Hydrogen Storage Technologies

The environmentally friendly, zero emission, renewable, high-energy, high-power & low-cost technology for the planet

Application of hydrogen storage

- Stationary application
  - Off-board
  - Residential life
  - Industrial application
- Moving application
  - Transportation (on-board)
    - Automobile, scooter, wheeler, bicycle
  - Portable appliance
    - Mobile phone
    - Notebook computer

Finding moving hydrogen storage solution is one of the major challenges in achieving the hydrogen economy.

Table 1. DOE Technical Targets: On-Board Hydrogen Storage Systems[a, b, c]				
Storage Parameter	Units	2005	2010	2015
Usable, specific-energy from H_2 (net useful energy/max system mass)[d]	kW hr/kg ($kg\ H_2$/kg)	1.5 (0.045)	2 (0.06)	3 (0.09)
Usable energy density from H_2 (net useful energy/max system volume)	kW hr/L ($kg\ H_2$/L)	1.2 (0.036)	1.5 (0.045)	2.7 (0.081)
Storage system cost[e]	$/kWe hr net ($/kg H_2)	6 (200)	4 (133)	2 (67)
Fuel cost[f]	$ per gallon gasoline equivalent at pump	3	1.5	1.5
Operating ambient temperature[g]	°C	-20/50 (sun)	-30/50 (sun)	-40/60 (sun)
Cycle life (1/4 tank to full)[h]	Cycles	500	1000	1500
Cycle life variation[i]	% of mean (min) @ % confidence	N/A	90/90	99/90
Minimum and Maximum delivery temperature of H_2 from tank	°C	-20/100	-30/100	-40/100
Minimum full flow	(g/sec)/kW	0.02	0.027	0.033
Minimum delivery pressure of H_2 from tank FC=fuel cell, I=ICE	Atm (abs)	2.5 FC 10 ICE	2.5 FC 35 ICE	2 FC 35 ICE
Transient response 10%-90% and 90%-0%[j]	Sec	0.5	0.5	0.5
Start time to full flow at 20°C	Sec	4	0.5	0.5
Start time to full flow at minimum ambient	Sec	8	4	2
Refueling rate[k]	$kg\ H_2$/min	0.5	1.5	2
Loss of useable hydrogen[l]	(g/hr)/kg H_2 stored	1	0.1	0.05
Permeation and leakage[m]	Scc/hr	Federal enclosed-area safety-standard		
Toxicity		Meets or exceeds applicable standards		
Safety		Meets or exceeds applicable standards		

Hydrogen Storage Options

current hydrogen storage for fuel cells application

- high pressure hydrogen gas
- cryogenic storage of liquid hydrogen at low temperature.
- metal hydride, where hydrogen is chemically bound to a metallic material
- complex hydride
- carbon fibres and nanotubes
- hydrocarbon reforming : NG, LPG, Gasoline, CH_4, CH_3OH

Solid-state Storage : safer and more efficient

Safe, efficient and cost-effective storage is a key element in the development of hydrogen as an energy carrier

Common requirement for hydrogen storage

- Weight and volume
- Cost
- Efficiency
- Safety
- Life cycle
- Environmental impact

Compressed hydrogen storage

Pressure:	150bar →	350bar →	700bar
	(steel)	(fiber reinforced aluminum)	
Gravimetric Density(wt%)			
Volumetric Density(g/L)		23	38

Drawback: small volumetric density

spend more energy


TOYOTA
FUEL CELL
三河330
さ 53-04


350bar


Iwatani Group

Max speed : 108.3 km/h

Distance: 231km

Max speed: 63km/h

Accumulative distance: 2000km

250bar

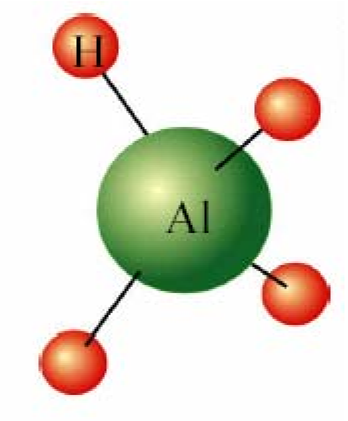
Fuel Cell Vehicle in China

Cryogenic storage of liquid hydrogen

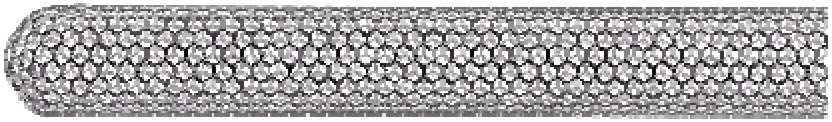
- Appropriate hydrogen storage density (70.8g/L)
- Major drawback:
  - Large quantity of energy required for liquefaction(about more than 30% energy loss)
  - Evaporation loss → safety?

