Technical Assessment of Organic Liquid Carrier Hydrogen Storage Systems for Automotive Applications

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Executive Summary

In 2007-2009, the DOE Hydrogen Program conducted a technical assessment of organic liquid carrier based hydrogen storage systems for automotive applications, consistent with the Program's Multiyear Research, Development, and Demonstration Plan. This joint performance (ANL) and cost analysis (TIAX) report summarizes the results of this assessment. These results should be considered only in conjunction with the assumptions used in selecting, evaluating, and costing the systems discussed here and in the Appendices.

Organic liquid carriers (LC) refer to a class of materials that can be reversibly hydrogenated in large central plants using established industrial methods with high efficiency through recovery and utilization of the heat liberated in the exothermic hydrogenation reaction [1, 2]. The hydrogenated carrier (LCH_2) is delivered to the refueling station for dispensing to the vehicles. On demand, hydrogen is released from LCH_2 in a catalytic reactor on-board the vehicle and the liquid carrier (LC) is recycled to the central plant for rehydrogenation. The challenge has been to find suitable organic carriers that have sufficient hydrogen capacity, optimal heat of reaction (ΔH), rapid decomposition kinetics, low volatility and long cycle life, and that remain liquid over the working temperature range. Air Products and Chemicals Inc (APCI) investigated many candidates for potential liquid carriers but no one material could satisfy all the requirements for a viable hydrogen storage system.

We based our assessment of liquid organic carriers on N-ethylcarbazole ($C_{14}H_{13}N$), an early APCI candidate molecule, recognizing that a practical storage system cannot be built with this polycyclic aromatic hydrocarbon. The assessment, however, does show the potential of meeting the storage targets with other yet-undiscovered organic liquid carriers that may have the right properties. We analyzed an LCH_2 hydrogen storage system with a capacity of 5.6-kg usable H_2 for its potential to meet the DOE 2010, 2017, and ultimate hydrogen storage targets for fuel cell vehicles [3]. The analysis assumed Year 2009 technology status for the major components and projected their performance in a complete system. The analysis also projected the system cost at production volumes of 500,000 vehicles/year. The presentations by Argonne and TIAX describing their analyses in detail are given in Appendices A and B, respectively. Key findings are summarized below.

On-board Assessments

We developed a trickle-bed reactor model for on-board release of hydrogen from perhydro N-ethylcarbazole ($C_{14}H_{19}N$) and validated the model against APCI's test data. We also developed a model for the on-board hydrogen storage system and evaluated the potential performance of the system with respect to storage capacity and efficiency. Figure 1 shows a schematic of the fuel cell system with organic liquid carrier hydrogen storage. The system includes a circuit with an oil-based heat transfer fluid and a combustor to supply the ΔH for thermal decomposition of perhydro N-ethylcarbazole. It shows one method of integrating the storage system with the fuel cell system by controlling the hydrogen utilization in such a manner that the thermal energy needed for the dehydrogenation reaction is provided by burning the remaining hydrogen with the spent cathode air. Waste heat from the fuel cell stack (or an internal combustion engine power plant) cannot be used for this purpose because hydrogen desorbs rapidly from N-ethylcarbazole only at a temperature (>200°C) higher than the temperature at which the waste heat is available.

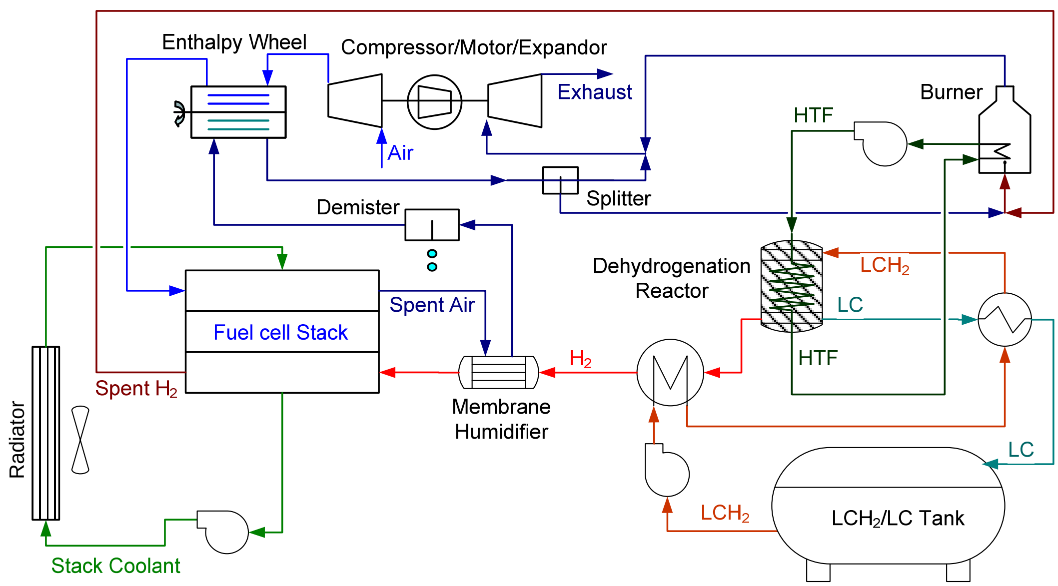

Figure 1 Automotive fuel cell system with organic liquid carrier hydrogen

Our analysis showed that a dehydrogenation reactor with a pelletized, palladium (Pd) on lithium aluminate catalyst produces unacceptably low conversions of the hydrogenated organic liquid carrier due to mass transfer resistances through the pore structure. To achieve conversions >95%, a compact on-board dehydrogenation reactor will likely require dispersing the catalyst on a high surface area support and operating the reactor at a liquid hourly space velocity (LHSV) >20 h^{-1}. To power an 80-kW_e fuel cell system using perhydro N-ethylcarbazole ($\Delta H \approx 51$ kJ/mole H_2), the reactor needs to produce 2.4 g/s of H_2, of which 1.6 g/s is electrochemically oxidized in the fuel cell system, and 0.8 g/s is burned to provide the thermal energy needed for the dehydrogenation reaction.

For N-ethylcarbazole (material capacity of 5.8- wt% H_2), the system-level storage capacities are 4.4 wt% and 35 g-H_2/L (on a stored H_2 basis), which translate to 2.8 wt% and 23 g/L of usable hydrogen (hydrogen converted to electricity in the fuel cell). These usable storage capacities fail to meet the 2010 targets of 4.5 wt% and 28 g/L.

Our system analysis is based on a volume-exchange tank with a flexible bladder to separate the fresh and spent fuels. Although this concept appears feasible, it has not been demonstrated in practice. We have assumed that an organic liquid carrier with a melting point lower than -40^{o}C will be found so that the fuel and the carrier remain liquid at all ambient conditions. N-ethylcarbazole, however, melts between 66 and 70^{o}C and would require that the tank be heated to prevent solidification. The downflow trickle-bed reactor configuration is likely inappropriate for use on-board vehicles. It would be desirable to build and analyze a compact horizontal flow reactor taking advantages of the recent developments in microchannel heat exchanger technology. Similarly, a more active, robust, non-precious metal catalyst is needed to achieve complete conversion at space velocities exceeding 120 h^{-1}.

The results from our "reverse engineering" analyses suggest that the on-board storage inefficiency can be largely eliminated if we had a liquid carrier with $\Delta H < 40$ kJ/mol and a catalyst that allows rapid dehydrogenation at temperatures below the temperature at which the waste heat is available from the fuel cell stack. The carrier would also need to have a material capacity >7.5-8 wt% H_2 for the storage system to satisfy the 2017 DOE targets of 5.5 wt% gravimetric and 40 g/L volumetric capacities. The intrinsic material capacity would need to be >11 wt% H_2 to meet the ultimate system target of 7.5 wt%.

Table 1 Summary results of the assessment for organic liquid carrier based hydrogen storage systems compared to DOE targets

Performance and Cost Metric	Units	LCH_2	DOE Targets		
			2010	2017	Ultimate
System Gravimetric Capacity	wt%	2.8	4.5	5.5	7.5
System Volumetric Capacity	g-H_2/L	23.0	28	40	70
Storage System Cost	$/kWh	15.7	TBD	TBD	TBD
Fuel Cost	$/gge*	3.27	3-7	2-6	2-4
WTE Efficiency (LHV)**	%	43.3	60	60	60

*gge: gallon gasoline equivalent

**Lower heating value

The results of the cost assessment showed that the LCH_2 on-board storage system will cost $15.7/kWh. The main contributor to the onboard system cost was the dehydrogenation reactor, which accounted for nearly 40% of the total system cost. In turn, the dehydrogenation reactor cost was primarily driven by the cost of the palladium catalyst. Other high cost components include pumps, the burner, and the LCH_2 medium itself. The results from multi-variable sensitivity analysis indicated a likely range of \$14 to \$21.5/kWh. Detailed cost results are presented in the Appendix B. The system capacities and cost results are compared to the DOE targets in Table 1.

Off-board Assessments

We constructed a flowsheet for rehydrogenation of N-ethylcarbazole in multi-stage, catalytic, trickle-bed reactors, with regenerative intercooling between the stages to achieve a declining temperature profile. Hydrogen is introduced at multiple quench locations within each stage of a reactor to maintain a nearly isothermal temperature profile. In this manner, H_2 far in excess of the stoichiometric amount (15-21 times, depending on the number of stages) is used to absorb the heat of reaction. The excess H_2 is recovered downstream of the final stage, recompressed, mixed with compressed makeup H_2, and recycled. We considered two scenarios, one in which the heat of reaction is discarded as low-grade waste heat and the second in which an organic Rankine cycle system is used to produce electricity from the waste heat (~1 kWh/kg-H_2 in the liquid carrier).

We estimated that the LCH_2 option has one of the highest well-to-tank (WTT) efficiencies of all hydrogen storage options since regeneration of perhydro N-ethylcarbazole is an exothermic process. The WTT efficiency can be higher than 60% if the waste heat liberated in rehydrogenation can be used to co-produce electricity via the organic Rankine cycle. Our analysis showed that the well-to-engine (WTE) efficiency is 43.3% taking into account the ~68% efficiency of the on-board storage system (i.e., 32% of H_2 produced is burned on-board to provide the dehydrogenation heat of reaction).

The off-board refueling cost of the LCH_2 system was projected to be \$3.27, meeting the 2010 and 2017 targets, as well as the ultimate target of \$2-4/kg. In contrast to the on-board system, sensitivity analysis suggested that there are several viable pathways to reducing the off-board refueling cost. These cost reduction opportunities include reducing the cost of the carrier material, reducing hydrogen production costs, or reducing the size of the liquid carrier storage buffer at the regeneration facilities.

Using a series of simplified economic assumptions, the off-board cost estimated was combined with the on-board system base case cost projection of \$15.7/kWh H_2 to calculate the fuel system ownership cost on a per-mile basis. The results projected an ownership cost of \$0.12/mile for the LCH_2 system. Slightly more than half of this cost was due to the amortized purchased cost of the on-board storage system; the remainder was due to the off-board refueling cost. This projected ownership cost for the LCH_2 system may be compared with about \$0.10/mile for the fuel costs of a conventional gasoline internal combustion engine vehicle (ICEV) when gasoline is at \$3.00/gal, untaxed.

References

1. Cooper, A. and Pez, G., "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers," APCI, 2007 DOE H_2 Program Review, May 2007.

2. Toseland, B. and Pez, G., "Reversible Liquid Carriers for an Integrated Production, Storage and Delivery of Hydrogen," APCI, 2008 DOE H_2 Program Review, June 2008.

3. "Targets for onboard hydrogen storage systems for light-duty vehicles," US Department of Energy, Office of Energy Efficiency and Renewable Energy and The FreedomCAR and Fuel Partnership, Revision 4.0, p. 9, Sep. 2009.

APPENDIX A

Performance Assessment of Organic Liquid Carrier Hydrogen Storage Systems

On-Board Hydrogen Storage Systems for Liquid Carriers

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September 2007

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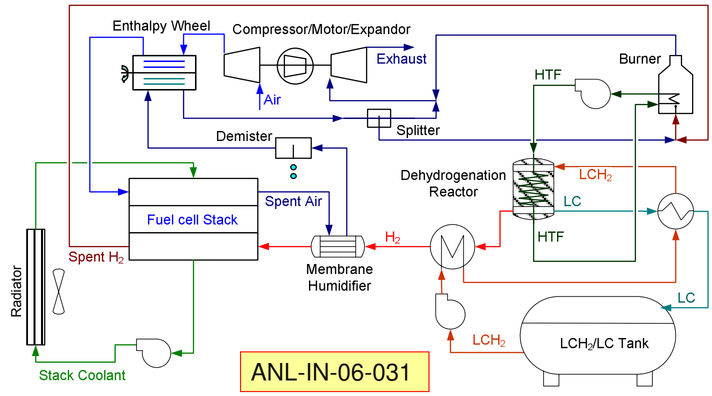
On-Board Hydrogen Storage Systems for Liquid Carriers

Objective: To determine the performance of the on-board system relative to the storage targets (capacity, efficiency, etc)

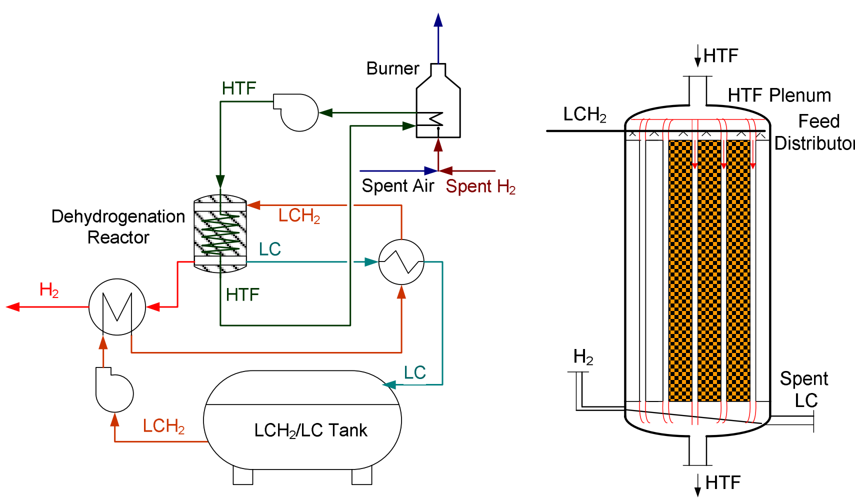
1. On-Board System Configuration
2. Dehydrogenation Reactor
   - Dehydrogenation kinetics
   - Trickle bed hydrodynamics
   - Dehydrogenation reactor model
   - Reactor performance with pelletized and supported catalysts
3. System Performance
   - Storage efficiency
   - Storage capacity

