



# A REVIEW ON THE PROGRESS OF INTERMETALLIC SOLID-STATE HYDROGEN STORAGE MATERIAL FOR FUEL CELL VEHICLES

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**Abstract:** The world is swiftly moving towards the renewable sources of energy owing to the depletion of fossil fuel reserves and detrimental impacts of green house gases on mankind and environment. Hydrogen is gaining more importance in the technical community around the globe as an energy carrier for the on-board vehicular applications. Solid state hydrogen storage is relatively emerged as an alternative option for storing hydrogen on-board as the conventional technologies viz., high pressure compression and cryogenic liquefaction failed to meet the storage goals. Profound research has been done to improve the hydrogenation properties of intermetallic compounds. The current paper aims at reviewing the latest advancements in the properties of intermetallic compounds for solid-state hydrogen storage applications viz., adsorption/desorption pressure and temperature, kinetics, hydrogen-storage capacity and cyclic stability.

**Keywords:** Hydrogen storage; Intermetallic compounds; fuel cell vehicles; adsorption/desorption pressure and temperature; Kinetics; Storage capacity; cyclic stability.

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## INTRODUCTION

The escalating growth of the human population and rapid evolution of heavy industrial sectors results in a continuing increase in energy demands [1]. In order to fulfill the ever increasing energy demands, current and future energy systems should be cost-effective, practical, reliable and sustainable, with low impact on the environment [2]. The depletion of fossil fuels and other non-renewable energy sources is a prevalent issue [3], and one of the greatest challenges nowadays is to develop energy systems which will fulfill energy demands by harnessing energy from renewable and sustainable sources [4]. Even though fossil fuels are widely used for energy provision, the burning of fossil fuels also releases high amounts of greenhouse gas emissions (resulting in air pollution and global warming) and have detrimental impact on ecological systems [5]. Hence, scientists and researchers strive continuously to develop energy systems which harness energy from renewable and sustainable sources such as solar, wind, wave and geothermal energy. Solar and wind energy are generally

dependent on weather conditions. Wave energy is harnessed from the oceans whereas geothermal energy is harnessed from the hot rocks and fluids within the Earth's crust, and therefore these two forms of energy are generally location dependent. More importantly, these sources of energy are difficult to store and transport [6].

For these reasons, there is growing interest in hydrogen fuel-based technologies in recent years. Hydrogen is a promising energy carrier since it is capable of storing and delivering energy in usable form. The energy density of hydrogen is between 120 MJ/kg (LHV) and 142 MJ/kg (HHV), which is about three times higher than the energy density for petroleum [7,8]. Hydrogen is renewable and available in abundance, and more importantly, it is a clean fuel which releases only water vapour into the environment during combustion [9]. Moreover, hydrogen can be stored in portable and transportable systems, making it an attractive alternative source of energy for motor vehicles [10]. The development of hydrogen energy systems involves three main steps: generation, storage and utilization of hydrogen [11]. In order to make hydrogen fuel-based transportation a norm in the future, it is imperative to design and develop hydrogen storage systems that are cost-effective, safe, efficient and practical for onboard vehicular applications. This calls for cutting-edge research which encompasses various fields of science and engineering in order to produce such systems [12]. Hydrogen storage materials should possess the following characteristics: low absorption/desorption temperatures, rapid hydrogenation and dehydrogenation rates, good reversibility and high volumetric hydrogen storage densities [13]. Above all, hydrogen storage materials should be inexpensive in order to make hydrogen fuel-based transportation affordable for vehicle users.

Hydrogen can be stored in gaseous, liquid or solid states in either one of the following forms: (1) as compressed gas in highly pressurized tanks, (2) as liquid in cryogenic tanks, or (3) as solids in metallic hydrides or nano structured

materials [14, 15]. The first hydrogen storage method is undesirable since compressed hydrogen gas requires highly pressurized vessels and the materials used to construct these vessels should be strong, lightweight, and highly resistant to explosions in the event of vehicle collisions. In addition, compressed hydrogen gas systems have low volumetric hydrogen storage densities. In contrast, the liquefaction method increases the volumetric hydrogen storage density, but it requires cooling the hydrogen to 20 K. Furthermore, the hydrogen storage system needs to be maintained at

temperatures below 20 K in order to ensure that the hydrogen remains in liquid form [16]. For these reasons, both compressed hydrogen gas and cryogenic hydrogen liquid technologies are impractical for on-board vehicular applications [17].

Department of Energy for on-board vehicular applications [18]. The reader may refer to Ref. [19] for a detailed treatment on the targets set by the United States Department of Energy and only a brief summary is given in Table 1.

**Table 1.** Brief summary on the targets for hydrogen storage systems set by the US Department of Energy for on-board vehicular applications in year 2017.

S.No	Parameter	Unit	2017 goal
1	System gravimetric capacity	kg H <sub>2</sub> /kg system	0.055
2	System volumetric capacity	kg H <sub>2</sub> /L system	0.040
3	Operating temperature	°C	40/60
4	Cycle life	cycles	1500
5	System fill time (5 kg)	min	3.3

The real challenge for realizing “hydrogen economy” is hydrogen storage. The different intermetallic compounds which have been used so far include the FeTi, LaNi<sub>5</sub>, LiBH<sub>4</sub> etc. An ideal hydrogen-storage material should have high hydrogen capacity per unit mass and unit volume, low dissociation temperature, high stability against O<sub>2</sub>, limited energy loss during charge and discharge of hydrogen, fast kinetics, and moisture for long cycle life, low cost of recycling and high safety. Hydrogen storage with intermetallic hydrides was investigated 20 years ago. The current progress of intermetallic compounds for solid-state hydrogen storage applications is given in Table 2. It is believed that this article will be beneficial to all scientists, researchers, and practitioners involved in hydrogen storage materials research.