Solid state storage

- Hydride
  - – Metal hydride
  - – Complex hydride
- Nanostructured materials



High volumetric density (100g H_2/L)



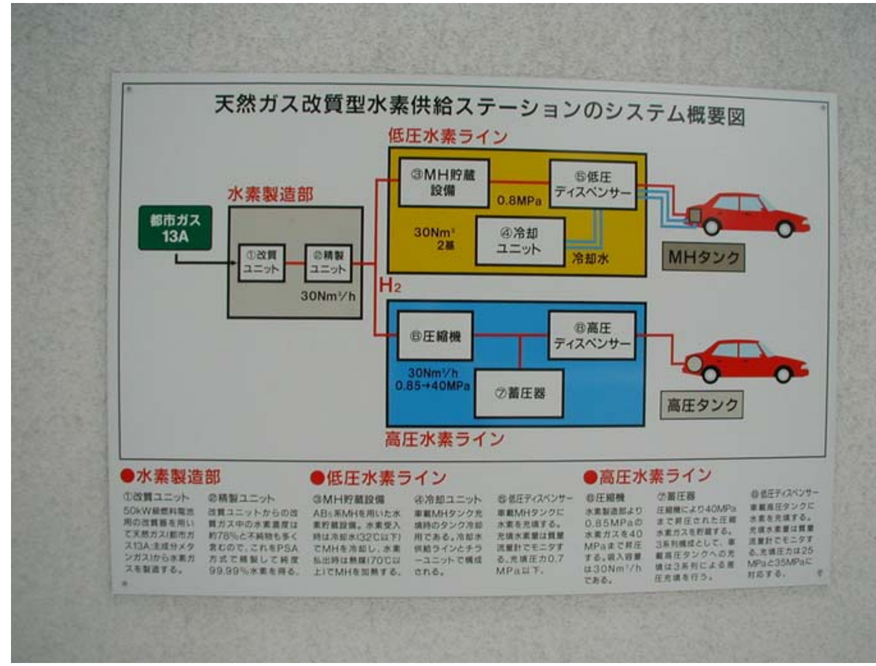
Basic characteristics of different metal hydride

alloy	materials	Capacity (wt%)	Density (g/cm³)	Equi;ibrium pressure (MPa)	Reaction enthalpy ΔH(hj/molH$_2$)	Cycle life	cost
RE-Ni	$LaNi_5$	1.4	8.3	0.2(20°C)	30.1	>1000	$$$
	$MlNi_5$	1.6	8.4	0.35	26.5	>1000	$$
	$Ml_{1-x}Mm_x(MnNiAlCo)_5$	1.5	8.3	0.5	-	-	$$$
Ti-Fe	$TiFe_{0.9}Mn_{0.1}$	1.78	6.5	0.5	29.3	>1000	$
	$Ti_{1-x}Fe_{1-y}Mn_yMm_z$	1.9	6.5	0.5	29.3	>1000	$
Ti-Mn	TiZrCrMnV	2.1	6.5	0.8	29.4	-	$$$$
	TiZrCrMnCu	1.7	6.5	0.85	23.4	>1000	$$$
	TiZrCrMnVFe	1.9	6.5	0.25	29.8	>2000	$$$$
	$Ti_{0.9}Zr_{0.2}Cr_{0.4}Mn_{1.4}(VFe)_{0.2}$	2.0	6.5	0.45	25.2	-	$$
Mg	Mg_2Ni	3.6	3.2	0.1(250 °C)	64.4	-	$

Increase reversible gravimetric density

2002 Ovonic Hydrogen Prius

Left: Ovonic Onboard Vessel, 3 Kg H_2 @ 1,500 psi; 150 miles
Right: Compressed H2 Vessel, 0.78 Kg H_2 @ 5,000 psi; 40 miles



FCHV3 built in 2001 with the top speed of 150 km/hr and 300 km cruising distance used some 100 kg hydrogen storage alloy of around 2wt% hydrogen capacity.