Fuel Cell System with H_2 Stored in a Liquid Carrier: Argonne FCS-HTCH

- Once-through anode gas system with controlled H_2 utilization
- Burner uses depleted air split-off from spent cathode stream
- Burner exhaust expanded in gas turbine to recover additional power



Argonne HTCHS: High-Temperature Chemical Hydrogen Storage System

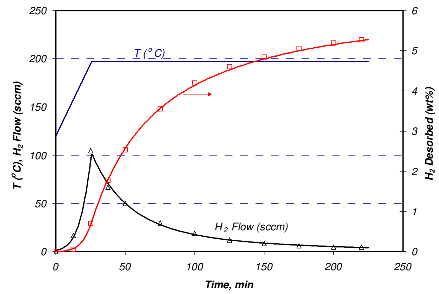


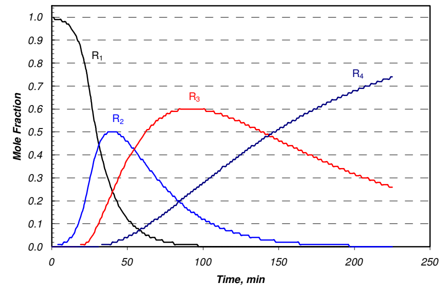
Argonne HTCHS

Dehydrogenation Reactor

Dehydrogenation Kinetics (Batch Reactor)

- Sequential reaction kinetics
  - $R_1 = R_2 + 2H_2$
    $R_2 = R_3 + 2H_2$
    $R_3 = R_4 + 2H_2$
- Kinetic constants from batch reactor data
  - APCI Patent US 2005/0002857
  - 8 g N-ethylcarbazole, 20-cc reactor volume
  - Powder catalyst: 0.2-g 4% Pd on Li aluminate
  - Heating from 50°C to 197°C at 3°C/min
  - P = 1 atm
  - 96% conversion: 5.6 wt% H_2





Trickle Bed Reactor Hydrodynamics Neural Network Model

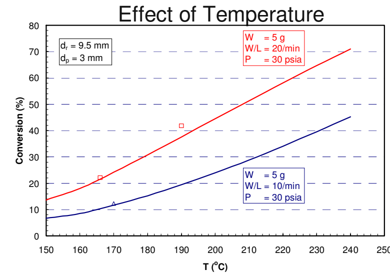
Parameter	Re_l	Re_g	Fr_l	Fr_g	We_l	X_l	X_g	St_l	St_g	Sc_l	Sc_g	Ga_l	Ca_l	Ca_g	Bi	Pe_l	Pe_g	$\rho_{g,l}$	α	$d_{p,r}$	Φ	ε
Slip factors: f_s, f_v	√	√	√		√	√		√														
Ergun constants: E_1, E_2																				√	√	√
Liquid-catalyst mass transfer coefficient	√	√						√		√		√							√			
Volumetric liquid-side mass transfer coefficient		√			√			√	√	√			√	√					√	√		
Volumetric gas-side mass transfer coefficient	√	√		√				√			√								√			
Liquid-wall heat transfer coefficient	√			√	√			√								√	√			√		
Bed radial thermal conductivity	√			√	√										√	√	√					
Wetting efficiency	√	√	√		√	√	√	√				√						√	√	√	√	√
Pressure drop	√	√			√	√						√							√			
Liquid holdup	√	√			√		√												√			

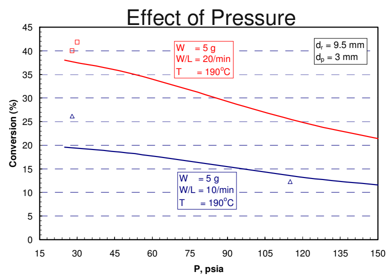
Re Reynolds number
Fr Froud number
We Weber number
X Lockhart-Martinelli number
St Stokes number
Sc Schmidt number
Ga Galileo number
Ca Capillary number
Pe Peclet number
Bi Biot number
ρ Density
α Bed correction factor
d_p Catalyst diameter
d_r Reactor diameter
Φ Sphericity factor
ε Void fraction
Subscripts:
l Liquid **g** Gas

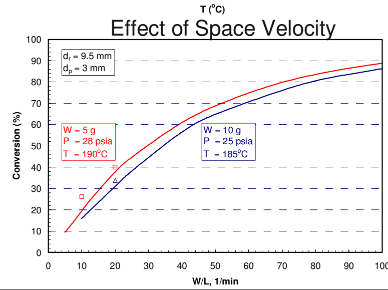
References: Ind. Eng. Chem. Res., 37 (1998), 4542-4550
Ind. Eng. Chem. Res. 42 (2003) 222-242
Chem. Eng. Sci., 54 (1999) 5229-5337

Tubular Trickle Bed Reactor Comparison with APCI Data

- Models written on GCtool platform
  - First-order kinetics with internal & external mass transfer
  - Trickle bed hydrodynamics
  - ODEs for T and species flow
- TBR data for 5% Pd on alumina catalyst, kinetic data for 4% Pd on Li aluminate







Conversion with Pelletized Catalysts

- Reactor Parameters
  - Pellet diameter = 3 mm
  - Bulk density = 800 kg/m^3
  - HX tube diameter = 3/8”
  - AL 2219-T81 construction
- Analysis Method

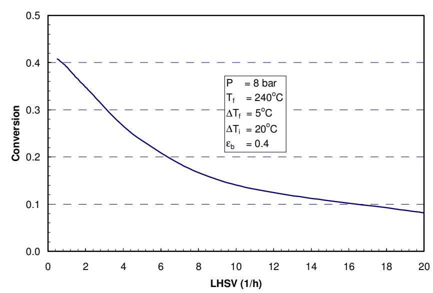
Variable	Constraint
LCH_2 flow rate	1.6 g/s[a] H_2 to FCS[b]
HTF flow rate	ΔT_f = 5°C
No. of tubes	Q = (Q_s + 61) kW[c]

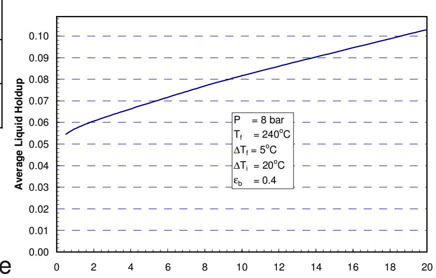
[A]2.4 g/s total H_2 for N-ethylcarbazole

[b]80-kWe FCS

[c]ΔH = 51 kJ/mol for N-ethylcarbazol

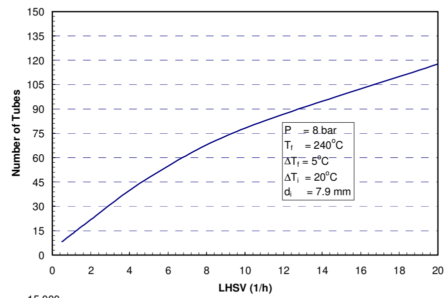
LHSV=volumetric flow rate/reactor volume

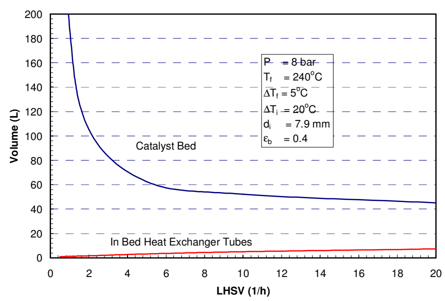


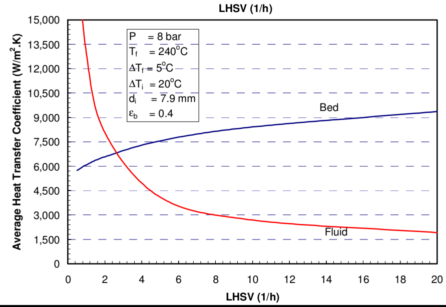


Heat Transfer

- Reactor size is not heat transfer limited
  - High h because of tube-side liquid flow and shell-side two-phase trickle flow
  - Can be a concern if the catalyst is very active







Conversion with Dispersed Catalyst

- Low conversion with pellets because of mass transfer limitations
  - Effectiveness factors for the three reactions: 0.08 - 0.3
- Marked improvement in catalyst effectiveness if supported on foam although the wetting efficiency decreases
  - 40-ppi Al-6101 foam, 92% porosity
  - 50-µm catalyst washcoat, 224 kg/m³ bulk density
  - Trickle flow on foam has not been demonstrated

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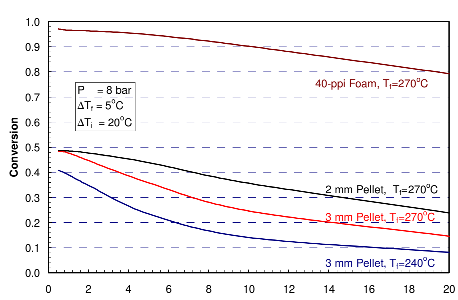
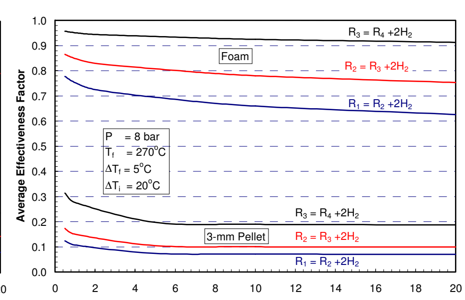
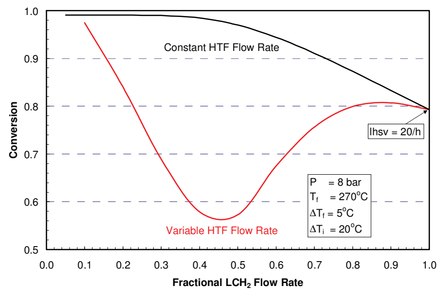
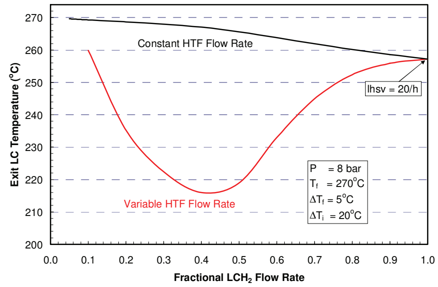




Part-Load Performance

- Higher conversion with constant HTF flow rate especially at low loads
- Transient performance
  - Actual conversion on a drive cycle may be higher or lower than the steady-state value
  - Response time
  - Pressure control?
  - Buffer storage?





Argonne HTCHS: System Analysis

Dehydrogenation Reactor
- T_R function of $P(H_2)$, conversion, ΔH, ΔS, and ΔT_{eq}
- Trickle flow, 20 h^{-1} LHSV
- Catalyst supported on 40-PPI foam
- HX tubes with 90° inserts
- AL-2219-T81 alloy, 2.25 SF
- 2 cm insulation thickness

Heat Transfer Fluid
- XCELTHERM ®
- 5°C ΔT in DeH2-HX, $T_{HTF} - T_R = 50$°C

HEX Burner
- Non-catalytic, spent H_2 and 5% excess spent air
- Counterflow microchannel, inconel
- 100°C approach temperature

H_2 Cooler
- LCH2 coolant, $T_{outlet} = T_{FC}$
- Counterflow, microchannel, SS

Recuperator
- LC/LCH2 HX, $T_{LCH2} = T_R - 10$°C
- Counterflow, microchannel, SS

LC Radiator
- $T_{LC} = 70$°C
- Integrated with FCS radiator
- W and V not included in HTCHS

LCH_2/LC Storage Tank
- Single tank design, HPDE construction
- 10-kg H_2 storage, 10% excess volume

Pumps
- HTF pressure head: 1 bar
- LCH2 pressure head: 8 bar

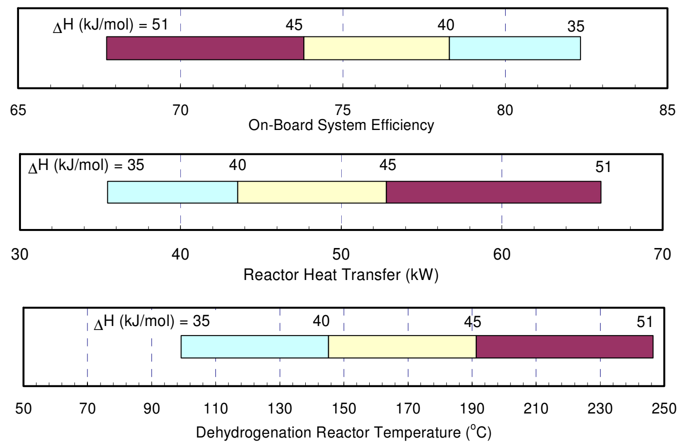
H_2 Separation
- Coagulating filter

H_2 Buffer Storage
- 20 g H_2 at 80°C, $P(H_2)$
- AL-2219-T81 alloy tank, 2.25 SF

Miscellaneous

On-Board Storage System Efficiency

- Storage system efficiency defined as fraction of H_2 librated in dehydrogenation reactor that is available for use in fuel cell stack
- Efficiency could be ~100% if $\Delta H < 40$ kJ/mol <u>and</u> $T_R < T_{FC}$



- LC: 0.95-1.2 g/cc, 5.8 wt% H_2
- 95% conversion
- DeH$_2$ LHSV: 20 h^{-1}
- ΔT_{eq}: 50°C
- Burner HX: 100°C approach T
- 2 g/s net H_2 output
- $P(H_2)$: 8 bar
- 0.8-1.4 kWe HTF pump
- Start-up energy not included

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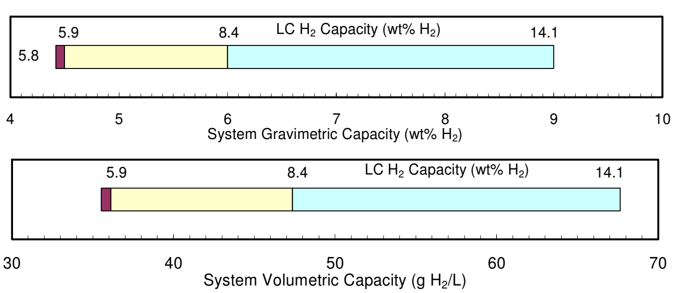
Reverse Engineering: H_2 Storage Capacity