The intermetallic compounds are prepared by different methods viz., Ball Milling (BM), Melting - arc melting, RF melting, induction melting, HF melting, HF-Induction Levitation Melting, RF Levitation Melting, Vacuum Induction Melting and Magnetic Levitation Melting, Ball milling + Melting, Powder Sintering Process, CO Surface Treatment, Hydriding Combustion Synthesis, Activated by HPT, Twin-Rolling, Solid-State Sintering Method, Diffusion Method, Ball milling + diffusion synthesis etc. The hydrogen adsorption and desorption properties of intermetallic compounds for solid-state hydrogen storage applications and the ongoing research work in this area are shown in Table 2 along with the references [20-106].

**Table 2.** Current progress of intermetallic compounds for solid-state hydrogen storage applications

Reference	Material	Method	Temperature (°C)		Pressure (bar)		Kinetics (min)		Max Hydrogen Wt%	Cycling Stability	Reference
			T <sub>ads</sub>	T <sub>des</sub>	P <sub>ads</sub>	P <sub>des</sub>	t <sub>ads</sub>	t <sub>des</sub>			
Aoyagi et al (1995)	LaNi <sub>5</sub>	BM	20	-	20	-	1.6	-	0.25	8 Cycles :: Not Stable	[20]
Zhao et al (2012)	Ti <sub>1.6</sub> Zr <sub>0.4</sub> Ni	BM	40	-	1	-	-	-	0.78	100 Cycles :: Stable	[79]
Zhao et al (2012)	Ti <sub>1.8</sub> Zr <sub>0.2</sub> Ni	BM	40	-	1	-	-	-	0.93	20 Cycles :: Stable	[79]
Goo NH et al (2005)	Mgs	BM	-196	-	50	-	-	-	0.95	-	[21]
Iosub et al (2006)	La <sub>0.9</sub> Ce <sub>0.05</sub> Nd <sub>0.04</sub> Pr <sub>0.01</sub> Ni <sub>4.63</sub> Sn <sub>0.32</sub>	Melting	100	25	5-10	0.2-4	6.6	6.6	0.95	-	[22]
Bououdina et al (2000)	Zr(Cr <sub>0.8</sub> Mo <sub>0.2</sub> ) <sub>2</sub>	Induction Melting	120	-	30	-	-	-	0.99	-	[23]
Kadir et al (2002)	YMgNi <sub>4</sub>	Melting	40	-	40	-	-	-	1.05	-	[96]
Chen Y et al (2003)	Ml <sub>0.85</sub> Ca <sub>0.15</sub> Ni <sub>5</sub>	RF Melting	-	25	-	60	-	60	1.10	100 Cycles :: Stable	[24]
Lee et al (2000)	Ti <sub>1.1</sub> FeB <sub>0.001</sub>	Arc Melting	50	-	10	-	-	-	1.10	-	[49]
Young et al (2013)	Zr <sub>21.5</sub> V <sub>10</sub> Cr <sub>7.5</sub> Mn <sub>8.1</sub> Co <sub>8.0</sub>	Arc Melting	60	-	0.2-4	-	-	-	1.11	-	[78]

