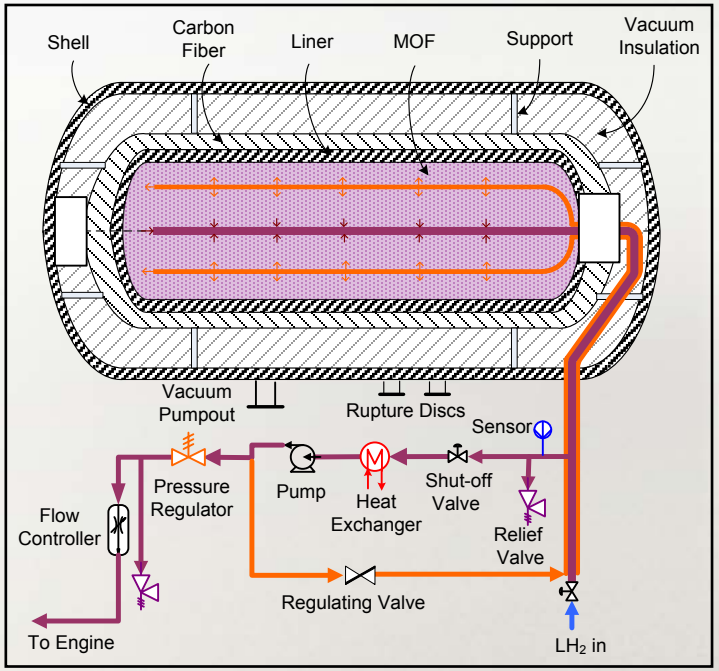
Proposed Future Work

- **Continue BOP Analysis – FY14/FY15**
  - Consider further cost reduction by component integration and alternative materials
  - Examination of lesser BOP components

- **Cost analysis/validation of PNNL estimated pressure vessel improvements – FY14/early FY15**
  - Validate cost savings from lower cost resin, resin additive, and alternative tank winding pattern.

- **Compressed Cold Gas Storage System – FY15**
  - Validate sizing/performance/cost using SA modeling tools
  - Apply DFMA cost analysis techniques
  - Cost assessment of evacuated multilayer insulation (MLI)
  - Base performance on PNNL experimental burst test results

- **Cost analysis of other concepts to be selected by DOE**
  - SBIR projects



Cold Tank Concept
Source: ANL/LLNL

Collaborations

Institution	Activities and Contributions
Argonne National Lab (ANL) • Rajesh Ahluwalia • Thanh Quoc Hua	• Contributed support for the validation of low manufacturing volume compressed tank cost through comparison with current CNG tank costs • Provided modeling data for CNG tank composite mass and dimensions • Initiated project to cost model recent advances at PNNL (low cost resin, nano-additives, and improved winding patterns)
National Renewable Energy Laboratory (NREL) • Lin Simpson • Mike Penev	• Assisted validation of low manufacturing volume compressed tank cost • Participated in discussions of CNG tank manufacturing industry to help identify a suitable tank size for the validation case
Pacific Northwest National Laboratory (PNNL) • Kevin Simmons • Kenneth Johnson	• Exchange of compressed gas vessel manufacturing parameters for comparison to SA's DFMA model • Scheduled to provide additional testing data (when available) for both ambient and cold gas tank configurations.
Industry Collaborators **Tank Manufacturers** Hexagon Lincoln Quantum Technologies 3M **BOP Comp. Manufacturers** Luxfer OMB Saleri Parker EV Metals Norman Filters	• **Tank Manufacturers** shared valuable information on H_2 and/or CNG tank manufacturing volumes, prices, dimensions, and weights • **BOP Component Manufacturers** provided info on component details for system design and cost, and on component manufacturing industry