- System capacity presented in terms of stored H_2
  - Recoverable H_2: 95% intrinsic material capacity (conversion)
  - Usable H_2 = Storage system efficiency x Recoverable H_2
- System capacity with N-ethylcarbazole: 4.4% wt% H_2, 35 g/L H_2 (H_2 stored basis); 2.8% wt% H_2, 23 g/L H_2 including losses
  - 95% conversion, 67.7% storage system efficiency



- LC: 0.95-1.2 g/cc
- LC tank: 10% excess volume
- ΔH_2 LHSV: 20 h^{-1}
- ΔT_{eq}: 50°C
- Burner HX: 100°C approach
- 2 g/s net H_2
- 20-g H_2 buffer
- $P(H_2)$: 8 bar

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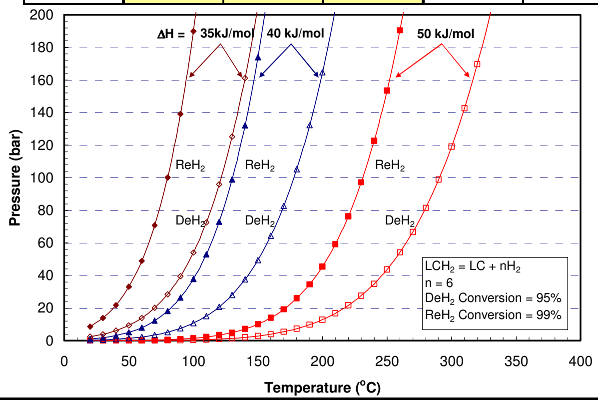
Need Catalysts Active at Low T and 35<ΔH<40 kJ/mol

Minimum DeH_2 and Maximum ReH_2 Temperatures

	DeH_2 Pressure			ReH_2 Pressure	
ΔH	3 bar	4 bar	8 bar	100 bar	200 bar
50 kJ/mol	151°C	160°C	183°C	231°C	262°C
40 kJ/mol	66°C	73°C	92°C	130°C	155°C
35 kJ/mol	24°C	30°C	46°C	80°C	102°C



Summary

1. Dehydrogenation reactor will need a supported catalyst
   - Desirable to have LHSV > 20 h^{-1} for >95% conversion
   - May need ΔT > 50°C for compact HX ($\Delta T = T_{HTF} - T_R$)
2. Need ΔH < 40 kJ/mol for >90% on-board storage efficiency
3. Material capacities to meet system storage targets

	System Capacity[a]	
Material Capacity	Gravimetric	Volumetric
wt% H_2	wt% H_2	g-H_2/L
5.8	4.4	35.1
5.9	4.5	36.1
8.4	6.0	47.4
14.1	9.0	67.6[b]

[a]Stored H_2 basis

[b]H_2 buffer has to decrease for 81 g/L volumetric capacity

WTT Efficiency and Greenhouse Gas Analysis of Hydrogen Storage with an Organic Liquid Carrier

T. Q. Hua and R. K. Ahluwalia

December 18, 2008

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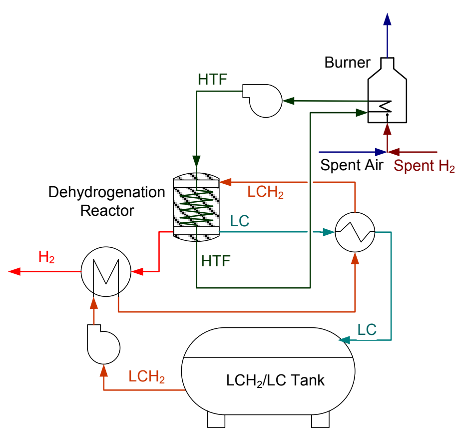
On-board Hydrogen Storage with Organic Liquid Carrier (N-ethylcarbazole)

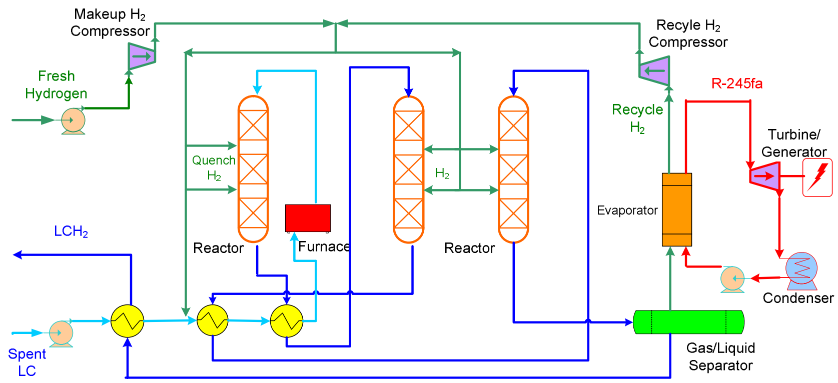
Reference: R. Ahluwalia, T. Hua, J-K. Peng and R. Kumar, "System Level Analysis of Hydrogen Storage Options," DOE Program review 2007, ST-31

- Dehydrogenation reactions are endothermic (Δh ~ 51 kJ/mole H_2)
  - $C_{14}H_{25}N \rightarrow C_{14}H_{21}N + 2H_2$
  - $C_{14}H_{21}N \rightarrow C_{14}H_{17}N + 2H_2$
  - $C_{14}H_{17}N \rightarrow C_{14}H_{13}N + 2H_2$
- Heat of reaction provided by burning a fraction of H_2 produced on-board
  - System storage efficiency = 68%
  - Need ΔH < 40 kJ/mol for >90% on-board storage efficiency
- Net gravimetric capacity = 2.8 wt%, net volumetric capacity = 23 g/L



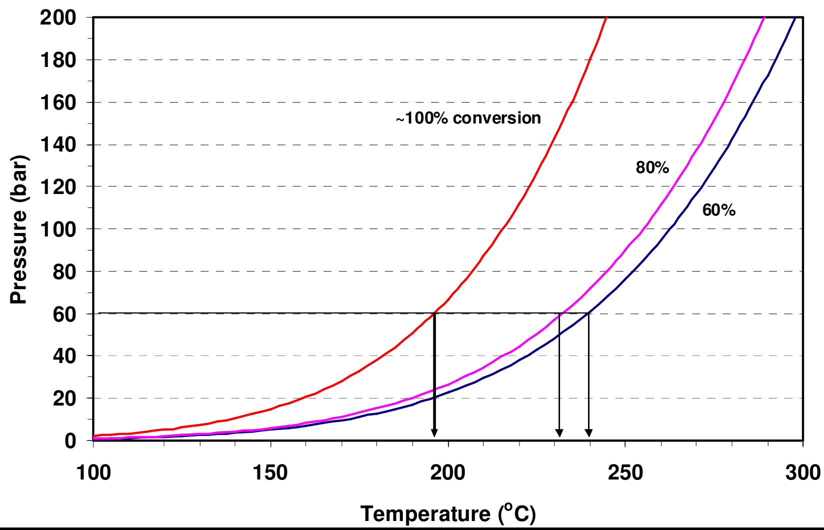
Off-board Regeneration

- Multi-stage hydrogenation reactors with declining T profile, H_2 quench, and inter-stage regenerative cooling
- Hydrogenation reactions are exothermic. Waste heat (~150 ^oC) can be recovered to produce low grade steam or electricity (Organic Rankine cycle)



Hydrogenation Operating Map

- Hydrogenation/dehydrogenation model validated with APCI's test data



Operating Conditions and Process Energy Consumption (Per kg H_2 hydrogenated in LC)

Parameter	1-Stage	3-Stage
Temperature, ^oC	196	240/232/196
Pressure, bar	60	60
Cumulative Conversion	1.0	0.6/0.8/1.0
H_2 Circulation Ratio	21.7	16.2
Electricity (H_2 compression), kWh	2.0	1.7
Thermal, MJ	0.8	0.8
Electricity (co-production), kWh	-0.9	-0.9

Primary Energy Consumption and WTT Efficiency (Per kg H_2 to Fuel Cell)

Process	Primary Energy (MJ)
H_2 Production by SMR	260
Hydrogenation of LC	29
Delivery	2
Electricity Co-production	-16
WTT Efficiency, %	43.2

Note: energy consumption and WTT efficiency include on-board system storage efficiency of 68%

FCHtool Analysis of Greenhouse Gas Emissions

- g/kg H_2 hydrogenated in LC

Process	VOC	CO	NO_x	PM10	SO_x	CH_4	N_2O	CO_2	GHGs
H_2 Production (SMR)	1.55	3.62	7.34	2.20	2.71	29.93	0.06	14,068	14,774
Regeneration	0.06	0.17	0.64	0.70	1.29	0.92	0.01	603	627
Delivery	0.01	0.03	0.02	0.01	0.02	0.03	0.00	21	22
Total	**1.6**	**3.8**	**8.0**	**2.9**	**4.0**	**30.9**	**0.1**	**14,692**	**15,423**

- g/kg H_2 delivered to fuel cell

Process	VOC	CO	NO_x	PM10	SO_x	CH_4	N_2O	CO_2	GHGs
H_2 Production (SMR)	2.28	5.35	10.84	3.25	4.01	44.21	0.09	20,780	21,823
Regeneration	0.08	0.25	0.94	1.04	1.90	1.36	0.01	891	926
Delivery	0.01	0.04	0.03	0.02	0.03	0.04	0.00	31	32
Total	**2.4**	**5.6**	**11.8**	**4.3**	**5.9**	**45.6**	**0.1**	**21,702**	**22,781**

APPENDIX B

Cost Assessment of Organic Liquid Carrier Hydrogen Storage Systems

Analyses of Hydrogen Storage Materials and On-Board Systems

H_2 Storage using a Liquid Carrier: Off-board and On-board System Cost Assessments

September 14, 2010

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TIAX has been engaged since 2004 in an ongoing effort to perform onboard and offboard analysis of hydrogen storage system costs

Technology Focus	2004-2007	2008-2010
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 • MOF-177
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.

Over the course of this project, we have evaluated on-board and off-board hydrogen storage systems for 11 storage technologies.

Analysis To Date		cH_2	Alanate	MgH_2	SBH	LCH_2	CcH_2	LH_2	AC	MOF-177	Cold Gas	AB
On-Board	Review developer estimates	√	√		√	√	√	√	√	√		
	Develop process flow diagrams/system energy balances (ANL lead)	√	√		√	√	√	√		√		
	Performance assessment (ANL lead)	√	√		√	√	√	√ *		√		
	Independent cost assessment	√	√		√	√	√	√ *	√*	√*		
Off-Board	Review developer estimates	√		√	√	√	√	√			√	√
	Develop process flow diagrams/system energy balances	√		√	√	√					√	√
	Performance assessment (energy, GHG)[a]	√			√	√					√	
	Independent cost assessment[a]	√			√	√		√			√	
Overall	Ownership cost projection[a]	√			√	√		√		√	√ *	
	Solicit input on TIAX analysis	√	√		√	√	√	√ *	√	√		
	Analysis update	√			√		√	WIP		WIP		

* Preliminary results under review.
[a] Work with SSAWG, ANL and SSAWG participants on WTT analysis.

[grey box] = Not part of current SOW
WIP = Work in progress

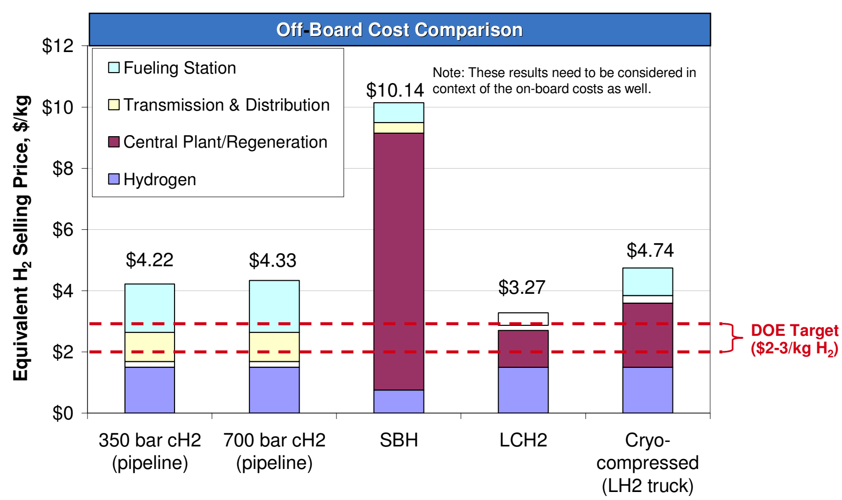
Executive Summary Overview

This report summarizes TIAX's assessment of the off-board fuel cost and the onboard high-volume (500,000 units/yr) manufactured cost of hydrogen storage systems using a liquid hydrogen carrier (LCH_2)

- **Scope:**
  - **Onboard LCH_2 Storage System:** Cost estimates for an onboard storage system using 5.8 wt% N-ethylcarbazole
  - **Off-board Fuel Costs:** Cost estimates for the price of hydrogen generated from steam-methane reforming of natural gas and transported in an N-ethylcarbazole liquid hydrogen carrier medium
- **Approach:**
  - Onboard cost analysis is based on an onboard system design developed by Argonne National Laboratory to meet critical performance criteria.
  - Onboard costs are projected from bottom-up estimate of raw material costs and manufacturing process costs, plus purchased components balance-of-plant components
  - Off-board cost estimates use a modified version of the H2A Components model to incorporate design parameters provided through discussions with industry

Executive Summary Off-board Assessment *Hydrogen Cost Comparison*

The results of this study project a liquid hydrogen carrier (LCH_2) fuel cost of \$3.27/kg H_2, close to the DOE target of \$2-3/kg H_2.



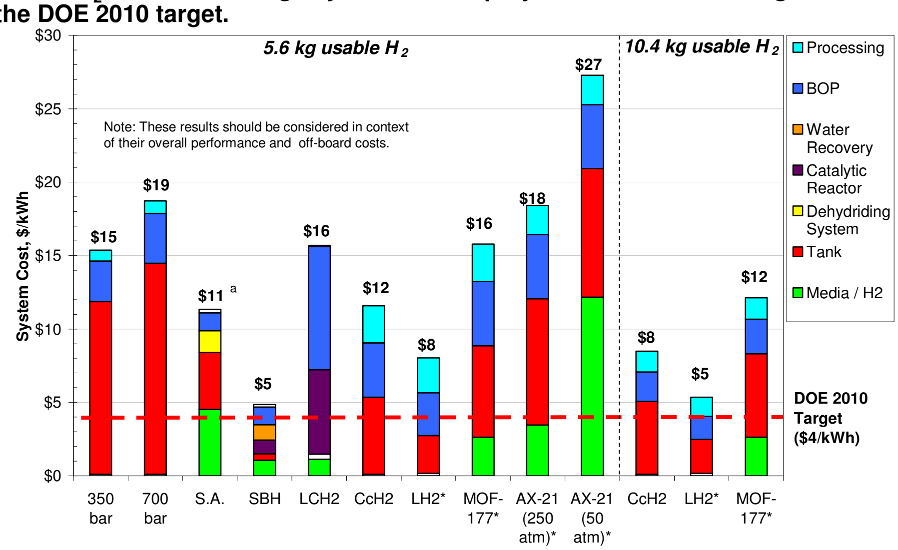
Note: See footnotes and details in the Off-board Cost Assessment section.