	Ni <sub>32.2</sub> Sn <sub>0.3</sub> Al <sub>0.4</sub> (Y content of 4% in exchange for Co)										
Zhao et al (2012)	Ti <sub>1.8</sub> Zr <sub>0.2</sub> Ni	Solid-State Sintering Method	20		1				1.11		[79]
Stoyan et al (2008)	MmNi <sub>4.6</sub> Co <sub>0.6</sub> Al <sub>0.8</sub>	Induction Melting	30		1				1.12		[80]
Dehouche et al (2005)	LaNi <sub>4.8</sub> Sn <sub>0.2</sub>	Arc Melting	80	80	-	3-4	-	-	1.16	1000 Cycles :: Stable	[25]
Yao et al (2014)	LaNi <sub>4.5</sub> Co <sub>0.25</sub> Al <sub>0.25</sub>	Arc Melting	28						1.17	50 Cycles :: Stable	[93]
Cuevas et al (2012)	Ti <sub>0.64</sub> Zr <sub>0.36</sub> Ni	Induction Melting	127		10				1.20		[76]
Mitrokhin et al (2013)	V <sub>0.6</sub> Cr <sub>0.4</sub>	Arc Melting	20	20	130	32.6			1.20		[77]
Kazakov et al (2020)	La <sub>0.6</sub> Ce <sub>0.2</sub> Nd <sub>0.2</sub> Ni <sub>4</sub> Co <sub>0.4</sub> Mn <sub>0.3</sub> Al <sub>0.3</sub>	Arc Melting				1			1.23	100 Cycles :: Stable	[93]
Young et al (2013)	Zr <sub>21.5</sub> V <sub>10</sub> Cr <sub>7.5</sub> Mn <sub>8.1</sub> Co <sub>8.0</sub> Ni <sub>32.2</sub> Sn <sub>0.3</sub> Al <sub>0.4</sub> (Y content of 2% in exchange for Co)	Arc Melting	30		0.17				1.24		[78]
Georgiadis et al (2009)	Zr <sub>0.9</sub> Ti <sub>0.1</sub> Cr <sub>0.8</sub> V <sub>0.8</sub> Ni <sub>0.4</sub>	Arc Melting		65		1		70	1.25		[74]
Peng Lv et al (2016)	Ti <sub>0.95</sub> FeZr <sub>0.05</sub>	Arc Melting	30		20		114		1.25		[101]
Li et al (2016)	YFe <sub>1.3</sub> Al <sub>0.7</sub>	Arc Melting	100		15				1.25		[105]
Lu D et al (2006)	La <sub>0.59</sub> Ce <sub>0.29</sub> Pr <sub>0.03</sub> Ni <sub>4</sub> Co <sub>0.45</sub> Mn <sub>0.45</sub> Al <sub>0.3</sub>	Twin-Rolling	60	-	10	0.6	-	-	1.27	-	[26]
Young et al (2013)	Zr <sub>21.5</sub> V <sub>10</sub> Cr <sub>7.5</sub> Mn <sub>8.1</sub> Co <sub>8.0</sub> Ni <sub>32.2</sub> Sn <sub>0.3</sub> Al <sub>0.4</sub> (Y content of 0% in exchange for Co)	Arc Melting	30		0.56				1.29		[78]
Kazakov et al (2016)	LaNi <sub>4.6</sub> Fe <sub>0.2</sub> Sn <sub>0.2</sub>	Arc Melting		40-60		30			1.29		[86]
Challet et al (2006)	La <sub>0.55</sub> Y <sub>0.45</sub> Ni <sub>5</sub>	Induction Melting	-	-20	-	3.5	-	-	1.30	5 Cycles :: Stable	[27]
Chen Y et al (2003)	Ti <sub>0.9</sub> Zr <sub>0.15</sub> Mn <sub>1.6</sub> Cr <sub>0.2</sub> V <sub>0.2</sub>	RF Melting	-	25	-	10	-	60	1.30	100 Cycles :: Stable	[24]
Muthukumar et al (2005)	MmNi <sub>4.6</sub> Al <sub>0.4</sub>	Melting	25	25	-	25	-	5	1.30	11 Cycles :: Stable after 9 <sup>th</sup> cycle	[28]
Lee et al (2000)	Ti <sub>1.1</sub> FeC <sub>0.001</sub>	Arc Melting	50		6				1.30		[49]
Kesavan et al (2000)	Zr <sub>2</sub> Ho <sub>0.8</sub> Fe <sub>5</sub> Co <sub>1.5</sub>	Arc Melting	27		4				1.30		[53]
Bowman et al (2002)	LaNi <sub>5-y</sub> Sn <sub>y</sub>	Arc/Induction Melting	27		0.3-0.72				1.30		[67]
Rodyskakić et al (2000)	LaNi <sub>5-y</sub> Zn <sub>y</sub>	Arc Melting	20		0.1-1.6				1.30		[68]
Kazakov et al (2016)	LaNi <sub>4.8</sub> Sn <sub>0.1</sub> Al <sub>0.1</sub>	Arc Melting		40-60		25			1.30		[86]
Kaveh et al (2016)	TiFe <sub>0.85</sub> Mn <sub>0.15</sub>	BM	30		21		1		1.30		[95]

Kaveh et al (2016)	TiFe <sub>0.7</sub> Mn <sub>0.3</sub>	BM	30		21		1		1.30		[95]
Peng Lv et al (2016)	TiFe <sub>0.95</sub> Zr <sub>0.05</sub>	Arc Melting	30		20		20 5		1.30		[101]
Emami et al (2015)	TiFe	Activated by BM	30		10				1.30		[103]
Kazakov et al (2016)	LaNi <sub>4.6</sub> Fe <sub>0.2</sub> Al <sub>0.2</sub>	Arc Melting		40-60			25		1.32		[86]
Young et al (2013)	Zr <sub>21.5</sub> V <sub>10</sub> Cr <sub>7.5</sub> Mn <sub>8.1</sub> Co <sub>8.0</sub> Ni <sub>32.2</sub> Sn <sub>0.3</sub> Al <sub>0.4</sub> (Y content of 3% in exchange for Co)	Arc Melting	60		0.2 9				1.33		[78]
Wang et al (2009)	Ti <sub>0.1</sub> Zr <sub>0.15</sub> V <sub>0.35</sub> Cr <sub>0.1</sub> Ni <sub>0.3</sub> + 5% (La <sub>0.85</sub> Mg <sub>0.25</sub> Ni <sub>4.5</sub> Co <sub>0.3</sub> 5Al <sub>0.15</sub> ) TVS Alloy+5% AB <sub>5</sub> Intermetallic	Arc Melting	30		5- 10				1.34	100 Cycles :: Stable	[83]
Jain et al (2015)	TiFe+4 wt% Zr <sub>7</sub> Ni <sub>10</sub>	Arc Melting		40			20 20		1.34		[102]
Kazakov et al (2016)	LaNi <sub>4.6</sub> Fe <sub>0.2</sub> Sn <sub>0.2</sub>	Arc Melting		20			30		1.35		[86]
Young et al (2013)	Zr <sub>21.5</sub> V <sub>10</sub> Cr <sub>7.5</sub> Mn <sub>8.1</sub> Co <sub>8.0</sub> Ni <sub>32.2</sub> Sn <sub>0.3</sub> Al <sub>0.4</sub> (Y content of 2% in exchange for Co)	Arc Melting	60		0.5 6				1.36		[78]
Kazakov et al (2016)	LaNi <sub>4.8</sub> Sn <sub>0.1</sub> Al <sub>0.1</sub>	Arc Melting		20			25		1.37		[86]
Li et al (2016)	YFe <sub>1.5</sub> Al <sub>0.5</sub>	Arc Melting	100		15				1.37		[105]
Young et al (2013)	Zr <sub>21.5</sub> V <sub>10</sub> Cr <sub>7.5</sub> Mn <sub>8.1</sub> Co <sub>8.0</sub> Ni <sub>32.2</sub> Sn <sub>0.3</sub> Al <sub>0.4</sub> (Y content of 0% in exchange for Co)	Arc Melting	30		0.5 6				1.38		[78]
Corre S et al (1998)	La <sub>0.9</sub> Ce <sub>0.1</sub> Ni <sub>5</sub>	CO Surface Treatment	0-100	25	50	-	-	1.8	1.40	20 Cycles :: Stable after 5 <sup>th</sup> cycle	[29]
Bobet et al (2000)	Ti <sub>1.95</sub> Zr <sub>0.05</sub> Mn <sub>1.45</sub> Al <sub>1.5</sub>	Induction Melting	25		21				1.40		[57]
Nakamura et al (2000)	LaNi <sub>4.75</sub> Al <sub>1.25</sub>	R.F Induction Melting	50		1				1.40		[62]
Zadorozhny et al (2012)	TiFe	BM			3-4				1.40	20 Cycles :: Stable	[71]
Kazakov et al (2016)	LaNi <sub>4.6</sub> Fe <sub>0.2</sub> Al <sub>0.2</sub>	Arc Melting		20			25		1.40		[86]
Odysseos et al (2013)	La <sub>0.5</sub> Ce <sub>0.5</sub> Ni <sub>5</sub>	HF-Induction Levitation Melting	20		42				1.40		[92]
Peng Lv et al (2016)	TiFeZr <sub>0.05</sub>	Arc Melting	30		20		24 0		1.40		[101]
Sharma et al (2014)	LaNi <sub>4.6</sub> Al <sub>0.4</sub>	Arc Melting	20	20	20- 30	20- 30			1.41		[73]
Sharma et al (2015)	LaNi <sub>4.7</sub> Al <sub>0.3</sub>	Arc Melting	20		20- 30				1.41		[94]
Li et al	YFe <sub>2</sub>	Arc Melting	100		15				1.42		[105]