Application

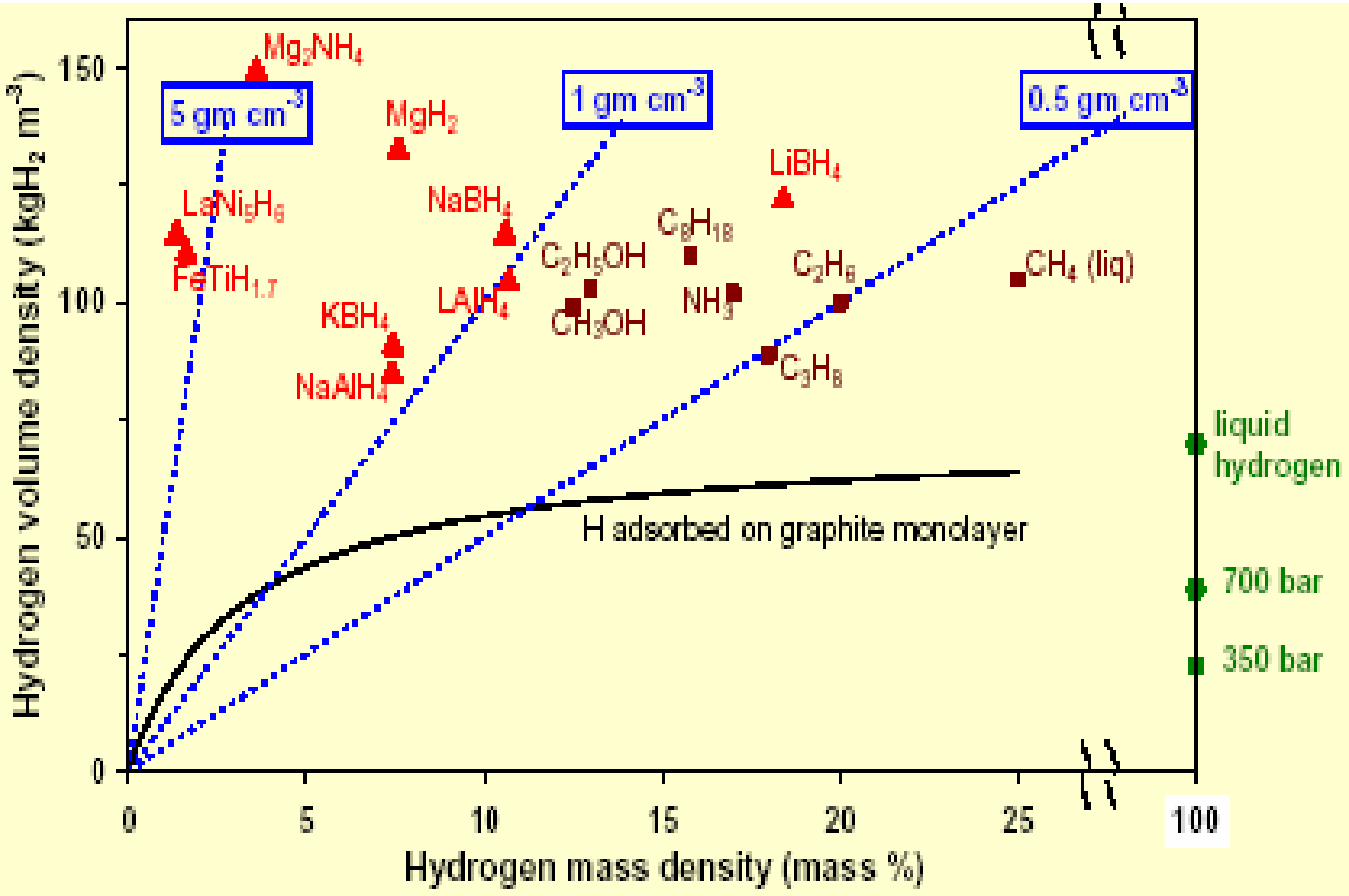
More than 3000 tons metal hydride were produced in China