The LCH_2 fuel cost projection is lower cost than both compressed and cryo-compressed hydrogen fuel cost projections.

- The equivalent H_2 price from LCH_2 is 1.1-1.6 times more expensive than the DOE target, but it is 25 to 40% cheaper than cH_2 pipelines or cryo-compressed options
- Additional LCH_2 off-board cost reductions are possible if:
  - Carrier material cost is at the low end of the potential cost range of $2-12/gal
  - Working capital in the system is reduced (i.e., less LCH_2 storage and higher on-board efficiencies)
  - Steam or electricity by-products may be used or sold at the regeneration facility
- In addition, LCH_2 has the potential to be more attractive than the other hydrogen options due to:
  - Relative ease of transport and dispensing
  - Smaller capital investment than cH_2 pipelines, especially for small-medium volumes
  - No boil-off issues and lower overall energy use and GHG emissions than LH_2 pathway[1]

[1] Well-to-Wheel energy use and GHG emissions to be determined by ANL.

The LCH_2 on-board storage system cost is projected to be 4 times higher than the DOE 2010 target.



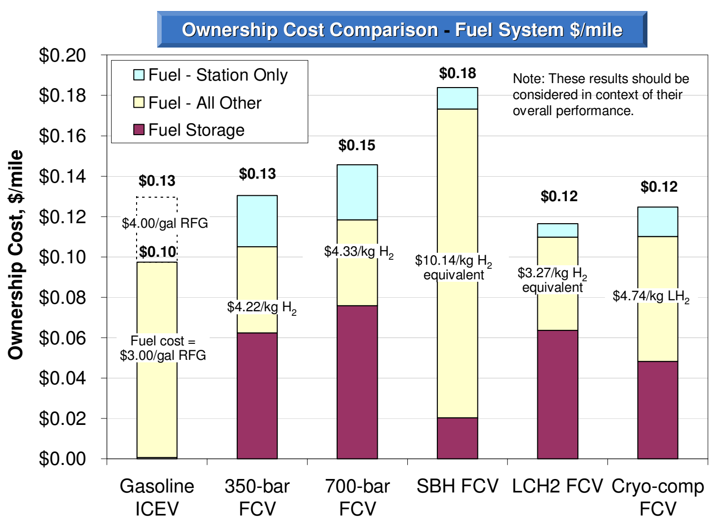
*Denotes preliminary estimate, to be reviewed prior to completion of TIAX's cost analysis.
[a]The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

There is currently no clear path to achieving on-board storage system cost targets with the LCH_2 system.

- The LCH_2 system evaluated here was $15.7/kWh, almost 4 times more expensive than the DOE 2010 target of $4/kWh
- Substantial cost reductions/performance improvements are needed for the on-board reactor and BOP components
- Even assuming an improved LCH_2 material with 6.7 wt% H_2 and 100% on-board storage efficiency, cost is reduced by less than 5% (see Appendix). However, these changes do offer significant weight and volume reductions.
- On-board conversion reactor performance and system design has not been proven
  - 95% conversion efficiency assumed in this study vs. only 85% demonstrated (double pass) for a continuous reactor with thin-film catalyst[1]
  - Trickle bed reactor hydrodynamics on foam has not been demonstrated[2]
  - The proposed system design uses an unproven single-tank concept with a flexible bladder separating the spent carrier material from the hydrogenated material. A two tank system may be necessary to ensure the system's technical functionality
  - The onboard storage efficiency does not account for the energy needed to maintain the dehydrogenated carrier above its melting point of 70°C

[1] "Reversible Liquid Carriers for an Integrated Production, Storage and Delivery of Hydrogen", Toseland, B. and Pez, G., 2008 DOE H_2 Program Review
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE H2 Program Review, May 2007

When on-board and off-board costs are combined, we see that the LCH_2 system has <u>potential</u> to have roughly the same ownership cost as a gasoline ICEV.



Note: All fuel costs exclude fuel taxes.

When the on-board and off-board fuel system costs are combined, the LCH_2 system has potential to be competitive with other fuel options.

- The LCH_2 system evaluated here is 1 to 3 cents per mile cheaper than our assessment of compressed H_2 storage systems with pipeline delivery
  - Different assumptions for annual discount factor, markups, annual mileage and fuel economy would yield slightly different results
  - Note that the impact of on-board storage system weight and volume were not taken into account, but the heavier LCH_2 system would likely result in lower fuel economy than the cH_2 system
- The LCH_2 system is also ~1 cent/mile cheaper than a conventional ICEV when only the fuel system is considered and gasoline is $4/gal
  - However, when the whole vehicle, including the powertrain purchased cost, is included, the conventional gasoline ICEV will likely be noticeably cheaper (see Appendix)
  - Note that a detailed assessment of the FCV and ICEV maintenance and other non-fuel operating costs has not been conducted

However, even ownership cost is not the whole story: WTW energy use/GHG emissions, vehicle performance impacts and other metrics must be considered.

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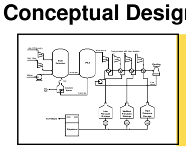
This cost assessment is based on a liquid carrier (N-ethylcarbazole) being developed by Air Products (APCI) to reversibly adsorb and desorb hydrogen.

- Despite having a moderate hydrogen storage density of 5.8 wt% (3.7 wt% net[1]), N-ethylcarbazole has many positive attributes, including:
  - Regeneration (i.e., hydrogenation) process adsorbs H_2 at a pressure of 60 bar, which does not add significantly to capital and energy costs at the regeneration facility
  - No additional reactants besides hydrogen are required
  - Regeneration process produces low-quality steam that can be used as a by-product or to generate electricity (not included in this cost analysis)
  - The hydrogenated carrier can be stored and transported in tanks designed for standard hydrocarbons (e.g., gasoline, diesel)
- Dehydrogenation of the carrier on-board the vehicle adds some complexity and cost to the on-board storage system
  - Thermal requirements during the dehydrogenation process are significant (~25 MJ/kg H_2) and the temperature requirement (240-270℃) is significantly greater than current PEM operating temperatures[2]
  - The dehydrogenated carrier must be kept above a melting point of 70℃ necessitating insulated or heated storage and transport tanks

[1] Assuming 95% conversion efficiency in the dehydrogenation reactor and 68% on-board storage efficiency (i.e., 32% of the stored H_2 must be burned to generate the heat required for on-board dehydrogenation).
[2] If dehydrogenated at the fueling station, natural gas will likely provide the thermal energy required for dehydrogenation.

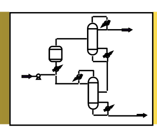
Our off-board assessment makes use of existing models to calculate cost and performance for each technology on a consistent basis.

Conceptual Design



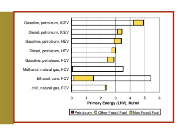
- System layout and equipment requirements

Process Simulation



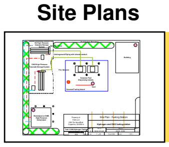
- Energy requirements
- Equipment size/ specs

GREET Model



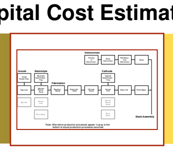
- WTT energy use
- WTT GHG

Site Plans



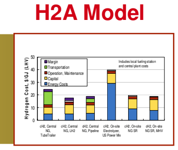
- Safety equipment, site prep, land costs

Capital Cost Estimates



- High and low volume equipment costs

H2A Model

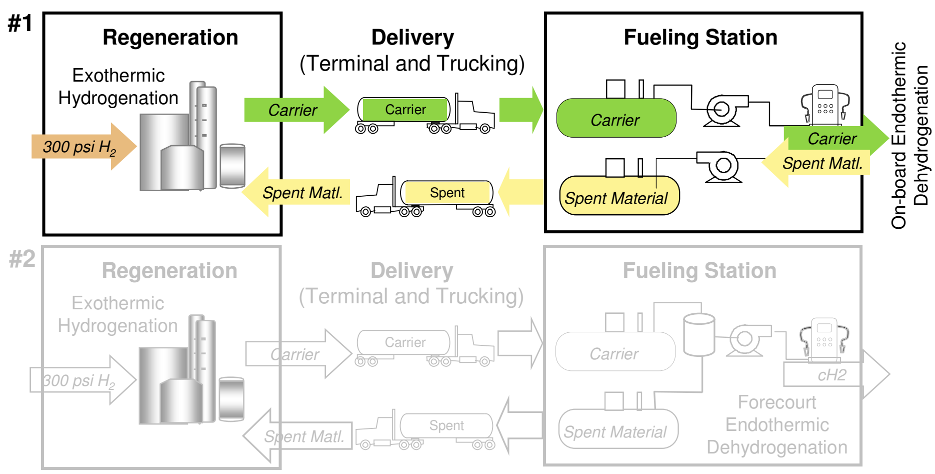


- Equivalent hydrogen selling price

The H2A Carrier model was used to allow for direct cost comparison to compressed, liquefied, and sodium borohydride (SBH)-based H_2 options.

- Most financial assumptions are maintained from the original H2A Model
- New calculation tabs were added as part of the DOE Delivery Project
  - Regeneration – calculates material regeneration costs based on capital and operating costs of a central plant
  - 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 fueling vehicles with novel carrier
- Calculation tabs were populated with inputs based on industry and developer feedback
  - TIAX made initial estimates consistent with H2A methodology
  - Model and estimates were reviewed with developers (primarily APCI)
  - Model inputs and results were updated

The off-board assessment for novel carriers requires evaluation of regeneration, delivery and forecourt technologies.



This analysis assumes that the LCH_2 will be employed for on-board storage as illustrated in Pathway #1 above.

The regeneration facility includes equipment and material for hydrogenation, purification and storage.

- Hydrogen
  - Hydrogen is purchased as a pure gas at 20 bar for $1.50/kg (H2A Central Plant target)
  - No losses are assumed
- Material Storage Tanks
  - Storage for a 10-day plant shutdown and a 120-day summer peak period (10% above average demand) is included for hydrogenated material
  - Equal amount of storage included for dehydrogenated material
  - Two quarantine tanks are included for substandard material (five days of material)
  - Assumed cost: $0.42/gal (based on similar tanks in H2A)
- Carrier Material
  - N-ethylcarbazole is estimated to cost between $2-12/gal; $7/gal used for baseline (industry estimate, in 2008$)
  - Material replacement is estimated to be 0.1% of plant throughput (APCI estimate)
  - Material allocation equals that required to fill all hydrogenated storage tanks
- Capital Cost
  - Includes: compressors, reactors, tankage, distillation, heat exchangers, fluid power equipment, and power and instrumentation (combination of H2A and industry cost estimates)
  - Range of 50-150% of estimated equipment capital cost used for sensitivity analysis
- Catalyst Loading and Replacement
  - Assumed initial catalyst cost is $170/kg and cost for replacement catalyst is $155/kg (industry estimate)
  - Catalysts lifetime based on material processed: 350,000-1,000,000 kg_m/kg_c; 500,000 baseline (industry estimate)

Capital cost estimates are derived from developer feedback and baseline H2A model assumptions.

Regeneration Plant Capital Equipment	Installed Cost ($millions)	Basis
Carrier Material	$258	Personal communication with APCI, 2008
Indirect Capital (permitting, project contingency, engineering, site prep, land)	$155	H2A Baseline
Storage (Including quarantine)	$41.7	Personal communication with APCI, 2008
Piping & Instrumentation	$25.7	Personal communication with APCI, 2008
Catalyst	$21.3	Personal communication with APCI, 2008
Compressors	$14.8	H2A Baseline
Pumps	$6.8	Personal communication with APCI, 2008
Reactor	$1.5	Personal communication with APCI, 2008
Heat Exchangers	$1.4	Personal communication with APCI, 2008
Distillation	$0.2	Personal communication with APCI, 2008
Total	**$526**	

The ability of the liquid carrier to be transported in relatively standard, insulated tank trucks makes for cost efficient transportation.

- Transport capacity: determined by the liquid carrier yield (3.7 wt% net) and the mass of material that can be transported within an insulated aluminum trailer (24,750 kg GVW)
- Insulation: will be able to maintain the temperature of the carrier for up to 1 day
- Trailer cost: $90,000 based on quotes from Heil and Polar trailer companies
- Loading/unloading time: 1.5 hrs combined (trailer unloads hydrogenated carrier and picks up dehydrogenated carrier)
- Baseline H2A assumptions include:

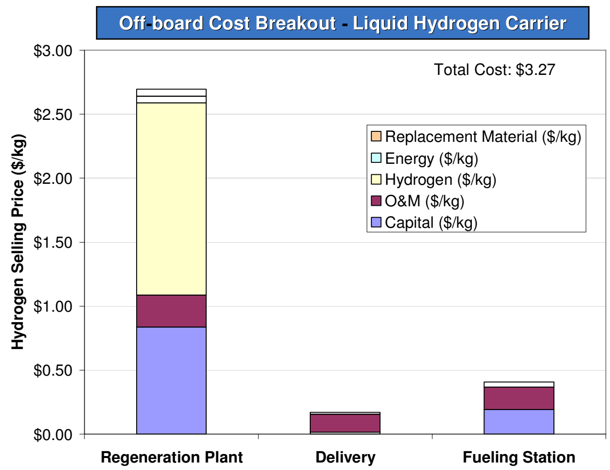
H2A Delivery Assumption	Value
Round trip delivery distance	160 km
Delivery labor rate	$50
Truck capital cost	$75,000
Fuel cost	0.44 $(2005)/L

This analysis assumes the fueling station receives the liquid carrier via tanker trucks where the carrier is stored and dispensed to vehicles for on-board dehydrogenation.

