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ANL/09-33

Technical Assessment of Cryo-Compressed Hydrogen Storage Tank Systems for Automotive Applications

Nuclear Engineering Division

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Abstract

On-board and off-board performance and cost of cryo-compressed hydrogen storage has been assessed and compared to the DOE 2010, 2015 and ultimate targets for automotive applications. The Gen-3 prototype system of Lawrence Livermore National Laboratory was modeled to project the performance of a scaled-down 5.6-kg usable hydrogen storage system. The on-board performance of the system and high-volume manufacturing cost were determined for liquid hydrogen refueling with a single-flow nozzle and a pump that delivers 1.5 kg/min of liquid H_2 to the insulated cryogenic tank capable of being pressurized to 272 atm (4000 psi). The off-board performance and cost of delivering liquid hydrogen were determined for two scenarios in which hydrogen is produced by central steam methane reforming (SMR) and by central electrolysis using electricity from renewable sources. The main conclusions from the assessment are that the cryo-compressed storage system has the potential of meeting the ultimate target for system gravimetric capacity and the 2015 target for system volumetric capacity (see Table I). The system compares favorably with targets for durability and operability although additional work is needed to understand failure modes for combined pressure and temperature cycling. The system may meet the targets for hydrogen loss during dormancy under certain conditions of minimum daily driving. The high-volume manufacturing cost is projected to be 2-4 times the current 2010 target of $4/kWh. For the reference conditions considered most applicable, the fuel cost for the SMR hydrogen production and liquid H_2 delivery scenario is 60%-140% higher than the current target of $2-$3/gge while the well-to-tank efficiency is well short of the 60% target specified for off-board regenerable materials.

Table I. Executive summary of the performance of the prototype (10.4 kg usable H_2) and scaled (5.6 kg usable H_2) Gen-3 systems

Performance and Cost Metric	Units	Scaled Gen-3	Prototype Gen-3	2010 Targets	2015 Targets	Ultimate Targets
Usable Storage Capacity (Nominal)	kg-H_2	5.6	10.4			
Usable Storage Capacity (Maximum)	kg-H_2	6.6	12.3			
System Gravimetric Capacity	wt%	5.5-9.2	7.1-12	4.5	5.5	7.5
System Volumetric Capacity	kg-H_2/m^3	41.8-44.7	44.5-47.1	28	40	70
Storage System Cost	$/kWh	12	8	4	2	TBD

Introduction

The DOE Fuel Cell Technologies Program has conducted a technical assessment of cryo-compressed hydrogen storage tank systems for automotive applications, consistent with the Program's Multiyear Research, Development, and Demonstration Plan. Cryo-compressed hydrogen storage refers to the storage of hydrogen at cryogenic temperatures in a vessel that can be pressurized (nominally to 250-350 atm), in contrast to current cryogenic vessels that store liquid hydrogen at near-ambient pressures. Cryo-compressed hydrogen storage can include liquid hydrogen, cold compressed hydrogen, or hydrogen in a two-phase region (saturated liquid and vapor). This assessment was based primarily on publicly available information and design schematics of the Gen-3 tank design and prototype vessel [1] built by Lawrence Livermore National Laboratory (LLNL) and Structural Composites Industries (SCI). The assessment included an independent review of the tank system design and technical performance by Argonne National Laboratory [2], an independent cost assessment by TIAX, LLC [3], and comments received from automotive manufacturers, tank developers, and LLNL. Argonne and TIAX analyzed the LLNL Gen-3 system concept for its potential to meet the DOE 2010, 2015, and ultimate hydrogen storage targets for fuel cell and other hydrogen-fueled vehicles [4].

These assessments established the baseline system performance and cost of cryo-compressed tank systems of the Gen-3 design suitable for automotive applications. Results include both "on-board" metrics (i.e., for the hydrogen storage system required on the vehicle) and "off-board" (i.e., thermal management, fuel cycle and energy costs, and infrastructure necessary to refuel the on-board storage system).

- On-Board Assessment: Performance metrics include the on-board system weight and volume, refueling and discharge dynamics and energetics, and dormancy and boil-off losses for a variety of initial and operating conditions. Cost metrics include the on-board system high-volume (i.e., 500,000 units/year) manufactured cost.
- Off-Board Assessment: Performance metrics include the off-board thermal management requirements, and well-to-tank (WTT) energy efficiency and greenhouse gas (GHG) emissions. Cost metrics include the refueling costs and combined fuel system "ownership cost" on a $/mile-driven basis.

Results of the assessments are compared to DOE Technical Targets for the on-board fuel system gravimetric and volumetric capacities and charging, discharging, and H_2 loss rates, as well as the off-board fueling infrastructure energy efficiency, GHG emissions, and refueling cost. The manufactured factory cost assessment may also be compared to the DOE targets; however, the cost targets are currently under revision (as of September 30, 2009). Other DOE Technical Targets, including on-board system operability and fuel purity are expected to be met easily by cryo-compressed hydrogen storage systems, so they were not included explicitly in these assessments. However, system durability may be a concern because of the requirement to maintain a high vacuum within the superinsulation jacket and material fatigue due to deep pressure and temperature cycling. The bases and results of the assessments are discussed in the following.

On-Board Assessments

Argonne and TIAX cooperatively, but independently, evaluated the LLNL Gen-3 cryo-compressed tank system for performance and high-volume manufacturing in automotive applications, in particular hydrogen fuel cell vehicles (FCV). The LLNL prototype has a hydrogen storage volume of 151 L and a nominal capacity to store 10.7 kg of liquid hydrogen (LH_2) at 20.3 K and 1 atm pressure (70.9 kg/m^3 nominal LH_2 density). The corresponding nominal usable H_2 storage capacity is 10.4 kg, if the tank is discharged to 4 atm final pressure and 50 K final temperature. In earlier drive-cycle modeling of a mid-size hydrogen fuel cell vehicle, Argonne had determined that, as a reference base case, 5.6 kg of usable hydrogen would be sufficient to provide a 350-mile driving range between vehicle refuelings [5, 6]. As such, in addition to analyzing the Gen-3 prototype built by LLNL, Argonne also analyzed a storage vessel of a similar design but sized for 5.6 kg of usable hydrogen. The Argonne model of the cryo-compressed tank system was first validated by comparison with the LLNL prototype vessel. Design details of both the larger Gen-3 prototype and the smaller tank system (referred to here as the scaled Gen-3) were then used by TIAX for their on-board manufacturing cost assessment.

In the LLNL Gen-3 system, hydrogen is stored in an insulated pressure vessel that is capable of operating at cryogenic temperatures. The vessel itself is not designed to cool or liquefy the supplied hydrogen; rather, it can be filled with liquid or gaseous hydrogen at low, intermediate, or ambient temperatures, and at low or high pressures (up to ~272 atm, 4,000 psia). Argonne worked closely with LLNL to define and model the Gen-3 system in sufficient detail to be able to analyze its performance, and to scale it to a hydrogen storage capacity that is different from that of the LLNL prototype. The Argonne performance analysis required that the specified minimum delivery pressure (4 atm for fuel cell vehicles) and minimum full flow rate (1.6 g/s for an 80-kW fuel cell system) be met at all times, regardless of the “state-of-charge” of the hydrogen storage system.

The LLNL Gen-3 Cryo-Compressed H_2 Storage Tank System

A schematic of the LLNL Gen-3 cryo-compressed tank system is shown in Fig. 1. The Type-3 pressure vessel consists of a 9.5-mm-thick aluminum liner wrapped with a 10-mm-thick T700S carbon fiber composite (CF, 60% fiber volume). The fiber-wound vessel is surrounded by a 17-mm-wide 10^{-5}-torr vacuum gap filled with multi-layer vacuum superinsulation (MLVSI). As designed and built, a 3-mm-thick stainless steel Type 304 (low-carbon steel in the cost study) outer shell completes the main tank. Other in-tank equipment includes tubing for liquid H_2 fill, gaseous H_2 fill and discharge, and a heat-exchange gas recirculation line. Significant balance-of-plant (BOP) components include a pressure regulator, fill tube/port, control valves, pressure relief valves, rupture discs, LH_2 level sensor (which may be needed if the tank is allowed to operate in two-phase region), pressure gauges and transducers, and thermocouples.

This system has a hydrogen storage volume of 151 L and a total system volume of 235 L. The storage vessel weighs 123 kg (system weight 145 kg), and it can nominally store 10.7 kg of LH_2 at 1 atm, of which we estimate that 10.4 kg is usable over a typical vehicle duty-cycle. When filled with gaseous H_2, the system can store 2.8 kg of compressed H_2 (cH_2) at 272 atm and 300 K. When filled with LH_2, the system’s nominal usable volumetric capacity is 44.5 kg/m^3 (1.5 kWh/L) and the gravimetric capacity is 7.1 wt% (2.3 kWh/kg). Since LH_2 is slightly compressible, the actual capacity depends on the refueling conditions and the final pressure and temperature to which the tank is charged with H_2.

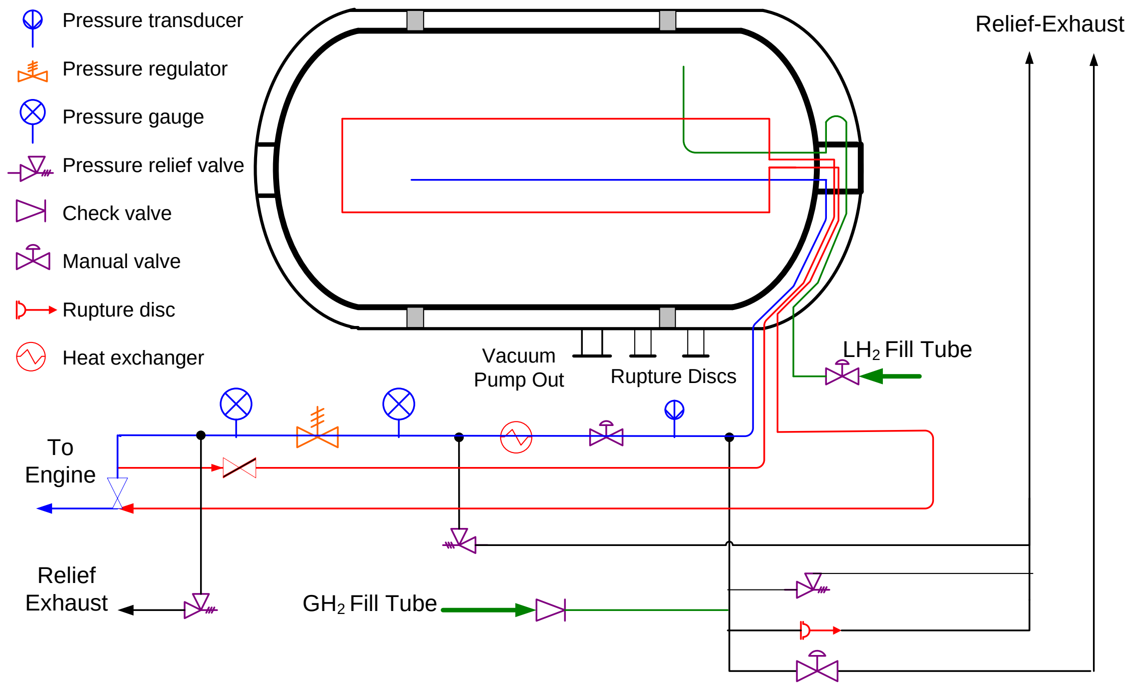

Fig. 1. Design schematic of the LLNL Gen-3 cryo-compressed H_2 storage tank system.

Argonne Performance Model and Model Validation for the Gen-3 Design

Working very closely with LLNL, Argonne set up a design and performance model of the Gen-3 tank system. Developing such a model enabled Argonne to scale the Gen-3 system design to different sizes, for example, for providing 5.6 kg of usable H_2 rather than the 10.4 kg of usable H_2 in the LLNL prototype. The model could then be used to assess the charging, discharging, and dynamic performance of the system, as well as its dormancy and boil-off characteristics.

The Argonne model used a netting analysis algorithm to determine the optimal dome shape with a geodesic winding pattern, and to determine the thickness of the geodesic and hoop windings in the cylindrical section for specified maximum storage pressure and length-to-diameter ratio. In calculating the carbon fiber composite thickness, the model applied a safety factor of 2.25 and a translation strength of 86% to the tensile strength of the composite (2550 MPa). The model assumed that heat transfer through the superinsulation could be calculated using the thermal properties of aluminized Mylar sheets (28 layers/cm) with Dacron spacers. The insulation thickness was determined so as to limit the heat in-leakage to 1.5 W through the sheets at the H_2 storage temperature. It was assumed that an equal or greater heat transfer rate might occur through other conductive leakage paths. A combined, radiative and conductive, average heat transfer rate of 5 W was assumed in estimating dormancy and hydrogen loss rate.

Argonne consulted SCI for the design basis of liner thickness [7]. SCI designs the hydrogen tank in compliance with DOT FMVSS-304 regulation (Federal Motor Vehicle Safety Standard), which specifies requirements for the integrity of compressed natural gas containers. SCI assumes that DOT regulations (safety factor 2.25, 18,000 warm pressure cycles) supersede the DOE target of 1500 cycles for hydrogen vehicles. For a 4000-psi nominal storage pressure, SCI determined the aluminum liner thickness to be approximately 9.5 mm (3/8"), which thickness depends primarily on the maximum tank pressure and only weakly on the tank size. Independent analysis and validation are needed to understand the mechanisms of liner failure as influenced by storage pressures and temperatures, overlapping pressure and temperature cycles, tank size and geometry, and carbon fiber type, quality and thickness.

The Argonne model was initially validated by comparing the computed weights and volumes with the measured data for the LLNL Gen-3 prototype system. Beyond the main tank assembly, the model included a comprehensive listing of the significant balance-of-plant (BOP) components. The good agreement between the modeled and actual weights and volumes is shown in Table 1. The last two columns in Table 1 show the model results for the scaled Gen-3 system sized to provide a nominal usable H_2 storage of 5.6 kg of LH_2 required for a mid-size fuel cell vehicle, as mentioned above. The weights and volumes of many of the significant BOP components are included in Table 1; a more complete listing of the BOP components is given in Appendix A-3.

Table 1. Comparison of the modeled component and system weights and volumes of prototype and scaled LLNL Gen-3 cryo-compressed tank system

	ANL		**LLNL Gen-3**		**ANL**	
	Wt (kg)	**Vol (L)**	**Wt (kg)**	**Vol (L)**	**Wt (kg)**	**Vol (L)**
Stored Hydrogen	**10.7**	**151.0**	**10.7**	**151.0**	**5.7**	**80.8**
Usable Hydrogen	**10.4**	**151.0**			**5.6**	**80.8**
Pressure Vessel (4000 psi)	**62.4**	**29.0**	**61.0**	**28.0**	**39.1**	**17.7**
Aluminum liner (9.5 mm)	38.8	14.4			25.7	9.5
Carbon fiber	22.7	14.1			12.4	7.7
Boss	0.4	0.4			0.4	0.4
Plug	0.3	0.1			0.3	0.1
In-tank heat exchanger	0.3	0.0			0.3	0.0
Insulation and Vacuum Shell	**52.3**	**43.7**	**51.0**	**45.0**	**34.6**	**24.4**
Support rings	1.2	0.7			0.5	0.3
Insulation material	2.2	36.8			1.2	20.0
Vacuum shell (SS 304, 3.2 mm)	48.9	6.2			32.9	4.2
Mounting Brackets	**6.0**	**1.0**	**6.0**	**1.0**	**6.0**	**1.0**
Balance-of-Plant (BOP)	**16.0**	**10.0**	**16.0**	**10.0**	**16.0**	**10.0**
Computer	0.2	0.5	0.2	0.5	0.2	0.5
Electronic boards	2.2	5.0	2.2	5.0	2.2	5.0
Valves and valve box	6.9	0.8	6.9	0.8	6.9	0.8
Pressure transmitter, gauge, regulator, and rupture discs	1.1	0.6	1.1	0.6	1.1	0.6
Heat exchanger	1.5	1.8	1.5	1.8	1.5	1.8
Miscellaneous tubing, fittings, etc.	4.0	1.5	4.0	1.5	4.0	1.5
Total	**147.4**	**234.7**	**144.7**	**235.0**	**101.4**	**133.9**
Gravimetric Capacity, wt% H_2	**7.1**		**7.4**		**5.5**	
Volumetric Capacity, g-H_2/L		**44.5**		**45.5**		**41.8**

TIAX Cost Model

We have applied a proprietary technology-costing methodology that has been customized to analyze and quantify the processes used in the manufacture of hydrogen storage tanks and BOP components. The bottom-up, activities-based cost model is used in conjunction with the conventional Boothroyd-Dewhurst Design for Manufacturing & Assembly (DFMA®) software. The TIAX bottom-up cost model and the DFMA® model are both bottom-up costing tools. The model was used to develop costs for all the major tank components, balance-of-tank, tank assembly, and system assembly. DFMA® concurrent costing software was used to develop bottom-up costs for other BOP components. "Bottom-up" costing refers to developing a manufacturing cost of a component based on:

- Technology Assessment – Seek developer input, conduct literature and patent review
- Cost Model Development – Define manufacturing process unit operations, specify equipment, obtain cost of raw materials and capital equipment cost, define labor rates, building cost, utilities' cost, tooling cost, and cost of operating & non-operating capital with appropriate financial assumptions
    - Fixed Operating Costs include Tooling & Fixtures Amortization, Equipment Maintenance, Indirect Labor, and Cost of Operating Capital
    - Fixed Non-Operating Costs include Equipment & Building Depreciation, Cost of Non-Operating Capital
    - Variable Costs include Manufactured Materials, Purchased Materials, Direct Labor (Fabrication & Assembly), Indirect Materials, and Utilities
- Model Refinement – Seek developer and stakeholder feedback, perform single-variable sensitivity and multi-variable Monte Carlo analyses

We contacted developers/vendors, and performed a literature and patent search to explicate the component parts, specifications, material type and manufacturing process. Subsequently, we documented the bill of materials (BOM) based on the system performance modeling provided by ANL, determined material costs at the assumed production volume, developed process flow charts, and identified appropriate manufacturing equipment. We also performed single-variable and multi-variable (Monte Carlo) sensitivity analyses to identify the major cost drivers and the impact of material price and process assumptions on the high-volume hydrogen storage system cost results. Finally, we solicited developer and stakeholder feedback on the key performance assumptions, process parameters, and material cost assumptions; and we calibrated the cost model using this feedback. A brief discussion of the key performance, process and cost assumptions is presented below.

Performance Parameters

Key performance assumptions such as those presented in Table 2 were developed by ANL based on modeling and data from LLNL's Gen 3 tank design. We used sensitivity analyses to capture the impact of variation in key performance assumptions including tank safety factor, composite tensile strength, translation efficiency, and tank liner thickness.

Table 2. On-board storage system design assumptions [3]

Design Parameter	Base Case Value	Basis/Comment
Nominal pressure	272 atm	Tank design assumption based on discussions with LLNL
Maximum pressure	340 atm [1]	125% of nominal design pressure is assumed required for dormancy
Filling pressure (max)	340 atm	ANL assumption for "Cryo-compressed H_2 Storage Option"
"Empty" pressure	4 atm	ANL assumption; depending on initial temperature and H_2 charge
Usable LH_2 storage capacity	5.6 and 10.4 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range (5.6 kg) and LLNL tank design (10.4 kg)
Tank size (water capacity)	81 and 151 L	Required for 5.6 kg and 10.4 kg useable H_2 capacity (5.7 and 10.7 kg total H_2 capacity), calculated by ANL
Safety factor	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure (i.e., 272 bar)
L/D ratio	2.0	ANL assumption based on discussions with LLNL and SCI design, 2008; based on the outside of the CF wrapped tank
Carbon fiber type	Toray T700S	Discussions with LLNL, Quantum and other developers, 2008
Composite tensile strength	2,550 MPa	Toray material data sheet for 60% fiber by volume
Translation strength factor	86%	ANL assumption based on discussions and data from Quantum, 2004-09
Tank liner thickness	9.5 mm Al	ANL assumption based on discussions with LLNL and SCI design, 2008
Minimum temperature	-253 ºC	Typical for liquid hydrogen storage
Vacuum gap	10 and 17 mm	ANL assumption to achieve ~1.5 W heat transfer rate with Mylar layers
Outer shell	3.2 mm Steel	Discussions with LLNL and industry, 2008-09

Carbon Fiber Price

The cost of carbon fiber is a significant factor in all high pressure systems. In order to maintain a common basis of comparison with previous cost analyses, we chose a base case carbon fiber price of $13/lb ($28.6/kg) based on discussions with Toray in 2007 regarding the price of T700S fiber at high volumes. Carbon fiber is already produced at very high-volumes for the aerospace and other industries, so it isn't expected to become significantly less expensive in the near term. However, there are DOE programs that are looking at ways to significantly reduce carbon fiber costs (e.g., see Abdallah [8]). We used sensitivity analyses to capture the impact of the uncertainty in carbon fiber prices, using $10/lb at the low end and $16/lb at the high end.

[1] Tank design based on nominal pressure (272 atm) not maximum pressure.

We assumed the hydrogen storage system manufacturer purchases pre-impregnated (i.e., "prepreg") carbon fiber composite at a price that is 1.27 (prepreg/fiber ratio) times higher than the raw carbon fiber material [9]. An alternative approach would be to assume a wet resin winding process that would allow the purchase of raw carbon fiber material instead of buying prepreg tow fiber. We chose a prepreg winding process based on the assumption that this process results in greater product throughput and reduced environmental hazards (including VOCs, ODCs, and GHG emissions) compared to a wet winding process. According to Du Vall [9], greater throughput is typically achieved because prepreg tow allows for more precise control of resin content, yielding less variability in the cured part mechanical properties and ensuring a more consistent, repeatable, and controllable material compared to wet winding. In addition, wet winding delivery speeds are limited due to the time required to achieve good fiber/resin wet out. The downside is that the prepreg raw material costs are higher than for wet winding. But, when all aspects of the finished product cost are considered (i.e., labor, raw materials, throughput, scrap, downtime for cleanup, and costs associated with being environmentally compliant), Du Vall found that prepreg materials provided an economic advantage compared to wet winding for high-volume production of Type II and IV CNG tanks.

It might be possible to reduce the overall manufactured cost of the composite, perhaps closer to the cost per pound of the carbon fiber itself ($13/lb) or ever lower (since the resin is less expensive per pound), if the wet winding process is proven to be more effective. In particular, if wet winding throughputs are increased. However, the detailed evaluation that is required to explore these cost trade-offs was beyond the current scope of work. Instead, we address the potential for significantly lower carbon fiber composite costs in the sensitivity analysis.

BOP Cost Projections

BOP costs were estimated using the Delphi method with validation from top-down and bottom-up estimates described below (see Appendix for details for each cost estimation approach):

- Delphi Method: Projections solicited from industry experts, including suppliers, tank developers, and end users
    - End users (e.g., automotive OEMs) and, to some extent, tank developers, are considering the issue of automotive scale production
    - In some cases, end-user or developer estimates are optimistic or based on reasonable targets; in other cases estimates may be pessimistic by not taking into account process or technology changes that would be required for automotive-scale production
    - We used our judgment of the projections and results from top-down and bottom-up estimations to select a reasonable base case cost for each component
- Top-Down: High-volume discounts applied to low-volume vendor quotes using progress ratios (PR)
    - Provides a consistent way to discount low-volume quotes
    - Attempts to take into account process or technology developments that would be required for automotive-scale production
    - Requires an understanding of current base costs, production volumes, and markups

- Bottom-Up: Cost Modeling using DFMA® software
  - Calculates component costs using material, machining, and assembly costs, plus an assumed 15% markup for component supplier overhead and profit
  - May not be done at the level of detail necessary for estimating the true high-volume cost of the component

Durability and Life Requirements

The impact of meeting durability and life requirements has not been factored into cost; however, this was discussed with the Tech Team and developers. For the moment, we assume that the developments that will increase the life of the hydrogen storage systems, if necessary, will not involve increased costs.

Vertically Integrated Process vs. Outsourcing of Tank Components

In reporting the "Factory Cost" or "Manufactured Cost" of the hydrogen storage system, we have assumed a vertically integrated tank manufacturing process; i.e., we assume that the automotive OEM or car company makes all the tank components in-house. Therefore, intermediate supply chain markups are not included for individual tank components. The major tank costs (liner & fittings, carbon fiber layer, multi-layer vacuum insulation, outer shell, and tank assembly) are "bottom-up" estimated, and reported with no added supplier markup. In reality, the manufacturing process would be a combination of horizontally and vertically integrated, with appropriate markups.

Markup of BOP Components

In our model, some major BOP costs (e.g., fill tube/port, pressure regulator, pressure relief valve) are "bottom-up" estimated as well (similar to the major tank costs). Since we assume that the automotive OEM buys all the BOP components/subsystems from suppliers, and assembles the overall system in-house, we assume a uniform supplier-to-automotive OEM markup of 15% for all major BOP components. Raw materials, and some BOP, hardware are purchased and implicitly include (an unknown) markup. We assume that supplier markup includes:

- Profit
- Sales (Transportation) & Marketing
- R&D - Research & Development
- G&A - General & Administration (Human Resources, Accounting, Purchasing, Legal, and Contracting), Retirement, Health
- Warranty
- Taxes

Based on discussions with industry, we learned that automotive Tier 1 suppliers would most likely not have any Sales & Marketing expense since they often have guaranteed 5-year supply contracts with the OEM. Also, the warranty and R&D cost is increasingly being shared by the supplier and the OEM. (Previously, the OEM covered the warranty costs themselves; now the supplier supports their own warranty. Furthermore, the OEM's share in some of the R&D cost). The OEMs usually negotiate 5% per year cost reduction for 5 years with the supplier, further squeezing the supplier's margin. Therefore, currently, profit margins for Tier 1 suppliers are typically only in the single-digits (perhaps 5-8%), and a supplier who can negotiate 15% markup, is doing very well. We address these markup uncertainties and other BOP component cost uncertainties in the sensitivity analyses[2].

Tank QC and System QC

At high-production volume of 500,000 units/year, we have assumed that the hydrogen storage system production process is mature and that all quality issues are "learned out". We have included rudimentary tank and system Quality Control (QC) such as leak tests and visual and ultrasonic inspections.

Process Yield, Material Scrap and Reject Rate

The cost models include assumptions about process yield (i.e., the percentage of acceptable parts out of the total parts which are produced), material scrap rate (i.e., the recyclable left-over material out of the total materials used in the process) and reject rate (i.e., the percentage of unacceptable parts out of the total parts which are produced based on experience from similar manufacturing processes at high volumes). An appropriate material scrap credit is applied to the left-over material; however the material recycling process is not included within the bounds of our analysis. We address uncertainties in these assumptions in the sensitivity analysis.

Other Technical Issues

The goal of this assessment is to capture the major cost contributions to the overall hydrogen storage system cost. Within the scope of a project of this type, the system chosen for assessment does not claim to solve all of the technical issues facing developers today. For example, the added vehicle controls required to operate the storage system and hydrogen leak detection sensors are not included. These BOP components are not expected to make a significant contribution now; however, if the cost of the tank and major BOP components decrease, the balance of system may represent a larger share of the system cost in the future.