(2016)												
Sharma et al (2014)	LaNi <sub>4.7</sub> Al <sub>0.3</sub>	Arc Melting	20	20	20-30	20-30				1.43		[73]
Sharma et al (2015)	LaNi <sub>4.7</sub> Al <sub>0.3</sub>	Arc Melting	20		20-30					1.43		[94]
Corre S et al (1998)	LaNi <sub>5</sub>	CO Surface Treatment	0-100	25	50	-	-	13.6		1.44	20 Cycles :: Stable after 5 <sup>th</sup> cycle	[29]
Wang X et al (2006)	Ml <sub>0.75</sub> Ca <sub>0.25</sub> Ni <sub>5</sub>	RF Levitation Melting	20	-	100	6.8	-	-		1.45	-	[28]
Jain et al (2000)	MmNi <sub>4.5</sub> Al <sub>1.5</sub>	----	30		3					1.45	16 Cycles :: Stable	[64]
Liu et al (2015)	La <sub>0.85-x</sub> (Sm <sub>0.75</sub> Mg <sub>0.25</sub> ) <sub>x</sub> Mg <sub>0.15</sub> Ni <sub>3.65</sub>	Powder Sintering Process	30		3.7	6				1.46		[106]
Sharma et al (2015)	La <sub>0.9</sub> Ce <sub>0.1</sub> Ni <sub>5</sub>	Arc Melting	20		20-30					1.48		[94]
Santos DS dos et al (2003)	80 wt% TiCr <sub>1.1</sub> V <sub>0.9</sub> -20 wt%LaNi <sub>5</sub>	Melting + BM	30	30	17	0.5	-	-		1.50	-	[30]
Balema et al (2000)	Sc <sub>1-x</sub> Ti <sub>x</sub> Ni	Arc Melting	25		0.1					1.50		[51]
Bobet et al (2000)	TiMn <sub>1.45</sub> Al <sub>1.5</sub>	Induction Melting	25		22					1.50		[59]
Singh et al (2000)	TiMn <sub>1.5</sub>	R.F Induction Melting	22		5					1.50		[60]
Georgiadis et al (2009)	Zr <sub>0.9</sub> Ti <sub>0.1</sub> Cr <sub>0.8</sub> V <sub>0.8</sub> Ni <sub>0.4</sub>	Arc Melting		100		1		90		1.50		[74]
Odysseos et al (2013)	La <sub>0.4</sub> Ce <sub>0.6</sub> Ni <sub>5</sub>	HF-Induction Levitation Melting	20		30					1.50		[92]
Sharma et al (2015)	La <sub>0.8</sub> Ce <sub>0.2</sub> Ni <sub>5</sub>	Arc Melting	20		20-30					1.52		[94]
Wang X et al (2006)	Ti <sub>0.97</sub> Zr <sub>0.03</sub> Cr <sub>1.6</sub> Mn <sub>0.4</sub>	RF Levitation Melting	20	-	100	81	-	-		1.55	-	[28]
Liu Y et al (2005)	La <sub>0.7</sub> Mg <sub>0.3</sub> Ni <sub>2.65</sub> Mn <sub>0.1</sub> Co <sub>0.9</sub>	Melting	30	30	5	0.3	-	-		1.56	-	[31]
Li et al (2016)	YFe <sub>1.7</sub> Al <sub>0.3</sub>	Arc Melting	100		15					1.56		[105]
Pickering et al (2013)	Ti <sub>0.47</sub> V <sub>0.46</sub> Mn	Arc Melting	30		120					1.58		[81]
Lee et al (2000)	Ti <sub>1.1</sub> Fe	Arc Melting	50		5					1.60		[49]
Ma et al (2000)	Ti <sub>1.3</sub> Fe + 1.5 wt.% Mm (misch metal)	Induction Melting	25		1.5					1.60		[50]
Lee et al (2000)	Zr <sub>0.7</sub> Ti <sub>0.3</sub> (Mn <sub>0.2</sub> V <sub>0.2</sub> Cr <sub>y</sub> Ni <sub>6-y</sub> ) <sub>1.8</sub> y=0-0.15	Arc Melting	30		0.0	4-0.0				1.60		[54]
Lee et al (2000)	Zr <sub>1-x</sub> Ti <sub>x</sub> (Mn <sub>0.2</sub> V <sub>0.2</sub> Ni <sub>0.6</sub> ) <sub>1.8</sub> x=0-0.6	Arc Melting	30		0.0	2-0.2				1.60		[54]
Song et al (2001)	Zr <sub>0.5</sub> Ti <sub>0.5</sub> Mn <sub>0.4</sub> V <sub>0.6</sub> Ni <sub>0.85</sub> Al <sub>0.15</sub>	Arc Melting	30		0.0	2				1.60		[55]
Song et al (2001)	Zr <sub>0.5</sub> Ti <sub>0.5</sub> Mn <sub>0.4</sub> V <sub>0.6</sub> Ni <sub>0.85</sub> Co <sub>0.15</sub>	Arc Melting	30		0.1	5				1.60		[55]
Song et al (2001)	Zr <sub>0.5</sub> Ti <sub>0.5</sub> Mn <sub>0.4</sub> V <sub>0.6</sub> Ni <sub>0.85</sub> Cu <sub>0.15</sub>	Arc Melting	30		0.0	7				1.60		[55]
Song et al (2001)	Zr <sub>0.5</sub> Ti <sub>0.5</sub> Mn <sub>0.4</sub> V <sub>0.6</sub> Ni <sub>0.85</sub> Fe <sub>0.15</sub>	Arc Melting	30		0.1					1.60		[55]
Song et al (2001)	Zr <sub>0.5</sub> Ti <sub>0.5</sub> Mn <sub>0.4</sub> V <sub>0.6</sub> Ni <sub>0.85</sub> Mn <sub>0.15</sub>	Arc Melting	30		0.0	4				1.60		[55]
Hsu et al (2000)	ZrMn <sub>0.6</sub> V <sub>0.2</sub> Co <sub>0.1</sub> Ni <sub>1.2</sub>	Arc Melting	25		0.5					1.60		[56]
Bobet et al	Ti <sub>0.95</sub> Zr <sub>0.05</sub> Mn <sub>2-y</sub>	Induction	25		25					1.60		[59]