- All components (e.g., storage tanks, pumps, dispensers) are specified according to previously established methods for chemical hydrogen systems
- On-site storage in each of the hydrogenated and spent carrier tanks is equal to 1.5 truck deliveries
- Overall cost includes enough carrier material to fill 1/3 of the hydrogenated carrier tank and the full spent carrier tank
- Electricity consumption due to carrier pumping and other miscellaneous loads are the same as for sodium borohydride (SBH) = 0.50 kWh/kg
- A range of labor costs were used: $7.75/hr (minimum wage in CA) - $15/hr, with the baseline value of $10/hr

Off-board Assessment Results *Cost Breakout*

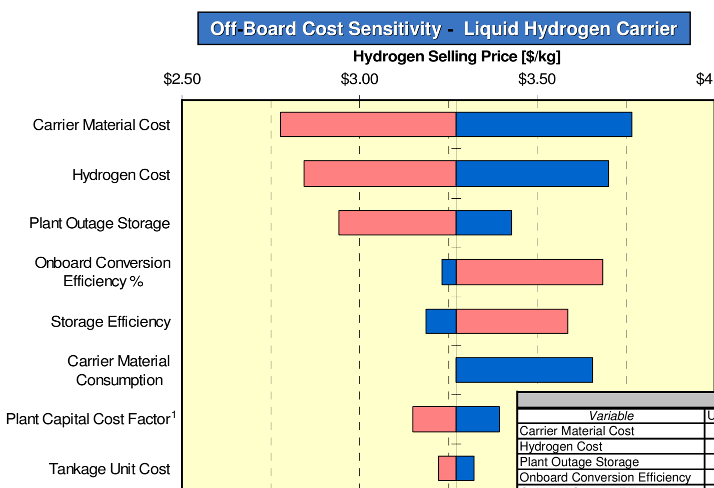
The cost results indicate that the major non-hydrogen cost is the capital cost of the regeneration plant.



If the carrier is used as an off-board transportation media only (i.e., fueling station dehydrogenation), the H_2 selling price would increase to about $4.14/kg.

Off-board Assessment Results *Total Cost Sensitivity*

Factors effecting the initial and replacement costs of carrier material have the greatest affect on the hydrogen selling price sensitivity.



		Input		
Variable	Units	*Min*	*Baseline*	*Max*
Carrier Material Cost	$/gal	$2	$7	$12
Hydrogen Cost	$/kg	$1.0	$1.5	$2.0
Plant Outage Storage	days	0	10	15
Onboard Conversion Efficiency	%	68%	95%	100%
Onboard Storage Efficiency	%	50%	65%	75%
Carrier Material Consumption	%	0.1%	0.1%	1.0%
Plant Capital Cost Factor	%	50%	100%	150%
Tankage Unit Cost	$/gal	$0.21	$0.42	$0.63

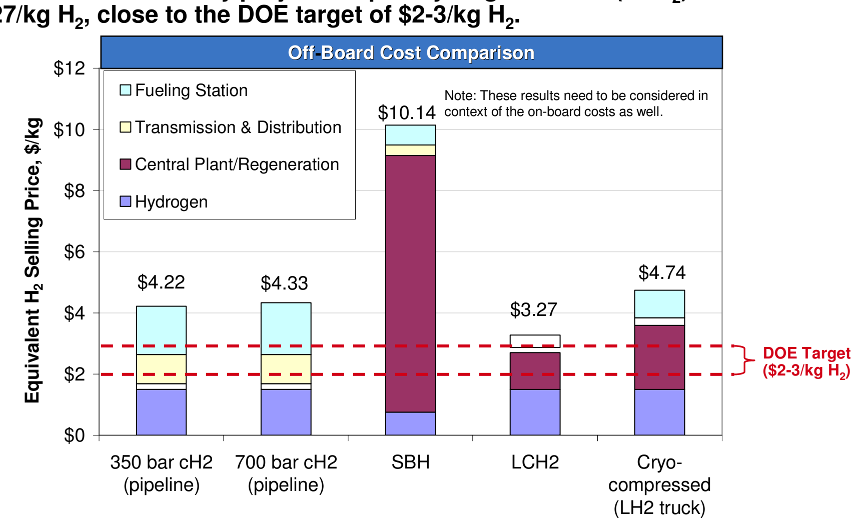
[1] Capital cost factor applied to hardware specific for liquid hydrogen infrastructure.

Compared to the preliminary LCH_2 results presented at the 2009 AMR, changes to TIAX's assumptions resulted in a significant decrease in the cost of hydrogen.

- Decreased the carrier material replacement at the regeneration facility from 2.75% of plant throughput to 0.1%:
  - The prior estimate provided by APCI (0.5 to 5%, 2.75% baseline) corresponded to an *annual* replacement rate, given a fixed number of cycles, but was erroneously interpreted as a *per-cycle* replacement rate.
  - Feedback from APCI [2010] indicated that this prior estimate was an order of magnitude higher than that seen during real-world testing.
- Adjusted offboard cost of liquid carrier material from 2008$ ($7/gal) to 2005$ ($6.35/gal)

2010 Updated Results Compared to 2009 AMR Results	2009 AMR	2010 Update	% Change
Fuel Cost, $/kg H_2	$4.75	$3.27	-31%

The results of this study project a liquid hydrogen carrier (LCH_2) fuel cost of $3.27/kg H_2, close to the DOE target of $2-3/kg H_2.



Note: Production costs assume $1.50/kg H2 (H2A target). Regeneration costs assume 100 TPD H2 equivalent SBH plant based on hydrogen assisted electrolysis and a 250 TPD H2 equivalent LCH2 plant based on N-ethylcarbazole hydrogenation. Delivery and forecourt costs assume 80 km truck delivery from a central plant to the fueling station designed for 1000 kg/day H2. cH2 (pipeline) and LH2 cases assume compressed hydrogen dispensing at 6,250 psi.

"Ownership cost" provides a useful metric for comparing storage technologies on an equal footing, accounting for both on- and off-board (i.e., refueling) costs.

Simple Ownership Cost (OC) Calculation:

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

C = Factory 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)

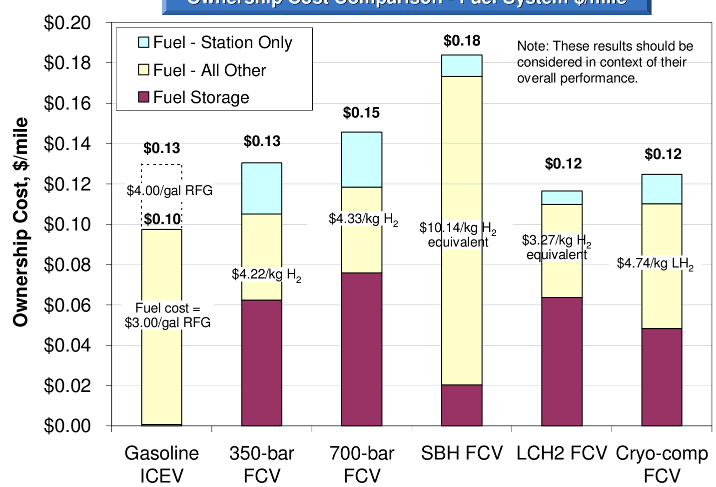
Ownership Cost Assumptions	Gasoline ICEV	Hydrogen FCV	Basis/Comment
Annual Discount Factor on Capital	15%	15%	Input assumption
Manufacturer + Dealer Markup	1.74	1.74	Assumed mark-up from factory cost estimates[1]
Annual Mileage (mi/yr)	12,000	12,000	H2A Assumption
Vehicle Energy Efficiency Ratio	1.0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

This ownership cost assessment implicitly assumes that each fuel system and vehicle has similar maintenance costs and operating lifetime.

When on-board and off-board costs are combined, we see that the LCH_2 system has <u>potential</u> to have roughly the same ownership cost as a gasoline ICEV.

Ownership Cost Comparison - Fuel System $/mile



Note: All fuel costs exclude fuel taxes.

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We evaluated the high-volume manufactured cost of a liquid hydrogen carrier (LCH_2) on-board storage system based on N-ethylcarbazole.

- We based on cost analysis on ANL's performance assessment[2] of the Air Products (APCI) regenerable organic liquid carrier, N-ethylcarbazole[1]
- Key features of the LCH_2 system include:
  - **Single tank design:** Uses a flexible bladder to separate the spent carrier material from the hydrogenated material. Resistance heat is used to maintain the dehydrogenated carrier above its melting point of 70°C.
  - **Dehydrogenation reactor:** An onboard trickle-bed reactor dehydrogenates the carrier at high temperature (270 C) using a thin-film palladium catalyst
  - **Balance-of-Plant:** Heats/cools and circulates carrier media. Main cost contributors are the burner and circulation pumps
- Key advantages of the APCI liquid carrier are its competitive off-board (i.e., refueling) cost and relative ease of transport and dispensing
- The key disadvantage of this liquid carrier is its low system storage efficiency of 68% (i.e., a large fraction of stored H_2 has to be burned to provide the heat for dehydrogenation)

[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez, G., 2007 DOE H_2 Program Review
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE H_2 Program Review, May 2007

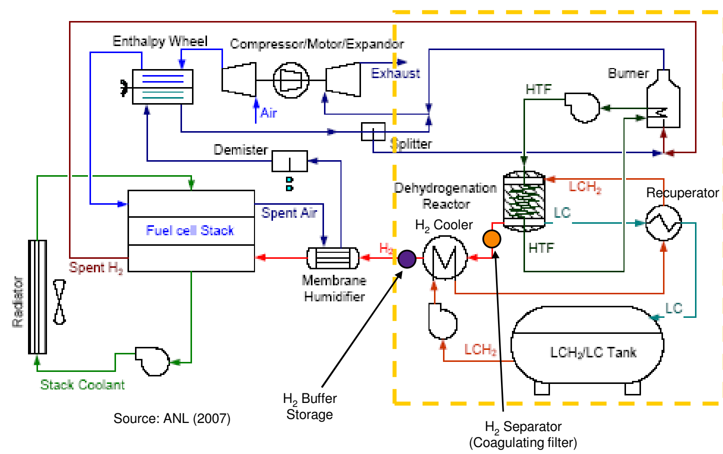
The LCH_2 system design incorporates a number of design assumptions that have not been validated with real-world results.

- **Onboard performance:** Key differences between the APCI demonstrated results and ANL analysis, include:
  - ANL assumes 95% conversion efficiency, whereas APCI has demonstrated 65% (single pass) to 85% (double pass) for a continuous reactor with thin-film catalyst[2]
  - Trickle bed reactor hydrodynamics on foam has not been demonstrated[1]
- **Tank Design:** The proposed system design uses an unproven single-tank concept with a flexible bladder to separate fresh and spent media. A two tank system may be necessary to ensure the system's technical functionality.
- **Carrier Media Temperature Management:** The system design uses resistance heaters to maintain the dehydrogenated carrier above its melting point of 70°C
  - The onboard storage efficiency does not account for the energy needed to operate the resistance heaters, and the tank design does not include insulation that may be necessary to reduce energy losses or prevent solidification of the media.
  - We did not perform a tradeoff analysis to compare the additional operating cost associated with maintaining the tank's temperature against the additional capital expense, size, and weight of adding insulation to the storage tank
  - A lower melting-point carrier may need to be engineered to avoid this efficiency penalty.

[1] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE H_2 Program Review, May 2007
[2] "Reversible Liquid Carriers for an Integrated Production, Storage and Delivery of Hydrogen", Toseland, B. and Pez, G., 2008 DOE H_2 Program Review

We used the onboard system definition and design developed by APCI[1] and ANL[2] as the basis of our cost assessment.

On-Board Storage System[2] to be Evaluated (yellow dashed box)



Source: ANL (2007)

[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez, G., 2007 DOE H_2 Program Review
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE H_2 Program Review, May 2007

The high volume (500,000 units/year) manufactured cost for the LCH_2 system was estimated from raw material prices, capital equipment, labor, and other operating costs.

LCH_2 Storage System – Major Components

- Dehydrogenation Reactor
- Liquid Carrier Storage Tank
- HEX Burner
- H_2 Cooler
- H_2 Separator
- Recuperator
- H_2 Buffer Storage

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)

- We used a bottom-up approach to determine manufactured cost for the dehydrogenation reactor and LCH_2/LC storage tank.
- We costed the microchannel heat exchangers for the HEX burner, H_2 cooler and recuperator based on direct materials and 1.5X bottom-up process costs for tube-fin heat exchangers.
- We costed the H_2 buffer storage tank based on direct materials.
- We based the cost of purchased components (i.e. Heat Transfer Fluid (HTF) pump, Liquid Carrier (LCH_2) pump, H_2 burner, H_2 blower, coagulating filter, LCH_2 tank heater, piping, sensors, controls, valves and regulators) on vendor quotes/catalog prices, adjusted for high-volume production.

We based our media and storage tank assumptions and specifications on discussions with APCI and ANL and their 2007 Merit Review presentations[1,2].

System Element	Design Parameter	Value	Basis/Comment
Media/System	Media/Material	N-ethylcarbazole	ANL[2], APCI[1]
	Material H_2 storage capacity	5.8 wt%	ANL[2], APCI[1]
	Storage system efficiency	67.7%	ANL[2]; includes H_2 utilized to fire burner only (does not include 95% reactor conversion efficiency)
	LCH_2 solution density	1200 kg/m^3	ANL[2]
	LC solution density	950 kg/m^3	ANL[2]
LCH_2/LC Storage Tank	Tank material of construction	HDPE	ANL[2]
	% excess tank volume	10%	Over fuel volume, to account for sloshing
	Usable H_2 capacity	5.6 kg	Design basis; note: ANL[2] analysis done for 6.4 kg usable H_2
	Stored H_2 capacity	8.7 kg	Calculated based on 95% conversion efficiency and 67.7% storage efficiency; note: ANL[2] analysis done for 10 kg stored H_2
	Bladder/separator?	Yes	Single tank design; needed to separate LCH_2 from LC
	Temperature	70 ºC	Needed to prevent solidification

[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez, G., 2007 DOE Hydrogen Program Review
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

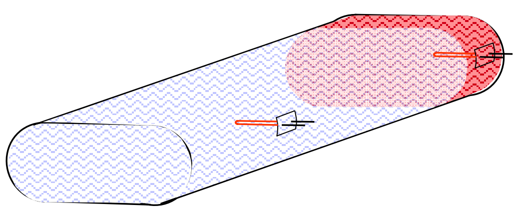
The dehydrogenation reactor design was also based on information from APCI and ANL.