Performance Results

Liquid Hydrogen Storage

The discussion that follows refers to the results obtained using the Argonne model for weights, volumes, and performance, including sensitivity analyses for different thicknesses of the aluminum liner, and different materials (aluminum, stainless steel) for the outer shell.

a) Weight and Volume Distributions for the Prototype and Scaled Gen-3 Tank Systems

As shown in Table 1, the modeled nominal gravimetric capacity of the prototype Gen-3 system is 7.1 wt% H_2 and the corresponding volumetric capacity is 44.5 g-H_2/L. For the scaled version of

[2] The supplier markup does not include the markup for the hydrogen storage system manufacturer (e.g., automotive OEM), that sells the final assembled system.

the Gen-3 system (scaled to a usable H_2 storage capacity of 5.6 kg), the corresponding nominal values are 5.5 wt% H_2 and 41.8 g-H_2/L. Thus, these systems meet or exceed the DOE 2015 targets of 5.5 wt% and 40 g-H_2/L for automotive hydrogen storage.

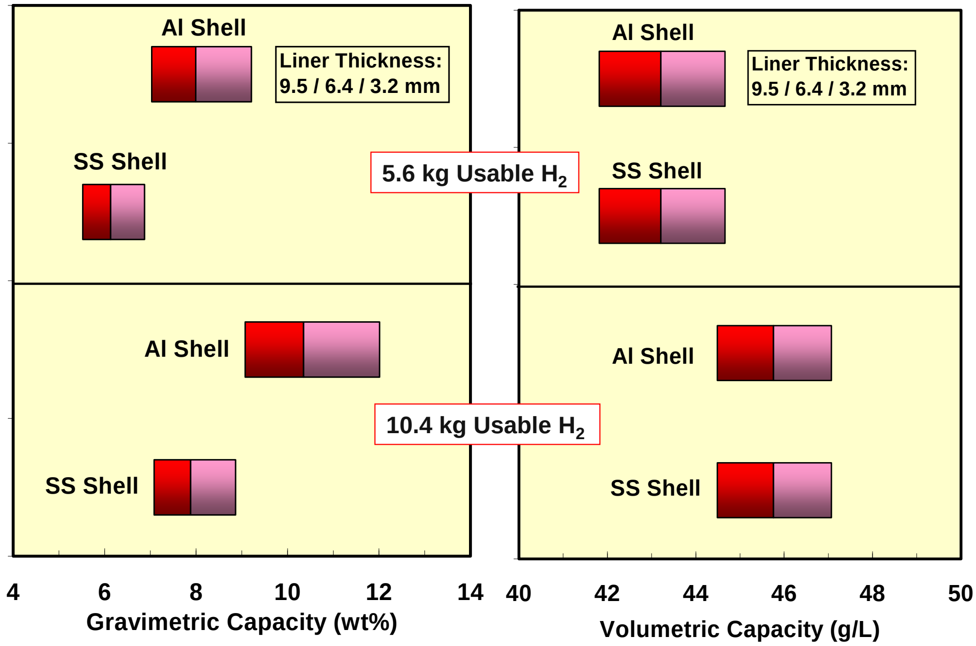

Fig. 2. Gravimetric and volumetric capacities of the LLNL and scaled Gen-3 cryo-compressed H_2 storage systems, and their sensitivity to Al liner thickness and the shell material.

Different tank manufacturers have different design approaches, and some may choose to use a thinner liner in order to reduce the weight, volume, and potentially, the overall cost of the cryo-compressed tank. If the Al liner thickness can be reduced to 3.2 mm, the tank performance parameters increase to 8.9 wt% and 47.1 g-H_2/L for the prototype system and to 6.9 wt% and 44.7 g-H_2/L for the scaled Gen-3 system. Further, the stainless steel outer shell could be replaced with an aluminum shell to decrease the tank weight even further. If this is done, the gravimetric capacities improve to 12 wt% for the prototype system and 9.2 wt% for the scaled system, meeting the ultimate DOE gravimetric capacity target; the shell material change does not affect the volumetric capacities of the systems, which remain less than the ultimate DOE target of 70 g-H_2/L. These results are summarized graphically in Fig. 2.

The contributions of the various tank components and the BOP to the weight and volume distributions of these tank systems are shown in Fig 3. The shell and the liner are the heaviest components of the tanks, making up 58% to 61% of the total system weight, while the stored H_2 is the largest volume contributor, representing 61% to 65% of the total system volume. Other significant contributors to the system weight are the carbon fiber/resin composite and the BOP components, while the other large contributors to the system volume are the MLVSI, the liner, carbon fiber, and the BOP components.

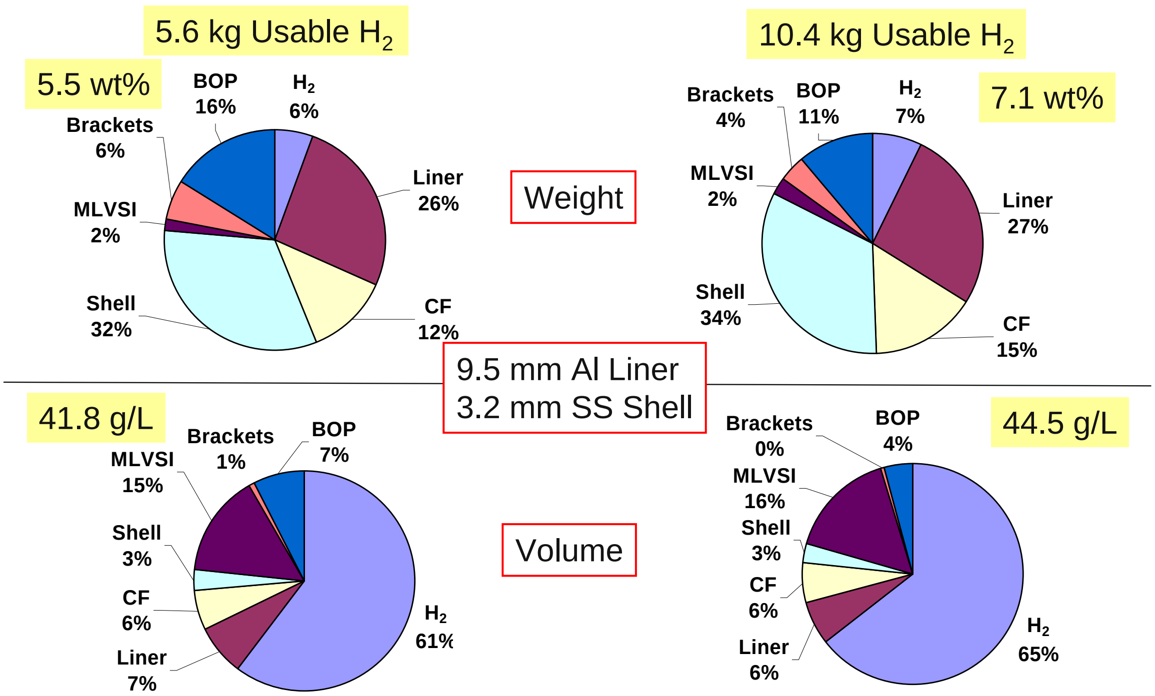

Fig. 3. Component weight and volume distributions in the LLNL and scaled Gen-3 cryo-compressed H_2 storage tank systems. CF: carbon fiber resin composite; MLVSI: multi-layer vacuum super insulation; BOP: balance-of-plant.

b) Performance of the Scaled Gen-3 Cryo-Compressed Tank System

The results discussed from this point forward in the report are for the scaled Gen-3 system with a nominal storage capacity 5.6 kg of recoverable H_2 under the automotive demand conditions of 4 atm minimum delivery pressure and 1.6 g/s of H_2 discharge rate from the system to the fuel cell power plant on-board the vehicle.

Similar analytical results for the larger Gen-3 prototype are summarized graphically in Appendix A-1, while Appendix A-2 shows the modeled results for the LLNL Gen-3 prototype operated in the supercritical H_2 storage mode.

Compressed Hydrogen Storage

When filled with room-temperature cH_2 rather than LH_2, the amount of H_2 that can be charged into the LLNL Gen-3 system is a function of the tank temperature at the start of the filling operation. For this mode of refueling, the Argonne model assumed that:

- the tank is refueled adiabatically with compressed H_2 at 300 K and 272 atm (4,000 psia);
- the aluminum liner, carbon fiber/resin composite, and H_2 gas in the tank are isothermal during refueling; and
- the initial pressure at the start of refueling is 4 atm, regardless of the initial temperature (which may vary from 50 K for a previous LH_2 fill to 300 K for a fully depleted tank).

Under these assumptions, Fig. 4 shows the mass of H_2 that can be charged to the tank, and the final temperature of the tank, as a function of the tank's temperature at the start of the fueling operation. For an initial tank temperature of 300 K, ~1.4 kg of cH_2 can be charged into the scaled Gen-3 system, which would then correspond to a gravimetric H_2 storage capacity of 1.3 wt%. The maximum amount of cH_2 that can be charged is 1.7 kg if the initial tank temperature is <90 K, which corresponds to a gravimetric storage capacity of 1.7 wt%. A slightly greater amount of cH_2 can be charged into the tank if the H_2 is pre-cooled to -40°C (as proposed for fast-fill of future 350 and 700-bar systems, Release A SAE J2601) and if the tank is filled to a pressure higher than the nominal design maximum operating pressure of 272 atm. Naturally, the lower the initial tank temperature, the smaller is the effect of pre-cooling H_2.

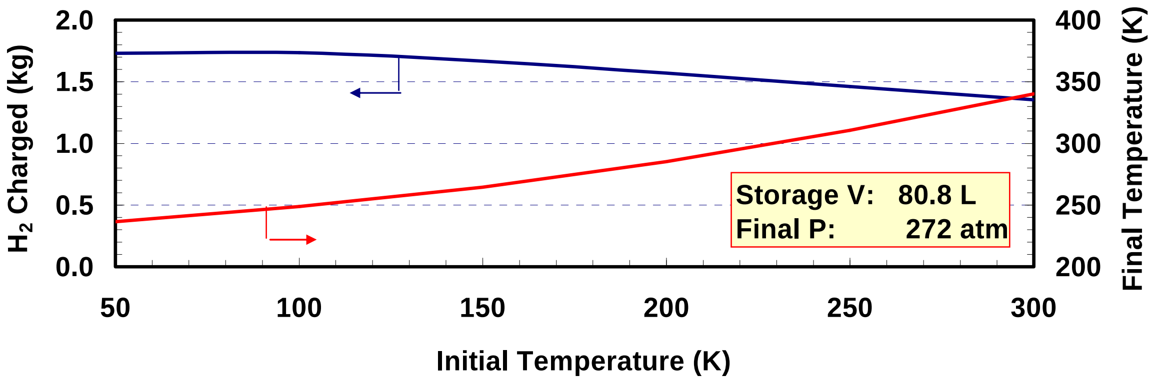

Fig. 4. Effect of initial tank temperature on the maximum amount of room-temperature cH_2 that can be charged into the tank and the final temperature of the tank, with an initial pressure of 4 atm and a final pressure of 272 atm.

Liquid Hydrogen Refueling and Discharge

Fueling with LH_2 has been analyzed for two different modes of operation of LH_2 storage, cryo-compressed and cryo-supercritical. For either mode, the refueling system uses a single-flow nozzle and a high-pressure LH_2 pump that delivers 1.5 kg/min to the system at a variable pressure (25% above the prevailing pressure in the tank) with an average isentropic efficiency of 80%. A LH_2 pump is available that can supply hydrogen at even higher flow rate and pressure [10]. The key features of the two refueling modes analyzed in this report are:

1. Cryo-compressed H_2 storage
   – Allows the tank to operate mostly in the two-phase region (saturated vapor and liquid)
   – Heat is supplied only during discharge
   – Would need a liquid level sensor to serve as a fuel gauge
2. Cryo-supercritical H_2 storage
   – No phase change
   – Level sensor not needed
   – Heat needs to be supplied during both refueling and discharge.

Results of the liquid-fueled cryo-compressed H_2 storage analysis are discussed here. The cryo-supercritical operating mode was analyzed only for the LLNL Gen-3 prototype. As such, those results are not included here; rather, they are given in Appendix A-2 in graphical summary form.

It is worth mentioning that there are other modes of refueling the cryo-compressed system, especially if a double-flow nozzle is used [11] and the station is equipped with additional hardware and cooling arrangement [12]. All the results presented in this report for the dynamics of cryo-compressed hydrogen refueling, discharge and dormancy were obtained using models described elsewhere [11]. The models employ the Benedict–Webb–Rubin (BWR) equation of state for equilibrium composition of para and ortho phases of H_2. Also, the specific heats of structural components (liner and carbon fiber) are strong functions of temperature, particularly at cryogenic conditions [11].

LH_2 Refueling Dynamics and H_2 Storage Capacity

The amount of LH_2 that can be charged to the system is a function of the initial tank temperature, as shown in Fig. 5 for refueling scenarios in which the tank is initially depleted to the 4-atm minimum allowable pressure. The results in Fig. 5 are for two different modes of refueling, one where the tank is filled to 272 atm regardless of the starting temperature, and the other where the maximum density of the H_2 in the tank is limited to 71 kg/m^3, the density of LH_2 at 1 atm and 20.3 K. The top plot in Fig. 5 shows the results for the first mode of filling to 272 atm, while the bottom plot shows the results for filling to 71 kg/m^3 maximum LH_2 density. In the first mode, the maximum amount of H_2 charged is 6.4 kg corresponding to a stored H_2 density of 81 kg/m^3. In the second mode, the maximum amount of H_2 charged is 5.6 kg, and the final pressure is less than 272 atm if the initial tank temperature is less than 125 K. For both modes of refueling, the maximum amount of H_2 that can be charged into the tank is just slightly greater than 2.1 kg if the initial tank temperature is 300 K.

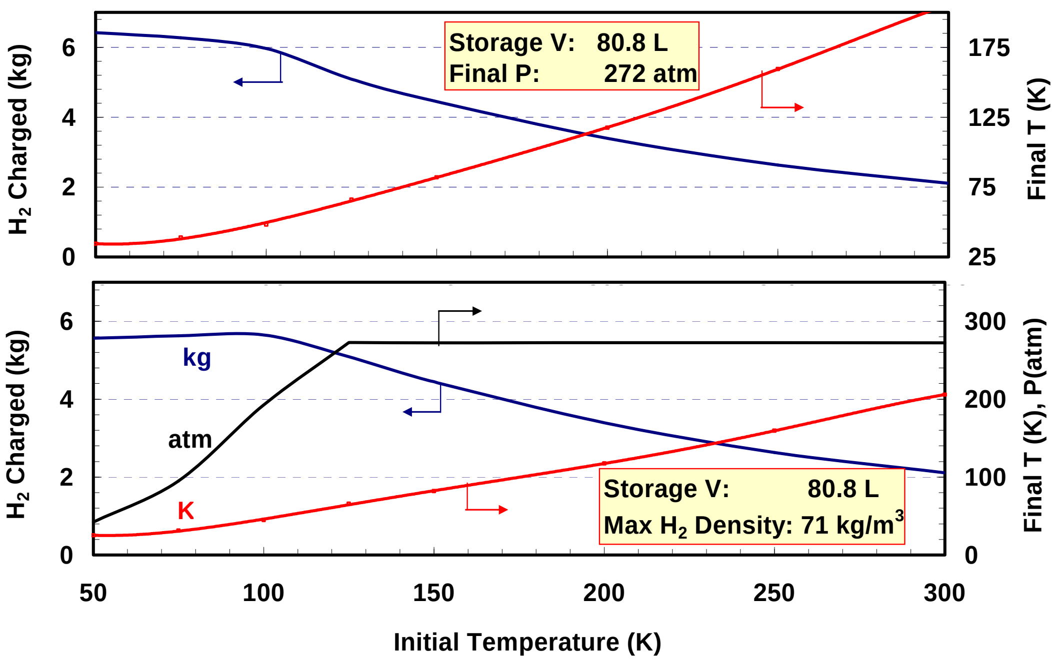

Fig. 5. Effect of initial tank temperature on the amount of H_2 that can be stored in the scaled Gen-3 system for two different modes of filling with LH_2. Top plot, final pressure is 272 atm, regardless of initial tank temperature. Bottom plot, maximum LH_2 density is limited to that of LH_2 at 1 atm, i.e., 71 kg/m^3.

The system conditions and the mass of liquid and gaseous H_2 in the tank during refueling under the cryo-compressed option are shown in Fig. 6. These results are based on initial tank conditions of 4 atm and 50 K at the start of the fueling operation. For a stored H_2 mass up to 0.4 kg, all of the H_2 is present as a gas. Initially, the tank temperature decreases towards 22 K and the pressure decreases below 4 atm as the LH_2 fed to the tank cools its contents. As the mass of stored H_2 increases above 0.4 kg, the distribution between the liquid and gaseous phases of H_2 changes as shown in the bottom plot of Fig. 6; the liquid fraction increases and the gaseous fraction decreases, until at a stored amount of 5.4 kg, all of the hydrogen is present as a saturated liquid in the tank. With continued addition of pumped LH_2, the stored H_2 turns first into a subcooled liquid and then into a supercritical fluid (SCF) when the stored mass exceeds 6.5 kg. The maximum storage capacity of the system is a function of the final pressure, being 5.7 kg at 37.7 atm and 6.6 kg at 272 atm.

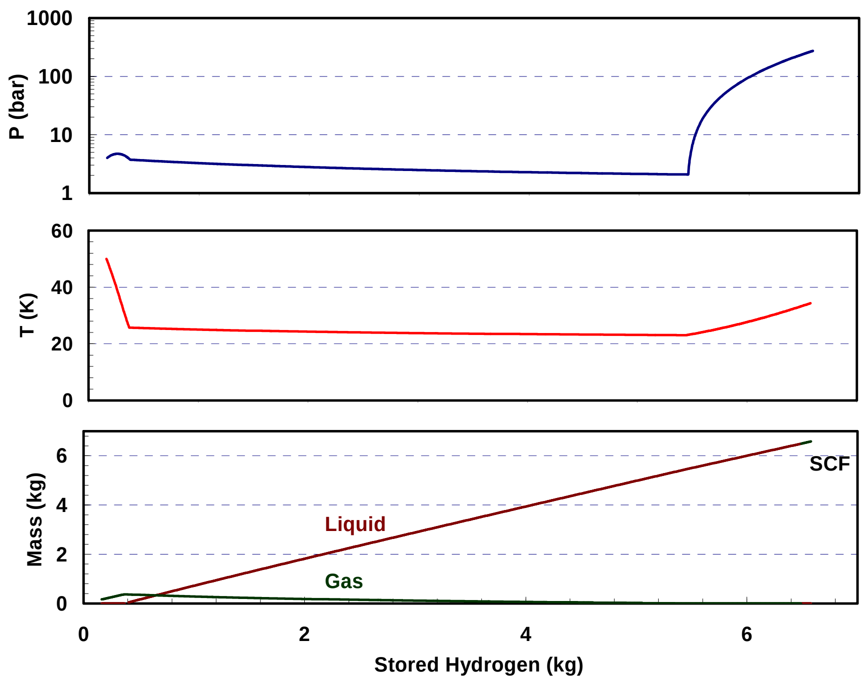

Fig. 6. System conditions and the mass of liquid and gaseous H_2 in the tank during refueling under the cryo-compressed option. Stored amounts in excess of 6.5 kg result in the H_2 being present as a supercritical fluid (SCF).

LH_2 Discharge Dynamics and Behavior

The amount of H_2 that can be discharged is primarily a function of the amount stored in the tank. Figure 7 presents results from discharge simulations in which the initial amount of H_2 stored, pressure and temperature correspond to the conditions after refueling as determined in Fig. 6. The top plot in Fig. 7 shows the amount of H_2 that can be recovered, the heat input and the final temperature after discharging a completely full tank at 272 atm down to the final pressure of 4 atm. The lower plot shows similar results for the case where the maximum H_2 density is limited to 71 kg/m^3, in which case the maximum amount of recoverable H_2 is 5.6 kg. In either case, no external heat input is needed if the initial tank temperature is greater than 155 K, for a maximum recovered amount of 2.8 kg of H_2. In the first case, the total amount of heat required to discharge the entire 6.4 kg of H_2 is 2.3 MJ at a maximum heat input rate of 3 kW (max Q in Fig. 7). The total amount of heat input required for the second case to discharge 5.6 kg of H_2 is 2.5 MJ for the same maximum heat input rate.

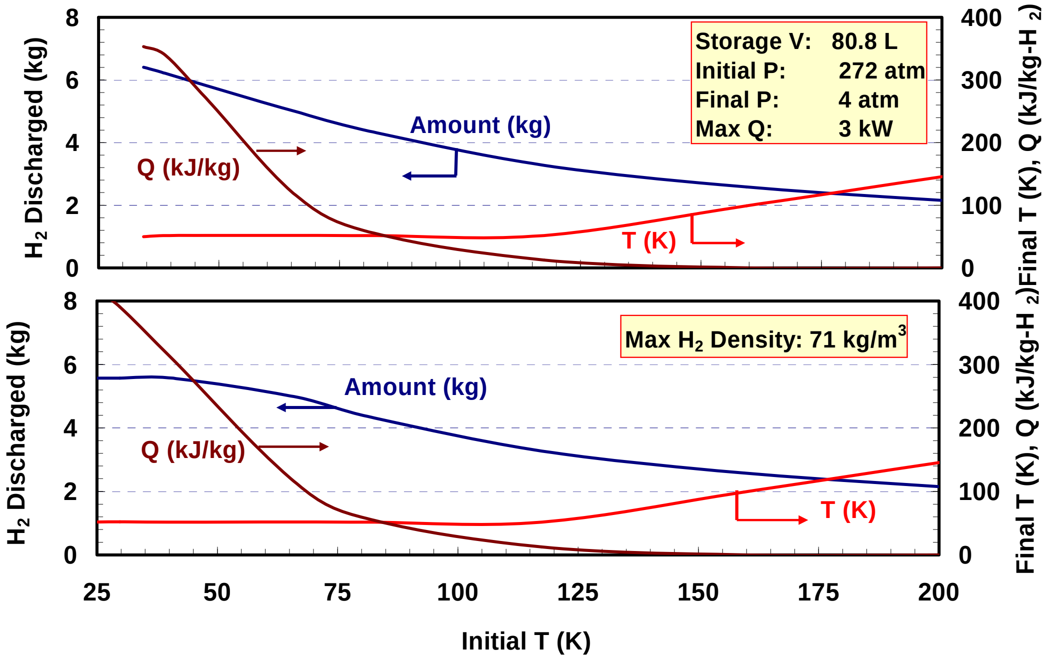

Fig. 7. Effect of the initial tank temperature at the start of the fueling operation on the maximum amount of recoverable H_2, the final tank temperature, and the heat input required to maintain the minimum delivery pressure.

As the stored H_2 is discharged from the scaled Gen-3 system, the tank pressure, temperature, and the remaining mass of H_2 in the tank all change, as shown in Fig. 8. This figure also shows the amount of thermal energy that must be provided to the tank (by the recirculation of warmed hydrogen through it) to maintain the 4 atm minimum pressure of the H_2 delivered to the fuel cell power system. The curves in Fig. 8 are for an initially full tank at 272 atm and 34.3 K, containing 6.6 kg of H_2.

The simulations for discharge dynamics were run assuming that the H_2 is withdrawn from the system continuously at the 1.6 g/s full flow rate. The results, however, are presented on the basis of stored H_2 so as to be essentially independent of the instantaneous withdrawal rate. In interpreting the results, the in-leakage of heat from the ambient environment should be included with the heat supplied (Q).

As shown in Fig. 8, the tank pressure decreases from 272 atm at the start of discharge to 4 atm when the remaining mass of H_2 decreases to 5.4 kg and the tank temperature drops to 23 K. With continued further withdrawal of H_2 from the tank, maintaining the 4-atm delivery pressure requires the addition of heat to the tank, as shown in the lower-middle plot in Fig. 8. The tank temperature and pressure do not change as the H_2 in the tank is maintained in the saturated liquid-vapor form by the addition of ~340 J/g of H_2 withdrawn (~550 W at 1.6 g/s H_2 withdrawal rate), down to a remaining inventory of approximately 0.4 kg. At this point, all of the remaining H_2 exists as a gas, and further withdrawals require increasing heat input to maintain the 4-atm delivery pressure, which thermal energy requirement reaches a maximum of 3 kW.

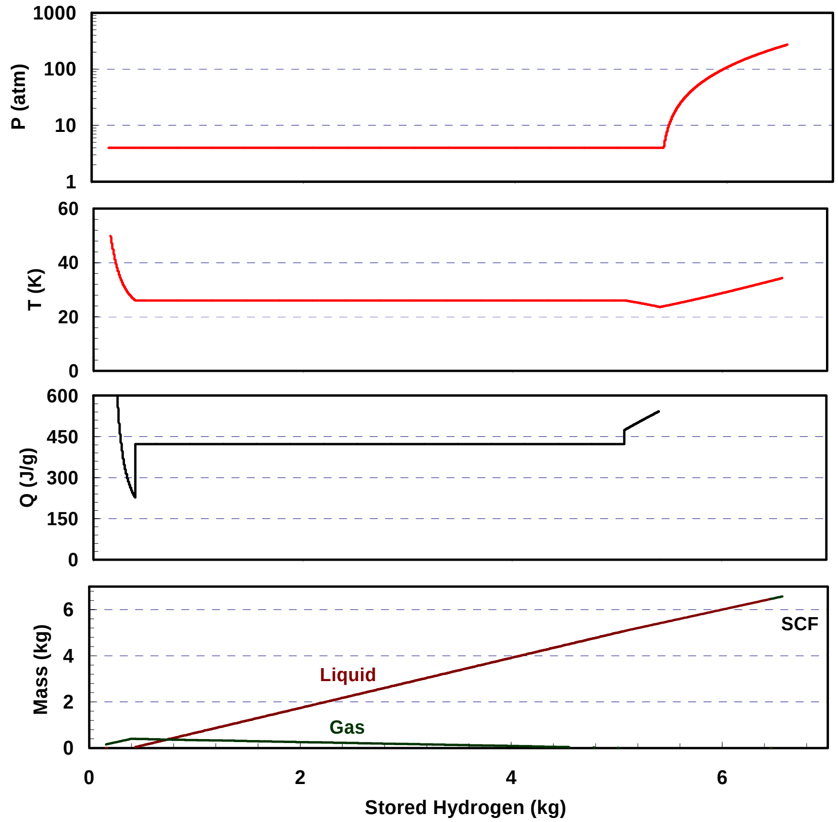

Fig. 8. Pressure, temperature, and heat input profiles during the discharge of H_2 from an initially full tank at 272 atm, 34.3 K (supercritical fluid, SCF), containing 6.6 kg of H_2. The H_2 is withdrawn continuously at the 1.6 g/s full flow rate until the tank pressure drops below 4 atm.

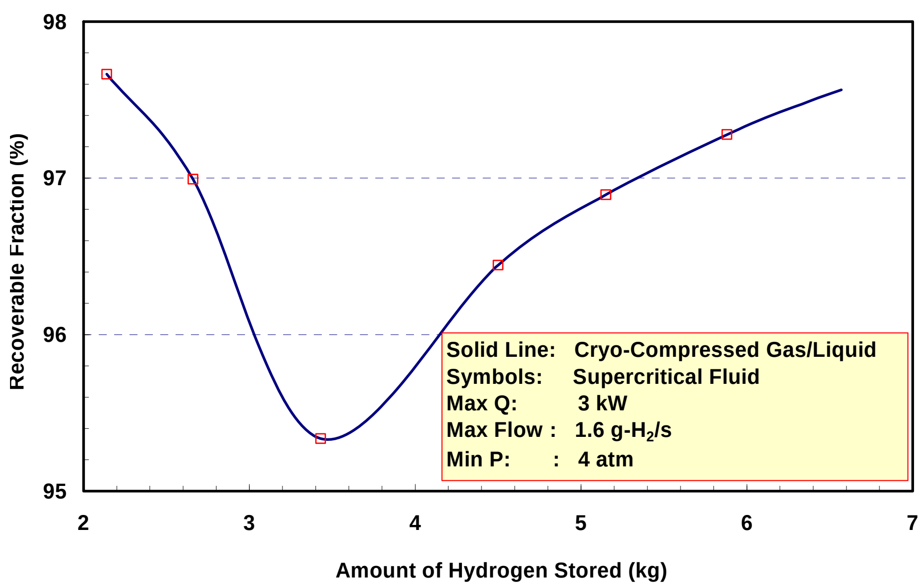

Fig. 9. The recoverable fraction of the total H_2 as a function of the H_2 inventory.