(2000)	y=0.05-0.35	Melting									
Jain et al (2002)	MmNi <sub>4.5</sub> Al <sub>5</sub>	----	22		2.1				1.60		[65]
Jain et al (2015)	TiFe+4 wt% Zr	Arc Melting		40		20	20		1.60		[102]
Mitrokhin et al (2013)	ZrFe <sub>1.8</sub> Mo <sub>0.2</sub>	Arc Melting	25	25	65	20			1.62		[77]
Pickering et al (2013)	Ti <sub>0.5</sub> V <sub>0.5</sub> Mn	Arc Melting	30		120				1.63		[81]
Mitrokhin et al (2013)	ZrFe <sub>1.8</sub> CU <sub>0.2</sub>	Arc Melting		25		215			1.65		[77]
Liu et al (2000)	Zr <sub>9</sub> Ti <sub>1</sub> Mn <sub>6</sub> V <sub>2</sub> Co <sub>1</sub> Ni <sub>1</sub>	Vacuum Induction Melting	40		0.5				1.60		[61]
Lee et al (2000)	Zr(Mn <sub>2</sub> V <sub>2</sub> Ni <sub>6</sub> ) <sub>2-y</sub> y=0.1-0.4	Arc Melting	30		0.0 2- 0.0 6				1.65		[54]
Mitrokhin et al (2013)	ZrFe <sub>1.8</sub> Co <sub>0.2</sub>	Arc Melting	25	25	725	360			1.69		[77]
Lee et al (2000)	Zr(Mn <sub>4</sub> Ni <sub>6</sub> ) <sub>1.9</sub>	Arc Melting	30		0.1 5				1.70		[54]
Hsu et al (2000)	ZrMn <sub>8</sub> Ni <sub>1.2</sub>	Arc Melting	25		0.5				1.70		[56]
Sarma et al (2000)	MmNi <sub>4.6</sub> Fe <sub>4</sub>	Diffusion Method	30		18				1.70		[66]
Kaveh et al (2013)	TiFe	BM	30		7				1.70		[72]
Mitrokhin et al (2013)	V <sub>0.5</sub> Cr <sub>0.5</sub>	Arc Melting	20	20	340	66			1.70		[77]
Yang et al (2016)	LaMgNi <sub>3.6</sub> Mo <sub>0.4</sub> (M=Ni, Co, Mn, Cu, Al)	Vacuum Induction Melting	50		30		10		1.70	20 Cycles :: Stable	[97]
Okada et al (2002)	Cr-22Ti-35V	Arc Melting		40		10			1.70		[88]
Keveh et al (2013)	TiFe	Activated by HPT	30		10				1.70		[104]
Mitrokhin et al (2013)	ZrFe <sub>2</sub>	Arc Melting	25	25	690	325			1.72		[77]
Bououdina et al (1998)	Zr <sub>0.75</sub> Ti <sub>0.25</sub> Cr <sub>1.5</sub> Ni <sub>0.5</sub>	Arc Melting	40	-	47	-	-	-	1.75	-	[32]
Jain et al (2002)	LaNi <sub>4.82</sub> Si <sub>0.25</sub>		40-70		1.1				1.75	16 Cycles :: Stable	[63]
Mitrokhin et al (2013)	ZrFe <sub>1.8</sub> Mn <sub>0.2</sub>	Arc Melting	25	25	290	140			1.78		[77]
Mitrokhin et al (2013)	ZrFe <sub>1.8</sub> Cr <sub>0.2</sub>	Arc Melting	20	20	80	85			1.79		[77]
Mitrokhin et al (2013)	ZrFe <sub>1.8</sub> V <sub>0.2</sub>	Arc Melting		20		12			1.79		[77]
Mitrokhin et al (2013)	ZrFe <sub>1.8</sub> Cr <sub>0.2</sub>	Arc Melting	25	25	80	55			1.79		[77]
Mitrokhin et al (2013)	ZrFe <sub>1.8</sub> Ni <sub>0.2</sub>	Arc Melting	25	25	455	250			1.72		[77]
Kojima et al (2005)	Ti <sub>1.1</sub> CrMn	Arc Melting	23	23	33	1	1	5	1.80	1000 Cycles :: Stable	[33]
Ma et al (2000)	Ti <sub>1.3</sub> Fe + 6 wt.% Mm (misch metal)	Induction Melting	25		1.5				1.80		[50]
Park et al (2001)	(Ti <sub>0.75</sub> Zr <sub>0.25</sub> ) <sub>1.05</sub> Mn <sub>0.8</sub> Cr <sub>1.05</sub> V <sub>0.05</sub> Cu <sub>0.1</sub>	Arc Melting	30		3				1.80		[52]
Park et al (2001)	(Ti <sub>0.8</sub> Zr <sub>0.2</sub> ) <sub>1+x</sub> Mn <sub>0.8</sub> Cr <sub>1.2</sub>	Arc Melting	30		3-9				1.80		[52]
Park et al	Ti <sub>0.8</sub> Zr <sub>0.2</sub> MnCr	Arc Melting	30		10				1.80		[52]