MH hydrogen storage units for hydrogen recovery and purification

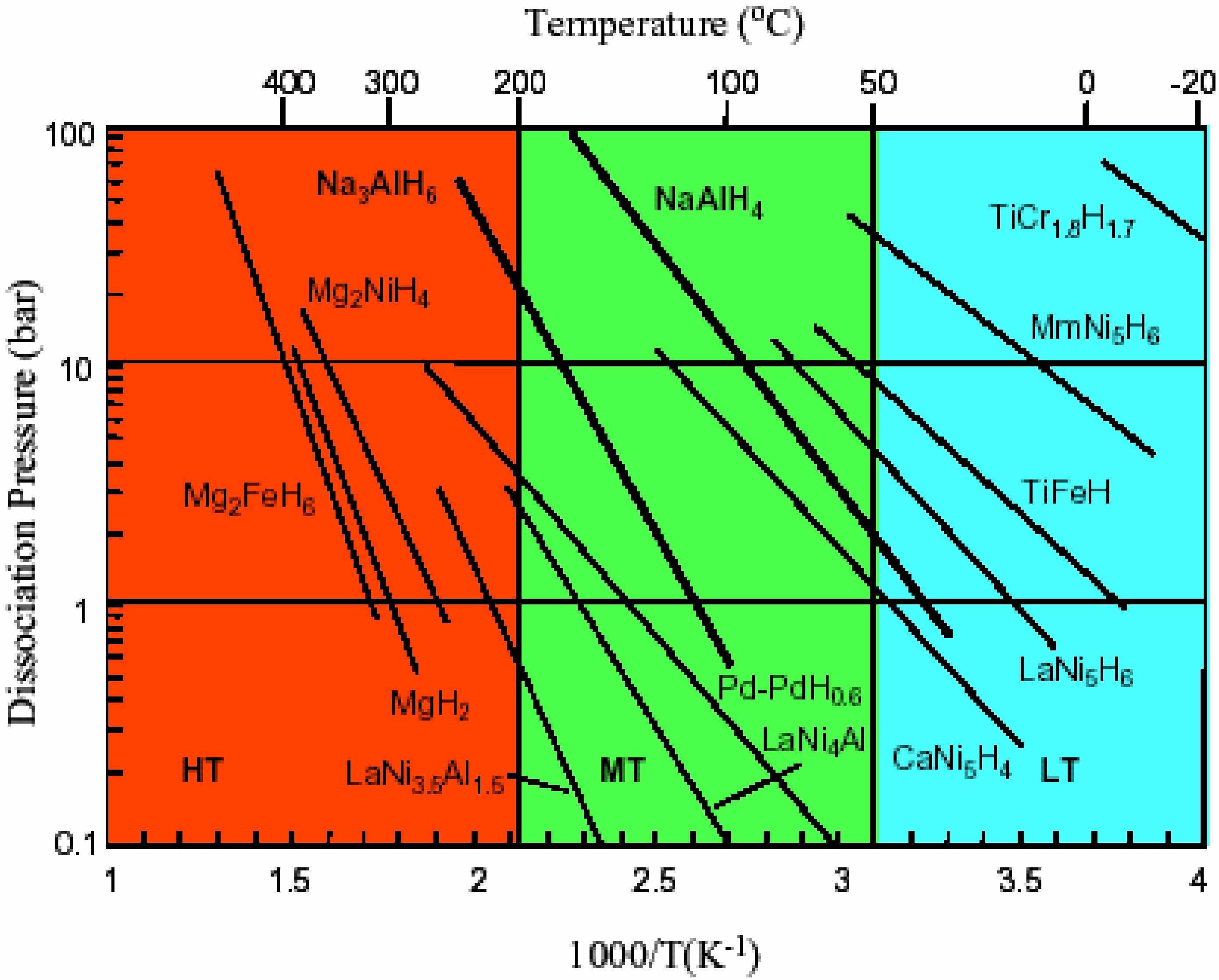
MH hydrogen storage units for hydrogen purification and compression