Of the total inventory of H_2 in the tank, the fraction that is recoverable is shown in Fig. 9 as a function of the total amount of H_2 contained in the tank. This recoverable fraction varies from a maximum of 97.6% to a minimum of 95.4%, and it is nearly the same whether the H_2 is initially stored as a cryo-compressed two-phase vapor-liquid mixture, or as a single-phase supercritical fluid.

Dormancy and Heat Absorption

The dormancy of the stagnant cryo-compressed tank, where the only heat input is by in-leakage from the ambient environment, is a strong function of the initial amount of hydrogen in the tank, initial temperature and the relief pressure. Figure 10 shows the dormancy, expressed as watt-days (W-d), and the total amount of heat absorbed before the tank thermally equilibrates with the ambient, under the assumption that the over-pressure relief valve is set at 125% of the design pressure, i.e., it is set to relieve if the tank pressure exceeds 340 atm. The upper plot in Fig. 10 shows the results for a tank that is only 50% full at the start of the dormancy period, while the lower plot in Fig. 10 shows the results for the case where the dormancy period begins immediately after filling the tank to the quantity of H_2 indicated on the x-axis. For the initial 50%-full case, the dormancy ranges from 52 W-d to 76 W-d; for the 100%-full case, the dormancy is lower, ranging from 4 W-d to ~30 W-d. For these analyses, it was assumed that the heat in-leakage approached zero as the tank temperature reached the ambient temperature (50ºC).

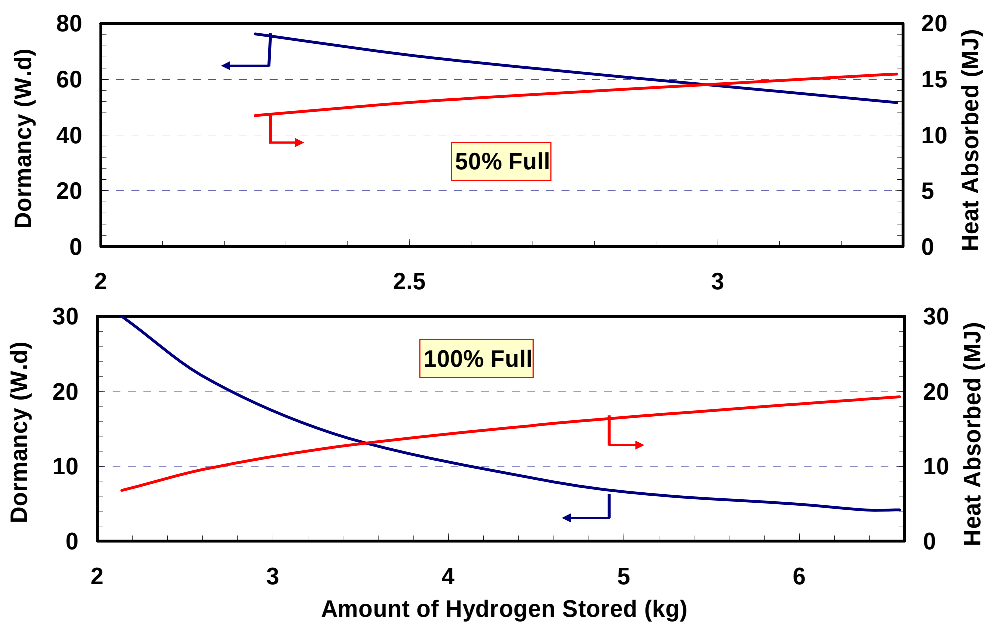

Fig. 10. Gen-3 system dormancy and heat absorption as a function of the amount of H_2 stored in the tank for (upper plot) when the dormancy begins after the tank has discharged 50% of the filled H_2, and (lower plot) when the dormancy begins immediately after the tank is filled to the given amount of stored H_2. Pressure relief valve set to relieve at 340 atm.

The rate of H_2 loss from the system once the dormancy is exceeded is shown in Fig. 11 as a function of the amount of H_2 stored in the tank. The maximum loss rate varies from 0.4 g/h/W to 2.1 g/h/W, while the average H_2 loss rate ranges from 0.2 g/h/W to 0.85 g/h/W. As indicated above, there is no further venting of H_2 once the tank temperature reaches 323 K (50ºC).

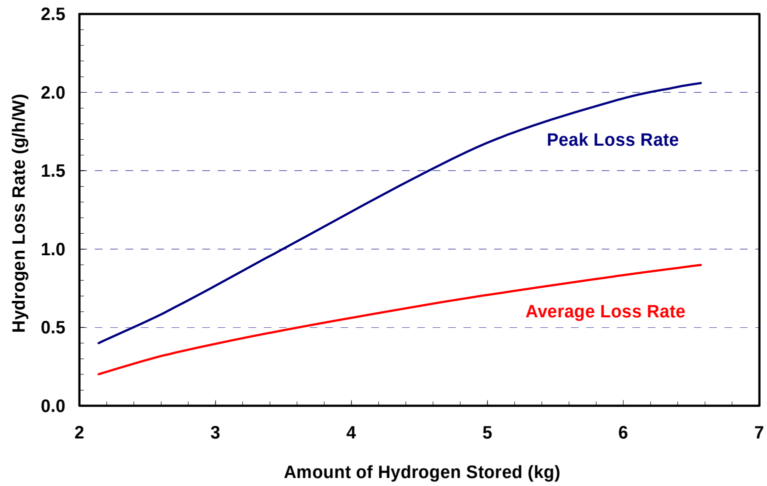

Fig. 11. The average and maximum loss rate of H_2 as a function of the amount of H_2 stored in the tank, once the dormancy is exceeded.

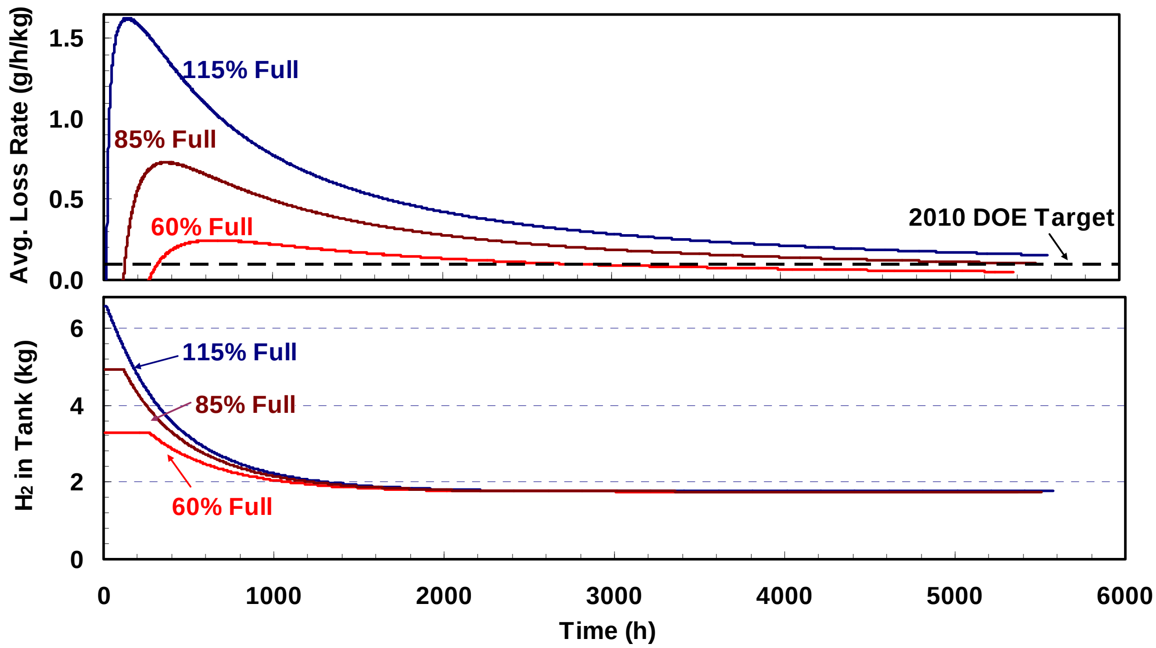

Fig. 12. The average loss rate of H_2 as a function of the amount of H_2 stored in the tank

The results in Figs. 10 and 11 can be used to estimate the average H_2 loss rate for different conditions. Shown in Fig. 12 are illustrative results for a specific scenario in which the heat in-leakage rate is 5 W, 30% by radiation and 70% by conduction, at reference conditions of 300-K ambient and 20-K storage temperatures. The results are presented on the basis of cumulative H_2 loss divided by the elapsed time and normalized by the nominal storage capacity of the tank (5.6 kg). The initial conditions are 34 K and 272 atm for the 115% initially full tank, and 26 K and 4 atm for 85% or 60% initially full tank. There is no loss of H_2 until 17 h for the 115% full tank, 120 h for the 85% full tank, and 280 h for the 60% full tank. Beyond these dormancy periods, the average loss rate first increases with elapsed time to reach a peak value and then decreases with time, and can considerably exceed the DOE targets of 0.1 g/h/kg-H_2 for 2010 and 0.05 g/h/kg-H_2 for 2015. However, the loss rate can be zero or very small if the vehicle is driven for some distance anytime during the scenario since the tank will depressurize and cool down as H_2 is withdrawn. We estimate that at the venting pressure, for every g of H_2 withdrawn as the vehicle is withdrawn, the tank depressurizes by 0.3 atm and cools by 0.01 K if the initial temperature is 40 K (conditions at start of venting of the initially 115% full tank) and by 0.2 atm and 0.02 K if the initial temperature is 120 K (conditions at start of venting of the initially 60% full tank).

Cost Results

The results of the cost assessment estimate that the scaled Gen-3 system (5.6 kg useable LH_2 capacity) and the prototype Gen-3 system (10.4 kg useable LH_2 capacity) will cost 2-3 times the old DOE 2010 cost target of $4/kWh, even at high production volumes, using a set of base-case assumptions considered to be most likely. As seen in Fig. 13, the carbon fiber layer is the most expensive single component and accounts for about 25% and 35% of the base case 5.6-kg and 10.4-kg systems costs. BOP component costs are also important, accounting for approximately 30% and 25% of the base case 5.6-kg and 10.4-kg system costs, respectively.

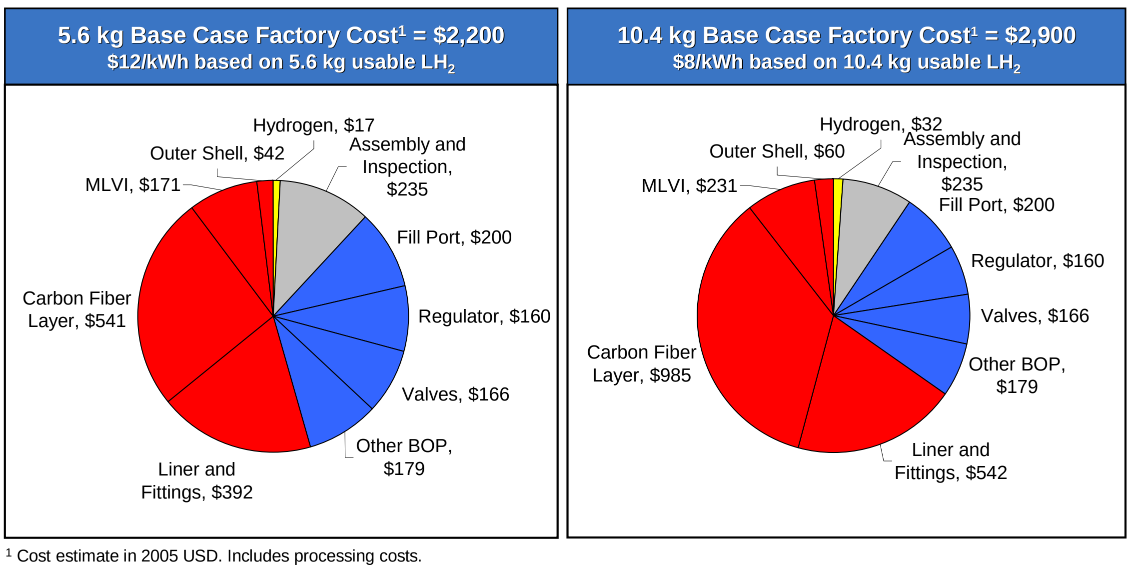

Fig. 13. Base case component cost breakout for the cryo-compressed systems

As shown in Table 3, processing cost makes up 15–20% of the total system cost, which is high compared to projections for other tank designs (e.g., 350 and 700-bar compressed hydrogen storage) but very low compared to the current cost to manufacture similar tank systems. Manufacturing a cryo-compressed tank today using relatively low volume production techniques requires complex and very labor intensive processes due to the simultaneous high pressure (e.g., carbon fiber wrapped tank) and low temperature (e.g., vacuum insulation) requirements. There is uncertainty and disagreement among different developers and automotive OEMs about the level of automation that can be achieved in the future, but we have assumed that substantial cost savings could occur with economies of scale, once high production volumes are achieve over a sustained period of time. For example, we based our MLVSI processing costs on the assumption that insulation wrapping could be done at high speeds with automated equipment, akin to wrapping packages. This is far different from the slow and meticulous hand-wrapping process that is used today. Similarly, we have assumed BOP component costs are much lower than today's vendor quotes for similar components. See Appendix B for details.

Table 3. Base case material versus processing cost breakout for the cryo-compressed systems

On-board System Cost Breakout – Cryo-compressed	5.6 kg Base Case			10.4 kg Base Case		
	Material, $	Processing, $	Processing Fraction	Material, $	Processing, $	Processing Fraction
Hydrogen	$17	(purchased)	-	$32	(purchased)	-
Cryo-compressed Vessel	$1,027	$238	19%	$1,678	$259	13%
Liner & Fittings	*$292*	*$99*	*25%*	*$439*	*$103*	*19%*
Carbon Fiber Layer	*$516*	*$25*	*5%*	*$945*	*$40*	*4%*
MLVI	*$65*	*$106*	*62%*	*$123*	*$108*	*47%*
Outer Shell	*$35*	*$7*	*17%*	*$52*	*$7*	*12%*
Balance of Tank	*$118*	*(purchased)*	*-*	*$118*	*(purchased)*	*-*
Fill Port	$200	(purchased)	-	$200	(purchased)	-
Regulator	$160	(purchased)	-	$160	(purchased)	-
Valves	$166	(purchased)	-	$166	(purchased)	-
Other BOP	$179	(purchased)	-	$179	(purchased)	-
Final Assembly & Inspection	-	$235	-	-	$235	-
Total Factory Cost	**$1,748**	**$473**	**21%**	**$2,414**	**$494**	**17%**

Single-variable sensitivity analysis was performed by varying one parameter at a time, while holding all others constant. TIAX varied overall manufacturing assumptions, economic assumptions, key performance parameters, direct material cost, capital equipment cost, and process cycle time for individual components. According to the single variable sensitivity analysis results, the range of uncertainty for aluminum and carbon fiber cost assumptions have the biggest impact on the system cost projections (i.e., sensitivity results for these assumptions are roughly 15-20% of the total system cost each).

Multi-variable (Monte Carlo) sensitivity analysis was performed by varying all the parameters simultaneously, over a specified number of trials, to determine the probability distribution of the cost. TIAX assumed a triangular Probability Distribution Function (PDF) for the parameters, with the "high" and "low" value of the parameter corresponding to a minimum probability of occurrence, and the base case value of the parameter corresponding to a maximum probability of occurrence. The parameters and range of values considered were the same as for the single-variable sensitivity analysis. According to the multi-variable sensitivity analysis results, the system factory cost will likely range between \$11.4 and \$15.8/kWh for the 5.6 kg system and between \$7.57 and \$10.7/kWh ($\pm 2\sigma$) for the 10.4 kg system.[3] These results are compared to DOE cost targets in Table 4. Detailed assumptions and results are presented in the Appendix.

Table 4. On-board storage system cost targets vs. cryo-compressed tank systems

Cost Projections, $/kWh	5.6 kg System	10.4 kg System	2010 Target	2015 Target
High[3]	15.8	10.7	4	2
Base Case	11.9	8.39		
Low[3]	11.4	7.57		

[3] Range is defined here as the ~95% confidence interval based on the data fit for the sensitivity analysis.

Off-Board Assessments

Argonne and TIAX have evaluated the fuel cycle and the infrastructure needed to support refueling the cryo-compressed H_2 storage system of the Gen-3 design for automotive applications. These off-board assessments make use of existing, publicly available models to calculate the cost and performance of the hydrogen fuel cycle on a consistent basis. The performance and cost assessments use results from Argonne's GREET and FCHtool models for GHG emissions, DOE's H2A model for H_2 production costs and efficiencies, and DOE's Hydrogen Delivery Scenarios Analysis Model (HDSAM) for delivery costs, efficiencies, and losses. Details of each model can be found elsewhere [13-16]. The analysis assumes 40% H_2 market penetration for a mid-size city – Sacramento, CA. In this scenario, the H_2 demand is about 270,000 kg/day for about 488,000 fuel cell vehicles in the city. To serve this market, a total of 269 refueling stations are needed, where each station has a storage capacity of ~7,000 kg and dispenses an average of 1,000 kg H_2/day. The vehicles are assumed to have an average fuel economy of 63.4 mpgge (mile per gallon gasoline equivalent), typical for a 2015 mid-sized fuel cell vehicle [17], and an annual mileage of 12,000 miles. Also in this scenario, H_2 is produced at a central plant by steam reforming of natural gas without CO_2 sequestration. The LH2 terminal stores a 10-day reserve to accommodate scheduled and unplanned plant outages. Additional design assumptions and details are given in Table 5.

Table 5. Assumptions for the well-to-tank (WTT) efficiency calculation

Process/Process Fuels	Nominal Value	Source/Comment
Electricity production	32.2% thermal efficiency	EIA projected U.S. grid for 2015, inclusive of 8% transmission loss from power plant to user site
North American natural gas production	93.5% efficiency	GREET data
H_2 production by SMR	73% efficiency	H2A
H_2 Liquefaction	8.2 kWh/kg	HDSAM, 150 tons/day liquefier
Liquid H_2 (LH_2) delivery by truck	284 km round trip	HDSAM
Truck capacity	4300 kg	HDSAM
Boil-off losses	9.5%	HDSAM: liquefaction 0.5%, storage 0.25%/day, loading 0.5 %, unloading 2%, cryopump 3%
Vehicle refueling with LH_2	2 kg/min; 80% isentropic efficiency	BMW LH_2 pump data
Greenhouse gas emissions	range	Emission factors data from GREET

We performed an ownership cost analysis that included both on-board and off-board costs. The off-board cost is converted to the refueling portion of the ownership cost by making assumptions about the fuel economy of the hydrogen FCV. The on-board storage system cost is converted to the fuel system purchased cost portion of the ownership cost by applying the appropriate Retail Price Equivalent (RPE) multiplier (MSRP relative to the cost of manufacturing) as well as other assumptions (e.g., Annual Discount Factor and Annual Mileage) to convert the purchased cost to an equivalent $/mile estimate.

The RPE multiplier actually consists of two markups to go from automotive OEM "Factory Cost" to MSRP – the hydrogen storage system manufacturer markup and the dealer markup.

Based on the literature, the RPE multiplier (MSRP relative to the cost of manufacturing) ranges between 1.46 and 2.00. Vyas et al. [18] suggest that the RPE multiplier should be 2.00. However, a recent report by RTI to the EPA [19] develops an automobile industry average weighted RPE multiplier of 1.46 (based on 2007 data), and also calculates an RPE multiplier of 1.70 based on McKinsey data for the automobile manufacturing industry. We assume a markup of 1.74 based on a recent DOE Report to Congress [20].

Performance Results

The results from the analysis of one pathway, hydrogen production by steam methane reforming (SMR) at a central plant, liquefaction, and tanker delivery of LH2, are included in this section. The analysis assumed 93.5% efficiency for delivery of natural gas from the production well to the central plant and 73% efficiency for producing fuel cell quality hydrogen by SMR at the central plant (see Table 4 for a summary and bases for all assumptions). The analysis considered that H_2 liquefaction at the central plant consumes 8.2 kWh of electricity per kg of H_2, and that LH_2 is delivered to the refueling stations by 4300-kg tankers (4100-kg refueling capacity). The analysis includes 9.5% H_2 loss from central plant to vehicle including losses during liquefaction, LH_2 storage at the terminal and fueling station, loading of tankers at the terminal, unloading of tankers at the fueling stations, and pumping of LH_2 at the stations. We further assumed that the dispensing pumps at the stations operate at 80% isentropic efficiency.

The pathway assumed that the electricity used in the H_2 production, delivery, and dispensing process is generated using the U. S. Energy Information Administration (EIA) projected 2015 grid mix at 32.2% efficiency, inclusive of 8% transmission losses from the power plant to the central H_2 production and liquefaction plant. Using these assumptions, we estimated that the WTT efficiency for LH2 refueling of the Gen-3 systems is 41.1%, based on the lower heating values of the H_2 delivered to the Gen-3 tank and the feedstock natural gas consumed in the process.

Table 6. Greenhouse gas emissions, g/kg-H_2 delivered to the vehicle

Process	VOC	CO	NO_x	PM_{10}	SO_x	CH_4	N_2O	CO_2	GHG
H_2 Production	-	-	-	-	-	0.02	0.00	11,613	12,180
Liquefaction	0.63	1.66	10.93	9.52	24.20	9.17	0.10	6,995	7,234
Refueling Station	0.02	0.05	0.30	0.26	0.67	0.26	0.00	195	201
Truck Delivery	0.04	0.12	0.45	0.02	0.03	0.10	0.00	86	89
Total:	0.69	1.83	11.68	9.80	24.90	9.55	0.10	18,889	19,704

For this pathway, Table 6 gives a breakdown of the GHG species emitted as grams of GHG per kilogram of H_2 delivered to the fuel cell vehicle's storage tank. The total GHG emissions are 19.7 kg/kg-H_2 (expressed as CO_2 equivalent emissions). The production of H_2 contributes ~62% of the total emissions, including the emissions due to the 9.5% loss of H_2 during on-site storage and distribution. Most of the rest of the GHG emissions, ~37%, are attributed to the central H_2 liquefaction plant. About 1% of the total GHG emissions are due to the LH_2 tanker truck delivery and refueling station components of the overall pathway. The well-to-wheel emissions are 0.31

kg/mile, about 12% lower than conventional gasoline internal combustion engine vehicle (assuming 31 mpg fuel economy for the gasoline ICE vehicle).

Cost Results

Argonne and TIAX performed an ownership cost analysis that included both on-board and off-board (i.e., refueling) costs. The refueling cost consists of the costs for H_2 production, liquefaction, terminal storage, transport, and refueling station. Assuming that the natural gas costs $0.22/Nm^3 and that the industrial electricity costs $0.05/kWh, the total refueling cost is $4.57 per kilogram of H_2 delivered to the fuel cell vehicle's storage tank, of which about 34% is due to production and 66% is due to storage and delivery. Table 7 gives a breakdown of the refueling cost (results from H2A and HDSAM) by component in the overall pathway. The H_2 production cost includes the cost for producing the amount of H_2 that is lost downstream from the production plant gate to the vehicle storage tank. The H_2 production cost is dominated by fuel cost (77%), with smaller contributions from capital (14%) and operations and maintenance (O&M, 9%). The delivery cost is dominated by capital costs (55%), due primarily to the two liquefiers, which account for more than half of the total capital cost. Other significant contributions are from O&M (27%) and fuel (18%). Combining these off-board refueling costs with the on-board system base case storage system cost projection of $12/kWh resulted in a fuel system ownership cost estimate of $0.12/mile. About 40% of this cost is due to the purchased cost of the on-board storage system and 60% is due to the refueling or off-board cost. This ownership cost is 20% more expensive than the $0.10/mile estimated for a 30-mpg ICE vehicle operating on gasoline at $3.00/gal (untaxed).

Table 7. Refueling cost, \$/kg-H_2 delivered to the vehicle

	Production	Liquefaction	Storage	Truck	Station
Capital	0.22	0.85	0.55	0.06	0.21
O&M	1.20	0.21	0.24	0.15	0.22
Fuel	0.13	0.50	-	0.01	0.02
Total	1.55	1.56	0.79	0.22	0.45

The initial infrastructure capital investment necessary to support the market considered in this report includes $134 million for the SMR central plant, $474 million for the two liquefiers, $330 million for 269 refueling stations, $148 million for the LH_2 terminal, and $35 million for 50 LH_2 tanker trucks.

Similar analyses were performed for the 2% and 15% market penetration scenarios in Sacramento, CA. The analyses assumed that H_2 is co-produced by an SMR central plant that also supplies H_2 to other industrial users. The cost of H_2 production, therefore, remains unchanged for these smaller markets. For the 2% market penetration case, refueling stations dispense an average of 400 kg H_2/day, the electricity requirement for H_2 liquefaction increases to 11.8 kWh/kg-H_2, the ownership cost increases to $0.17/mile (due to significantly higher station capital cost per kilogram H_2 and higher H_2 losses of 11.7%). For the 15% market penetration scenario, the electricity requirement for H_2 liquefaction is 8.6 kWh/kg-H_2, and the ownership cost is $0.123/mile. The WTT efficiency is 35.6% and 40.5%, and GHG emissions are 23.4 and

20.0 kg CO_2 equivalent per kilogram H_2 for the 2% and 15% market penetration scenarios, respectively.