Responses to Previous Year Reviewers' Comments

FY13 Reviewer Comment	FY14 Response to Comment
"The approach could be improved by including further cost details on certain BOP components."	Further cost details of BOP components were investigated.
"Further cost sensitivity analyses would be useful to highlight the key cost drivers within the tank and BOP, including the effects of certain design assumptions such as pressure and burst factors."	The effect of pressure is assessed for the tank and further investigation of BOP components (particularly for fittings, integrated valve, and pressure regulator) was completed for FY14.
"A clarification on the correlation of vessel length to diameter (L/D) ratio with cost is required. …The principal investigator (PI) should provide more insight to show why both L/D cost curves are equal."	L/D was found to have only a small affect over the relatively limited range examined. L/D affects cost through: mass of fiber needed, winding speed (affected by vessel diameter), number of vessels simultaneously in winding machine (affected by vessel diameter).
"It appears that collaboration exists, but it is difficult to ascertain the extent of the collaboration. The partners are listed and properly noted. Their areas of expertise are also noted. It would be helpful to determine the extent of the work of each collaborating partner on the pertinent slide where that partner provided information and research. More collaboration could be sought."	The extent of work for each collaborating partner is listed on "Collaborators" slide. New collaboration with PNNL is occurring as part of examination of the PNNL Cold Tank concept. Industry collaboration was a vital aspect of this year's analysis for investigating both CNG and H_2 PV tanks and BOP components.
"The system layout represents the current state of the technology. It is unclear what an advanced system layout could look like and what the impact would be on the BOP costs."	An advanced system is not yet considered for this work. The main focus of the FY14 work was to refine BOP costs and validated the pressure vessel model. Further consideration will be given to integrating the functionality of the low pressure BOP components.

23

Overall Project Summary

- **Overview**
  - Cost and performance examinations for selected H_2 storage systems
  - In Year 2 of 3 year analysis project
- **Relevance**
  - Independently assess storage system cost at various manufacturing rates
  - Identify key cost drivers and impact of remaining R&D challenges
  - Assess technical progress, benefits, and limitations
  - Analyses assist DOE in setting research direction & priorities
- **Approach**
  - Analysis based on performance and cost modeling of systems
  - Design for Manufacturing and Assembly (DFMA) process-based cost modeling
  - Validation against industry inputs and price quotes (when available)
- **Accomplishments**
  - Investigation of primary compressed H_2 system Balance of Plant (BOP) components: integrated valve, fittings, and pressure regulator
  - Validation of H_2 tank cost model by modeling CNG vessels, comparing to vendor prices
- **Collaborations**
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
- **Future Work**
  - Continued BOP component investigation
  - Cost and performance evaluation of Compressed Cold Gas systems
  - Examination of other storage systems as specified by DOE

Acknowledgements

This research is supported by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Fuel Cell Technologies (FCT) Office, under award number DE-E005253.

The authors wish to thank the following individuals for their technical and programmatic contributions and oversight:

Ms. Grace Ordaz (Technology Development Manager),

Dr. Ned Stetson (Hydrogen Storage Team Leader), and

Dr. Sunita Satyapal (Fuel Cell Technologies Office Director)

Technical Back-Up Slides

26

Fitting & Piping Cost Updated for 2014

- DFMA of Parker O-ring Seal-Lok™ fittings used as basis for 2014 fitting cost
  - Low pressure fittings: $12.44 - $26.72 each
  - High pressure fittings: $11.80 - $27.32 each

Effectively the same price

Calculated costs based on DFMA analysis (All Values in 2013$)

Cost associated with 1st vessel.	Annual Production Rate, Systems per Year 10,000	30,000	80,000	100,000	500,000
Single Vessel Fittings Cost Summary					
HP line	$6.28	$5.80	$5.38	$5.28	$4.58
HP fittings	$163.94	$98.69	$81.56	$78.99	$70.78
HP fasteners	$0.36	$0.36	$0.36	$0.36	$0.36
HP bends	$7.45	$6.30	$5.43	$5.25	$4.11
HP welds	$13.00	$13.00	$13.00	$13.00	$13.00
HP weldment components	$13.24	$11.20	$9.65	$9.33	$7.30
LP line	$18.42	$16.90	$15.56	$15.25	$13.04
LP fittings	$213.75	$134.17	$112.43	$110.64	$99.50
LP fasteners	$1.20	$1.20	$1.20	$1.20	$1.20
LP bends	$24.83	$21.01	$18.10	$17.50	$13.70
LP welds	$16.00	$16.00	$16.00	$16.00	$16.00
LP weldment components	$13.24	$11.20	$9.65	$9.33	$7.30
2014 Totals	**$491.71**	**$335.85**	**$288.32**	**$282.11**	**$250.88**
2013 Totals (2013$)	**$481.16**	**$407.16**	**$350.76**	**$339.06**	**$265.48**