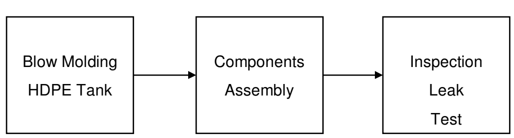
System Element	Design Parameter	Value	Basis/Comment
Dehydrogenation Reactor	Type	Vertical, tubular trickle bed reactor	ANL[2]
	Heat of dehydrogenation	+51 kJ/mol H_2	APCI[1], ANL[2]; =25 MJ/kg H_2
	Catalyst	Pd on Li Aluminate	Dispersed wash-coat (thin-film) catalyst, 50 micron, 363 mm active length
	Catalyst concentration	4% wt. of substrate	
	Catalyst substrate	40-ppi Al-6101 foam	92% porosity, 224 kg/m^3 bulk density
	Conversion efficiency	95%	ANL[2]
	Liquid Hourly Space Velocity (LHSV)	20 h^{-1}	ANL[2]; H_2 volumetric flow rate/liter reactor volume
	Peak operating temp.	240-270 °C	ANL[2]
	Max. operating pressure	8 bar (116 psi)	ANL[2]
	HX tube material	Al-2219-T81	ANL[2]; 40 tubes (11.1 mm OD, 0.8 mm wall, 400 mm length)
	Reactor vessel material	Al-2219-T81	ANL[2]; 182 mm OD, 0.8 mm wall, 460 mm total length, 2.25 safety factor

[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez, G., 2007 DOE Hydrogen Program Review
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

Other component design assumptions are presented in the Appendix.

A single high-density polyethylene (HDPE) tank holds the LCH_2 and spent carrier (LC), separated by a moving bladder[1]. Resistance heaters maintain the solutions above 70 °C[2].





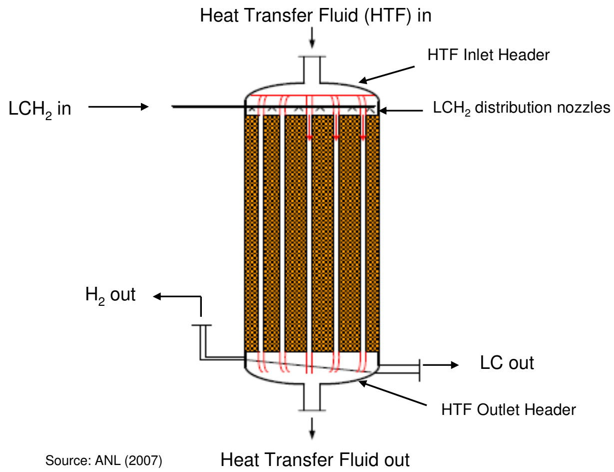
LCH_2/LC Storage Tank Manufacturing Flow Chart

Storage Tank Bill-of-Materials

1. HDPE tank
2. Bladder
3. LCH_2 inlet with O-ring (fill in)
4. LCH_2 outlet with O-ring (delivery)
5. LC inlet with O-ring (return from reactor)
6. LC outlet with O-ring (drain out)
7. LCH_2 side resistance heater
8. LC side resistance heater
9. LCH_2 side level sensor
10. LCH_2 side drain
11. LC side drain
12. LCH_2 side pressure release valve
13. LC side pressure release valve
14. Mounting steel brackets (2)
15. Bolts (4)
16. Nuts (4)
17. Washers (4)

[1] LCH_2/LC storage tank design based on sodium borohydride (SBH) storage tank. Single tank/bladder design may be easier than for SBH tank since SBH is highly caustic and also tends to precipitate out of the solution.
[2] ANL system efficiency calculations of 67.7% do not include heater parasitics. A lower melting-point liquid carrier may need to be engineered to avoid efficiency penalty.

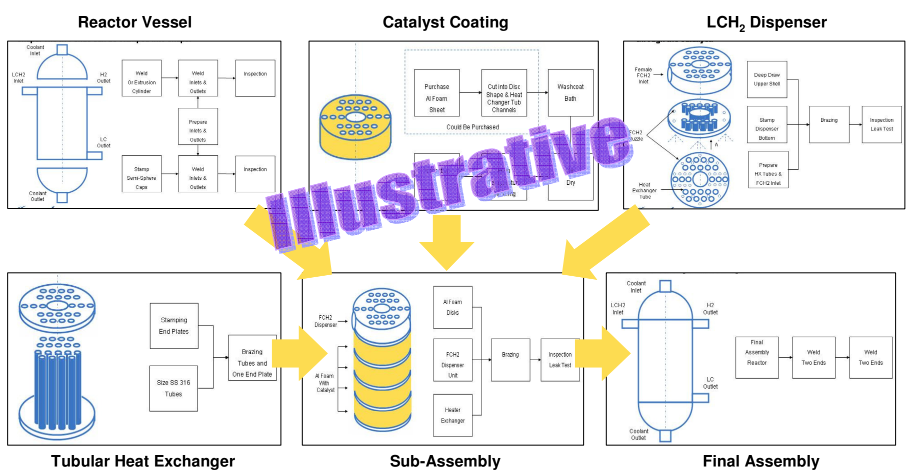
The dehydrogenation reactor was based on ANL's design of a vertical, tubular, trickle-bed reactor with dispersed thin-film catalyst (4% Pd on Li Aluminate) on 40-ppi Al-6101 foam[1].



Source: ANL (2007)

[1] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

The overall dehydrogenation reactor manufacturing process flow is shown below[1].



[1] Process flow chart is based on similar dehydriding reactor for sodium alanate hydrogen storage system.

On-board Assessment Analysis *Raw Material Prices*

We used Year 2008 prices for the key raw materials, which are listed below. Subsequently, we deflated all material prices by 9.27% to Year 2005 USD.

System Element	Raw Material	Price (2005$)	Basis/Comment
Media	N-ethylcarbazole	$6.35/gal	APCI; $2-12/gal range (2008$), deflated to 2005$; consistent with TIAX off-board LCH_2 storage system assessment
LCH_2/LC Storage Tank	HDPE	$1.6/kg	Plastics Technology, May 2008, pg. 95, deflated to 2005$
Dehydrogenation Reactor	Pd catalyst	$12.7/g ($395/tr.oz.)	www.metalprices.com; June, 2008, deflated to 2005$
	Li Aluminate	$43.8/kg	Sigma-Aldrich[1], deflated to 2005$
	Al-6101	$9.6/kg	Bulk price from Alcoa (2009), deflated to 2005$
	Al-2219-T81	$12.7/kg	Assumed 30% higher price than AL-6101, based on spread in price between Al-6101 and Al-2219 from 2008
	HTF (XCelTherm® 600)	$7.26/gal	RadCo Industries, Inc., June 2008, deflated to 2005$
HEX Burner	Inconel 600	$15.0/kg	www.metalprices.com; June, 2008, deflated to 2005$
H_2 Cooler, Recuperator	SS316	$7.26/kg	www.metalprices.com; June, 2008, 1-year avg, deflated to 2005$.

[1] https://www.sigmaaldrich.com/catalog/search/ProductDetail?ProdNo=336637&Brand=ALDRICH

On-board Assessment Analysis *Purchased Components*

We based the cost of purchased components on vendor quotes/catalog prices, using our judgment to adjust for high-volume production.

Purchased Component	Weight (kg)	Volume (L)	Cost ($)	Basis/Comment
HTF Pump	40	30	$400	0.4X McMaster-Carr catalog price; ANL[1]: XCelTherm® 600, 458 L/min, 320 °C, ΔP=1 bar
LCH_2 Pump	20	10	$200	0.4X McMaster-Carr catalog price; ANL[1]: LCH_2, 2.65 L/min, 70 °C, ΔP=8 bar
H_2/air Non-catalytic Burner	2	1	$400	0.4X McMaster-Carr catalog price $1,000 for NG burner, 180,000 Btu/h; ANL[1]: 82 kW, 5% excess O_2, Inconel
H_2 Blower	2.0	5	$18	0.5X Modine OEM $37 not including tooling and capital cost markup 1.2
Coagulating filter	1.8	0.8	$43	0.4X McMaster-Carr retail price of $105
LCH_2 Tank Heater	0.1	0.0	$4	Bottom-up costing using Boothroyd-Dewhurst DFMA® software, with 1.5X markup for component supplier overhead and profit
Piping & Fittings	7	3	$72	
Sensors & Controls	0.0	0.0	$30	
Valves & Connectors	3	2	$105	
Pressure Regulators	1	1	$44	

[1] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007
Note: A complete bill of materials is included in the appendix

We performed bottom-up costing (i.e., raw materials, process flow charts) on all other components.

On-board Assessment Results *Material vs.Process Cost*

Processing cost makes up just ~5% of the total system cost due to the high production volume assumption and large fraction of purchased components.

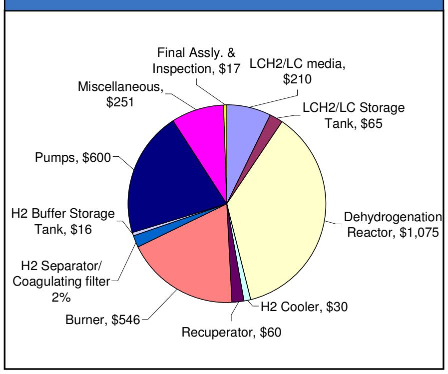
On-board System Cost Breakout Liquid Hydrogen Carrier – 5.6 kg H_2	Material, $	Processing, $	Processing Fraction
LCH_2/LC Media[1]	**210**	**(purchased)**	**0%**
LCH_2/LC Storage Tank	**55**	**10**	**15.4%**
Dehydrogenation Reactor	**1,038**	**37**	**3.4%**
- Pd Catalyst	916	(purchased)	0%
- Li Aluminate	76	(purchased)	0%
- Al-6101 foam substrate	18	19	51.8%
- Reactor Vessel (Al-2219-T81)	9	2	18.1%
- HX tubes (Al-2219-T81)	15	16	51.7%
- Other (HTF, insulation, fittings)	5	(purchased)	0%
H_2 Cooler	**6**	**24**	**80%**
Recuperator	**36**	**24**	**40%**
Burner	**510**	**36**	**6.6%**
- Microchannel HX	92	36	28.2%
- H_2/air non-catalytic burner	400	(purchased)	0%
- H_2 blower	18	(purchased)	0%
H_2 Separator/Coagulating filter	**52**	**7**	**11.8%**
H_2 Buffer Storage Tank	**16**	**0.5**	**3.1%**
Pumps	**600**	**(purchased)**	**0%**
- HTF pump	400	(purchased)	0%
- LCH_2 pump	200	(purchased)	0%
Miscellaneous	**251**	**(purchased)**	**0%**
Final Assembly & Inspection	**0**	**17**	**100.0%**
Total Factory Cost	**2,774**	**156**	**5.3%**

[1] Cost is based on $7/gal LCH_2, consistent with TIAX off-board LCH_2 storage system assessment, which is based on input from APCI.

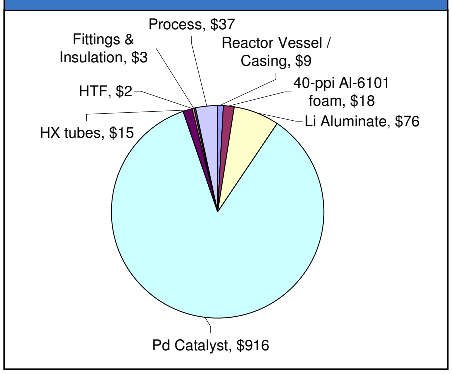
On-board Assessment Results *Cost Breakout*

We estimate the high-volume factory cost[1] of the system to be about $2,930, or $15.7/kWh, of which ~31% is due to the cost of the Pd catalyst.

LCH2 System Factory Cost = $2,930
$15.7/kWh based on 5.6 kg usable H2



Dehydrogenation Reactor Factory Cost = $1,075



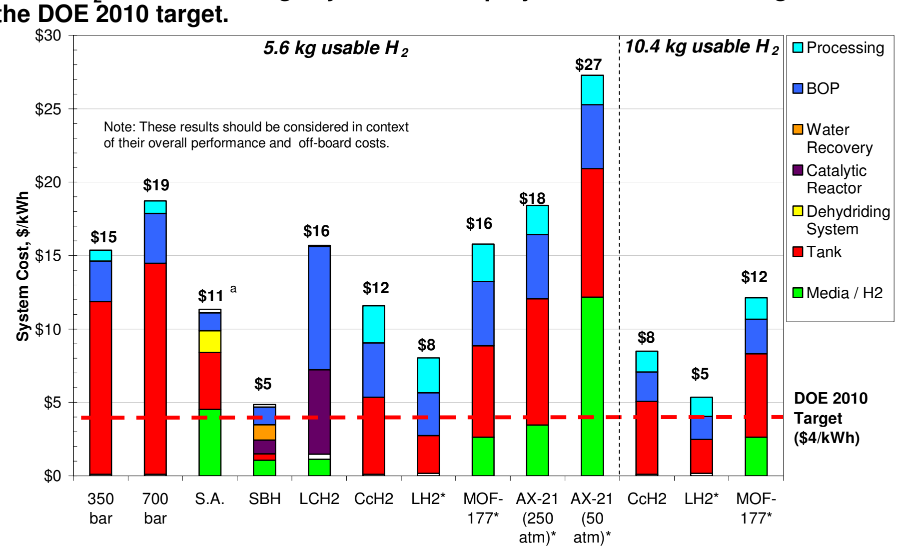
Note: A trade-off study was not performed on the size/cost of the pumps versus size/cost of the reactor sub-system and burner.
[1] Cost includes deflation by 9.27% to Year 2005 USD.

Compared to the preliminary LCH_2 results presented at the 2009 AMR, changes to TIAX's assumptions and calculations resulted in a minor adjustment in the onboard cost estimate.

- Corrected the volume, weight, and cost of the LCH2/LC Media and LCH2 Tank such that they are calculated based on the amount of LCH2, not LC.
- Increased the cost of the coagulator filter cost from $21 to $43. The new cost is based on a 60% discount from low volume catalog list price (consistent with other BOP components); the previous cost was based on an 80% discount.
- Increased the price of aluminum from $2.5/kg to $9.6/kg for AL-6101, and $3.7/kg to $12.7/kg for Al-2219

2010 Updated Results Compared to 2009 AMR Results	2009 AMR	2010 Update	% Change
System Cost, $/kWh	15.4	15.7	+2%

The LCH_2 on-board storage system cost is projected to be 4 times higher than the DOE 2010 target.