Table 8. Energy consumption, cost, and GHG emissions for two different H_2 production pathways and three market penetration scenarios

		NG/Standard U.S. Grid			Electrolysis/Renewable		
Sacramento Market Penetration		2%	15%	40%	2%	15%	40%
City H2 Use	kg/day	13,439	100,796	268,790	13,439	100,796	268,790
Hydrogen Production Cost	$/kg	1.59	1.55	1.55	3.92	3.77	3.76
Hydrogen Production Capital Cost	Millions $	134	134	134	12	90	241
Hydrogen Delivery Cost	$/kg	6.05	3.18	3.02	6.16	3.27	3.10
Hydrogen Delivery Capital Cost	Millions $	103	391	987	103	391	987
Refueling Cost	$/kg	7.64	4.73	4.57	10.08	7.04	6.86
	$/mile	0.120	0.075	0.072	0.159	0.111	0.108
Onboard System Factory Cost	$	2,221	2,221	2,221	2,221	2,221	2,221
Ownership Cost	$/mile	0.169	0.123	0.120	0.207	0.159	0.156
Primary Energy							
Production	MJ/kg	205	200	200	198	193	193
Delivery	MJ/kg	132	96	92	57	42	40
WTT Energy Efficiency	%	35.6	40.5	41.1			
Gravimetric Capacity	wt%	5.5	5.5	5.5	5.5	5.5	5.5
Volumetric Capacity	g/L	41.8	41.8	41.8	41.8	41.8	41.8
WTT GHG Emissions	kg CO2 (eq)/kg	23.4	20.0	19.7	0.3	0.3	0.3
	kg CO2 (eq)/mile	0.37	0.32	0.31	0.01	0.00	0.00
Vehicle Fueling Time	min	3	3	3	3	3	3
Vehicle Fuel Economy	mpgge	63.4	63.4	63.4	63.4	63.4	63.4
Vehicle Range	miles	355	355	355	355	355	355
Storage System Volume	L	134	134	134	134	134	134
Storage System Weight (incl. H2)	kg	101	101	101	101	101	101
Total Hydrogen On-board (Full Tank)	kg	5.7	5.7	5.7	5.7	5.7	5.7
Minimum Dormancy	W-d	4-30	4-30	4-30	4-30	4-30	4-30
Average Venting Rate	g/h/W	0.2-0.9	0.2-0.9	0.2-0.9	0.2-0.9	0.2-0.9	0.2-0.9
Station Coverage	%	4	12	31	4	12	31
# of Stations		34	101	269	34	101	269

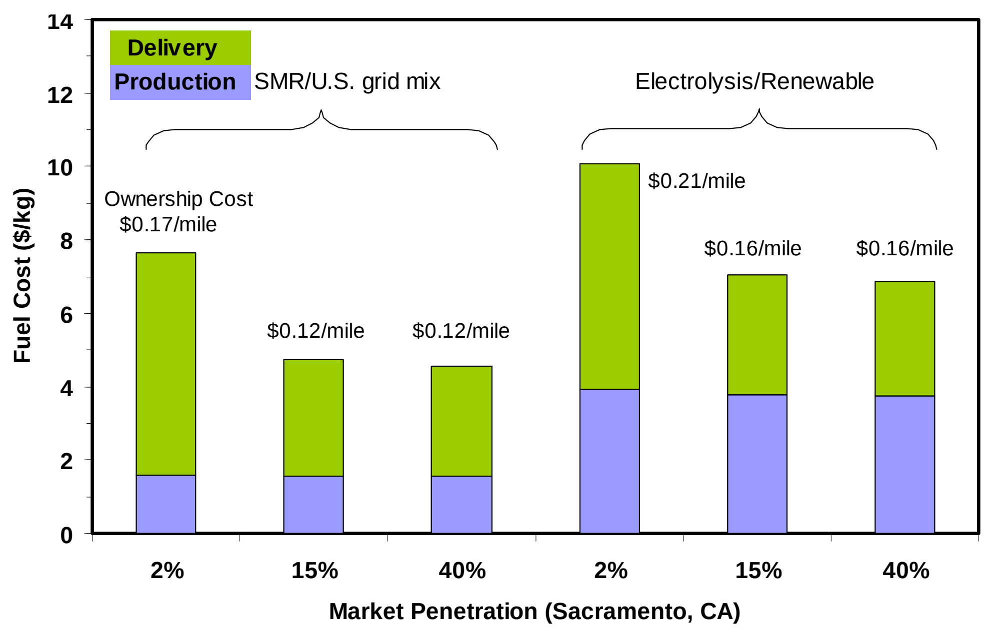

Fig. 14. Refueling and ownership costs for two H_2 production pathways

Analyses were also performed for another pathway, where the H_2 is produced in a central plant by electrolysis, with 74.7% process efficiency. The production capacity and capital cost of the central plant scale with the number of electrolyzers (1,046 kg-H_2/day/electrolyzer) needed to meet the market demand. The analyses assumed that the electricity supplied to the central plants (for production and liquefaction) is generated from renewable sources at a cost of $0.06/kWh. All other assumptions pertaining to market penetration (liquefier efficiency, storage, station size, truck delivery, H_2 city demand, etc) are the same as for the SMR/standard U.S. grid pathway. The results of the analyses show that the ownership cost is ~$0.21/mile for the 2% market penetration, which decreases to $0.16/mile for the cases of 15% and 40% market penetration. Ownership costs are 22–30% higher than those for the SMR/standard U.S. grid pathway, due entirely to higher hydrogen production cost. Emissions of GHG, however, are reduced to practically zero. The key performance and cost metrics discussed above are summarized in Table 8. The refueling and ownership costs for the two pathways are compared in Fig. 14.

Discussion and Conclusions

A technical assessment of the cryo-compressed hydrogen storage tank system for automotive applications has been conducted. The assessment criteria included the prospects of meeting the near-term and ultimate DOE targets for on-board hydrogen storage systems for light-duty vehicles with the LLNL Gen-3 design. The main conclusions from this assessment are discussed below and summarized in Table 9.

Table 9. Summary results of the assessment of the prototype and LLNL Gen-3 cryo-compressed H_2 storage systems

Performance and Cost Metric	Units	Scaled Gen-3	Prototype Gen-3	2010 Targets	2015 Targets	Ultimate Targets
Usable Storage Capacity (Nominal)	kg-H_2	5.6	10.4			
Usable Storage Capacity (Maximum)	kg-H_2	6.6	12.3			
System Gravimetric Capacity	wt%	5.5-9.2	7.1-12	4.5	5.5	7.5
System Volumetric Capacity	kg-H_2/m^3	41.8-44.7	44.5-47.1	28	40	70
Storage System Cost	$/kWh	12	8	4	2	TBD
Fuel Cost	$/gge	4.80		2-3	2-3	2-3
Cycle Life (1/4 tank to Full)	Cycles	18,000	18,000[1]	1000	1500	1500
Minimum Delivery Pressure, FC/ICE	atm	3-4	3-4	4/35	3/35	3/35
System Fill Rate	kg-H_2/min	1.5-2	1.5-2	1.2	1.5	2.0
Minimum Dormancy (Full Tank)	W-d	4-30	7-47			
H_2 Loss Rate (Maximum)	g/h/kg-H_2	0.2-1.6[2]		0.1	0.05	0.05
WTT Efficiency	%	41.1		60	60	60
GHG Emissions (CO_2 eq)	kg/kg-H_2	19.7				
Ownership Cost	$/mile	0.12				

1 Warm cycles
2 During vent time, tank 50%-100% initially full

Gravimetric Capacity: The Gen-3 cryo-compressed system scaled to 5.6 kg of recoverable H_2 (using the LH_2 fueling option) has a nominal usable gravimetric capacity of 5.5 wt% at 71 kg/m^3 H_2 density. The actual usable capacity is 6.5 wt% if credit is taken for LH_2 compressibility and the tank is refueled to the design pressure of 272 atm and 81 kg/m^3 H_2 density. The nominal capacity increases to 6.9 wt% if the liner thickness can be reduced to 3.2 mm (1/8") from 9.5 mm (3/8") in the current design. The nominal capacity further increases to 9.2 wt% if the shell is made of an Al alloy rather than steel. Thus, the cryo-compressed option easily exceeds the 2010 target of 4.5 wt%, meets the 2015 target of 5.5 wt% without any changes, and can also meet the ultimate target of 7.5 wt% since there is no technical risk in substituting the shell material with a lighter-density alloy that are only required to withstand the vacuum.

Volumetric Capacity: The scaled Gen-3 system has a nominal volumetric capacity of 41.8 g-H_2/L The actual volumetric capacity is 47.8 g-H_2/L if credit is taken for LH_2 compressibility and the tank is refueled to the design pressure of 272 atm. The nominal capacity increases to 44.7 g-H_2/L if the liner thickness can be reduced to 3.2 mm (1/8") from 9.5 mm (3/8") in the current design. Thus, the scaled Gen-3 system exceeds the 2010 target of 28 g-H_2/L, meets the 2015 target of 40 g-H_2/L without any changes, but cannot satisfy the ultimate DOE target of 70 g-H_2/L even with the credits and modifications considered in this assessment.

Storage System Cost (& Fuel Cost): The high-volume manufactured cost of the scaled Gen-3 system (i.e., 5.6 kg useable hydrogen) is \$12/kWh compared to \$8/kWh energy content of the stored H_2 for the larger prototype system (i.e., 10.4 kg useable hydrogen). These manufactured system costs, based on assumptions considered most likely to be applicable (i.e., base cases), are 2-3 times the current DOE 2010 cost target (\$4/kWh net). According to the multi-variable sensitivity analysis results, the factory costs will likely range between \$11.4 and \$15.8/kWh for the 5.6 kg system and between \$7.57 and \$10.7/kWh for the 10.4 kg system.[4] The fuel cost for the reference SMR production and LH_2 delivery scenario is \$4.57/gge at pump, which is 53%-130% higher than the current DOE target of \$2-\$3/gge. When on-board and off-board costs are combined, the cryo-compressed system has potential to have similar ownership costs as a gasoline ICEV, albeit about 20% (2 ¢/mi or \$240/yr) higher for the base case when gasoline is \$3.00/gal. Different assumptions for the annual discount factor, markups, annual mileage, and vehicle fuel economy would yield different results.

Efficiency and Greenhouse Gas Emissions: Whereas efficiency is not a specified DOE target, the systems are required to be energy efficient. A footnote in the target table requires the WTT efficiency for the off-board regenerable systems to be higher than 60%. The cryo-compressed option cannot meet this target since the WTT efficiency, at best, is only 41.1%. The corresponding estimated GHG emission for hydrogen production by SMR and LH_2 delivery is 19.7 kg-CO_2 (eq) per kg H_2 delivered to the vehicle.

Durability/Operability: The targets of -30^oC operating minimum ambient temperature and -40^oC minimum delivery temperature do not affect the cryo-compressed system that stores H_2 at much lower temperatures. Also, the Gen-3 system includes internal and external heat exchangers to warm the withdrawn H_2 and maintain the tank pressure above 4 atm. The DOE targets for cycle life, 1000 ¼-tank to full cycles for 2010 increasing to 1500 cycles for 2015, were addressed by selecting the liner thickness for 18,000 warm pressure cycles in compliance with the more stringent DOT FMVSS-304 regulation (Federal Motor Vehicle Safety Standard) for the integrity of compressed natural gas containers; the effect of temperature cycling on liner durability, however, remains to be resolved. The 2010 DOE target of 4 atm minimum delivery pressure for

[4] Range is defined here as the mean plus/minus two standard deviations (~95% confidence).

fuel cell vehicles was considered in this assessment. The lowering of minimum delivery pressure target to 3 atm for 2015 and beyond is not an issue since the usable gravimetric and volumetric capacities of the cryo-compressed system actually increase with decrease in the minimum pressure. The 35-atm target for ICE vehicles will require a different mode (supercritical mode) of operation and a re-analysis. Finally, the 0.75-s target response time for 10%-90% and 90%-10% flow has not been specifically considered in this assessment but is unlikely to be a difficult challenge for the automatic valves in the system.

Fuel Purity: The issue of impurities generated from the storage medium was not specifically addressed in this assessment. This issue is not considered to be as critical in a cryo-compressed system as in material based systems.

Environmental Health & Safety: The Type-3 pressure vessel system was selected because the high-density polyethylene (HDPE) liners used in Type-4 tanks turn brittle below 153 K (HDPE glass transition temperature) and, therefore, are not suitable for service at cryogenic temperatures. Toxicity is not regarded as critical with liquid H_2 although safety (beyond the scope of this assessment) considerations are paramount in all storage options. Our analysis of dormancy indicates that the average loss of usable H_2 can be as high as 1.6 g/h/kg H_2 stored under most unfavorable conditions if the heat gain can be kept below 5 W. Under realistic use conditions, the cryo-compressed tank system may meet the DOE H_2 loss rate target of 0.1 g/h/kg stored H_2 for 2010 decreasing to 0.05 g/h/kg stored H_2 for 2015 and beyond, if the vehicle is driven for some minimum distance on daily and weekly basis [21]. The so-called empty tank syndrome is not an issue with the cryo-compressed option since the tank in a parked vehicle cannot deplete below 2 kg of stored H_2.

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APPENDIX A

Analysis of Cryo-Compressed Hydrogen Storage Options

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... for a brighter future

Analysis of Cryo-Compressed Hydrogen Storage Options

R.K. Ahluwalia, J-K Peng and T. Q. Hua

November 17, 2009

Final Report

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U.S. Department of Energy

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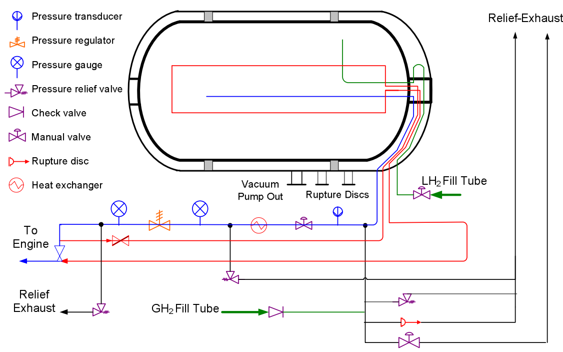
Analysis of Cryo-Compressed Hydrogen Storage Options

- Analysis of LLNL Gen3 Cryo-compressed Tank and System
  - Volumetric capacity
  - Gravimetric capacity
  - Scaling to 5.6 kg usable H_2 storage capacity
- ANL Analysis
  - Refueling dynamics
  - Discharge dynamics
  - Dormancy and boil-off losses
  - WTT efficiency
  - Greenhouse gas emissions
  - Refueling and ownership cost

LLNL Gen3 Cryo-Compressed H_2 Storage System

Modifications from Gen2

- Reduced insulation
- Better packaging
- Vacuum valve box eliminated
- In-tank heat exchanger
- 4000-psi pressure vessel rating

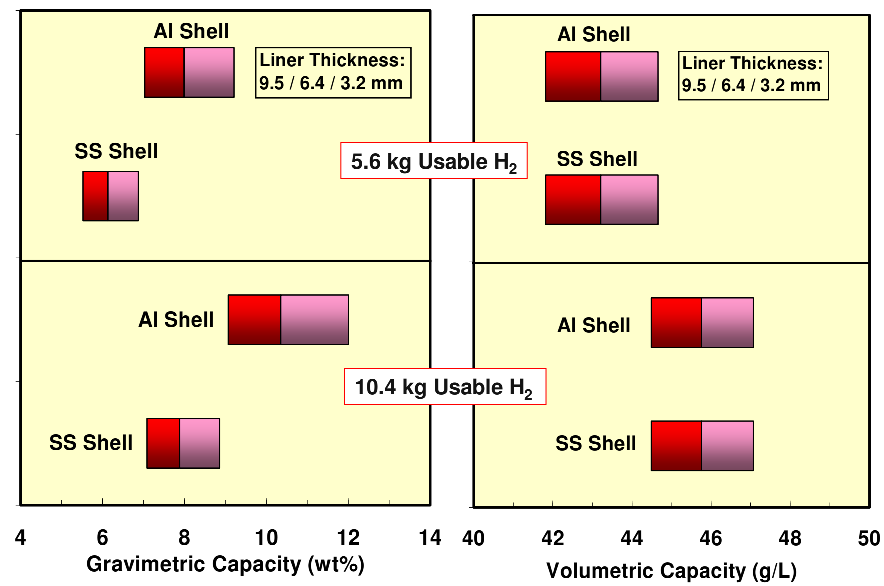


- System Volume: 235 L
  - Storage: 151 L
  - Vessel: 224 L
  - Ex-Vessel: 11 L
  - V Efficiency: 64.3%
- System Weight: 144.7 kg
  - LH_2 Stored: 10.7 kg
  - CH_2 Stored: 2.8 kg
  - Vessel: 122.7 kg
  - Ex-Vessel: 22.0 kg
- System Volumetric Capacity
  - 44.5 kg/m^3:1.5 kWh/L
  - LH_2 density: 70.9 kg/m^3 at 20.3 K, 1 atm
  - CH2 density: 18.8 kg/m^3 at 300 K, 272 atm
- System Gravimetric Capacity
  - 7.1 wt%: 2.3 kWh/kg

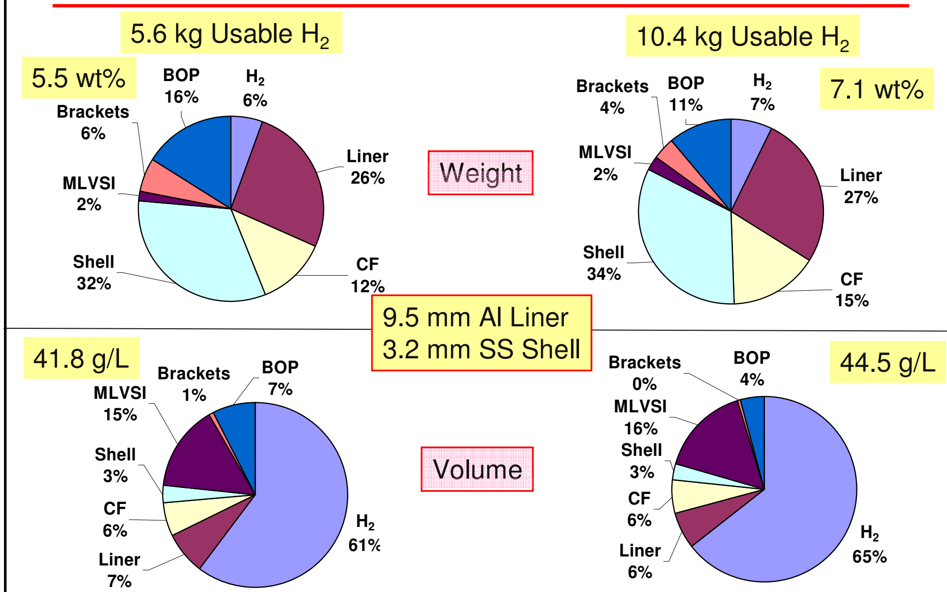
Model Validation and Application

	ANL		LLNL Gen 3		ANL	
	Wt (kg)	Vol (L)	Wt (kg)	Vol (L)	Wt (kg)	Vol (L)
Stored Hydrogen	**10.7**	**151.0**	**10.7**	**151.0**	**5.7**	**80.8**
Usable Hydrogen	**10.4**	**151.0**			**5.6**	**80.8**
Pressure Vessel (4000 psi)	**62.4**	**29.0**	**61.0**	**28.0**	**39.1**	**17.7**
Aluminum liner (9.5 mm)	38.8	14.4			25.7	9.5
Carbon fiber	22.7	14.1			12.4	7.7
Boss	0.4	0.4			0.4	0.4
Plug	0.3	0.1			0.3	0.1
In-tank heat exchanger	0.3	0.0	0.3	0.0	0.3	0.0
Insulation and Vacuum Shell	**52.3**	**43.7**	**51.0**	**45.0**	**34.6**	**24.4**
Support rings	1.2	0.7			0.5	0.3
Insulation material	2.2	36.8			1.2	20.0
Vacuum shell (SS 304, 3.2 mm)	48.9	6.2			32.9	4.2
Mounting Brackets	**6.0**	**1.0**	**6.0**	**1.0**	**6.0**	**1.0**
BOP	**16.0**	**10.0**	**16.0**	**10.0**	**16.0**	**10.0**
Computer	0.2	0.5	0.2	0.5	0.2	0.5
Electronic boards	2.2	5.0	2.2	5.0	2.2	5.0
Valves & valve box	6.9	0.8	6.9	0.8	6.9	0.8
Pressure transmitter, gauge, regulator & rupture discs	1.1	0.6	1.1	0.6	1.1	0.6
Heat exchanger	1.5	1.8	1.5	1.8	1.5	1.8
Misellaneous tubing, fittings, etc.	4.0	1.5	4.0	1.5	4.0	1.5
Total	**147.4**	**234.7**	**144.7**	**235.0**	**101.4**	**133.9**
Gravimetric Capacity, wt H_2	**7.1**		**7.4**		**5.5**	
Volumetric Capacity, g-H_2/L		**44.5**		**45.5**		**41.8**

Gravimetric and Volumetric Capacities



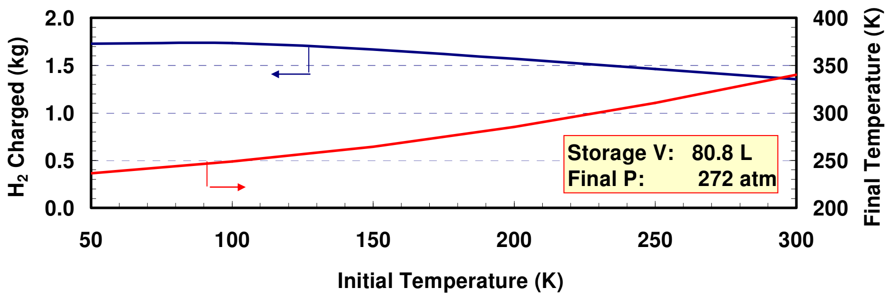
Weight and Volume Distributions



Storage Capacity: Compressed Hydrogen Option

Refueling with compressed H_2 at 300 K

- Adiabatic refueling assuming that liner, CF and gas are isothermal during refueling (maximum possible capacity)
- Tank refueled to 272-atm (4000 psi) peak pressure
- 4 atm initial pressure, variable initial temperature
- Additional storage capacity with pre-cooled H_2 and refueling to higher than design pressure

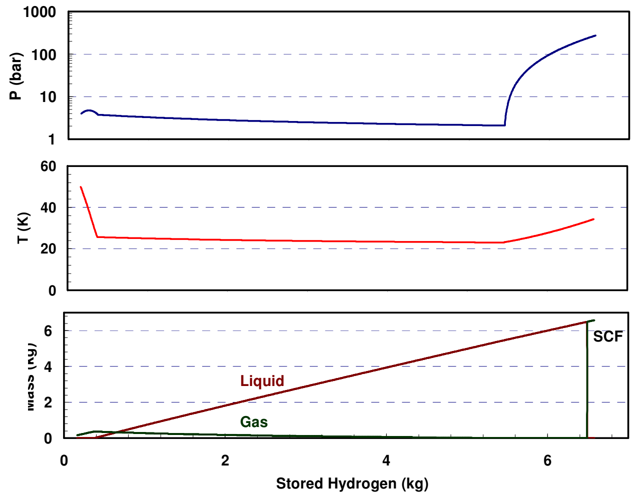


Analysis of Refueling and Discharge Options

- High pressure liquid hydrogen pump
  - 1.5 kg/min at variable pressure
  - Pump delivery pressure 25% above the tank pressure
  - 80% isentropic efficiency
- Cryo-Compressed H_2 Storage Option
  - Allows the tank to operate in two-phase dome
  - Heat is supplied only during discharge
  - Requires a liquid level sensor to serve as fuel gauge
- Cryo-supercritical H_2 Storage Option
  - No phase transfer
  - Level sensor not needed
  - Heat supplied during refueling and discharge
  - Results in Appendix A-2

Refueling with LH2: Cryo-compressed Option

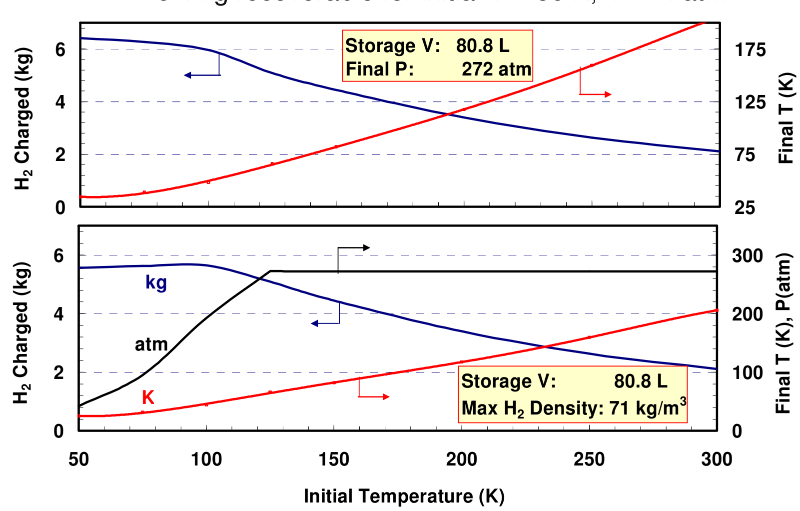
- Storage capacity function of final pressure, 5.7 kg for P = 37.7 atm
- Depending on initial T and H_2 charged, final P may be less than 4 atm



- **Initial conditions** P=4 atm, T=50 K
- **Gas** m < 0.4 kg
- **2-Phase** 0.4 < m < 5.4 kg
- **Sub-cooled Liquid** 5.4 < m < 6.5 kg
- **Supercritical Fluid** m > 6.5 kg

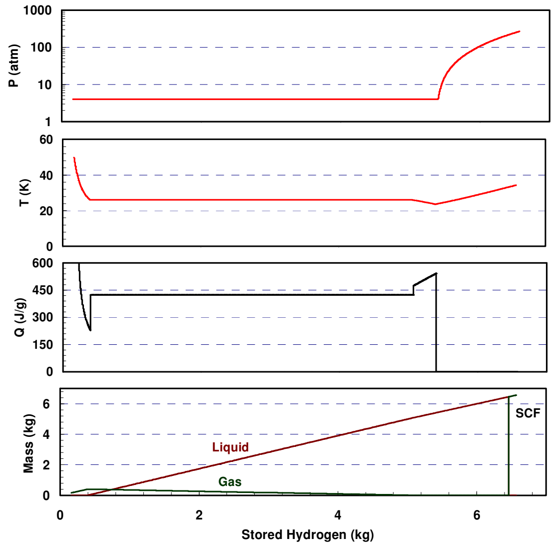
Storage Capacity: Cryo-compressed Option

- Storage capacity is a function of initial temperature
  - 6.4 kg recoverable for initial T = 50 K, P = 4 atm



Discharge Dynamics: Cryo-compressed Option

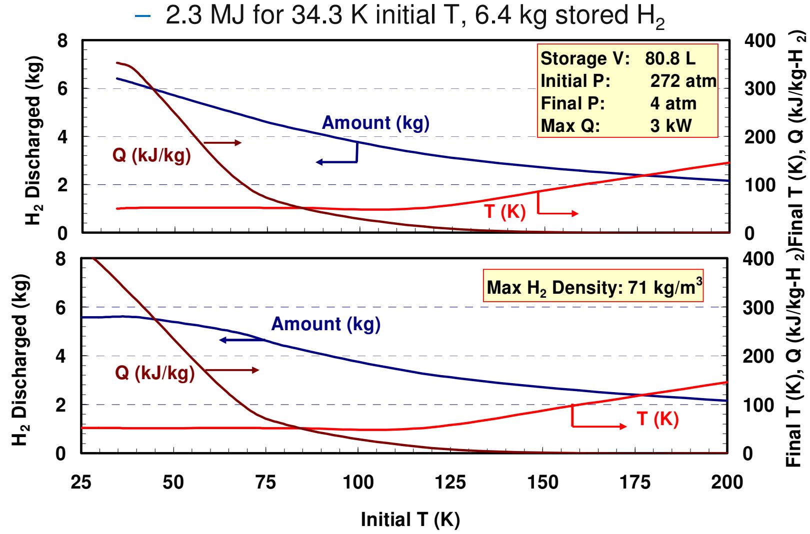
- Heat supplied to maintain 4-atm minimum delivery pressure