Mini-type MH hydrogen storage-purification unit

Mini-type MH hydrogen compressor



Hydrogen volume density (kgH2 m-3)
Hydrogen mass density (mass %)
150
100
50
0
0
5
10
15
20
25
100
5 gm cm-3
1 gm cm-3
0.5 gm cm-3
Mg2NH4
MgH2
LaNi5H6
FeTiH1.7
NaBH4
LiBH4
KBH4
NaAlH4
LAlH4
C2H5OH
CH3OH
C8H18
NH3
C2H6
C3H8
CH4 (liq)
H adsorbed on graphite monolayer
liquid hydrogen
700 bar
350 bar


Temperature (°C)
400
300
200
100
50
0
-20
Dissociation Pressure (bar)
100
10
1
0.1
Na3AlH6
NaAlH4
TiCr1.8H1.7
Mg2NiH4
MmNi5H6
Mg2FeH6
TiFeH
LaNi5H6
Pd-PdH0.6
MgH2
LaNi4Al
HT
LaNi3.5Al1.5
MT
CaNi5H4
LT
1
1.5
2
2.5
3
3.5
4
1000/T(K-1)

Nanostructured materials

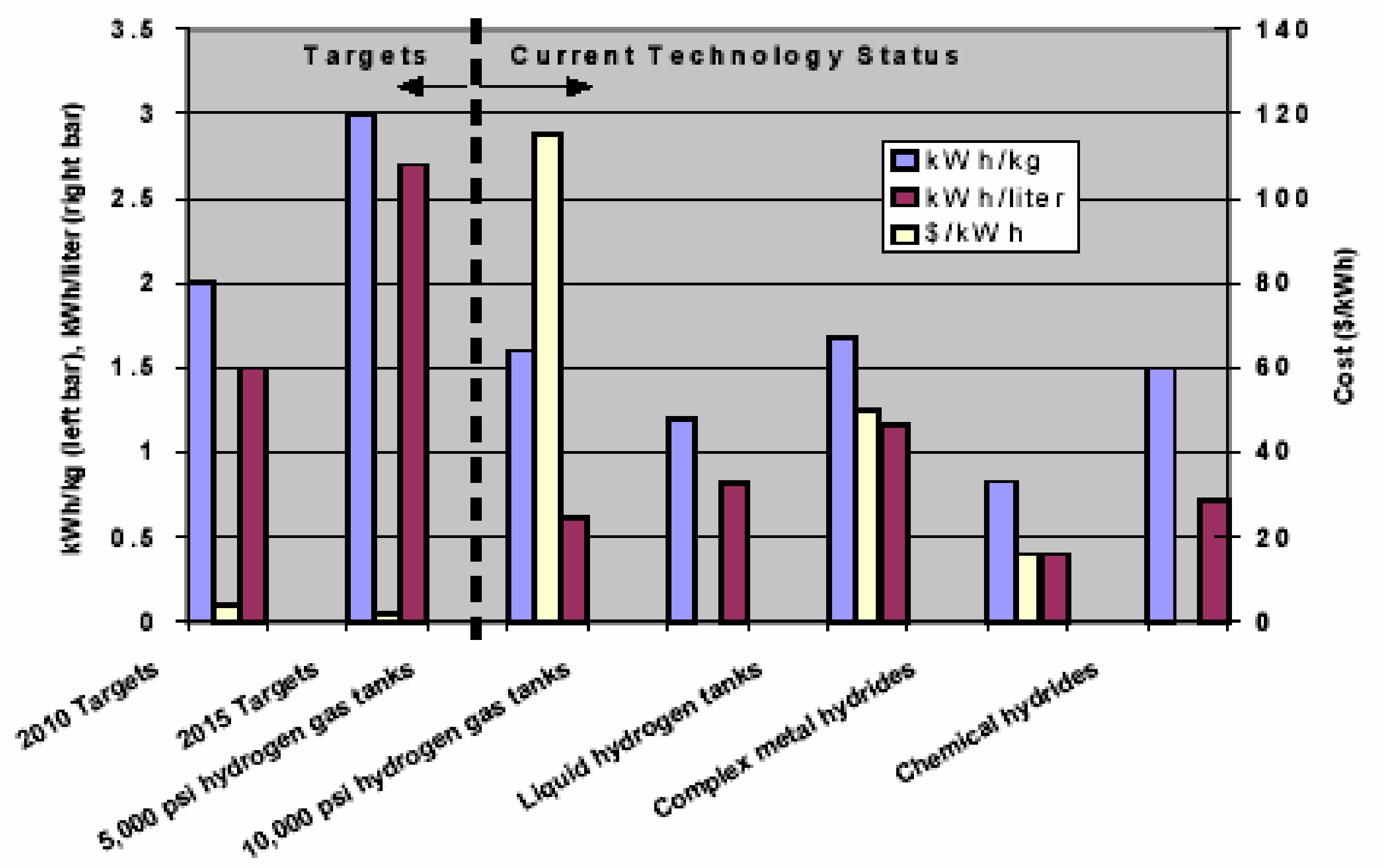
Technical Challenges	R&D Projects/Milestones
Theory 1. confirm interaction of H2-curved C 2. reliably predict heat and entropy of H2 adsorption to rank order candidate materials 3. optimize capacity by structural design	1. form team to examine existing results by 2003 2. identify tractable candidates, use variety of methods to obtain trends 3. develop potential models for cluster surrogates for adsorption sites by 2006 4.
Experiment 1. reproducible synthesis and process 2. develop universal reproducible measurement techniques 3. measurement on perturbation of H-H And C-C bond with degree of interaction 4. synthesize new compositions, esp highly curved C	1. 2. 3. 4.
Engineering 1. specify key transport and equilibrium sorption parameters for Freedom Car 2. address cyclability and durability 3. address poisoning 4.	1. 2. 3. 4.