*Denotes preliminary estimate, to be reviewed prior to completion of TIAX's cost analysis.
[a]The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

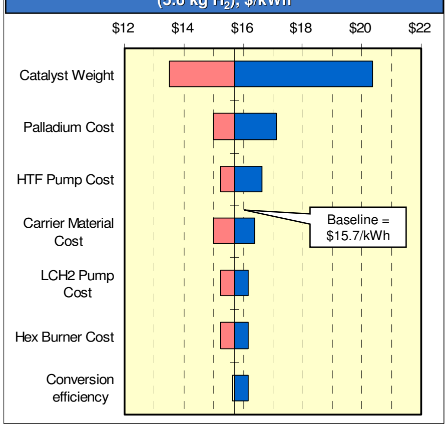
To account for the uncertainty in the onboard cost projections, we developed "low" and "high" cost estimates as inputs to the sensitivity analysis.

Key Sensitivity Parameters	On-board Cost Sensitivity – LCH_2			
	Baseline	Min	Max	Basis/Comment
Conversion Efficiency	95%	65%	100%	◆Baseline from ANL 2007 DOE AMR[1], min from APCI 2008 DOE AMR[2]
Catalyst Weight (kg)	1.8	0.9	3.6	◆Min and Max are one half and two times the baseline
Palladium Cost (2008$/troy oz.)	436	360	580	◆Baseline from metalprices.com annual average ◆Min and Max estimates from min and max LME values in 2008
HTF Pump Cost	$400	$300	$600	◆Baseline from catalog prices discounted by ~60%
LCH_2 Media Cost (2008$ per gal)	$7	$2	$12	◆Discussion with APCI
LCH_2 Pump Cost	$200	$100	$300	◆Baseline from catalog prices discounted by ~60%
Aluminum T6101 Cost ($/kg)	9.6	4.8	19.2	◆Min and Max are one half and two times the baseline
Aluminum T6101 Cost ($/kg)	12.7	6.4	25.4	◆Min and Max are one half and two times the baseline
HEX Burner Cost	$400	$300	$500	◆Baseline from catalog prices for natural gas burners discounted by ~60%.

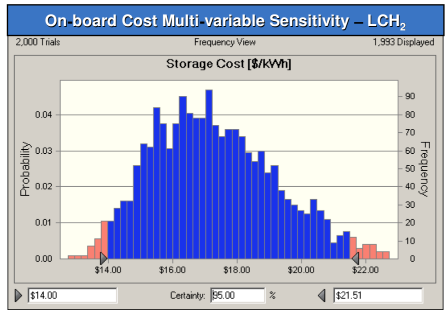
[1] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007
[2] "Reversible Liquid Carriers for an Integrated Production, Storage and Delivery of Hydrogen", Toseland, B. and Pez, G., 2008 DOE H_2 Program Review

The overall cost of the onboard liquid carrier system is most sensitive to the amount of catalyst, the catalyst cost, and purchased component prices

On-board Cost Sensitivity – Liquid Hydrogen Carrier (5.6 kg H_2), $/kWh



On-board Cost Multi-variable Sensitivity – LCH_2



System Cost	$/kWh
Base Case	15.7
Mean	17.3
Standard Deviation	1.94
"Low" Case	14.0
"High" Case	21.5

Sections

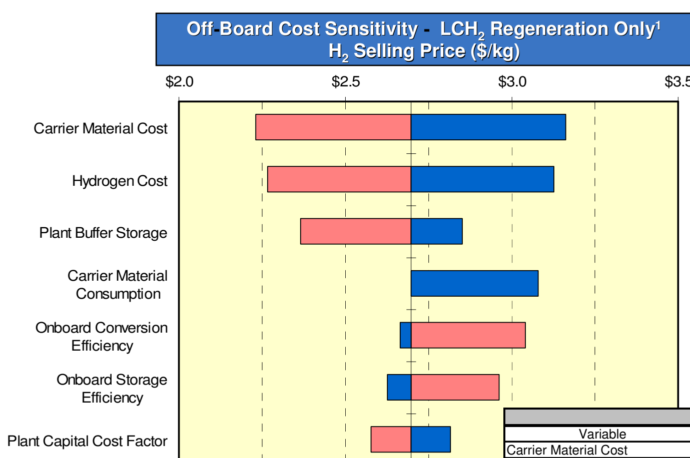
1 Summary Results
- Off board Assessment
- On board Assessment
- Ownership Cost

2 Off board Cost Assessment
- Background
- Analysis
- Results

3 On board Cost Assessment
- Background
- Analysis
- Results

A Appendix
- Off board Assessment
- On board Assessment

The sensitivity analysis shows the large affect that carrier cost and process efficiency assumptions have on the regeneration cost.

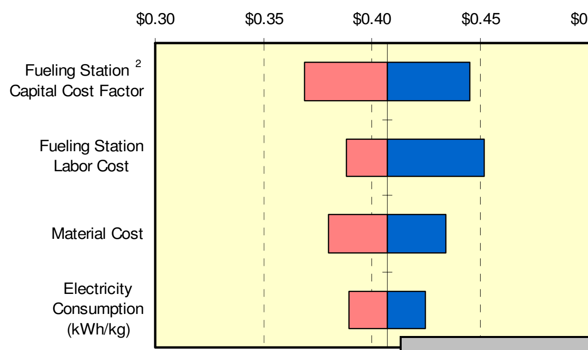


		Value		
Variable	Units	Min	Baseline	Max
Carrier Material Cost	$/gal	$2	$7	$12
Hydrogen Cost	$/kg	$1.0	$1.5	$2.0
Plant Buffer Storage	days	0	10	15
Carrier Material Consumption	%	0.1%	0.1%	1.0%
Onboard Conversion Efficiency	%	65%	95%	100%
Onboard Storage Efficiency	%	50%	68%	75%
Plant Capital Cost Factor	%	50%	100%	150%

[1] Delivery and fueling station parameters not included
[2] Applied to hardware specific for the LCH$_2$ infrastructure

Major LCH_2 fueling station cost drivers include capital, labor, carrier cost, and utilities.

Off-Board Cost Sensitivity - LCH_2 Fueling Station Only[1]
H_2 Selling Price ($/kg)



Variable	Units	Input Min	Input Baseline	Input Max
Fueling Station Capital Cost Factor	%	50%	100%	150%
Fueling Station Labor Cost	$/hr	$7.75	$10.00	$15.00
Material Cost	$/gal	$2	$7	$12
Electricity Consumption	kWh/kg	0.25	0.50	0.75

[1] Regeneration and delivery parameters not included
[2] Applied to hardware specific for the LCH_2 infrastructure

We based our system assumptions and component specifications on APCI[1] and ANL[2] 2007 DOE Merit Review presentations.

System Element	Design Parameter	Value	Basis/Comment
H_2 Buffer Storage Tank	Material	Al-2219-T81	ANL[2]; (249 mm OD, 0.5 mm wall, 744 mm total length, 2.25 safety factor)
	Peak Operating Temp	80 °C	ANL[2]
	Max. Operating Pressure	8 bar (116 psi)	ANL[2]
	Tank capacity	20 g H_2	ANL[2]
HEX Burner	Burner type	H_2/air (non-catalytic)	ANL[2]; 5% excess O_2, 1100 °C combustion products' exit temperature
	Burner fuel	32.3% by weight of stored H_2	
	Burner firing rate	82 kW (280,000 Btu/h)	
	HX Type	Counterflow Microchannel	ANL[2]; HTF=XCelTherm® 600, 100 °C approach temp., 310 microchannels (14.1 mm x 0.9 mm x 363 mm)
	HX Material	Inconel 600	
H_2 Cooler	HX Type	Counterflow Microchannel	ANL[2]; T_{outlet} = 80 °C, 90 microchannels (10.6 mm x 1.4 mm x 165 mm)
	HX Material	SS316	
Recuperator	HX Type	Counterflow Microchannel	ANL[2]; $T_{LCH2} = T_R$-10 °C, 610 microchannels (10.1 mm x 0.6 mm x 263 mm)
	HX Material	SS316	

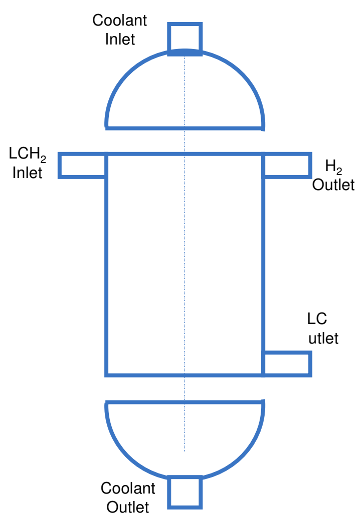
[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez., G, 2007 DOE Hydrogen Program Review
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

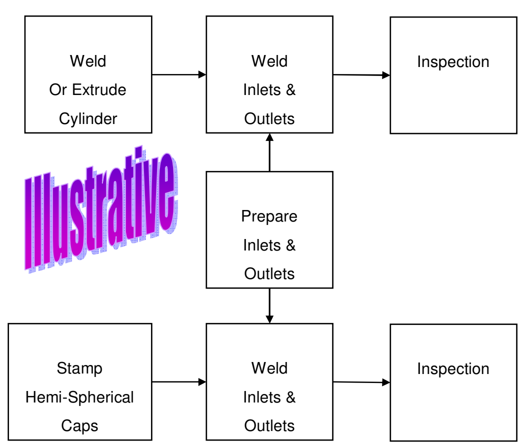
We based our system assumptions and component specifications on APCI[1] and ANL[2] 2007 DOE Merit Review presentations.

System Element	Design Parameter	Value	Basis
HTF Pump	Working fluid	XCelTherm® 600	ANL[2]
	Operating Temp	320 ºC	
	Pressure Head	1 bar (15 psi)	
	Density	850 kg/m^3	
	Flow rate	458 Liter/min (6.5 kg/s)	
LCH_2 Pump	Working fluid	LCH_2	ANL[2]
	Operating Temp	70 ºC	
	Pressure Head	8 bar (116 psi)	
	Density	1200 kg/m^3	
	Flow rate	2.65 Liter/min (0.053 kg/s)	

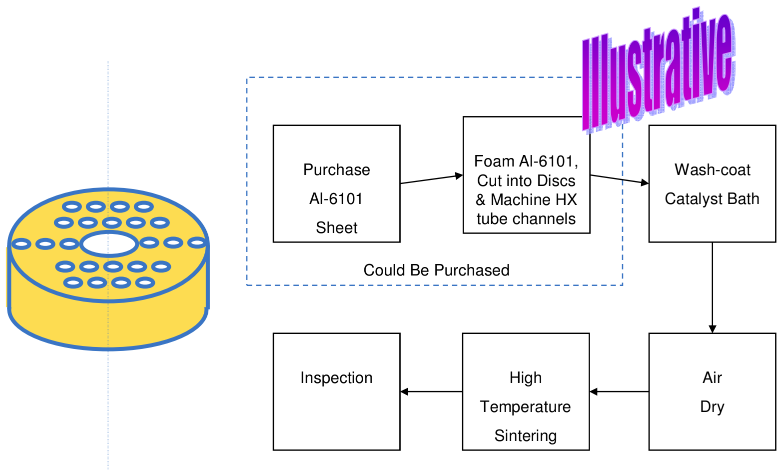
[1] "Hydrogen Storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers", Cooper, A.and Pez., G, 2007 DOE Hydrogen Program Review
[2] "System Level Analysis of Hydrogen Storage Options", Ahluwalia, R.K. et al., 2007 DOE Hydrogen Program Review, May 2007

The reactor vessel is assumed to be made of Al-2219-T81 alloy which can be welded or extruded into a cylindrical shape. The inlets and outlets as well as headers are stamped into shape.

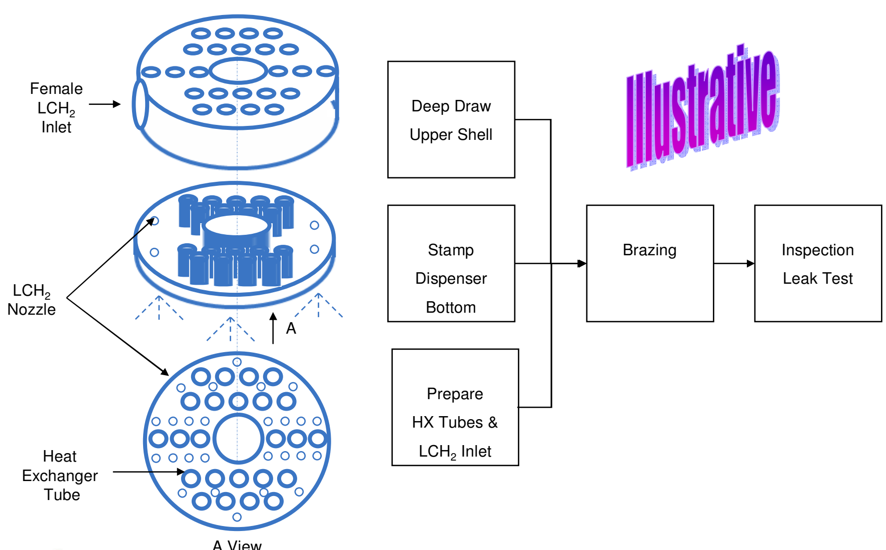




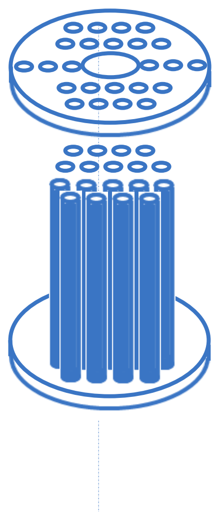
40-ppi Al-6101 foam (92% porosity) was picked as the catalyst substrate. The catalyst metals Pd and Li Aluminate are wash-coated onto the aluminum foam.

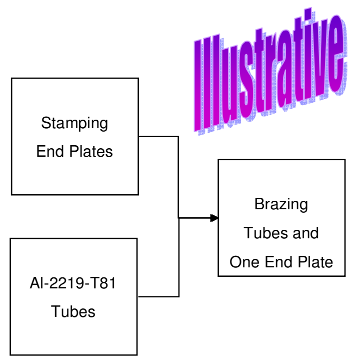


The LCH_2 dispenser was designed to evenly distribute the LCH_2 solution through the catalyst.