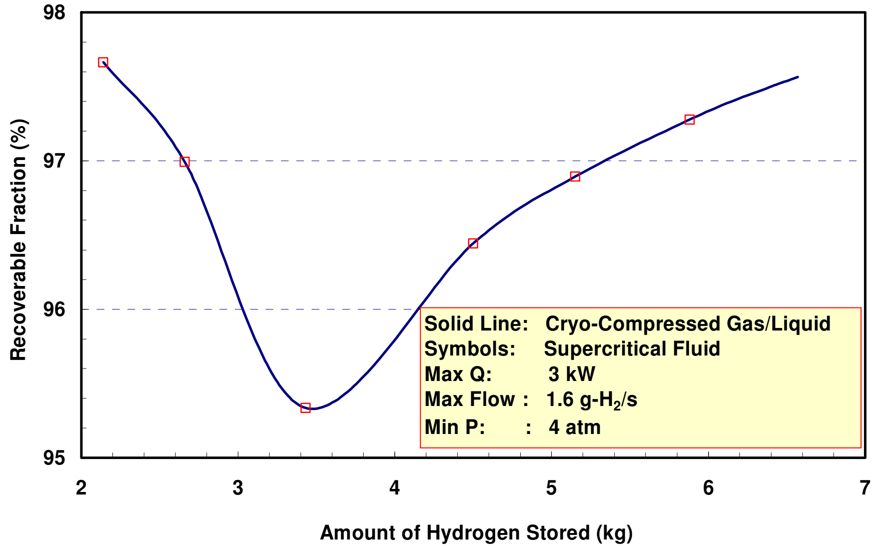
- Initial conditions:
  P = 272 atm
  T = 34.3 K
  m = 6.6 kg
- 1.6 g/s full flow rate of H_2
- Max Q = 3 kW

Discharge Behavior: Cryo-compressed Option

- Total heat load is a function of initial temperature
  - 2.3 MJ for 34.3 K initial T, 6.4 kg stored H_2

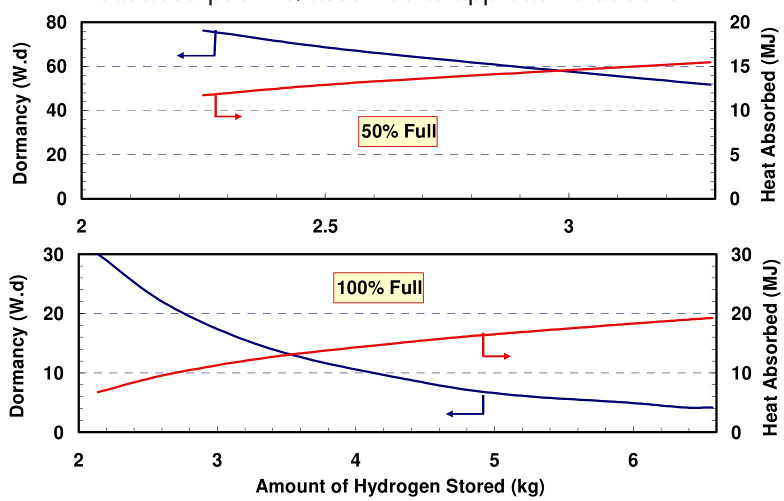


Recoverable Hydrogen



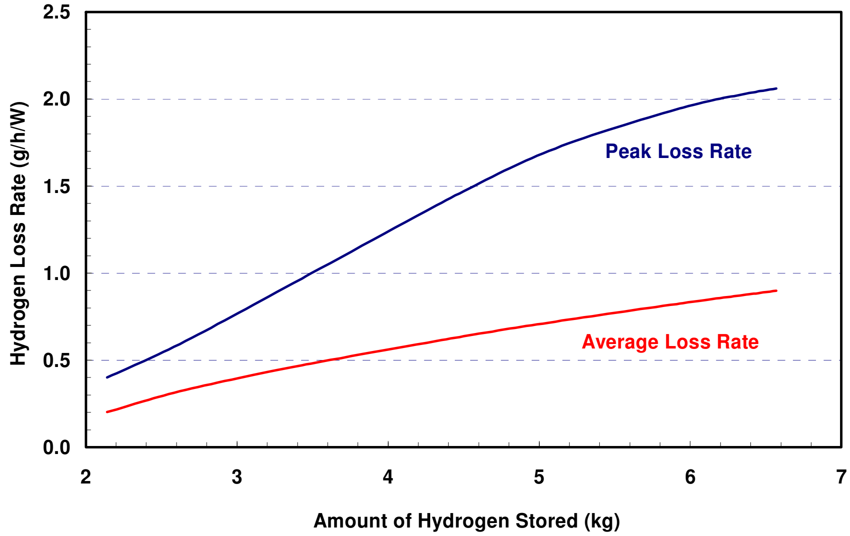
Dormancy and Heat Absorption

- Dormancy: relief valve set at 125% of design pressure
- Heat absorption: Q assumed to approach 0 at 50°C



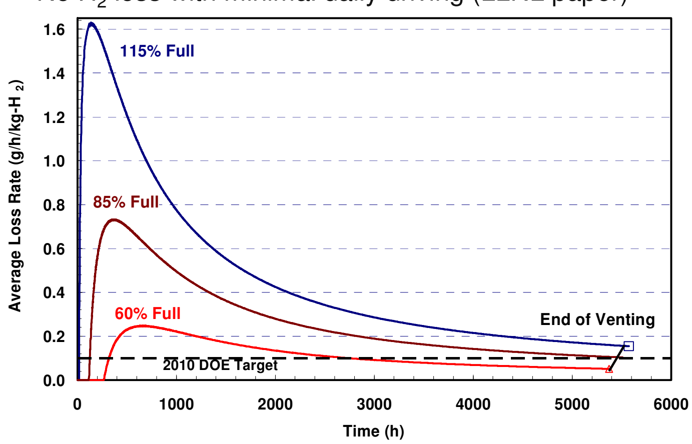
Hydrogen Loss Rate

- No loss of hydrogen after the temperature reaches 323 K



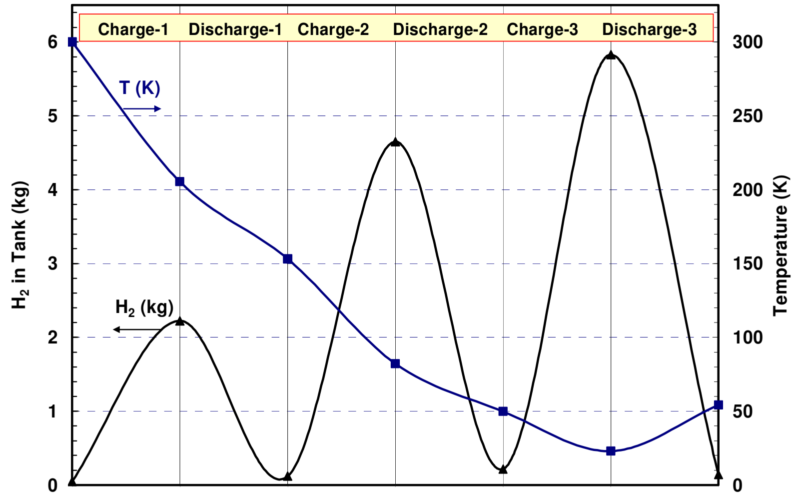
Dormancy and Hydrogen Loss Rate

- No loss of hydrogen after tank reaches 323 K, tank 30% full
- Difficult to always meet the targets of 0.1/0.05 g/h/kg-H_2 with 5 W reference heat in-leakage rate
- No H_2 loss with minimal daily driving (LLNL paper)



CH_2 to cCH_2 Transition

- Three complete charge-discharge cycles needed to reach 71 kg/m^3 hydrogen density



WTT Efficiency

- WTT efficiency = 41.1% (LH_2 refueling)
- Assumptions

Process/Process Fuels	Nominal Value	Source/Comment
Electricity production	32.2% thermal efficiency	EIA projected U.S. grid for 2015, inclusive of 8% transmission loss from power plant to user site
North American natural gas production	93.5% efficiency	GREET data
H_2 production by SMR	73% efficiency	H2A
H_2 Liquefaction	8.2 kWh/kg	HDSAM, 150 tons/day liquefier
Liquid H_2 (LH_2) delivery by truck	284 km round trip	HDSAM
Truck capacity	4300 kg	HDSAM
Boil-off losses	9.5%	HDSAM: liquefaction 0.5%, storage 0.25%/day, loading 0.5 %, unloading 2%, cryopump 3%
Vehicle refueling with LH_2	2 kg/min; 80% isentropic efficiency	BMW LH_2 pump data
Greenhouse gas emissions	range	Emission factors data from GREET

Greenhouse Gas Emissions

- Total GHG emissions = 19.7 kg/kg-H_2 (CO_2 equivalent)
  - Production: 62% (inclusive of 9.5% H_2 loss during on-site storage and distribution)
  - Storage: 37% (central liquefaction)
  - Distribution: <1% (truck delivery)
- g/kg-H_2 delivered to vehicle

Process	VOC	CO	NO_x	PM_{10}	SO_x	CH_4	N_2O	CO_2	GHG
H_2 Production	-	-	-	-	-	0.02	0.00	12	12,180
Liquefaction	0.63	1.66	10.93	9.52	24.20	9.17	0.10	6,995	7,234
Refueling Station	0.02	0.05	0.30	0.26	0.67	0.26	0.00	195	201
Truck Delivery	0.04	0.12	0.45	0.02	0.03	0.10	0.00	86	89
Total:	0.69	1.83	11.68	9.80	24.90	9.55	0.10	7,288	19,704

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H_2 Production (Central Plant)

- Production costs ~$1.6/kg by SMR, and ~$3.8/kg by central electrolysis (inclusive of hydrogen losses downstream)

Key Input Assumptions		Central NG without CO2 Seq.	Central Electrolysis		Source/Comment
SMR Central Plant Capacity	kg H2/day	341,448			H2A, turnkey from Krupp-Uhde
Central Electrolysis Capacity	kg H2/day		Variable		1046 kg/day/electrolyzer
Cost of Electricity	$/kWh	0.05	0.06		H2A
Cost of Natural Gas	$/Nm3	0.22			H2A
Vehicle Fuel Economy	mpgge	63.4	63.4		PSAT, mid-size 2015

Production by Central SMR , Standard U.S. Grid					Source/Comment
Sacramento Market Penetration		2%	15%	40%	
Hydrogen Cost	$/kg	1.59	1.55	1.55	Dedicated plant for 40% market, co-produced for 2-15% market penetration
Capital Cost	Millions $	134	134	134	H2A
City H2 Use	kg/day	13,439	100,796	268,790	HDSAM
Site Energy Use	MJ/kg	189	185	185	Include losses downstream
Primary Energy Use	MJ/kg	205	200	200	H2A/GREET data base
GHG Emissions	kg CO2 (eq)/kg	12.5	12.2	12.2	H2A/GREET data base

Production by Central Electrolysis , Renewable					Source/Comment
Sacramento Market Penetration		2%	15%	40%	
Hydrogen Cost	$/kg	3.92	3.77	3.76	Cost of electricity 6 cents/kWh
Capital Cost	Millions $	12	90	241	H2A, 15/110/293 electrolyzers
City H2 Use	kg/day	13,439	100,796	268,790	HDSAM
Site Energy Use	MJ/kg	182	178	178	74.5% process efficiency
Primary Energy Use	MJ/kg	198	193	193	
GHG Emissions	kg CO2 (eq)/kg	0	0	0	

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H Delivery (Central Plant to Vehicle)

- Delivery costs ~$3.2/kg for >15% market, and ~$6.1/kg for 2% market

Key Input Assumptions		2%	15%	40%	Source/Comment
Station Size	kg/day	400	1000	1000	HDSAM
Hydrogen Losses - Loading	%	0.5	0.5	0.5	HDSAM
Hydrogen Losses - Unloading	%	2	2	2	HDSAM
Hydrogen Losses - Storage	%/day	0.25	0.25	0.25	HDSAM
Hydrogen Losses - Cryopump	%	3	3	3	HDSAM

Standard U.S. Grid					Source/Comment
Sacramento Market Penetration		2%	15%	40%	
Hydrogen Cost	$/kg	6.05	3.18	3.02	Cost of electricity 5 cents/kWh
Capital Cost	Millions $	103	391	987	1 liquefier (2, 15% market), 2 liquefiers (40%)
City H2 Use	kg/day	13,439	100,796	268,790	# of trucks: 3/19/50 (2%/15%/40% market)
Energy Use	MJ/kg	49	37	35	Liquefaction energy: 11.8/8.6/8.2 kWh/kg
Primary Energy Use	MJ/kg	132	96	92	HDSAM/GREET data base
GHG Emissions	kg CO2 (eq)/kg	10.9	7.9	7.5	HDSAM/GREET data base
Number of Stations		34	101	269	Distance between stations: 3.3/1.9/1.2 miles
Station Coverage	%	4	12	31	H2 stations/gasoline stations

Renewable					Source/Comment
Sacramento Market Penetration		2%	15%	40%	
Hydrogen Cost	$/kg	6.16	3.27	3.10	Cost of electricity 6 cents/kWh
Capital Cost	Millions $	103	391	987	1 liquefier (2, 15% market), 2 liquefiers (40%)
City H2 Use	kg/day	13,439	100,796	268,790	# of trucks: 3/19/50 (2%/15%/40% market)
Energy Use	MJ/kg	51	37	35	Liquefaction energy: 11.8/8.6/8.2 kWh/kg
Primary Energy Use	MJ/kg	57	42	40	HDSAM/GREET data base
GHG Emissions	kg CO2 (eq)/kg	0.3	0.3	0.3	HDSAM/GREET data base
Number of Stations		34	101	269	Distance between stations: 3.3/1.9/1.2 miles
Station Coverage	%	4	12	31	H2 stations/gasoline stations

Cost and Performance Metrics

- Ownership cost
  - ~12 - 17 cents/mile (15%/2% market) for NG/standard grid scenario
  - ~16 - 21 cents/mile (15%/2% market) for electrolysis/renewable

Key Input Assumptions			Source
Discount Factor on Capital	%	15	
Manufacturer + Dealer Markup		1.74	DOE 2008
Annual Mileage	miles	12,000	H2A
Onboard System Capital Cost	$	2,221	TIAX

		NG/Standard U.S. Grid			Electrolysis/Renewable		
Sacramento Market Penetration		2%	15%	40%	2%	15%	40%
City H2 Use	kg/day	13,439	100,796	268,790	13,439	100,796	268,790
Hydrogen Production Cost	$/kg	1.59	1.55	1.55	3.92	3.77	3.76
Hydrogen Production Capital Cost	Millions $	134	134	134	12	90	241
Hydrogen Delivery Cost	$/kg	6.05	3.18	3.02	6.16	3.27	3.1
Hydrogen Delivery Capital Cost	Millions $	103	391	987	103	391	987
Refueling Cost	$/kg	7.64	4.73	4.57	10.08	7.04	6.86
	$/mile	0.120	0.075	0.072	0.159	0.111	0.108
Ownership Cost	$/mile	0.169	0.123	0.120	0.207	0.159	0.156
Primary Energy							
Production	MJ/kg	205	200	200	198	193	193
Delivery	MJ/kg	132	96	92	57	42	40
WTT Energy Efficiency	%	35.6	40.5	41.1			
WTT GHG Emissions	kg CO2 (eq)/kg	23.4	20.0	19.7	0.3	0.3	0.3
	kg CO2 (eq)/mile	0.37	0.32	0.31	0.01	0.00	0.00

Off-Board Cost and Performance Summary

- Hydrogen production cost is dominated by fuel cost
  - Central SMR ~ $1.6/kg (77% fuel, 14% capital)
  - Central electrolysis ~ $3.8/kg (6 cents/kWh, 80% fuel, 15% capital)
- Hydrogen delivery cost is dominated by capital cost
  - ~ $6.1/kg for 2% market (60% capital, 10% fuel)
  - ~ $3.2/kg for > 15% market (55% capital, 18% fuel)
- Ownership cost
  - ~12 - 17 cents/mile (15%/2% market) for NG/standard grid scenario
  - ~16 - 21 cents/mile (15%/2% market) for electrolysis/renewable
  - ~10 cents/mile for conventional gasoline ICEV ($3/gal untaxed)
- WTT efficiency: 36 - 41%
- GHG emissions
  - ~ 0.31 - 0.37 kg/mile for NG/standard grid scenario
  - ~ 0 kg/mile for electrolysis/renewable scenario
  - ~ 0.35 kg/mile for gasoline ICEV (31 mpg fuel economy)

Summary and Conclusions

Modes of operation with a single-flow nozzle

- Cryo-compressed: 71 kg/m³ max density or 272 atm max pressure
- Cryo-supercritical (Appendix A-2)

Performance and Cost Metric	Units	Scaled Gen-3	Prototype Gen-3	2010 Targets	2015 Targets	Ultimate Targets
Usable Storage Capacity (Nominal)	kg-H_2	5.6	10.4			
Usable Storage Capacity (Maximum)	kg-H_2	6.6	12.3			
System Gravimetric Capacity	wt%	5.5-9.2	7.1-12	4.5	5.5	7.5
System Volumetric Capacity	kg-H_2/m^3	41.8-44.7	44.5-47.1	28	40	70
Storage System Cost	$/kWh	12	8	4	2	TBD
Fuel Cost	$/gge	4.80		2-3	2-3	2-3
Cycle Life (1/4 tank to Full)	Cycles	18,000	18,000[1]	1000	1500	1500
Minimum Delivery Pressure, FC/ICE	atm	3-4	3-4	4/35	3/35	3/35
System Fill Rate	kg-H_2/min	1.5-2	1.5-2	1.2	1.5	2.0
Minimum Dormancy (Full Tank)	W-d	4-30	7-47			
H_2 Loss Rate (Maximum)	g/h/kg-H_2	0.2-1.6[2]		0.1	0.05	0.05
WTT Efficiency	%	41.1		60	60	60
GHG Emissions (CO_2 eq)	kg/kg-H_2	19.7				
Ownership Cost	$/mile	0.12				

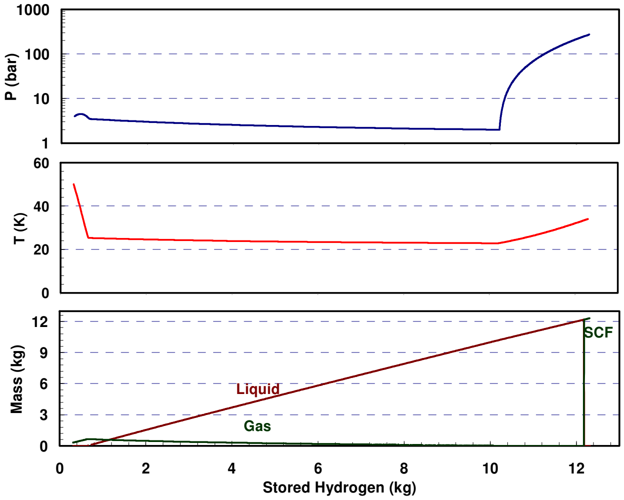
1 Warm cycles
2 During vent time, tank 50%-100% initially full

Appendix A-1

10.4-kg Recoverable H_2 Storage System

Refueling with LH2: Cryo-compressed Option

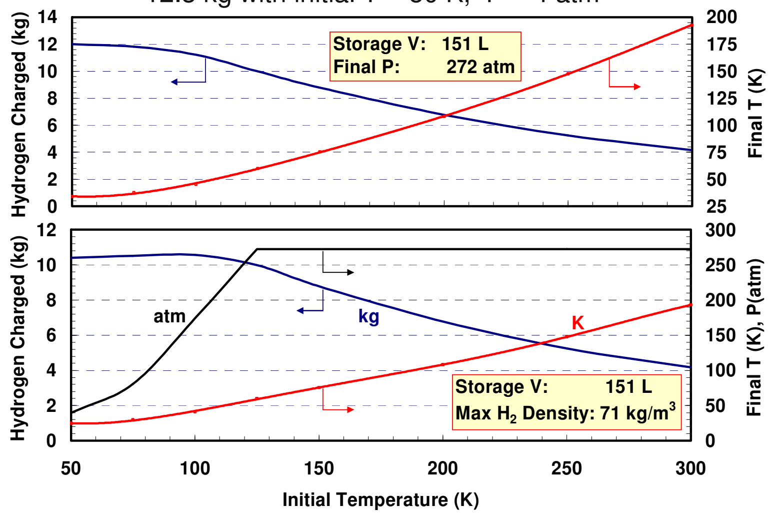
- Storage capacity function of final pressure, 10.7 kg for P = 39 atm
- Depending on initial T and H_2 charged, final P may be less than 4 atm



- **Initial conditions**
  P=4 atm, T=50 K
- **Gas**
  m < 0.65 kg
- **2-Phase**
  0.65 < m < 10.2 kg
- **Sub-cooled Liquid**
  10.2 < m < 12.2 kg
- **Supercritical Fluid**
  m > 12.2 kg

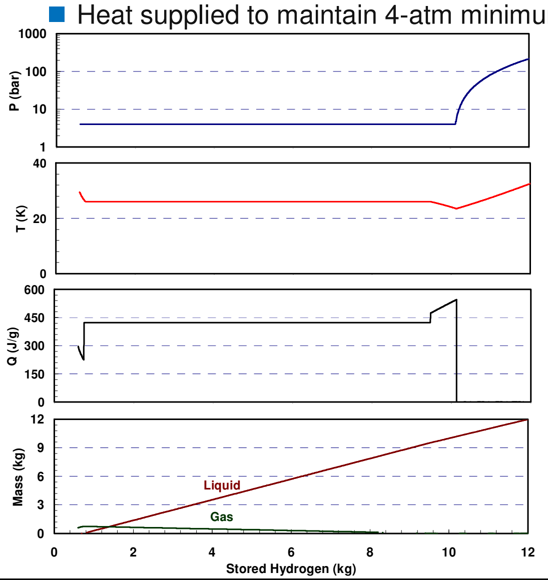
Storage Capacity: Cryo-compressed Option

- Storage capacity is a function of initial temperature
  - 12.3 kg with initial T = 50 K, P = 4 atm



Discharge Dynamics: Cryo-compressed Option

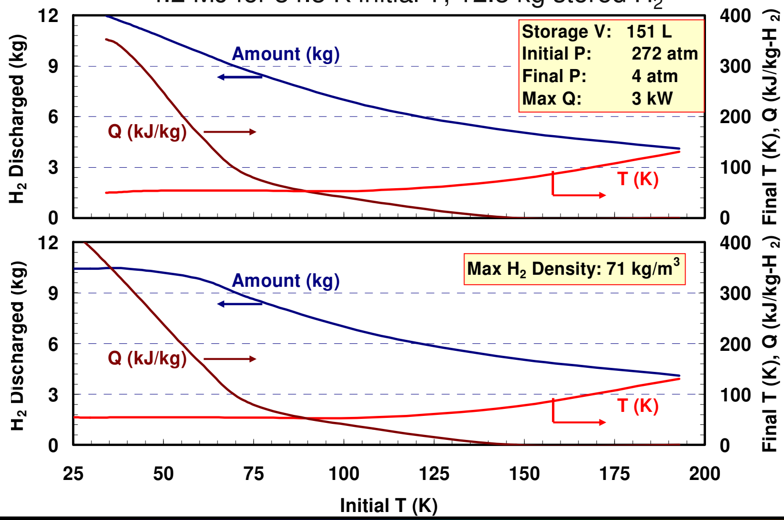
- Heat supplied to maintain 4-atm minimum delivery pressure



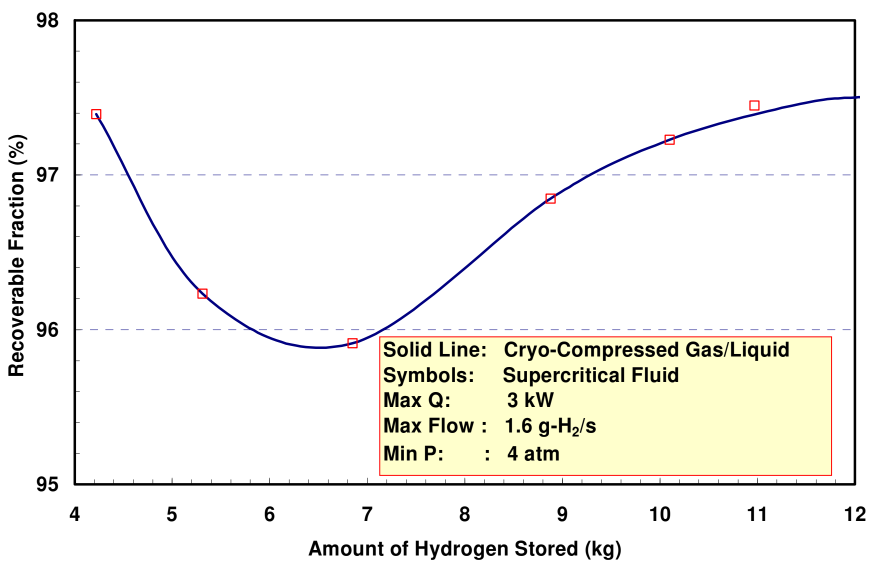
- Initial conditions:
  P=272 atm
  T =34.3 K
  m=12.3 kg
- 1.6 g/s full flow rate of H_2
- Max Q = 860 W

Discharge Behavior: Cryo-compressed Option

- Total heat load is a function of initial temperature
  - 4.2 MJ for 34.3 K initial T, 12.3 kg stored H_2

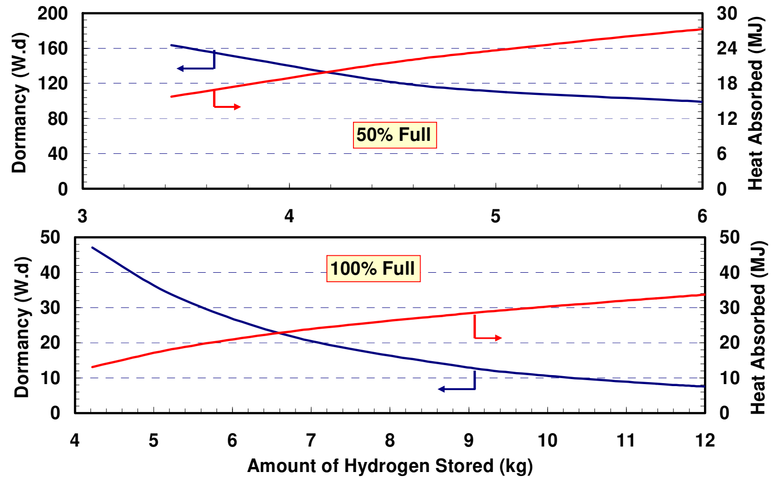


Recoverable Hydrogen



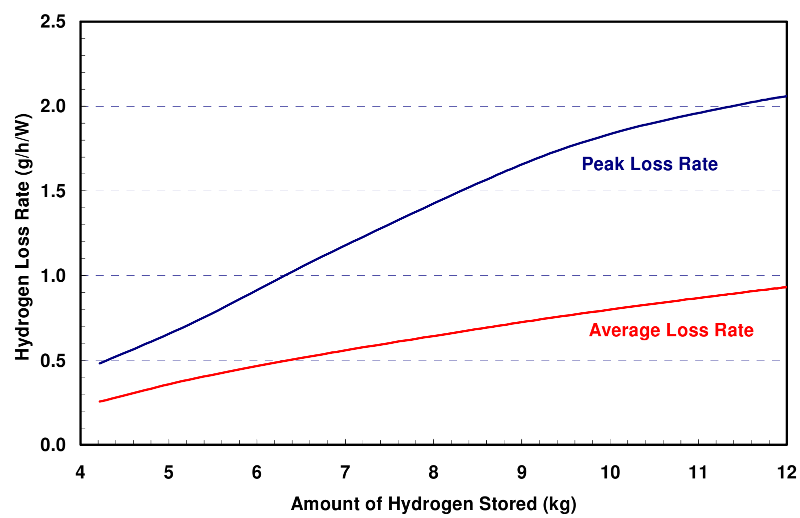
Dormancy and Heat Absorption

- Dormancy: relief valve set at 125% of design pressure
- Heat absorption: Q assumed to approach 0 at 50°C