Additional cost corresponding to 2nd vessel.	Annual Production Rate, Systems per Year 10,000	30,000	80,000	100,000	500,000
Additional Tank Fittings Cost Summary					
HP line	$ 4.18	$ 3.86	$ 3.57	$ 3.51	$ 3.04
HP fittings	$ 81.97	$ 49.34	$ 40.78	$ 39.49	$ 35.39
HP fasteners	$ 0.24	$ 0.24	$ 0.24	$ 0.24	$ 0.24
HP bends	$ 4.97	$ 4.20	$ 3.62	$ 3.50	$ 2.74
HP welds	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00
HP weldment components	$ 13.24	$ 11.20	$ 9.65	$ 9.33	$ 7.30
LP line	$ -	$ -	$ -	$ -	$ -
LP fittings	$ -	$ -	$ -	$ -	$ -
LP fasteners	$ -	$ -	$ -	$ -	$ -
LP bends	$ -	$ -	$ -	$ -	$ -
LP welds	$ -	$ -	$ -	$ -	$ -
LP weldment components	$ -	$ -	$ -	$ -	$ -
2014 Totals	**$ 114.59**	**$ 78.85**	**$ 67.86**	**$ 66.07**	**$ 58.71**
2013 Totals (2013$)	**$ 114.36**	**$ 96.78**	**$ 83.37**	**$ 80.59**	**$ 63.10**

Bottom line:

- **More detailed DFMA analysis for 2014**
- **Overall fitting/piping system cost drops by approximately 11%**

Further integration of components/functions may lead to additional cost savings.

Fitting Cost Summaries

DFMA HP Fitting Cost Summary						
Manufacturing Rate	**Sys/yr**	**10,000**	**30,000**	**80,000**	**100,000**	**500,000**
Total Nut Cost per fitting	$/fitting	$2.59	$2.59	$2.36	$2.41	$2.34
Total O-Ring Cost per fitting	$/fitting	$0.70	$0.70	$0.70	$0.70	$0.70
Total Stud Cost per fitting	$/fitting	$1.80	$0.61	$0.24	$0.20	$0.09
Fitting Cost Subtotal	$/fitting	$4.87	$3.68	$3.54	$3.62	$3.52
Total Engraving Cost per fitting	$/fitting	$0.10	$0.10	$0.10	$0.10	$0.10
Total Certification Cost per fitting	$/fitting	$0.80	$0.27	$0.10	$0.08	$0.02
Total Batch Testing Cost per fitting	$/fitting	$0.30	$0.30	$0.30	$0.30	$0.30
Total Individual Testing Cost per fitting	$/fitting	$7.07	$3.94	$3.53	$3.29	$3.20
Markup	$/fitting	$9.11	$4.26	$2.72	$2.46	$1.54
Total	$/fitting	$27.32	$16.45	$13.59	$13.16	$11.80

DFMA LP Fitting Cost Summary						
Manufacturing Rate	**Sys/yr**	**10,000**	**30,000**	**80,000**	**100,000**	**500,000**
Total Nut Cost per fitting	$/fitting	$3.47	$2.59	$2.47	$2.41	$2.33
Total O-Ring Cost per fitting	$/fitting	$0.70	$0.70	$0.70	$0.70	$0.70
Total Stud Cost per fitting	$/fitting	$1.35	$0.46	$0.19	$0.15	$0.10
Fitting Cost Subtotal	$/fitting	$4.47	$4.47	$4.14	$4.07	$4.07
Total Engraving Cost per fitting	$/fitting	$0.10	$0.10	$0.10	$0.10	$0.10
Total Certification Cost per fitting	$/fitting	$0.80	$0.27	$0.10	$0.08	$0.02
Total Batch Testing Cost per fitting	$/fitting	$0.45	$0.30	$0.31	$0.32	$0.30
Total Individual Testing Cost per fitting	$/fitting	$6.46	$3.53	$3.23	$3.41	$3.20
Markup	$/fitting	$8.91	$4.35	$2.81	$2.59	$1.62
Total	$/fitting	$26.72	$16.77	$14.05	$13.83	$12.44