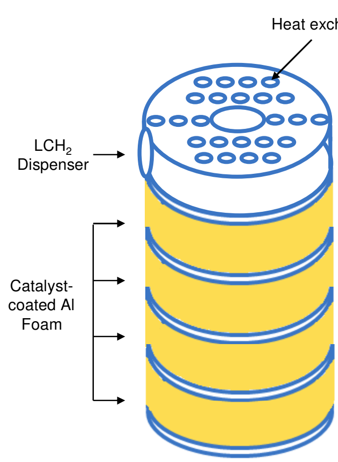


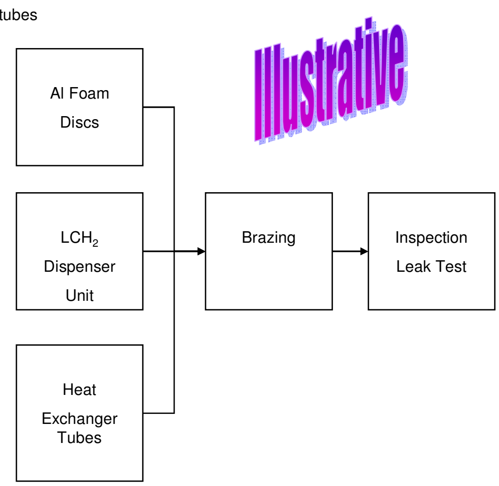
The heat exchanger tubes in the reactor are made of Al-2219-T81 alloy. They were assumed to be vacuum brazed.





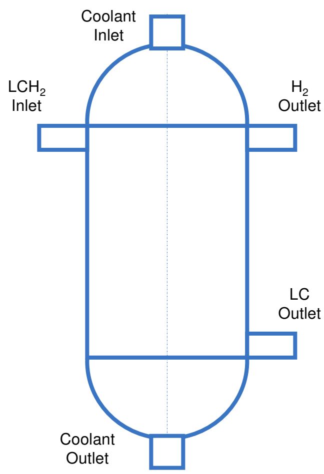
The LCH_2 solution dispenser and catalyst-coated Al foam discs were inserted into the tubular heat exchanger. A brazing process was used to firmly assemble them together.



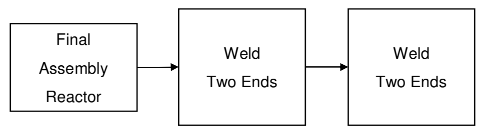


Appendix On-board Assessment *Dehydrogenation Reactor – Final Assembly*

The heat exchanger/LCH_2 solution dispenser/Al foam sub-assembly would be inserted into the reactor shell. The two reactor headers are assumed to be welded onto the cylindrical reactor shell.



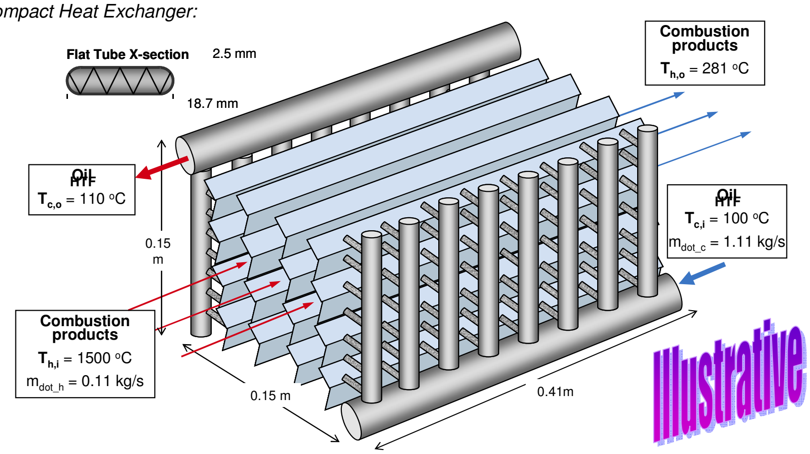
Illustrative



Appendix On-board Assessment *HEX Burner*

A non-catalytic H_2/air burner is assumed to supply the required heat of dehydrogenation by heating up the HTF[1] via a microchannel heat exchanger.

Compact Heat Exchanger:



Thermal integration with the stack was not considered at this time.

[1] HTF = Heat Transfer Fluid, assumed to be XCelTherm® 600

On-board system detailed breakout – Weight (kg), Volume (L), Cost[1] ($)

Component	System Weight (kg)	System Volume (L)	System Cost ($)
LCH2/LC media	150.1	125.1	$209.9
LCH2/LC Storage Tank	10.4	46.1	$64.6
Dehydrogenation Reactor	7.4	19.1	$1,075.2
H2 Cooler	0.8	0.3	$30.3
Recuperator	5.0	1.6	$60.1
Burner	10.1	8.0	$546.4
H2 Separator/Coagulating filter	3.1	0.8	$59.6
H2 Buffer Storage Tank	1.3	36.3	$15.9
Pumps	60.0	40.0	$600.0
Miscellaneous	7.9	5.5	$250.8
Final Assly. & Inspection	0.0	0.0	$17.0
Total	**256**	**283**	**$2,930**

[1] Cost includes deflation by 9.27% to Year 2005 USD.

Onboard System BOM: Storage Tank & Dehydrogenation Reactor

Description	Qty	Material	Volume (cm3)	Weight (kg)	Cost (USD)
LCH2/LC Storage Tank	1		**171,189**	**160.54**	**$264.26**
LCH2/LC Fuel Tank	1		171,189	0.00	$0.00
Fuel Tank Body	1	HDPE	7,056	6.70	$11.13
Solution Outlet Fitting	1	SS316	9	0.07	$1.00
Solution Inlet Fitting	1	SS316	9	0.07	$1.00
Solution Drain Fitting	1	SS316	9	0.07	$1.00
Drain Plug	1	SS316	5	0.05	$0.50
Mounting Bolt	6	Misc	5	0.05	$0.10
Nut	6	Misc	5	0.05	$0.05
Washer	6	Misc	5	0.05	$0.05
Level Transmitter	1	Misc	5	0.05	$5.00
Temperature Transmitter	1	Misc	5	0.05	$4.00
LCH2 Solution	1	LCH2	125,103	150.12	$209.91
Heater	2	Misc	10	0.10	$8.00
Separator Assembly	1	SS316	388	3.10	$22.52
Dehydrogenation Reactor	1		**19,116**	**7.36**	**$1,038.31**
Reactor Vessel / Casing	1	Al-2219-T81 alloy	12,008	0.71	$9.03
40-ppi Al-6101 foam	1	Al-6101 alloy	8,209	1.84	$17.65
Li Aluminate	1	Li Aluminate	665	1.73	$75.72
Pd Catalyst	1	Pd	6	0.07	$915.77
LCH2 Solution Inlet Fitting	1	SS316	9	0.30	$1.00
LC Solution Outlet Fitting	1	SS316	9	0.30	$1.00
HX tubes	1	Al-2219-T81 alloy	414	1.18	$14.94
HTF		XCELTHERM 600	1,134	0.96	$2.17
Insulation		GF	7,108	0.27	$1.01

Onboard System BOM: Support Systems

Description	Qty	Material	Volume (cm3)	Weight (kg)	Cost (USD)
H2 Cooler	1	Misc	**326**	**0.85**	**$6.13**
Microchannel HX	1	SS316	326	0.85	$6.13
Recuperator	1	SS316	**1,592**	**4.96**	**$36.00**
Microchannel HX	1	SS316	1,592	4.96	$36.00
Burner	1	Misc	**7,953**	**10.12**	**$510.26**
Microchannel HX	1	Inconel	2,153	6.12	$91.76
H2/air non-catalytic 82 kW burner	1	Misc	1,000	2.00	$400.00
H2 Blower	1	Misc	4,800	2.00	$18.50
H2 Separator/Coagulating filter			**784**	**3.08**	**$52.40**
Coagulation filter	1	Misc	783	1.80	$43.09
Separator	1	SS316	1	1.28	$9.31
Flow Components	1	Misc	**1,826**	**2.45**	**$59.50**
3-Way Valve	1	Misc	262	0.45	$40.00
Piping System	1	SS316	1,564	0.00	$15.00
Fitting	10	SS316	0	2.00	$4.50
H2 Buffer Storage Tank	1	Misc	**36,271**	**1.33**	**$15.87**
Buffer Storage Tank Body	1	Al-2219-T81 alloy	36,229	0.96	$12.22
Outlet Fitting	1	SS316	9	0.07	$1.00
Inlet Fitting	1	SS316	9	0.07	$1.00
Drain Fitting	1	SS316	9	0.07	$1.00
Drain Plug	1	SS316	5	0.05	$0.50
Mounting Bolt	6	Misc	5	0.05	$0.10
Nut	6	Misc	5	0.05	$0.05

Onboard System BOM: Support Systems

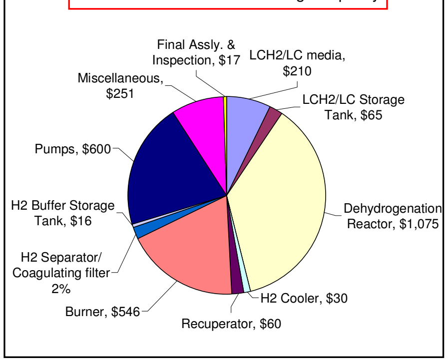
Description	Qty	Material	Volume (cm3)	Weight (kg)	Cost (USD)
Pumps	1		**40,000**	**60.00**	**$600.00**
HTF presure head: 1 bar	1		30,000	40.00	$400.00
LCH2 pressure head: 8 bar	1		10,000	20.00	$200.00
Fill port	1	Misc	**524**	**0.91**	**$28.00**
Inlet Quick Connector	1	Misc	262	0.45	$14.00
Outlet Quick Connector	1	Misc	262	0.45	$14.00
Valves	1	Misc	**1,311**	**2.50**	**$77.00**
Solenoid Valve	1	Misc	262	0.50	$25.00
Ball Valve	1	Misc	262	0.50	$13.00
Check Valve	1	Misc	262	0.50	$14.00
Pressure Relief Device	1	Misc	262	0.50	$5.00
Pressure Relief Valve	1	Misc	262	0.50	$20.00
Sensors	1	Misc			**$30.00**
Temperature Transducer	1	Misc			$10.00
Pressure Transducer	1	Misc			$20.00
Pipe & Fitting	1	Misc	**1,042**	**1.00**	**$12.25**
Piping	1	SS316	1,042	0.00	$10.00
Fitting	5	SS316		1.00	$2.25
Primary Pressure Regulator	1		**787**	**1**	**$44.00**

We conducted a "rough estimate" analysis of an autothermal liquid carrier by making simple modifications to our existing liquid hydrocarbon (LCH_2) model.

- We modified the original (i.e., N-ethylcarbazole) LCH_2 material assumptions based on input from APCI assuming a hypothetical autothermal carrier
  - Original System: 5.8% material capacity and 67.7% storage capacity (i.e., 32.3% of the stored hydrogen has to be burned to generate heat for dehydrogenation)
  - Modified System: 6.7% material capacity and 100% storage capacity (i.e., assume no hydrogen has to be burned)
- We maintained the 95% dehydrogenation reactor conversion efficiency
- The modified system would require an oxidation reactor, but would not require a HEX burner
  - The oxidation reactor would use a V_2O_5 catalyst
  - We roughly assumed there would be no net change in cost, weight, and volume from swapping the HEX burner with the oxidation reactor
- All other BOP components were assumed to be the same

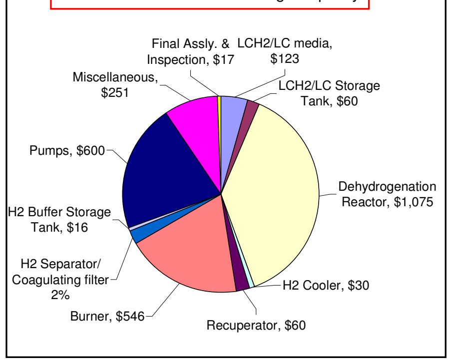
Although the system weight and volume are reduced by 25%, the improved material and storage capacities reduces the system cost by less than 5%.

Original LCH_2 System Cost
5.8% Material and 67.7% Storage Capacity



System Factory Cost = $2,930
\$15.7/kWh based on 5.6 kg usable H_2 (8.7 kg stored H_2)

Modified LCH_2 System Cost
6.7% Material and 100% Storage Capacity



System Factory Cost = $2,839
\$15.2/kWh based on 5.6 kg usable H_2 (5.9 kg stored H_2)

Note: a trade-off study was not performed on the size/cost of the pumps versus size/cost of the reactor sub-system.

Our "rough estimate" for an autothermal liquid carrier shows a 25% reduction in system weight and volume is possible, but cost savings are minimal.

- With improved material (5.8% → 6.7%) and storage (67.7% → 100%) capacities, the modified on-board system shows significant weight and volume reductions
  - However, additional material and BOP improvements would be required to meet the 2010 DOE weight and volume targets

Modified LCH_2 System Versus DOE Targets	Weight (kg)	Volume (L)
LCH_2 Material Only	88	73
-including tank	96	99
2010 DOE target for 5.6 kg usable H2	124	200
Net available for BOP	28	101
Current estimate for BOP	95	112

- Improvements to the material and storage capacities do little to decrease the system cost because the dehydrogenation reactor and BOP account for over 90% of the system cost
  - The dehydrogenation reactor accounts for ~40% of the system cost (Pd catalyst accounts for 85% of the reactor cost)
  - The system pumps and HEX burner/oxidation reactor account for another ~40% of the system cost

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

Vehicle Cost Assumptions[1] ($/vehicle)	Gasoline ICEV	cH_2 FCV[2]	SBH FCV	LCH_2 FCV	Basis/Comment
Glider	$7,148	$7,148	$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	$2,549	$2,549	Includes engine cooling radiator
Transmission, Traction Motor, PE	$1,085	$1,264	$1,264	$1,264	Includes electronics cooling radiator
Exhaust, Accessories	$500	$500	$500	$500	Assumes exhaust and accessories are $250 each
Energy Storage	$110	$1,755	$1,755	$1,755	Includes battery hardware, acc battery and energy storage cooling radiator
Fuel Storage	$51	$5,548	$1,632	$5,026	H_2 storage cost from On-board Cost Assessment
Manufacturing/ Assembly Markup	$5,500	$7,045	$7,045	$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	$3,445	$3,445	
Total Retail Price	**$19,191**	**$29,222**	**$25,328**	**$28,703**	

[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.
[2] cH_2 FCV option assumes 6,250 psi dispensing and 5,000 psi on-board storage system.

When the whole vehicle, including the powertrain purchased price, is included, the conventional gasoline ICEV will likely be noticeably cheaper than the FCV options.