(2001)											
Hsu et al (2000)	ZrMn <sub>6</sub> V <sub>2</sub> Ni <sub>1.2</sub>	Arc Melting	25			0.14				1.80	[56]
Ma et al (2014)	Ti <sub>0.7</sub> Zr <sub>0.3</sub> (Mn <sub>0.8</sub> V <sub>0.2</sub> ) <sub>2</sub>	Arc Melting	20			0.01-40				1.80	30 Cycles :: Stable [70]
Ma et al (2014)	Ti <sub>0.7</sub> Zr <sub>0.3</sub> (Mn <sub>0.7</sub> V <sub>0.3</sub> ) <sub>2</sub>	Arc Melting	20			0.01-40				1.80	30 Cycles :: Stable [70]
Park et al (2001)	(Ti <sub>0.75</sub> Zr <sub>0.25</sub> ) <sub>1+x</sub> Mn <sub>0.8</sub> Cr <sub>1.2</sub>	Arc Melting	30			1.5-6				1.85	[52]
N. Ohba et al (2005)	CaSi	RF Melting		200			0.09			1.90	[34]
Ma et al (2000)	Ti <sub>1.3</sub> Fe	Induction Melting	25			2				1.90	[50]
Bobet et al (2000)	Ti <sub>0.95</sub> Zr <sub>0.05</sub> Mn <sub>1.45</sub> Co <sub>0.5</sub>	Induction Melting	25			32				1.90	[57]
Bobet et al (2000)	Ti <sub>0.95</sub> Zr <sub>0.05</sub> Mn <sub>1.45</sub> Cr <sub>0.5</sub>	Induction Melting	25			28				1.90	[57]
Bobet et al (2000)	Ti <sub>0.95</sub> Zr <sub>0.05</sub> Mn <sub>1.45</sub> Ni <sub>0.5</sub>	Induction Melting	25			36				1.90	[57]
Bobet et al (2000)	Ti <sub>0.95</sub> Zr <sub>0.05</sub> Mn <sub>1.95</sub>	Induction Melting	25			29				1.90	[57]
Bobet et al (2000)	TiMn <sub>1.45</sub> Co <sub>0.5</sub>	Induction Melting	25			32				1.90	[59]
Bobet et al (2000)	TiMn <sub>1.45</sub> Cr <sub>0.5</sub>	Induction Melting	25			38				1.90	[59]
Bobet et al (2000)	TiMn <sub>1.45</sub> Ni <sub>0.5</sub>	Induction Melting	25			36				1.90	[59]
Ciric et al (2012)	TiFe <sub>1-x</sub> Ni <sub>x</sub>	Arc Melting	100			50				1.90	[75]
Mitrokhin et al (2013)	Zr <sub>0.8</sub> Ti <sub>0.2</sub> FeNi <sub>0.8</sub> V <sub>0.2</sub>	Arc Melting	20	20		28	27			1.90	[77]
Shibuya et al (2009)	Ti <sub>0.5</sub> V <sub>0.5</sub> Mn	Arc Melting	-13			350				1.90	[82]
Zaluski et al (1995)	FeTi	BM	25	-		100	-	-	-	1.92	- [35]
Bobet et al (2000)	Ti <sub>0.95</sub> Zr <sub>0.05</sub> Mn <sub>1.45</sub> V <sub>0.5</sub>	Induction Melting	25			20				2.00	[57]
Kuriwa et al (1999)	V – 7.4% Zr – 7.4% Ti – 7.4% Ni	Arc Melting	40	-		10	1	-	-	2.00	10 Cycles :: Not Stable [36]
Xu et al (2001)	Ti <sub>0.9</sub> Zr <sub>0.2</sub> Mn <sub>1.6</sub> Ni <sub>0.2</sub> (VFe) <sub>0.2</sub>	Induction Melting	25	25		9.6	3.6			2.00	[58]
Xu et al (2001)	Ti <sub>0.9</sub> Zr <sub>0.2</sub> Mn <sub>1.8</sub> (VFe) <sub>0.2</sub>	Induction Melting	25	25		9.8	3			2.00	[58]
Bobet et al (2000)	TiMn <sub>1.95</sub>	Induction Melting	25			31				2.00	[59]
Xu et al (2001)	Ti <sub>0.9</sub> Zr <sub>0.15</sub> Mn <sub>1.6</sub> Cr <sub>0.2</sub> V <sub>0.2</sub>	Induction Melting	25	25		20	6.96			2.10	[58]
Xu et al (2001)	Ti <sub>0.9</sub> Zr <sub>0.2</sub> Mn <sub>1.4</sub> Cr <sub>0.4</sub> (VFe) <sub>0.2</sub>	Induction Melting	25	25		10	3			2.10	[58]
Xu et al (2001)	Ti <sub>0.9</sub> Zr <sub>0.2</sub> Mn <sub>1.4</sub> Cr <sub>0.4</sub> V <sub>0.2</sub>	Induction Melting	25	25		3.4	1.9			2.10	[58]
Xu et al (2001)	Ti <sub>0.9</sub> Zr <sub>0.2</sub> Mn <sub>1.6</sub> Cr <sub>0.2</sub> (VFe) <sub>0.2</sub>	Induction Melting	25	25		14.7	7			2.10	[58]
Xu et al (2001)	Ti <sub>0.9</sub> Zr <sub>0.2</sub> Mn <sub>1.6</sub> Ni <sub>0.2</sub> V <sub>0.2</sub>	Induction Melting	25	25		6	2.7			2.10	[58]
Xu et al (2001)	Ti <sub>0.9</sub> Zr <sub>0.2</sub> Mn <sub>1.8</sub> V <sub>0.2</sub>	Induction Melting	25	25		10	3			2.10	[58]
Bobet et al (2000)	TiMn <sub>1.45</sub> V <sub>0.5</sub>	Induction Melting	25			20				2.10	[59]
Mitrokhin et al	Zr <sub>0.3</sub> Ti <sub>0.7</sub> Fe <sub>1.4</sub> V <sub>0.6</sub>	Arc Melting	20	20		5.1	4.2			2.10	[77]