Hydrogen Loss Rate

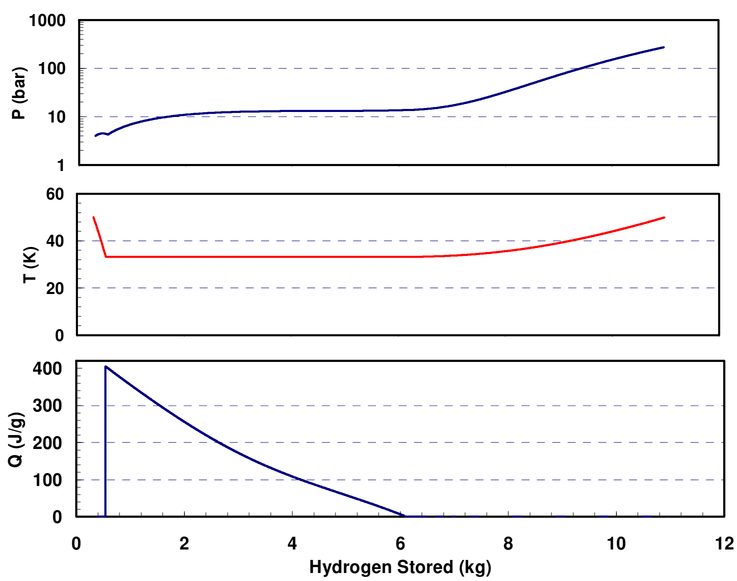
- No loss of hydrogen after the temperature reaches 323 K



Appendix A-2

Cryo-supercritical Option

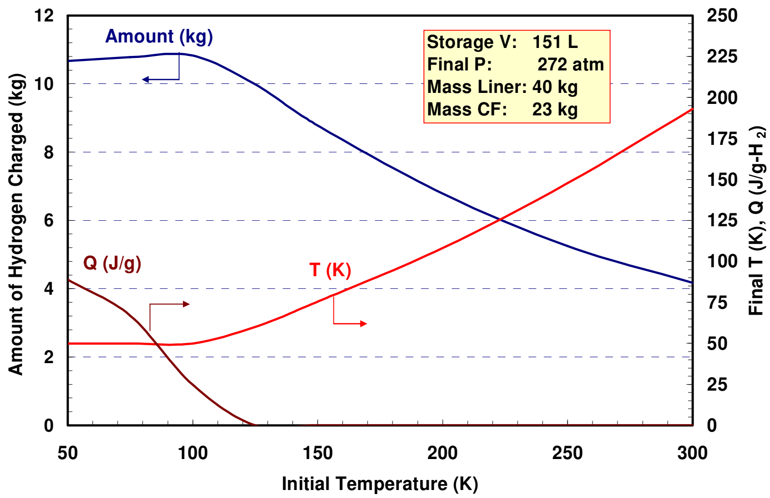
Refueling with LH2: Cryo-supercritical Option



- Storage capacity less than with cCG/L option
- Peak Q: 10 kW at 1.5 kg/min
- External heating
- Mix LH2/CH2 refueling option

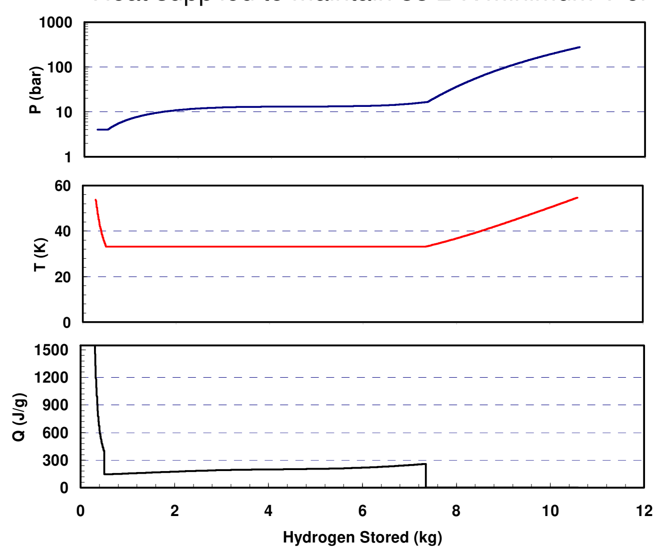
Storage Capacity: Cryo-supercritical Option

- Storage capacity same as with cCG/L option for initial T > 100 K
  - Total heat load: 950 kJ for 50 K initial T



Discharge Dynamics: Cryo-supercritical Option

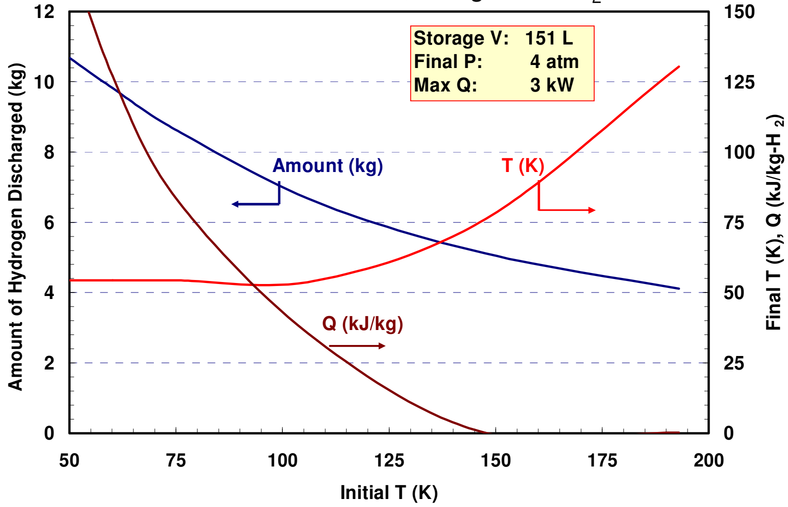
- Heat supplied to maintain 33.2-K minimum T or 4-atm minimum P



- Initial conditions:
  P = 272 atm
  T = 54.7 K
  m = 10.6 kg
- 1.6 g/s full flow rate of H_2
- Max Q = 3 kW

Discharge Behavior: Cryo-supercritical Option

- Total heat load is a function of initial temperature
  - 1.8 MJ for 50 K initial T, 11 kg stored H_2



Appendix A-3

BOP Parts List

BOP Parts List

Item #	Description	Wt (g)	Vol (L)	Dimensions	MAWP (psig)	Manufacturer/Model
Components in compressed hydrogen fill zone						
CV2	Check Valve				6000	Circle Seal Controls CV04-17
MV2	Manual Valve				6000	Circle Seal ES60T1-06W
PSV2	Pressure Relief Valve				4400	Flow Safe Inc., 01-3188SW-103SL
RuD3	Rupture Disc			1.25" x 31.8 mm	5000	Lamont 8131211A
PT2	Pressure Transducer	170		1" x 3"	7500	Taber Industries 2911H
MV1	Manual Valve				6000	Circle Seal ES60T1-06W
PRV1	Pressure Regulator	600		2.5" x 5.2"	10000	TESCOM 20-1263-24-01
PSV1	Pressure Relief Valve				4400	Flow Safe Inc., 01-3188SW-103SL
PG1	Pressure Gauge			2" diameter	10000	TESCOM 316 SS, 62837-1000N25
HX	Heat Exchanger				5500	Tube: 1/2" OD, 0.065" wall, 58" long
Components in engine feed zone						
PG2	Pressure Gauge				400	TESCOM 316 SS, 62837-0400N20
PSV3	Pressure Relief Valve				250	Swagelock SS-RL4S8
Components in liquid hydrogen fill zone						
HX1	Heat Exchanger				7000	Heat Exchanger Applied Technology
Components in vacuum space						
RuD1	Rupture Disc				25	MDC, 420030-1002
RuD2	Rupture Disc				25	MDC, 420030-1002
PT1	Vacuum Press. Transducer				30	MKS, 925 Micro Pirani
MV3	Manual Valve				6000	Circle Seal ES60T1-06W
Tubing						
	SS 304 Tubing			0.375" x 0.040"	4500	0.375" OD, 0.040" wall

Appendix A-4

LLNL Future Generation Projections

Lawrence Livermore National Lab Future Generation Projections

	Actual Generation 1 3600-psi Pickup	Actual Generation 2 5000-psi H2 Prius	Actual Generation 3 4000-psi H2 Prius	Projected High Pressure Refuel 4000-psi vessel	Theoretical 5000 psi Adiabatic Refuel 4000-psi vessel	Theoretical 2500 psi Adiabatic Refuel 2500-psi vessel, thin vacuum jacket
Refuel P,T	1 atm LH2	1 atm LH2	1 atm LH2	5000 psi, 50 K	5000 psi 31 K	2500 psi, 26.2K
H2 Fuel Density	70.86	70.86	70.86	76.8	86	80.4
Fuel Capacity (kg	9.6	10.7	10.7	11.6	13	13.1
H2 Volume (L)	135	151	151	151	151	163
Vessel Volume (L)	33	34	28	28	28	14
Total Weight (kg)	341	187	145	146	147	117
Total Volume (L)	493	323	235	235	235	210
Usable System Density (kg H2/m3), 300 g H2	19	32	44	48	54	61
System Wt% (kg H2/wt System)	2.7	5.3	6.7	7.2	7.9	9.9
Composite Cost ($/kWh)			$2.80	$2.59	$2.31	$1.15
Liner Cost ($/kWh)			$1.68	$1.55	$1.39	$0.69
Vessel Cost			$4.49	$4.14	$3.69	$1.83
BOP Rough-Const Cost($/kWh)			$3.65	$3.36	$3.00	$2.98
Storage System Cost Estimate			$8	$8	$7	$5
Storage System Cost Estimate ($)			$2,900	$2,676	$2,387	$1,715
Cost Delta per			Baseline 0	Savings $224	Savings $513	Savings $1,185
Minimum Days w/o venting from NBP	4.3	6.9	5.3	5.3	5.3	2.7

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APPENDIX B

Analysis of Cryo-Compressed Hydrogen Storage System Cost

Analyses of Hydrogen Storage Materials and On-Board Systems

H_2 Storage using Cryo-compressed: On-board System and Ownership Cost Assessment for Gen 3 Tank

Final Report
November 30, 2009

Stephen Lasher
Kurtis McKenney
Jayanti Sinha

TIAX LLC
15 Acorn Park
Cambridge, MA
02140-2390

Tel. 617- 498-6108
Fax 617-498-7054
www.TIAXLLC.com
Reference: D0268

Sections

We have completed certain aspects of on-board and off-board evaluations and updates for 10 hydrogen storage technologies.

Analysis To Date		Compressed		Metal Hydride	Chemical Hydride				Cryogenic		
		350 bar	700 bar	Sodium Alanate	SBH	LCH_2	MgH_2	AB	Cryo comp	LH_2	AC
On-Board	Review developer estimates	√	√	√	√	√			√	√	√
	Develop process flow diagrams and system energy balances	√	√	√	√	√			√	√	√
	Independent performance assessment (wt, vol)	√	√	√	√	√			√	√ *	√ *
	Independent cost assessment	√	√	√	√	√ *			√	WIP	WIP
Off-Board	Review developer estimates	√	√		√	√	√	√	√	√ *	
	Develop process flow diagrams and system energy balances				√	√	√	√			
	Independent performance assessment (energy, GHG)[a]				√	√ *					
	Independent cost assessment				√	√ *					
Overall	Ownership cost projection	√	√		√	√ *			√	WIP	
	Solicit input on TIAX analysis	√	√	√	√	WIP			√	WIP	WIP
	Analysis update	√	√		√	WIP			√		

(grey box) = Not part of current SOW
WIP = Work in Progress
SBH = Sodium Borohydride
LCH_2 = Liquid Hydrogen Carrier (n-ethylcarbazole like)
AB = Ammonia Borane
AC = Activated Carbon
LH_2 = Liquid Hydrogen (cryogenic)
* Preliminary results under review
[a] Work with SSAWG and ANL on WTW analyses

This report summarizes our updated cryo-compressed hydrogen storage assessment for a Gen 3 tank.

Technology Focus	2004-2007	2008-2009

On-Board Storage System Assessment	• Compressed Hydrogen
	  • 350 bar
	  • 700 bar
	• Metal Hydride
	  • Sodium Alanate
	• Chemical Hydride
	  • Sodium Borohydride (SBH)
	  • Magnesium Hydride (MgH_2)
	• Cryogenic Hydrogen
	  • Cryo-compressed
		• Compressed Hydrogen
		  • 350 bar – update
		  • 700 bar – update
		• Chemical Hydride
		  • Liquid Hydrogen Carrier (LCH_2)
		• Cryogenic Hydrogen
		  • Cryo-compressed – update
		  • Liquid Hydrogen (LH_2) – WIP
		  • Activated Carbon – WIP

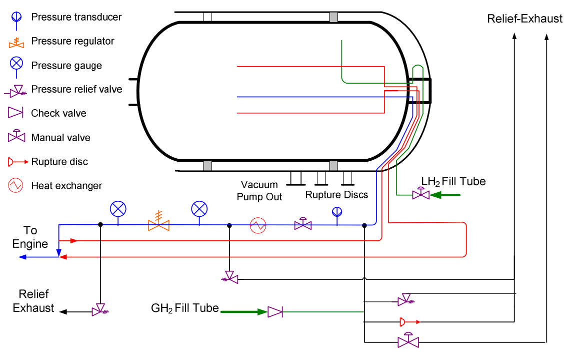
Off-Board Fuel Cycle Assessment	• Compressed Hydrogen
	  • 350 bar
	  • 700 bar
	• Chemical Hydride
	  • Sodium Borohydride (SBH)
		• Compressed Hydrogen
		  • 350 bar – update
		  • 700 bar – update
		• Chemical Hydride
		  • Liquid Hydrogen Carrier (LCH_2)
		  • Ammonia Borane
		• Cryogenic Hydrogen
		  • Cryo-compressed
		  • Liquid Hydrogen (LH_2) – WIP

Note: Previously analyzed systems will continually be updated based on feedback and new information.

Executive Summary Background *Schematic*

Lawrence Livermore National Labs (LLNL) prototype Gen 3 tank design was the basis of our updated cryo-compressed storage system assessment.

LLNL Gen 3 Design with ANL Modifications



Gen 3 Cryo-compressed Tank Specifications

- 80.8 & 151 liters for the "scaled" and prototype systems (5.6 kg & 10.4 kg usable LH_2), respectively
- 272 bar (4,000 psi) max pressure
- 12 mm T700S carbon fiber, 60% fiber vol, 2.25 SF, 86% translation strength
- 9.5 mm thick Al liner
- -253 ºC min temp
- 10 mm & 17 mm vacuum gap w/ MLVI, 10^{-5} torr (~1.5 W HT rate)
- 3.2 mm thick SS304 outer shell

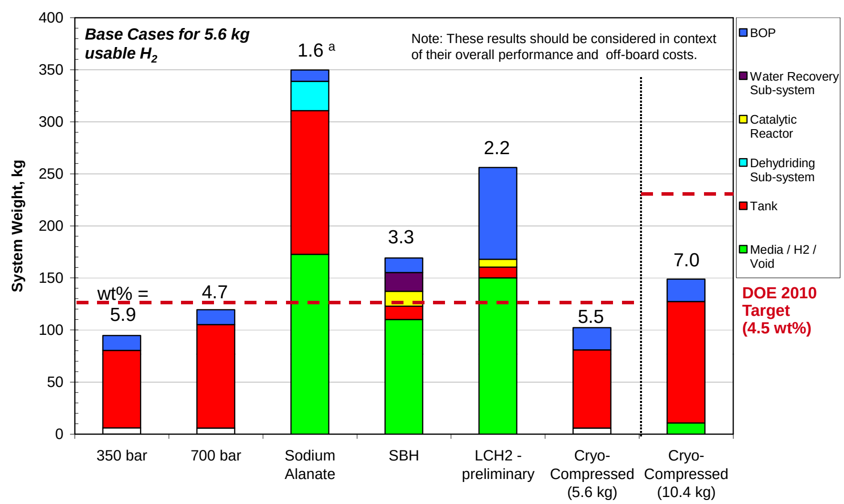
Additional modifications assumed for high-volume production

- Cryogenic valves assumed to be electronically controlled
- Added liquid level sensor[1]
- Valves and tubing assumed for in-tank heat exchange system
- Assumed low-carbon steel instead of SS304 for outer shell to save cost
- Did not include electronic boards and computer
- Insulated LH_2 fill/gas vent port included

[1] Other methods of accounting of fuel could be used (e.g. close mass -balance accounting with flow sensor).

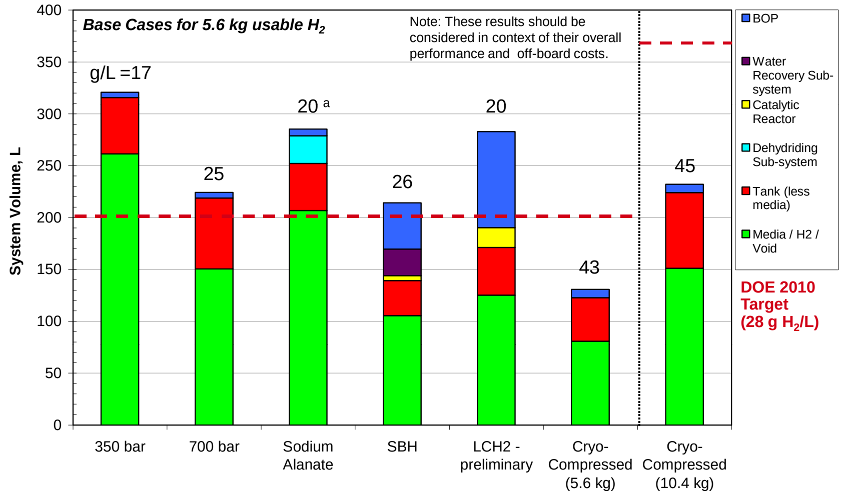
Executive Summary On-board Assessment *Weight Comparison – Base Cases*

Both the scaled (5.6 kg usable LH_2) and prototype Gen-3 (10.4 kg usable LH_2) cryo-compressed systems exceed the DOE 2010 gravimetric target of 4.5 wt%.



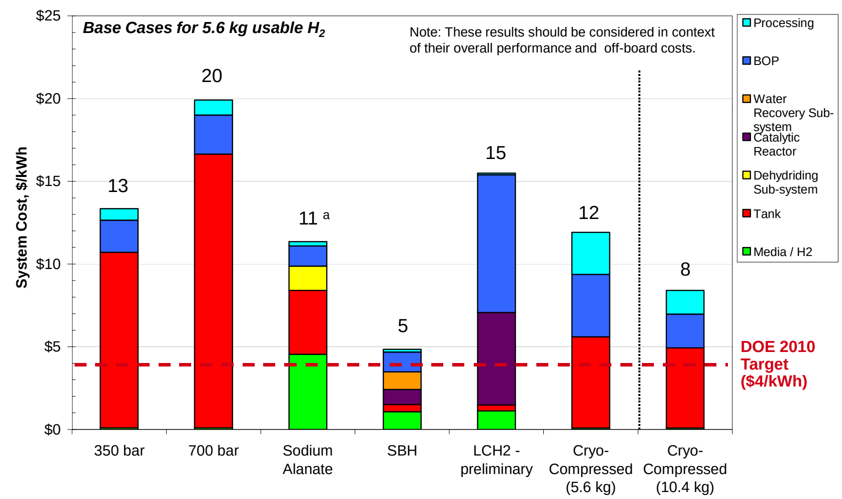
Note: not all hydrogen storage systems shown are at the same stage of development, and each would have different on-board performance characteristics.
[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

The volumetric capacities of both cryo-compressed systems also exceed the DOE 2010 volumetric target of 28 g H_2/liter.



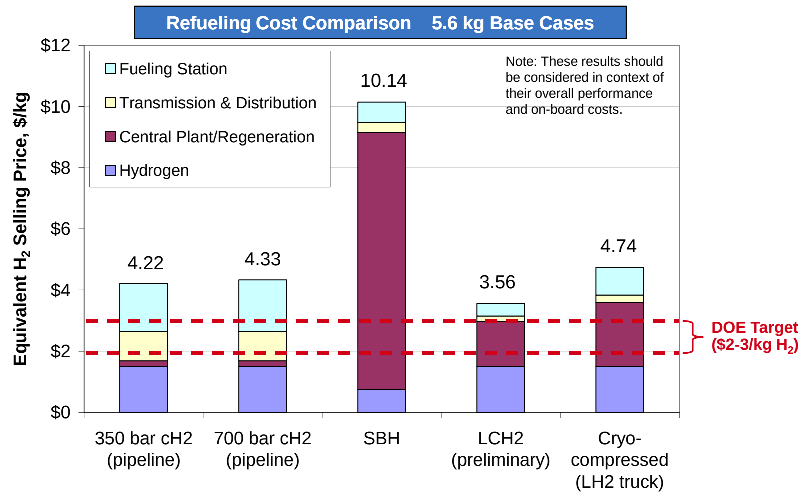
Note: not all hydrogen storage systems shown are at the same stage of development, and each would have different on-board performance characteristics.
[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

However, the base case cryo-compressed systems high-volume costs are projected to be 2-3 times more expensive than the current DOE 2010 cost target.



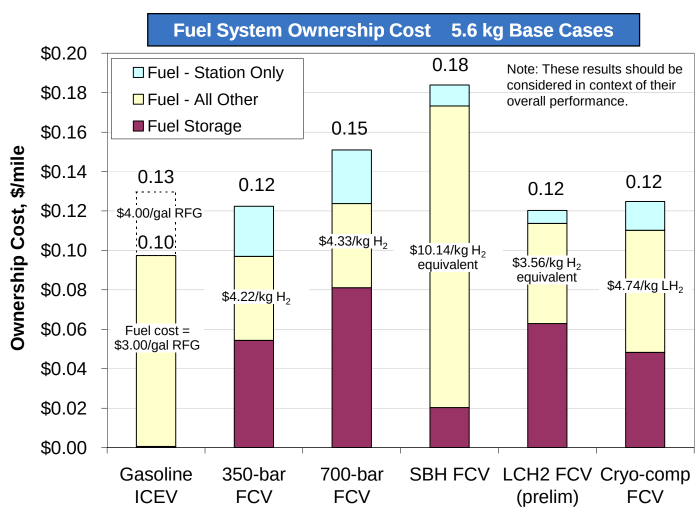
Note: not all hydrogen storage systems shown are at the same stage of development, and each would have different on-board performance characteristics.
[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

In addition, the cryo-compressed system refueling costs are projected to be 1.5-2.5 times more expensive than the current DOE target range.



Note: 350 bar, 700 bar and cryo-compressed results were calculated using the base case delivery scenarios in HDSAM v2.06. SBH and LCH_2 results were calculated using a modified H2A Delivery Components Carrier Model v34. All fuel costs exclude fuel taxes.

Fuel system ownership cost for the base case cryo-compressed system is projected to be 20-30% more expensive than gasoline at $3.00/gal.



Note: All fuel costs exclude fuel taxes.

Although on-board storage system weight and volume targets will likely be met, costs are still significantly higher than the current targets.

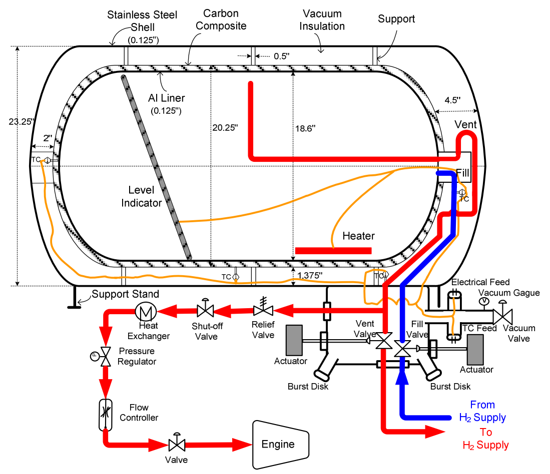
- Gravimetric and volumetric H_2 storage capacities of the system meet or exceed both the DOE 2010 (4.5 wt% and 28 g/L) and 2015 targets (5.5 wt% and 40 g/L)
- Factory costs of the on-board storage systems are 2-3 times the current DOE 2010 cost target based on assumptions considered to be most likely to be applicable
  - Scaled Gen-3 system (5.6 kg) = $12/kWh energy content of the stored H_2
  - Prototype Gen-3 system (10.4 kg) = $8/kWh energy content of the stored H_2
- Factory costs will likely range (95% confidence) between $11.4 and $15.8/kWh for the 5.6 kg system and between $7.57 and $10.7/kWh for the 10.4 kg system
- Refueling costs based on LH_2 delivery and high pressure LH_2 dispensing, are projected to be 1.5-2.5 times more expensive than the DOE cost target of $2-3/kg
- Ownership cost for the 5.6 kg system will likely be about 20-30% (2-3 ¢/mi or $250-350/yr) higher than a conventional gasoline ICEV when gasoline is $3.00/gal
  - Ownership costs would be comparable at a gasoline price of ~$4.00/gal

When on-board and off-board costs are combined, the cryo-compressed system has potential to have similar ownership costs as a gasoline ICEV.

Note: All fuel costs exclude fuel taxes.

In 2007, TIAX evaluated the cost of a cryo-compressed hydrogen storage system based on a Gen 2 design from LLNL capable of storing 10.1 kg usable LH_2.

LLNL Gen 2 Design with ANL Modifications



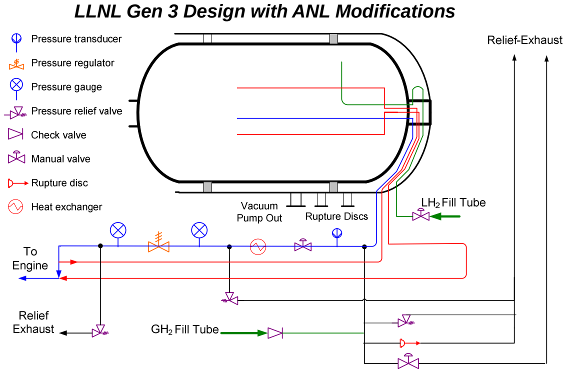
Gen 2 Cryo-compressed Tank Specifications

- 151 L for 10.1 kg usable LH_2 (10.7 kg stored LH_2)
- ~350 bar (5,000 psi) max pressure
- 12 mm T700S carbon fiber, 60% fiber vol, 2.25 SF, 82% translation strength
- 3 mm thick Al liner
- -253 ºC min temp
- 40 mm vacuum gap w/ 40 layer of MLVI, 10^{-5} torr (~1 W HT rate)
- 3.2 mm thick SS304 outer shell

Note: Additional modifications were made to the Gen 2 LLNL cryo-compressed design based on literature and developer feedback.

This year, we evaluated the cost of two cryo-compressed storage systems based on LLNL's Gen 3 design capable of storing 5.6 and 10.4 kg usable LH_2.