Storage Results on Nanocarbons Vary Widely

>10 wt%

< 1 wt%

Material	Density wt%	Temp (K)	Pressure (MPa)	Reference	Year
GNFs (herring bone)	67.55	RT	11.35	Chambers	1998
GNFs (platelet)	53.68	RT	11.35	Chambers	1998
Li-MWNTs	20	~473-673	0.1	Chen	1999
K-MWNTs	14	< 313	0.1	Chen	1999
GNFs (tubular)	11.26	RT	11.35	Chambers	1998
CNFs	~10	RT	10.1	Fan	1999
Li/K-GNTs (SWNT)	~10	RT	8-12	Gupta	2000
GNFs	~10	RT	8-12	Gupta	2000
SWNTs (lo purity)	5-10	273	0.04	Dillon	1997
SWNTs (hi purity)	8.25	80	7.18	Ye	1999
CN nanobells	8	573	0.1	Bai	2001
Nano graphite	7.4	RT	1	Orimo	2000
SWNTs (hi p + Ti alloy)	6-7	~300-700	0.07	Dillon	2000
GNFs	6.5	RT	~12	Browning	2000
CNFs	~5	RT	10.1	Cheng	2000
MWNTs	~5	RT	~10	Zhu	2000
SWNTs (hi p + Ti alloy)	3.5-4.5	~300-600	0.07	Dillon	1999
SWNTs (50% purity)	4.2	RT	10.1	Liu	1999
Li-MWNTs	~2.5	~473-673	0.1	Yang	2000
SWNT (50% purity)	~2	RT	echem	Nutzenadel	1999
K-MWNTs	~1.8	< 313	0.1	Yang	2000
(9,9) array	1.8	77	10	Wang	1999
MWNTs	< 1	RT	echem	Beguin	2000
CNF	0.1-0.7	RT	0.1-10.5	Poirier	2001
(9,9) array	0.5	RT	10	Wang	1999
SWNTs	~0.1	300-520	0.1	Hirscher	2000
Various	< 0.1	RT	3.5	Tibbets	2001
SWNT (+ Ti alloy)	0	RT	0.08	Hirscher	2001



Targets
Current Technology Status
kWh/kg
kWh/liter
$/kWh
kWh/kg (left bar), kWh/liter (right bar)
Cost ($/kWh)
3.5
3
2.5
2
1.5
1
0.5
0
140
120
100
80
60
40
20
0
2010 Targets
2015 Targets
5,000 psi hydrogen gas tanks
10,000 psi hydrogen gas tanks
Liquid hydrogen tanks
Complex metal hydrides
Chemical hydrides

Research content

- Solid state system
- Chemical hydrogen storage system
- Standardized testing
- System analyses

Cooperative way

- Exchange of information and personality
- Standard and criterion
- Public platform of test