al (2013)												
Singh et al (2014)	Ti <sub>0.32</sub> Cr <sub>0.43</sub> V <sub>0.25</sub> + 10 wt% La	Arc Melting	20		60					2.18		[100]
Seo C-Y et al (2003)	V <sub>0.375</sub> Ti <sub>0.25</sub> Cr <sub>0.3</sub> Mn <sub>0.075</sub>	Arc Melting	30	30	50	0.2	-	-		2.20	-	[37]
Takasaki et al (2006)	Ti <sub>45</sub> Zr <sub>38</sub> Ni <sub>17</sub>	BM	300	427	80	-	1200	-		2.23	-	[38]
Singh et al (2014)	Ti <sub>0.32</sub> Cr <sub>0.43</sub> V <sub>0.25</sub> + 2 wt% La	Arc Melting	20		60					2.23		[100]
Mitrokhin et al (2013)	V <sub>0.9</sub> Cr <sub>0.1</sub>	Arc Melting	20	20	29	15.5				2.30		[77]
Singh et al (2014)	Ti <sub>0.32</sub> Cr <sub>0.43</sub> V <sub>0.25</sub> + 5 wt% La	Arc Melting	20		60					2.31		[100]
Singh et al (2014)	Ti <sub>0.32</sub> Cr <sub>0.43</sub> V <sub>0.25</sub>	Arc Melting	20		60					2.35		[100]
Kuji et al (2002)	Mg <sub>1.5</sub> Ni	BM	300		3.7					2.60		[39]
Sanjay Kumar et al (2017)	Mg <sub>2</sub> Ni-10 wt.% V.	BM		200		20		5		2.60		[87]
Okada et al (2002)	Cr-25Ti-35V	Arc Melting		40		9-10				2.60		[88]
Okada M et al (2002)	Ti - V - Cr	Arc Melting	40	40	100					2.80	-	[40]
Jiang et al (2002)	YH <sub>3</sub> -MgH <sub>2</sub> -MgCu <sub>2</sub>	Induction Melting		277		0.001				3.00		[39]
Kuji et al (2002)	Mg <sub>2</sub> Ni	BM	300		3.7					3.10		[39]
Yuan et al (2001)	Mg <sub>1.9</sub> Ti <sub>0.1</sub> Ni <sub>0.9</sub> Mn <sub>0.1</sub>	Diffusion Method	250		0.8					3.10		[41]
Yu XB et al (2006)	Ti - 10Cr -18Mn - 27V - 5Fe	Magnetic Levitation Melting	60	-	30	1	8.3	-		3.10	-	[42]
Lin et al (2007)	Mg <sub>2</sub> Ni	BM		350	50-60					3.14		[89]
Yang et al (2002)	Mg <sub>2</sub> Ni <sub>0.75</sub> Ti <sub>0.25</sub>	Ball milling + diffusion synthesis	250		1-1.3					3.20		[48]
Yang et al (2002)	Mg <sub>2</sub> Ni	Ball milling + diffusion synthesis	250		1.1					3.20		[48]
Sanjay Kumar et al (2017)	Mg <sub>2</sub> Ni-5 wt.% V	BM		200		8		5		3.25		[87]
Yu XB et al (2006)	Ti - 10Cr -18Mn - 32V	Magnetic Levitation Melting	-20	300	30	1	8.3	-		3.36	-	[42]
Yang et al (2000)	Mg <sub>2</sub> Ni <sub>0.75</sub> Co <sub>0.25</sub>	BM	300		1					3.40		[69]
Santos DS dos et al (2003)	TiCr <sub>1.1</sub> V <sub>0.9</sub>	Melting + BM	30	30	17	0.5	-	-		3.50	-	[30]
Jain et al (2013)	CeNi <sub>4</sub> Cr	Arc Melting		20-60		32				3.50		[85]
Asheesh et al (2013)	Ti <sub>1.8</sub> CrVC <sub>0.2</sub>	Arc Melting	30		20		5			3.52		[98]
Asheesh et al (2013)	Ti <sub>1.8</sub> CrVNi <sub>0.2</sub>	Arc Melting	30		20		2.83			3.67		[98]
Asheesh et al (2013)	Ti <sub>1.9</sub> CrVC <sub>0.1</sub>	Arc Melting	30		20		5			3.68		[98]
Reiser et al	Mg <sub>2</sub> Fe	Melting		450		57				3.70		[46]