LLNL Gen 3 Design with ANL Modifications



Gen 3 Cryo-compressed Tank Modifications from Gen 2

- Two tank sizes: 80.8 & 151 liters (5.6 kg & 10.4 kg usable LH_2)
- Reduced pressure vessel rating: 272 bar (4,000 psi) max pressure
- Increased Al liner thickness: 9.5 mm
- Reduced insulation: 10 & 17 mm vacuum gap w/ MLVI, 10^{-5} torr (~1.5 W HT rate)
- Vacuum valve box eliminated
- Better packaging

Additional modifications assumed for high-volume production

- Cryogenic valves assumed to be electronically controlled
- Added liquid level sensor[1]
- Valves and tubing assumed for in-tank heat exchange system

- Assumed low-carbon steel instead of SS304 for outer shell to save cost
- Did not include electronic boards and computer
- Insulated LH_2 fill/gas vent port included

[1] Other methods of accounting of fuel could be used (e.g. close mass -balance accounting with flow sensor).

The high volume (500,000 units/year) manufactured cost for all H_2 storage systems is estimated from raw material prices, capital equipment, labor, and other operating costs.

BOP Bottom-up Costing Methodology

- Develop Bill of Materials (BOM)
- Obtain raw material prices from potential suppliers
- Develop production process flow chart for key subsystems and components
- Estimate manufacturing costs using TIAX cost models (capital equipment, raw material price, labor rates)

Tank
- Liner
- Composite Layers
- MLVI Wrap
- Vacuum Shell
- Bosses

\+

BOP (Purchased)
- Fill Port
- Regulator
- Valves
- Heat Exchanger
- Sensors

\+

Assembly and Inspection
- Vacuum Processing
- QC of finished components
- System assembly
- QC of system

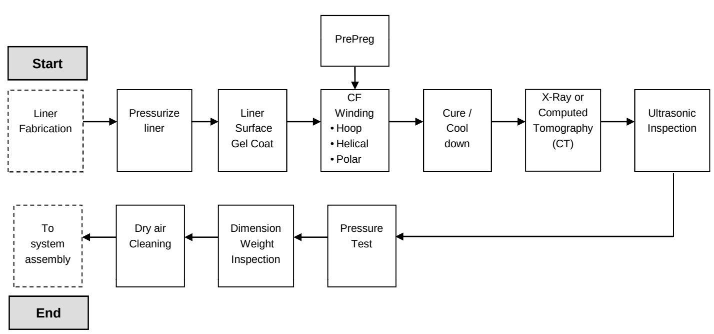
=

Cryo-compressed Hydrogen Storage System Cost

We modeled material and manufacturing process costs for the cryo-compressed tank, while the BOP is assumed to be purchased.

The high-pressure cryo-compressed tanks require composite winding steps that are well established by the Compressed Natural Gas Industry.

Carbon Fiber Tank Manufacturing Process Map

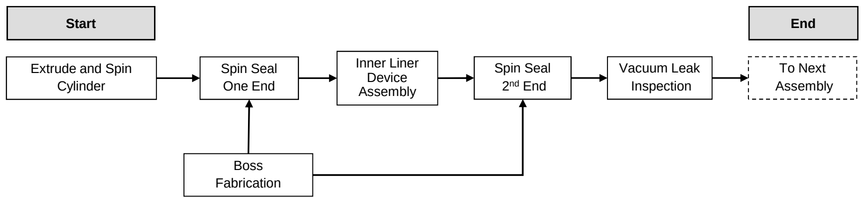


We also assume the system manufacturer purchases pre-impregnated (i.e., "prepreg") carbon fiber composite as apposed to raw carbon fiber.[1]

[1] See Appendix for details.

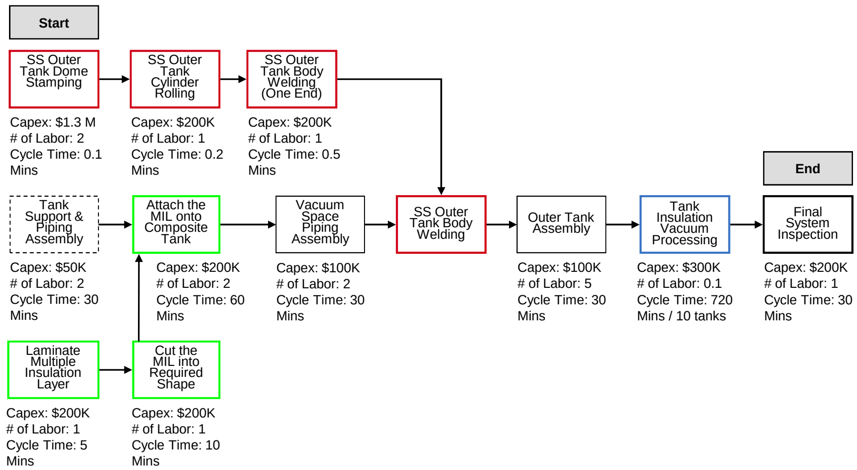
The cryo-compressed tanks also require an aluminum "liner" fabricated using standard pressure vessel manufacturing processes.

Aluminum Liner Manufacturing Process Map



Finally, multi-layer vacuum insulation (MLVI) requires a vacuum shell and labor intensive assembly process.

Cryo-tank Insulation, Assembly, and Inspection Process Map



We developed BOP cost projections for high-volume production using the Delphi method with validation from Top-down and Bottom-up estimates.

- We obtained input from developers on their cost projections for BOP components
  - Tank developers are considering the issue of automotive scale production
  - But, they do not produce tanks at such large scales today
- Some feedback from Automotive OEMs was that these projections did not account for process or technology changes that would be required for automotive scale production
  - Cryogenic and/or high pressure components are often built-to-order or produced in low volumes, so "processing costs" are typically high
  - Vendor quotes contain unspecified markups, which can be substantial in the industry these devices are currently used (unlike the automotive industry, purchasing power of individual buyers is not very strong)
  - Low-volume quotes are sometimes based on laboratory and/or custom components that often exceed the base case system requirements
- Therefore, we developed BOP cost projections that were more in-line with OEM estimates for high-volume production using the Delphi method with validation from:
  - Top-down estimates - high-volume discounts applied to low-volume vendor quotes using progress ratios
  - Bottom-up estimates - cost modeling using DFMA® software plus mark-ups

Details on each cost estimation approach are presented in the Appendix.

This year, we updated our previous cryo-compressed tank design assumptions based on the Gen 3 LLNL design and input from LLNL, ANL and industry.

Design Parameter	Base Case Value	Basis/Comment
Nominal pressure	272 bar	Tank design assumption based on discussions with LLNL
Maximum pressure	340 bar *	125% of nominal design pressure is assumed required for dormancy
Filling pressure (max)	340 bar *	ANL assumption for "Cryo-compressed H_2 Storage Option"
"Empty" pressure	4 bar	ANL assumption; depending on initial temperature and H_2 charge
Usable LH_2 storage capacity	5.6 and 10.4 kg	Design assumption based on ANL drive-cycle modeling for FCV 350 mile range (5.6 kg) and LLNL tank design (10.4 kg)
Tank size (water capacity)	81 and 151 L	Required for 5.6 kg and 10.4 kg useable H_2 capacity (5.7 and 10.7 kg total H_2 capacity), calculated by ANL
Safety factor	2.25	Industry standard criteria (e.g., ISO/TS 15869) applied to nominal storage pressure (i.e., 272 bar)
L/D ratio	2.0	ANL assumption based on discussions with LLNL and SCI design, 2008; based on the outside of the CF wrapped tank
Carbon fiber type	Toray T700S	Discussions with LLNL, Quantum and other developers, 2008
Composite tensile strength	2,550 MPa	Toray material data sheet for 60% fiber by volume
Translation strength factor	86%	ANL assumption based on discussions and data from Quantum, 2004-09
Tank liner thickness	9.5 mm Al	ANL assumption based on discussions with LLNL and SCI design, 2008
Minimum temperature	-253 ºC	Typical for liquid hydrogen storage
Vacuum gap	10 and 17 mm	ANL assumption to achieve ~1.5 W heat transfer rate with Mylar layers
Outer shell	3.2 mm Steel	Discussions with LLNL and industry, 2008-09

*Note: Tank design based on nominal pressure (272 bar) not maximum pressure.

We used sensitivity analysis to account for design assumptions that are either not very well established or could change significantly in the near future.

Design Parameter	Low	Base	High	High/Low Basis/Comment
Safety factor	1.80	2.25	3.00	Based on discussions with Quantum and Dynatek (2005)
Composite tensile strength, MPa	2,300	2,550	2,940	Low 10% below base case; high assumes 60% of fiber strength based on fiber volume fraction
Translation strength factor	0.80	0.86	1.00	Low based on discussions with developers for similar pressure tanks (e.g., 350-bar); high assumes theoretical maximum
Tank liner thickness, mm	3.0	9.5	10.0	Based on discussions with developers

The base case cost projections for the major BOP components range from $15-200 per unit assuming high-volume (i.e., 500,000 units/yr) production.

Purchased Component Cost Est.	Rating	Base Cases ($ per unit)	Comments/Basis
Fill tube/port	350 bar, cryogenic H_2	$200	Industry feedback; capable of 2-way flows at high pressures and low temperatures without leaks and accepting signals from the nozzle at the fueling station to open or close; includes control valve
Pressure regulator	350 bar cH_2	$160	Industry feedback validated with quotes and discussion with Emerson Process Management/Tescom/Northeast Engineering (2009) and DFMA® cost modeling software
Control valve	350 bar, cryogenic H_2	$94	Industry feedback validated with quotes and discussion with Bertram Controls for Circle Seal solenoid control valve (2009)
Heat exchangers	350 bar, cryogenic H_2	$50	Industry feedback; includes a valve, ~3 meters of tubing and a conventional flat plat heat exchanger (or connection to vehicle waste heat source)
Pressure transducers	350 bar and 10^{-5} Torr, cryogenic H_2	$30	Industry feedback validated with quotes and discussion with Taber Industries (2009)
Pressure relief valves	350 bar, cryogenic H_2	$28	Based on DFMA® cost modeling software
Level sensor (in tank)	350 bar LH_2	$25	Industry feedback validated with discussions with tank developers
Pressure gauge (in engine feed zone)	250 psi cH_2	$17	Based on quotes from Emerson Process Management/ Tescom/ Northeast Engineering (2009)
Boss and plug (in tank)	350 bar, cryogenic H_2	$15	Based on price estimate from tank developers (2009), validated with Al raw material price marked up for processing

Note: Additional purchased component cost projections, assumptions, and methods are presented in the Appendix.

To account for the inherent uncertainty of the BOP cost projections, we developed "low" and "high" cost estimates for input to the sensitivity analysis.

Purchased Component Cost Est.	Low	Base Cases	High	High/Low Comments/Basis
Fill tube/port	$100	$200	$400	Low and high are one half and double the base case, respectively
Pressure regulator	$80	$160	$360	Low and high based on discussions with tank developers and vendors (2009)
Control valve	$37	$94	$190	Low and high based on discussions with tank developers (2009), Circle Seal (2009), and Valcor (2007)
Heat exchangers	$44	$50	$200	Low is sum of control valve and check valve low costs; high based on discussions with developers
Pressure transducer	$15	$30	$60	Low and high are half and double the base case, respectively
Vacuum pressure transducer	$15	$30	$60	Low and high are half and double the base case, respectively
Pressure relief valves	$20	$28	$130	Low and high based on discussions with tank developers, Flow Safe (2009), Ham-Let (2009), and Swagelock (2009) venders
Level sensor (in tank)	$10	$25	$100	Low assumes simpler technology; high based on discussions with developers
Pressure gauge (in engine feed zone)	$9	$17	$34	Low and high are half and double the base case, respectively
Boss and plug (in tank)	$12	$15	$100	Low is 75% of base case; high assumes more complicated processing requirement

We based the cost of purchased raw materials on raw material databases and discussions with suppliers.

Raw Material Cost Estimates, $/kg	Base Cases	Comment/Basis
Hydrogen	3.0	Consistent with DOE H_2 delivery target
Aluminum (6061-T6)	9.6	Bulk price from Alcoa (2009)
Carbon fiber (T700S) prepreg	36.6	Discussion w/ Toray (2007) re: T700S fiber ($10-$16/lb, $13/lb base case); 1.27 prepreg/fiber ratio (Du Vall 2001)
Multi-layer vacuum insulation (MLVI)	50 ($0.15/ft^2)	Discussion with MPI (2007)
Stainless steel (304)	4.7	Average monthly costs from Sep '06 – Aug '07 (MEPS International 2007) deflated to 2005$s by ~6%/yr
Standard steel	1.0	Estimate based on monthly costs for 2008-2009 (MEPS International 2009)

We also developed low and high estimates for the cost of purchased raw materials for input to the sensitivity analysis.

Raw Material Cost Estimates, $/kg	Low	Base Cases	High	High/Low Comments/Basis
Hydrogen	1.5	3.0	6.0	Low and high are half and double the base case, respectively
Aluminum (6061-T6)	4.8	9.6	19.2	Low and high are half and double the base case, respectively
Carbon fiber (T700S) prepreg	18.5	36.6	44.9	Low based on 68% fiber (by weight) at $10/lb and 32% epoxy at $5/lb[a]; High based on discussion w/ Toray (2007) re: T700S fiber at $16/lb and 1.27 prepreg/fiber ratio (Du Vall 2001)
Multi-layer vacuum insulation	25	50	100	Low and high are half and double the base case, respectively
Stainless steel (304)	2.4	4.7	9.4	Low and high are half and double the base case, respectively
Standard steel	0.5	1.0	2.0	Low and high are half and double the base case, respectively

[a] Weighted raw material costs would be more relevant for a wet winding process, which may also alter fiber winding processing costs.
[1] However, there are DOE programs that are looking at ways to significantly reduce carbon fiber costs (e.g., Abdallah 2004).

Carbon fiber is already produced at very high-volumes for the Aerospace industry, so it isn't expected to become significantly cheaper in the near term.[1]

The costs of key processing steps are estimated from capital equipment, labor, and other operating costs assuming a high level of automation.

Key Processing Steps – Cryo-compressed Tank	5.6 kg Base Case	10.4 kg Base Case
Liner Fabrication, Assembly, & Inspection	$99	$103
Carbon Fiber Winding Process	$25	$40
MLVI Wrapping	$106	$108
Outer Shell Fabrication	$7	$7
In-vessel Assembly	$42	$42
Ex-vessel Assembly	$93	$93
Vacuum Processing	$59	$59
Final Inspection	$40	$40
Total	**$473**	**$494**

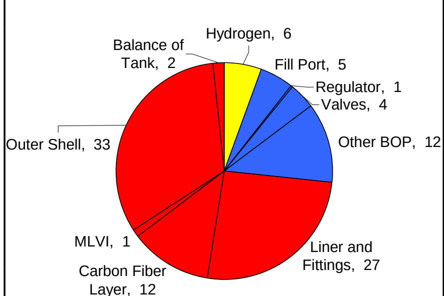
The larger tank size increases the cost of the liner fabrication, carbon fiber winding, and MLVI wrapping processes.

Processing cost makes up about 15-20% of the total system cost due to the time-consuming processing steps, even at assumed high production volumes.

On-board System Cost Breakout – Cryo-compressed	5.6 kg Base Case			10.4 kg Base Case		
	Material, $	Processing, $	Processing Fraction	Material, $	Processing, $	Processing Fraction
Hydrogen	$17	(purchased)	-	$32	(purchased)	-
Cryo-compressed Vessel	$1,027	$238	19%	$1,678	$259	13%
Liner & Fittings	*$292*	*$99*	*25%*	*$439*	*$103*	*19%*
Carbon Fiber Layer	*$516*	*$25*	*5%*	*$945*	*$40*	*4%*
MLVI	*$65*	*$106*	*62%*	*$123*	*$108*	*47%*
Outer Shell	*$35*	*$7*	*17%*	*$52*	*$7*	*12%*
Balance of Tank	*$118*	*(purchased)*	*-*	*$118*	*(purchased)*	*-*
Fill Port	$200	(purchased)	-	$200	(purchased)	-
Regulator	$160	(purchased)	-	$160	(purchased)	-
Valves	$166	(purchased)	-	$166	(purchased)	-
Other BOP	$179	(purchased)	-	$179	(purchased)	-
Final Assembly & Inspection	-	$235	-	-	$235	-
Total Factory Cost	**$1,748**	**$473**	**21%**	**$2,414**	**$494**	**17%**

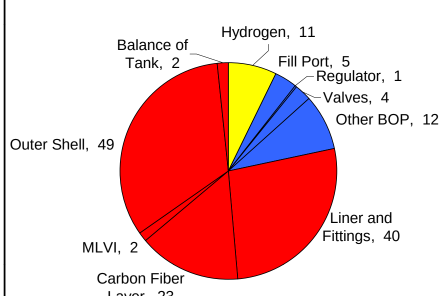
For the base case conditions, the outer shell accounts for about 30% of the total weight of the 5.6 kg and 10.4 kg systems.

5.6 kg Base Case Weight = 102 kg
5.5 wt% based on 5.6 kg usable LH_2



**Weights in kg*

10.4 kg Base Case Weight = 149 kg
7.0 wt% based on 10.4 kg usable LH_2

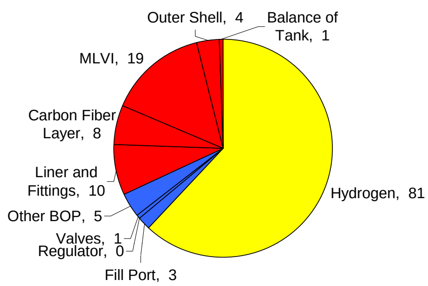


**Weights in kg*

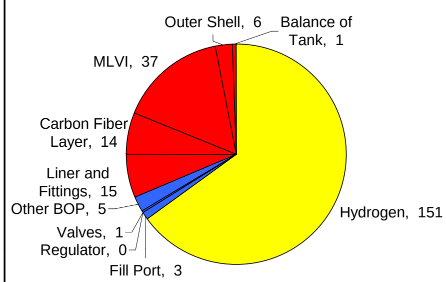
Weight savings of over 20% can be realized if aluminum rather than standard steel is used for the outer shell, but system cost would go up by about 15%.

For the base case conditions, the stored hydrogen accounts for about 65% of the total volume of the 5.6 kg and 10.4 kg systems.

5.6 kg Base Case Volume = 131 L
43 g H_2/L based on 5.6 kg usable LH_2



10.4 kg Base Case Volume = 232 L
45 g H_2/L based on 10.4 kg usable LH_2

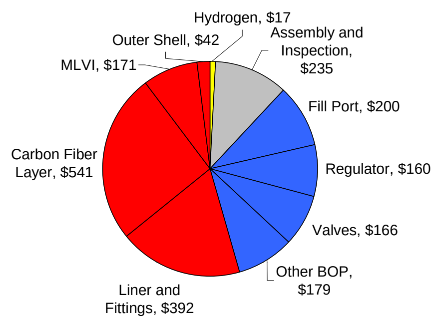


Note: Volume results do not include void spaces between components (i.e., no packing factor was applied).

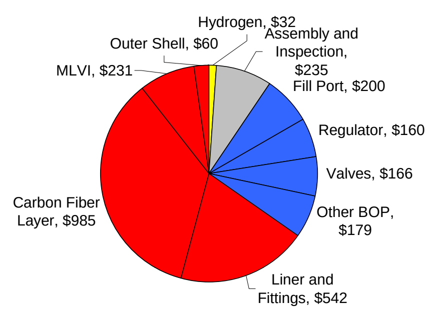
Volumetric, weight and cost savings can be realized if the Al liner thickness is reduced from the base case assumption of 9.5 mm.

The carbon fiber layer is the most expensive single component and accounts for about 25% and 35% of the base case 5.6 and 10.4 kg systems costs.

5.6 kg Base Case Factory Cost[1] = $2,200
$12/kWh based on 5.6 kg usable LH_2



10.4 kg Base Case Factory Cost[1] = $2,900
$8/kWh based on 10.4 kg usable LH_2

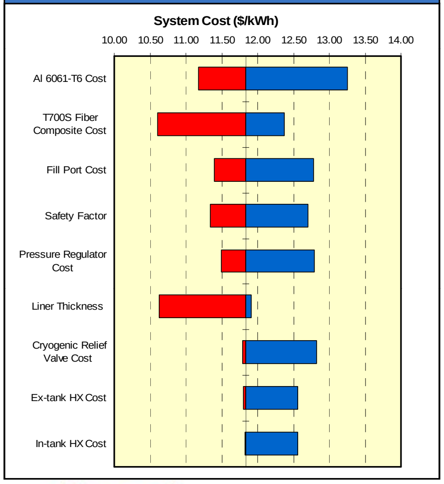


[1] Cost estimate in 2005 USD. Includes processing costs.

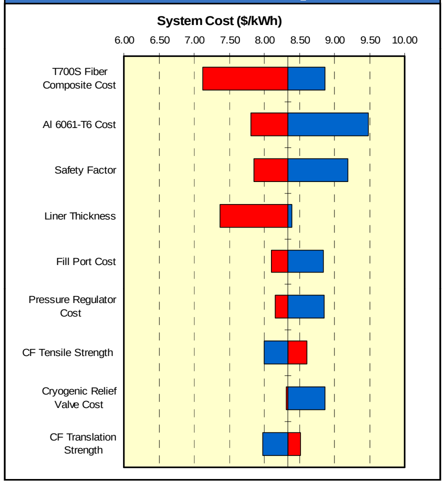
The BOP components account for about 30% and 25% of the base case 5.6 and 10.4 kg system costs, respectively.

Single variable sensitivity analysis shows that aluminum and carbon fiber cost assumptions have the biggest impact on our system cost projections.

5.6 kg Single Variable Cost Sensitivity
based on 5.6 kg useable LH_2, $/kWh

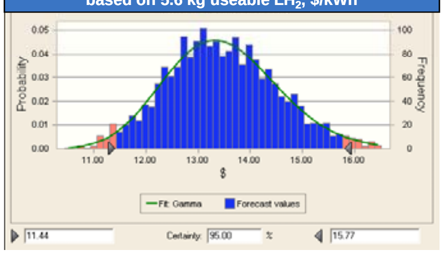


10.4 kg Single Variable Cost Sensitivity
based on 10.4 kg useable LH_2, $/kWh

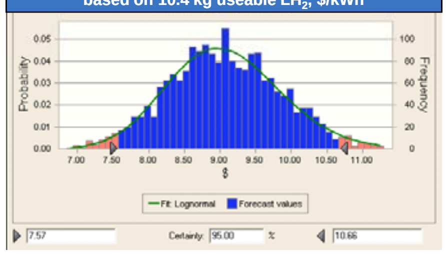


Multi variable sensitivity analysis shows the factory cost is likely to be between $11.4-15.8/kWh for 5.6 kg and $7.57-10.7/kWh for 10.4 kg tank systems.[1]

5.6 kg Multi Variable Cost Sensitivity
based on 5.6 kg useable LH_2, $/kWh



10.4 kg Multi Variable Cost Sensitivity
based on 10.4 kg useable LH_2, $/kWh

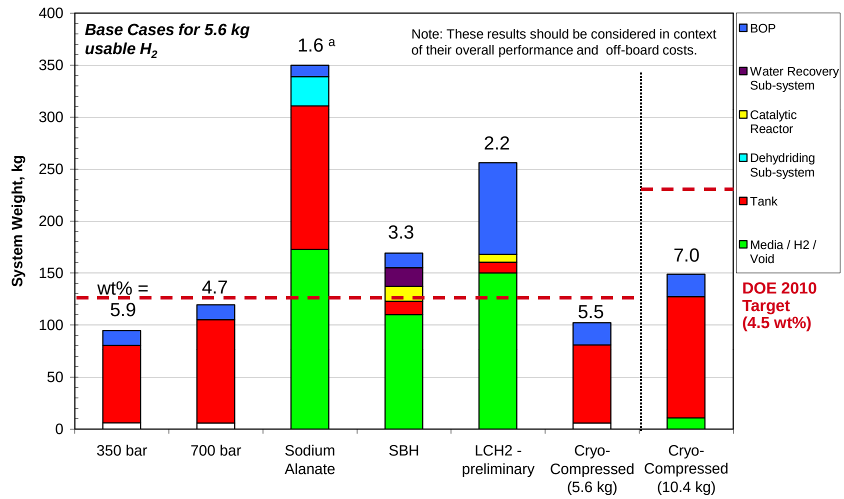


Base Case	11.9
Mean	13.5
Standard Deviation	1.08
"Low" Case[1]	11.4
"High" Case[1]	15.8

Base Case	8.39
Mean	9.07
Standard Deviation	0.80
"Low" Case[1]	7.57
"High" Case[1]	10.7

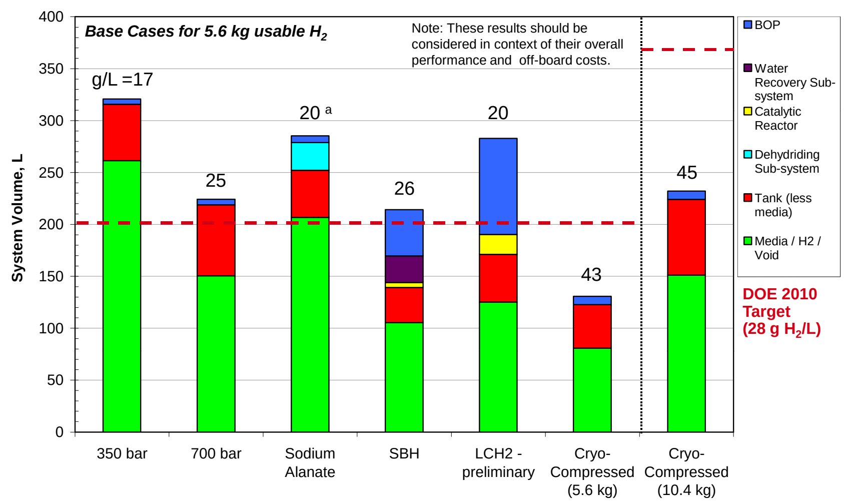
[1] The ranges shown here are the 95% confidence interval based on the data fit.

Both the scaled (5.6 kg usable LH2) and prototype Gen-3 (10.4 kg usable LH2) cryo-compressed systems exceed the DOE 2010 gravimetric target of 4.5 wt%.



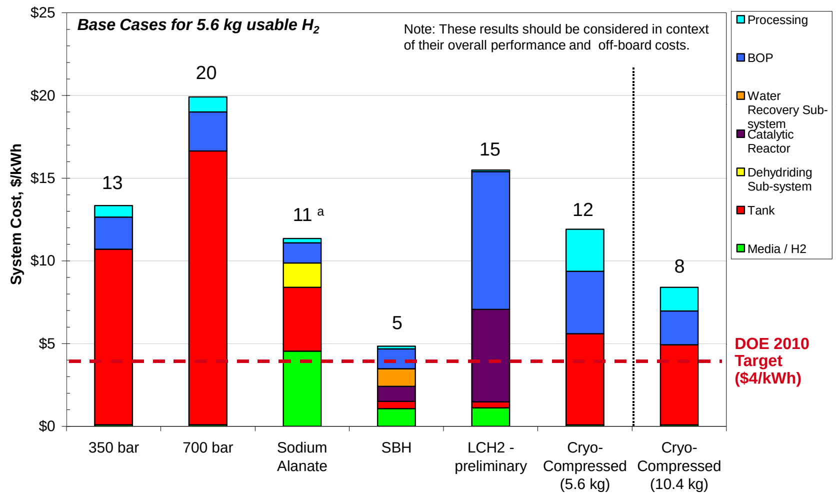
Note: not all hydrogen storage systems shown are at the same stage of development, and each would have different on-board performance characteristics.
[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

The volumetric capacities of both cryo-compressed systems also exceed the DOE 2010 volumetric target of 28 g H2/liter.