Integrated Valve Cost Summaries

Integrated In-Tank Valve Costs Per Tank						
		Annual Manufacturing Rate				
		10,000	30,000	80,000	100,000	500,000
Auto Solenoid Valve	$/sys	$124.34	$91.03	$75.34	$72.80	$57.14
Materials	$/sys	$39.32	$33.61	$29.67	$28.90	$24.30
Processing	$/sys	$47.50	$33.80	$27.30	$26.67	$20.33
Assembly	$/sys	$3.58	$3.58	$3.58	$3.58	$3.58
Markup	$/sys	$33.93	$20.04	$14.79	$13.66	$8.93
TPRD	$/sys	$36.64	$31.46	$27.04	$26.01	$19.27
Purchased Price	$/sys	$30.53	$26.66	$23.21	$22.42	$16.76
Markup	$/sys	$6.11	$4.80	$3.83	$3.59	$2.51
Excess Flow Valve	$/sys	$47.06	$37.94	$32.69	$31.40	$24.38
Materials	$/sys	$3.18	$2.82	$2.51	$2.44	$1.96
Processing	$/sys	$19.34	$17.15	$15.30	$14.89	$11.94
Assembly	$/sys	$2.50	$2.50	$2.50	$2.50	$2.50
Markup	$/sys	$22.04	$15.47	$12.37	$11.56	$7.98
Filter	$/sys	$31.61	$26.42	$23.51	$22.75	$18.85
Materials	$/sys	$6.65	$6.48	$6.32	$6.29	$6.04
Processing	$/sys	$11.35	$10.34	$9.44	$9.24	$7.77
Markup	$/sys	$13.62	$9.60	$7.74	$7.23	$5.05
Manual Override	$/sys	$6.80	$6.23	$5.99	$5.91	$5.67
Materials	$/sys	$2.57	$2.57	$2.57	$2.57	$2.57
Processing	$/sys	$2.31	$2.26	$2.24	$2.23	$2.23
Markup	$/sys	$1.92	$1.40	$1.18	$1.11	$0.87
Temperature Sensor	$/sys	$51.17	$33.96	$24.98	$23.21	$14.72
Materials	$/sys	$3.80	$2.81	$2.18	$2.06	$1.40
Processing	$/sys	$22.57	$16.57	$12.69	$11.96	$7.93
Assembly	$/sys	$0.33	$0.33	$0.33	$0.33	$0.33
Markup	$/sys	$24.47	$14.24	$9.78	$8.86	$5.06
Valve Body	$/sys	$47.45	$41.27	$39.00	$38.34	$36.07
Materials	$/sys	$13.74	$13.74	$13.74	$13.74	$13.74
Processing	$/sys	$16.07	$15.01	$14.67	$14.63	$14.50
Assembly	$/sys	$1.82	$1.82	$1.82	$1.82	$1.82
Markup	$/sys	$15.82	$10.70	$8.77	$8.15	$6.01
Insulated Leadwire Sealing Fitting	$/sys	$34.54	$23.84	$17.17	$15.91	$9.39
Materials	$/sys	$3.17	$2.22	$1.62	$1.51	$0.90
Processing (including assembly)	$/sys	$19.28	$13.54	$9.87	$9.19	$5.47
Markup	$/sys	$12.09	$8.08	$5.67	$5.21	$3.02
Valve Integration & Test	$/sys	$10.91	$9.82	$9.38	$9.24	$8.73
Testing	$/sys	$7.28	$7.28	$7.28	$7.28	$7.28
Markup	$/sys	$3.64	$2.55	$2.11	$1.96	$1.46
Total		$390.51	$301.98	$255.10	$245.58	$194.24