(2000)											
Jain et al (2013)	CeNi <sub>3</sub> Cr <sub>2</sub>	Arc Melting		20-60		32			3.80		[85]
Asheesh et al (2013)	Ti <sub>1.9</sub> CrVFe <sub>0.1</sub>	Arc Melting	30		20		5		3.80		[98]
Lin et al (2007)	(Mg <sub>2</sub> Ni) <sub>95</sub> Ti <sub>5</sub>	BM		350	50-60				3.88		[89]
Nomura et al (1995)	Ti <sub>43.5</sub> V <sub>49</sub> Fe <sub>7.5</sub>	Arc Melting	-20	300	100	10	20	-	3.90	50 Cycles :: Stable	[43]
Asheesh et al (2013)	Ti <sub>1.9</sub> CrVNi <sub>0.1</sub>	Arc Melting	30		20		2.83		3.91		[98]
Yu XB et al (2004)	Ti-V-Cr-Mn	Magnetic Levitation Melting	-	247-472	30	0.03	-	-	3.98	-	[44]
Jain et al (2013)	CeNi <sub>4</sub> Zr	Arc Melting		20-60		32			4.00		[84]
Asheesh et al (2013)	Ti <sub>2</sub> CrV	Arc Melting	30		20		3.75		4.01		[98]
Qian Li et al (2006)	La <sub>0.5</sub> Ni <sub>1.5</sub> Mg <sub>17</sub>	Hydriding combustion synthesis	280-400		2.21-11.34	0.03	15		4.03		[45]
Yu et al (2003)	Ti-40V-10Cr-10Mn	Arc Melting	20		30				4.20		[99]
Reiser et al (2000)	Mg <sub>2</sub> Co	Melting		450		16			4.50		[46]
Lass et al (2012)	Mg <sub>85</sub> Ni <sub>10</sub> Y <sub>2.5</sub> Pd <sub>2.5</sub>	Induction Melting	200-300		10-50		90	90	4.60	8-10 Cycles :: Stable	[91]
Gao L et al (2005)	La <sub>1.8</sub> Ca <sub>0.2</sub> Mg <sub>14</sub> Ni <sub>3</sub>	BM	27-327	27-327	40	1	15	10	5.00	6 Cycles :: Not Stable	[47]
Reiser et al (2000)	Mg <sub>2</sub> Fe	Melting		450		25			5.50		[46]
Ponthieu et al (2013)	Mg <sub>6</sub> Pd <sub>0.25</sub> Ni <sub>0.75</sub>	Induction Melting	377		30				5.60		[90]

## SUMMARY OF INTERMETALLIC STORAGE COMPOUNDS

There is no perfect choice of hydrogen store material to meet the set US DOE goals for transport applications. Although some results are encouraging, such as improved kinetics and lower decomposition temperatures for metal hydrides, further research is needed to develop materials satisfying the needs for technical applications. In the light of the achievements, there is high potential in developing better hydride materials with high reversible hydrogen capacity at ambient temperatures.

- Low hydrogen absorption/desorption temperature/pressure
- Multiple cycles are possible
- High volume storage capacity
- Good hydrogenation kinetics
- Low gravimetric storage capacity
- Not suited for mobile applications

## CONCLUSION

Hydrogen storage is a key issue in the success and realization of hydrogen technology and economy.

According to US DOE, the hydrogen-storage capacity target for commercialization is 6.5 wt% at the decomposition temperature between 60 and 120 °C with high cycle life. Although pure water contains 11.1 wt% of hydrogen, its decomposition requires much thermal, electric, or chemical energy.

Since the conventional hydrogen fuel storage methods of pressurized H<sub>2</sub> gas and cryogenic liquid H<sub>2</sub> pose safety and permeation problems along with high cost, they do not meet future on-board applications goals set for hydrogen economy. Solid state hydrogen fuel storage either absorption in the interstices of metals and metallic alloys or adsorption on high surface area materials such as activated carbons gain the attention for possible future hydrogen applications. The present article reviews the hydrogen-storage intermetallic storage materials for transport applications which require research into further aspects of tank technology, heat management and solid fuel recycling. The work is carried out in an attempt to facilitate prospectus material choice for further tank design aiming at on-board vehicle applications.

Hydrogen storage in inter metallic hydrides have more advantages in comparison to gaseous or liquid storage. Compared to other materials, metallic hydrides can hold up to 5.6 wt%. Although storage is safe, desorption limits its use.

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