Note: not all hydrogen storage systems shown are at the same stage of development, and each would have different on-board performance characteristics.
[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

However, the base case cryo-compressed systems high-volume costs are projected to be 2-3 times more expensive than the current DOE 2010 cost target.

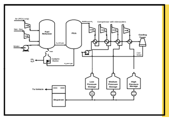


Note: not all hydrogen storage systems shown are at the same stage of development, and each would have different on-board performance characteristics.
[a] The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

Sections

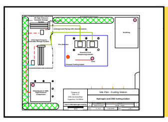
The off-board assessment makes use of existing models to calculate cost and performance for each technology on a consistent basis.

Conceptual Design



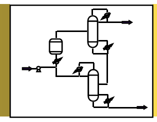
- System layout and requirements

Site Plans



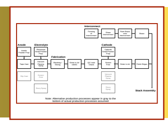
- Safety equipment, site prep, labor and land costs

Process Simulation



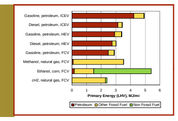
- Energy requirements
- Equipment size/specs

Capital Cost Estimates



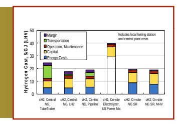
- High and low volume equipment costs

ANL/GREET Model



- WTT energy use
- WTT GHG

TIAX/H2A Model



- Equivalent hydrogen selling price

Cryo-compressed and compressed (350- and 700-bar) hydrogen off-board cost results were calculated using the base case delivery scenarios in HDSAM v2.06.

HDSAM Delivery Scenario Assumptions	350 and 700 bar Base Cases	Cryo-compressed Base Cases
Hydrogen Market	Urban	Urban
Market Penetration	30%	30%
City Selection	Indianapolis, IN (~1.2M people)	Indianapolis, IN (~1.2M people)
Central Plant H_2 Production Cost	\$1.50/kg H_2	\$1.50/kg H_2
Plant Outage/Summer Peak Storage	Geologic	Cryogenic liquid tanks
Transmission/Distribution Mode	Compressed gas pipeline	LH_2 tanker trucks (284 km round trip)
Transmission/Distribution Capacity	NA	4,100 kg LH_2
Refueling Station Size	1,000 kg H_2/day	1,000 kg H_2/day
Dispensing Temperature	350-bar = ambient (25ºC) 700-bar = -40ºC for fast fill	-253ºC
Dispensing Pressure	25% over-pressure for fast fill (up to 438 and 875 bar cH_2)	25% over-pressure for fast fill (up to 340 bar LH_2)
Hydrogen Losses	<1%	7.5% (0.5% each from liquefaction, storage and loading; 6% from unloading)
On-board Storage System	350 bar and 700 bar compressed gas	Cryogenic liquid and 272 bar compressed gas

The chemical hydride (i.e., SBH, LCH_2) off-board cost results were calculated using a modified version of the Delivery Components Carrier Model v34.

- Most financial assumptions are maintained from the original H2A Delivery Components Model
- New calculation tabs were added as part of the DOE Delivery Project for novel carriers, resulting in the H2A Deliver Components Carrier Model v34
  - Regeneration – calculates material regeneration costs based on capital and operating costs of a central plant and the storage capacity of the material
  - Storage Terminal – calculates required storage for fresh and spent materials
  - Trucking – calculates trucking costs for all novel carriers
  - Fueling Station – calculates fueling station costs for novel carrier storage and vehicle fueling
- These new calculation tabs were populated with inputs based on industry and developer feedback specifically for SBH (MCell, R&H)) and LCH_2 (APCI)
  - TIAX made initial estimates consistent with H2A methodology
  - Model and estimates were reviewed with developers
  - Model inputs and results were updated

"Ownership cost" provides a useful comparison metric that includes both on-board and off-board (i.e., refueling) costs on equal footing.

Simple Ownership Cost (OC) Calculation:

$$OC = \frac{PC \times DF \times Markup}{Annual\ Mileage} + \frac{FC}{FE}$$

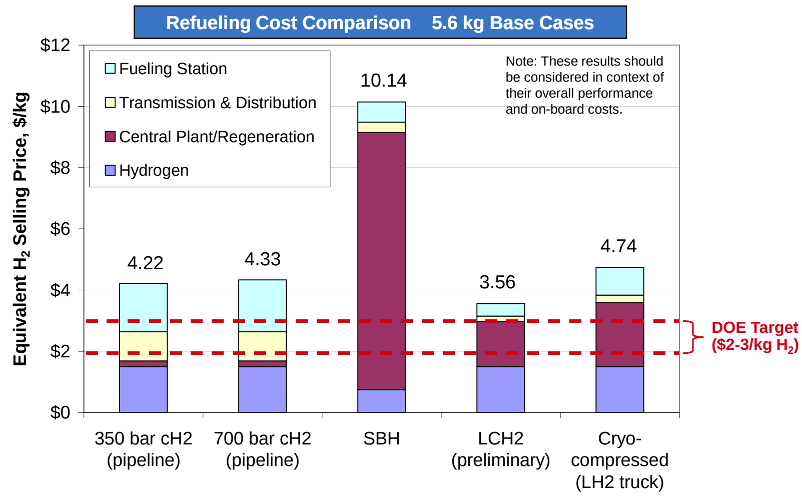
PC = Purchased Cost of the On-board Storage System
DF = Discount Factor (e.g., 15%)
FC = Fuel Cost of the Off-board Refueling System
FE = Fuel Economy (e.g., 62 mi/kg)

Ownership Cost Assumptions	Gasoline ICEV	Hydrogen FCV	Basis/Comment
Annual Discount Factor on Capital	15%	15%	Input assumption
Manufacturer + Dealer Markup	1.74	1.74	Assumed mark-up from factory cost estimates[1]
Annual Mileage (mi/yr)	12,000	12,000	H2A Assumption
Vehicle Energy Efficiency Ratio	1.0	2.0	Based on ANL drive-cycle modeling
Fuel Economy (mpgge)	31	62	ICEV: Car combined CAFE sales weighted FE estimate for MY 2007[2]
H_2 Storage Requirement (kg H_2)	NA	5.6	Design assumption based on ANL drive-cycle modeling

[1] Source: DOE, "Effects of a Transition to a Hydrogen Economy on Employment in the United States", Report to Congress, July 2008
[2] Source: U.S. Department of Transportation, NHTSA, "Summary of Fuel Economy Performance," Washington, DC, March 2007

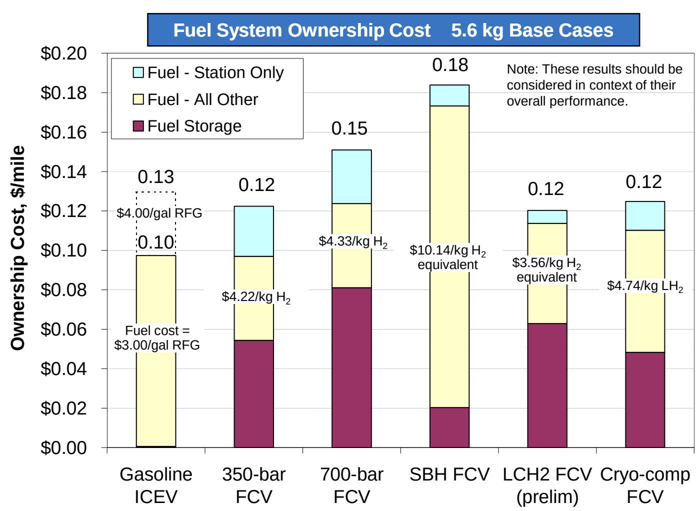
The implicit assumption in this ownership cost assessment is that each fuel system and vehicle perform equally well and have the same operating lifetime.

The cryo-compressed system refueling costs are projected to be 1.5-2.5 times more expensive than the current DOE target range.



Note: 350 bar, 700 bar and cryo-compressed results were calculated using the base case delivery scenarios in HDSAM v2.06. SBH and LCH_2 results were calculated using a modified H2A Delivery Components Carrier Model v34. All fuel costs exclude fuel axes.

Fuel system ownership cost for the base case cryo-compressed system is projected to be 20-30% more expensive than gasoline at $3.00/gal.



Note: All fuel costs exclude fuel taxes.

Although on-board storage system weight and volume targets will likely be met, costs are still significantly higher than the current targets.

- Gravimetric and volumetric H_2 storage capacities of the system meet or exceed both the DOE 2010 (4.5 wt% and 28 g/L) and 2015 targets (5.5 wt% and 40 g/L)
- Factory costs of the on-board storage systems are 2-3 times the current DOE 2010 cost target based on assumptions considered to be most likely to be applicable
  - Scaled Gen-3 system (5.6 kg) = $12/kWh energy content of the stored H_2
  - Prototype Gen-3 system (10.4 kg) = $8/kWh energy content of the stored H_2
- Factory costs will likely range (95% confidence) between $11.4 and $15.8/kWh for the 5.6 kg system and between $7.57 and $10.7/kWh for the 10.4 kg system
- Refueling costs based on LH_2 delivery and high pressure LH_2 dispensing, are projected to be 1.5-2.5 times more expensive than the DOE cost target of $2-3/kg
- Ownership cost for the 5.6 kg system will likely be about 20-30% (2-3 ¢/mi or $250-350/yr) higher than a conventional gasoline ICEV when gasoline is $3.00/gal
  - Ownership costs would be comparable at a gasoline price of ~$4.00/gal

When on-board and off-board costs are combined, the cryo-compressed system has potential to have similar ownership costs as a gasoline ICEV.

Note: All fuel costs exclude fuel taxes.

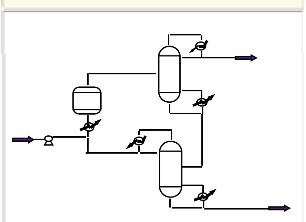
Sections

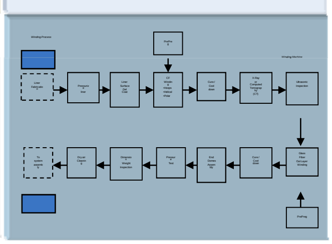
The on-board cost and performance analyses are based on detailed technology assessment and bottom-up cost modeling.

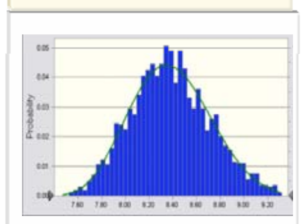
Technology Assessment
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Design Assumptions
- Obtain Developer Input

Cost Model and Estimates
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Processing Costs
- Develop Bulk Cost Assumptions

Overall Model Refinement
- Obtain Developer and Industry Feedback
- Revise Assumptions and Model Inputs
- Perform Sensitivity Analyses (single and multi-variable)







BOM = Bill of Materials

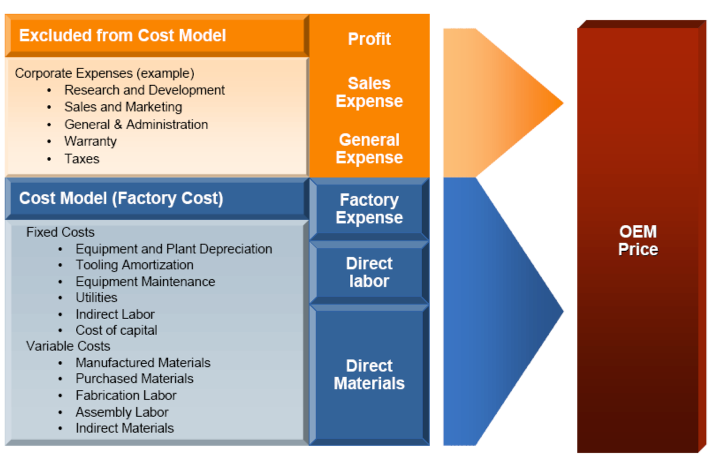
The cost of capital equipment, buildings, labor, utilities, etc. are included in our processing cost assessments.

- Variable Cost Elements
  - Material
  - Direct Labor
  - Utility
- Operating Fixed Costs
  - Tooling & Fixtures
  - Maintenance
  - Overhead Labor
  - Cost of Operating Capital →
- Non-Operating Fixed Costs
  - Equipment
  - Building
  - Cost of Non-Operating Capital →

- Working Capital
  - Including materials, labor, utility, tooling and maintenance cost
  - Working capital period: 3 months
- Equipment
- Building

We assume 100% debt financed with an annual interest rate of 15%, 10-year equipment life, and 25-year building life.

The cost model estimates system cost up to and including factory cost.



Profit, sales and general expenses are not included in the on-board system cost analysis consistent with other DOE cost analyses of PEMFC technology.

Tank end dome shape and carbon fiber thicknesses are based on ANL's latest performance analysis, which uses a composite pressure vessel algorithm.[1]

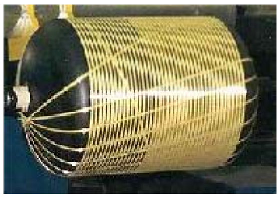
- Combination of geodesic and hoop windings assumed, with only geodesic windings on the end domes
- Non-uniform end dome thickness; thickest at dome peak (exit hole)
- Model yields carbon fiber weight calculations consistent with Quantum's models for compressed hydrogen (i.e., 350 and 700 bar) storage tanks
- Tank safety factor applied to the *nominal* tank pressure (i.e., 272 bar)
- Carbon fiber composite tensile strength assumed to be 2,550 MPa based on T700S Technical Data Sheet (Torayca® 2009)

[1] "Mechanics and Analysis of Composite Materials", Vasiliev and Morozov, New York: Elsevier Science, 2001

Fiber filament winding time is determined by the actual winding time plus setup time. Filament winding is an inherently slow process.

Tf = (Mf / Mu) / S / Ns / Nt + Ts

Tf: Actual winding time (min)
Mf: Carbon fiber weight (g)
Mu: Carbon fiber mass per unit length (g/1000m)
S: Winding speed (m/min)
Ns: Number of spindles
Nt: Number of tows
Ts: Setup time



Winding Process

Winding Machine

We assume the system manufacturer purchases pre-impregnated (i.e., "prepreg") carbon fiber composite as apposed to raw carbon fiber.

- We assume the system manufacturer purchases pre-impregnated (i.e., "prepreg") carbon fiber composite at a price that is 1.27 (prepreg/fiber ratio) times higher than the raw carbon fiber material (Du Vall 2001)
- An alternative approach would be to assume a wet resin winding process that would allow the purchase of raw carbon fiber material instead of buying prepreg tow fiber
- We selected the prepreg winding process based on the assumption that it results in greater product throughput and reduced environmental hazards (including VOCs, ODCs, and GHG emissions) compared to a wet winding process
  - According to Du Vall (2001), greater throughput is typically achieved because prepreg tow allows for more precise control of resin content, yielding less variability in the cured part mechanical properties and ensuring a more consistent, repeatable, and controllable material compared to wet winding
  - In addition, wet winding delivery speeds are limited due to the time required to achieve good fiber/resin wet out
  - The downside is that the prepreg raw material costs are higher than for wet winding
- It might be possible to reduce the overall manufactured cost of the composite, perhaps closer to the cost per pound of the carbon fiber itself ($13/lb) or ever lower (since the resin is cheaper per pound), if the wet winding process is proven to be more effective
  - A detailed evaluation that is required to explore these cost trade-offs is beyond our scope of work
  - Instead, we address the potential for lower carbon fiber composite costs in the sensitivity analysis

We developed BOP cost projections for high-volume production using the Delphi method with validation from Top-down and Bottom-up estimates.

- Delphi Method: Projections from industry experts, including suppliers, tank developers, and end users
  - End users (i.e., automotive OEMs) and, to some extent, tank developers, are considering the issue of automotive scale production
  - In some cases, end-user or developer estimates are optimistic or based on reasonable targets; in other cases estimates may be pessimistic by not taking into account process or technology changes that would be required for automotive-scale production
  - We used our judgment based on input from industry experts and results from Top-Down and Bottom-Up estimations to select a reasonable base case cost for each component
- Top-Down: High-volume discounts applied to low-volume vendor quotes using progress ratios
  - Provides a consistent way to discount low-volume quotes
  - Attempts to take into account process or technology developments that would be required for automotive-scale production
  - Requires an understanding of current base costs, production volumes, and markups
- Bottom-Up: Cost Modeling using DFMA® software
  - Calculates component costs using material, machining, and assembly costs, plus an assumed 15% markup for component supplier overhead and profit
  - May not be done at the level of detail necessary for estimating the true manufactured cost

In the top-down approach, we assume a progress ratio (PR) of 80% to determine the various discount factors based on lower-volume vendor quotes.

Equation to project high-volume cost using progress ratio (PR):

High Vol Cost = Current Cost * [High Prod Vol / Current Prod Vol]^(ln PR/2)

Illustration showing discount factors for various PRs and production volume assumptions:

High Production Volume, units/yr = 500,000 basis for cost assessment
Current Cost = $ 100 for illustration

Current Production Volume, units/yr = 10

Progress Ratio	75%	80%	85%
High Volume Cost, $	$ 1.12	$ 3.07	$ 7.91
High Volume Discount Factor	99%	97%	92%

Current Production Volume, units/yr = 1,000

Progress Ratio	75%	80%	85%
High Volume Cost, $	$ 7.58	$ 13.52	$ 23.29
High Volume Discount Factor	92%	86%	77%

Current Production Volume, units/yr = 100

Progress Ratio	75%	80%	85%
High Volume Cost, $	$ 2.92	$ 6.44	$ 13.57
High Volume Discount Factor	97%	94%	86%

Current Production Volume, units/yr = 10,000

Progress Ratio	75%	80%	85%
High Volume Cost, $	$ 19.72	$ 28.38	$ 39.96
High Volume Discount Factor	80%	72%	60%

If we assume 80% PR is appropriate, then we should use roughly:
~95% discount factor for components with current volumes in the 10's units/yr
~90% discount factor for components with current volumes in the 100's units/yr
~80% discount factor for components with current volumes in the 1,000s units/yr

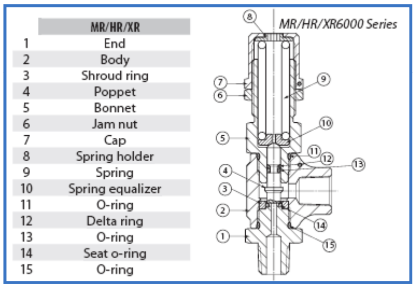
An 80% PR implies that the product cost has the potential to be reduced by 20% for every doubling of production volume.

Industry feedback was that the our top-down approach provided good cost projections for 80% of the BOP components.

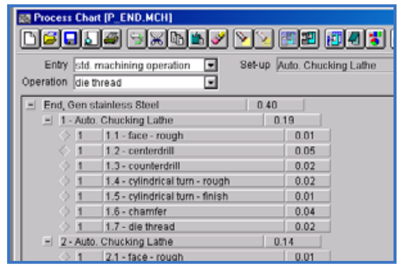
Purchased Component Cost Est.	Top-down Estimate	Vendor Cost for Highest Prod Vol	Vendor Highest Prod Vol Quote	Assumed Discount Factor	Comments/Basis
Pressure regulator	$258	$430	100,000	40%	Quotes and discussion with Emerson Process Management/ Tescom/ Northeast Engineering (2009)
Control valve	$37	$740	25-50	95%	Quotes and discussion with Circle Seal (2009); vendor estimates high-volume cost to be $150
Pressure transducer	$64	$1,060	100	94%	Quotes and discussion with Taber Industries (2009); unlikely that this particular "laboratory" configuration will be used if the project moves into quantities beyond a dozen or so prototype systems
Vacuum pressure transducer	$40	$285	1,000	86%	Quotes and discussion with MDS (2009)
Pressure relief valve	$94	$670	1,000	86%	Quotes and discussion with Flow Safe (2009); subtracted out costs associated with connection and 2-piece body; 316 SS, ASME certification, and large orifice may not be needed
Level sensor (in tank)	$56	$400	1,000 (est.)	86%	Discussion with tank developers (2009)
Pressure gauge (in engine feed zone)	$17	$60	10,000+	72%	Quotes and discussion with Emerson Process Management/ Tescom/ Northeast Engineering (2009); 316 SS may not be needed
Boss and plug (in tank)	$15	$500	10	97%	Discussion with tank developers (2009)
Pressure relief valve (in engine feed zone)	$14	$225	100	94%	Quotes and discussion with Swagelok (2009) for 316 SS part; brass cryogenic relief valves from McMaster are $40
Rupture disc	$1	$41	10	97%	Quotes and discussion with Continental Disc/ DL Equipment (2009); assumed to be simple part that could potentially be stamped directly on system at high production volumes

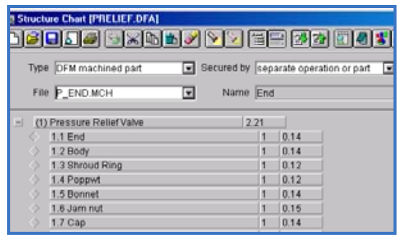
In the bottom-up approach, DFMA® software was used to estimate component costs based on material, machining, and assembly costs.

Example: Pressure Relief Valve



R6000 series pressure relief valve from Circle seal controls, inc.





We applied mark-ups because the BOP components modeled were based on a lower pressure and higher temperature system (i.e., Sodium Alanate)

- 25% markup to account for the increased pressure requirements of the cryo-compressed system (272 bar versus 150 bar)
- 50% markup to account for the cryogenic temperature requirement

Our bottom-up approach was based on DFMA® cost model results or material cost estimates with projected mark-ups.

Purchased Component Cost Est.	Bottom-up Estimate (w/ markup)	Cost Model Result	Comments/Basis
Fill tube/port	$20	$9	Quick connect for single flow only, must prevent air / water from entering; 115% markup (1.15 supplier, 1.25 pressure, 1.5 low temp factor)
Pressure regulator	$63	$29	1,500 psi max to < 30 psi delivery pressure; 115% markup (1.15 supplier, 1.25 pressure, 1.5 low temp factor)
Pressure relief valve	$28	$13	2,000 psi max; 115% markup (1.15 supplier, 1.25 pressure, 1.5 low temp factor)
Boss and plug (in tank)	$14	NA	Based on Al raw material price of $10/kg, marked up 100% for processing
Fittings and pipe	$14	NA	Based on SS304 raw material price of $4.7/kg, marked up 50% for processed parts
Mounting brackets	$6	NA	Based on standard steel raw material price of $1/kg
Wire	$5	NA	Based on copper raw material price of ~$7/kg, marked up 50% for wire processing

We projected the cost of the miscellaneous BOP components using a combination of industry feedback, top-down and bottom-up estimates.

Purchased Component Cost Est.	Rating	Base Cases ($ per unit)	Comments/Basis
Pressure relief valve (in engine feed zone)	250 psi cH_2	$14	Based on quotes from Swagelok (2009)
Fittings and pipe	350 bar, cryogenic H_2	$14	Based on SS304 raw material price marked up for processing
Communication interface	NA	$13	Industry feedback; thermally isolated comms interface
Getter (in vacuum space)	10^{-5} Torr vacuum	$13	Industry feedback; 25 psi MAWP
Mounting brackets	NA	$6	Based on standard steel raw material price of $1/kg
Wire	NA	$5	Based on copper raw material price marked up for processing
Evacuation port (in tank)	10^{-5} Torr vacuum	$5	Industry feedback; 25 psi MAWP
Rupture disc	350 bar, cryogenic H_2	$1	Based on quotes from Continental Disc/DL Equipment (2009)

We developed low and high estimates for key processing cost assumptions for input to the sensitivity analysis.

Processing Cost Assumptions	Low	Base Cases	High	Comments/Basis
Ex-vessel Assembly Time (lows)	15	30	60	Discussions with tank developers (2007); assumes 5 laborers
Vacuum Processing Time (lows)	360	720	1440	Discussion with tank developers (2007); assumes 1 laborer for 10 tanks
MLVI Assembly Time (lows)	30	60	120	Discussions with tank developers (2007); assumes 2 laborers
Inner Tank Assembly Time (lows)	15	30	60	Discussions with tank developers (2007); assumes 2 laborers
Vacuum Space Piping Assembly Time (lows)	15	30	60	Discussions with tank developers (2007); assumes 2 laborers
Final Inspection Time (lows)	15	30	60	Discussions with tank developers (2007); assumes 1 laborers
# Tows in the CF Winding	6	12	24	Discussions with tank developers (2007)
Filament Winding Speed (m/low)	15	30	60	Discussions with tank developers (2007)
Filament Winding Machine Cost ($1,000s)	150	200	300	Discussions with tank developers (2007)

In addition to fuel system ownership cost, we can also look at the overall vehicle ownership cost, where the vehicle purchased cost is included.

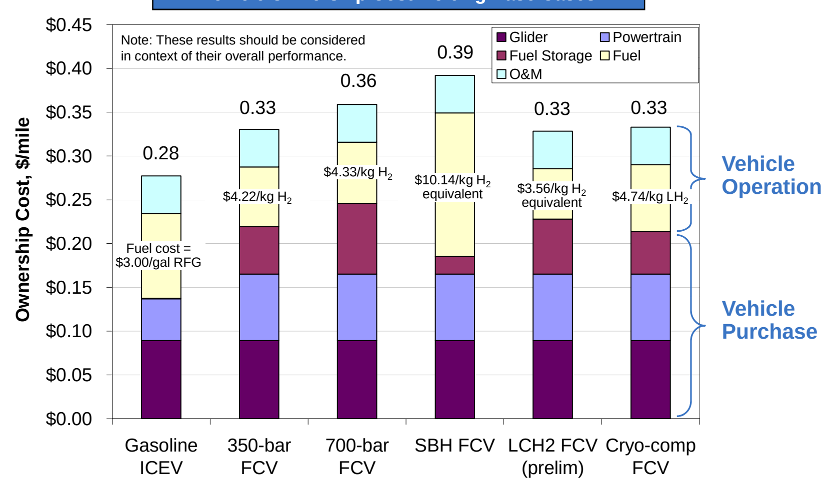
Vehicle Cost Assumptions[1]	Gasoline ICEV	Hydrogen FCV	Basis/Comment
Glider	$7,148	$7,148	Group of components (e.g., body, chassis, suspension) that will not undergo radical change
IC Engine/Fuel Cell Subsystem	$2,107	$2,549	Includes engine cooling radiator
Transmission, Traction Motor, PE	$1,085	$1,264	Includes electronics cooling radiator
Exhaust, Accessories	$500	$500	Assumes exhaust and accessories are $250 each
Energy Storage	$110	$1,755	Includes battery hardware, acc battery and energy storage cooling radiator
Fuel Storage	$51	$4,328 [a]	H_2 storage cost from On-board Cost Assessment
Manufacturing/ Assembly Markup	$5,500	$7,045	OEM manufacturing cost is marked up by a factor of 1.5 and a dealer mark-up of 1.16
Dealer Markup	$2,690	$3,445	
Total Retail Price	**$19,191**	**$28,034**	

[a] Fuel Storage cost for the Hydrogen FCV option assumes 350 bar compressed hydrogen on-board storage system at $13/kWh.
[1] Source: DOE, "Effects of a Transition to a Hydrogen Economy on Employment in the United States", Report to Congress, July 2008. All costs, except for the FCV Fuel Storage costs, are based on estimates for the Mid-sized Passenger Car case. See report for details.

Vehicle cost estimates assume that all FCV components, except the fuel storage system, meet DOE's cost goals for 2015 and beyond.[1]

When the whole vehicle is included, and using an O&M cost of $0.043/gge for all cases, the 5.6 kg cryo-compressed FCV ownership cost will likely be 20% higher than a conventional gasoline ICEV when gasoline is $3/gal.

Vehicle Ownership Cost 5.6 kg Base Cases



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