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Gas-based hydride applications: recent progress and future needs

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Abstract

Hydride applications can be cataloged under five main categories: H_2 storage, thermal compression (including closed thermodynamic systems), gas separation, electrochemical and processing and miscellaneous. Recent commercial and R&D hydride applications activities are reviewed herein (excluding the NiMH battery). Growing interest in fuel cell power has stimulated interest in hydride storage of H_2, with good near-term commercial potential in the subcategories of stationary, small portable and on-board vehicular storage. The competition for vehicular hydride storage is high pressure compressed H_2 held in lightweight composite cylinders. If hydrides are to compete, we must develop radical new concepts to substantially increase the gravimetric capacity at low desorption temperatures.
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Keywords: Hydrogen storage materials; Gas–solid reactions; Metal hydride applications

1. Professor Moshe Ron (1925–2001)

This paper is dedicated to the memory of Moshe Ron, an early pioneer in the properties and applications of reversible metal hydrides. One of his principal hydride applications interests was the hydride heat pump [1–3]. This spawned extensive work in the property areas of hydride heat transfer [4–6] and kinetics [7–9]. He led the development of ‘porous, metallic–matrix hydrides (PMH)’, whereby inert metallic matrices were used to simultaneously enhance the mechanical stability and heat conductivity of hydrides [4–6]. One of Professor Ron’s last publications gave us an extensive ‘normalized pressure dependence method’, a model for quantifying and generalizing hydride kinetics [9]. Extensive references to the work of him and his many students and coworkers can be found therein. The end to Moshe Ron’s direct contributions to the field of metal hydrides is to be regretted by the M–H community, but indirectly he will influence us for years to come.

2. Introduction

The ultimate utility of all our work on hydrogen–metal systems, be it fundamental or engineering, is to aid the development of practical applications. The history of hydride applications R&D is long and rich. It is not our intent in this brief paper to review the entire history of hydride applications. Previous applications reviews have set that stage [10–13]. We shall instead focus on progress during the last few years. In one important area, vehicular H_2 storage, applications progress has somewhat stalled. We shall examine the competition and redefine the targets necessary to capture that market.

The two most important factors in the applications of metal hydrides are the easily reversed gas–solid chemical reaction:

$$M + 0.5xH_2 \longleftarrow\!\!\longrightarrow MH_x + \text{heat} \qquad (1)$$

and the well known van ‘t Hoff relation relating plateau pressure P to temperature T:

$$\ln P = \frac{\Delta H}{RT} - \frac{\Delta S}{R} \qquad (2)$$

where ΔH and ΔS are the enthalpy and entropy changes of the hydriding reaction, respectively, T is absolute temperature and R is the gas constant. Of course, there are numerous other important hydride properties: plateau slope and hysteresis, H-capacity, activation, volume change, decrepitation, reaction kinetics, thermal conductivity, gaseous impurity resistance, cyclic stability, safety and cost [10,14].

Many applications for reversible metal hydrides have

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Table 1
List of hydride applications

- H_2 storage
  - Stationary
  - Portable
  - Vehicular
- Thermal compression
  - H_2 compression
  - Closed thermodynamic systems
    - Heat storage
    - Heat pump
    - Cryocooler
    - Temperature sensor
    - Gas gap heat switch
    - Heat engine
    - Actuator
- Gas separation
  - Isotope separation
  - H_2 gas concentration
    - Separation
    - Purification
    - Gettering
- Electrochemical and processing
  - Catalyst
  - Batteries
    - NiMH
    - Segmented
- Other
  - H_2 detector
  - Switchable mirror
  - Electrical devices
  - Miscellaneous

been proposed. A five-category list of the principal applications is shown in Table 1. Some of the applications listed have reached substantial commercial reality (e.g. NiMH batteries) and many have not. We shall briefly review recent activity on most of the hydride applications listed in Table 1. Because H_2 storage (especially for fuel cell vehicles) offers a large future potential (but with notable difficulties), we leave that area to last. We shall not cover the large electrochemical NiMH battery field, but will briefly mention the gas-phase 'segmented' hydride battery. In general, we shall not discuss the chemical hydrides that are hydrolyzed to generate H_2 gas and for which cyclic reversibility is a difficult task, e.g. the $NaBH_4$ solutions [15,16].

3. Non-storage hydride applications

3.1. Thermal compression

This broad category ranges from the open-ended compression of H_2 gas to closed-cycle thermodynamic systems that utilize a hydride compressor as the driver. In all cases, H_2 is effectively compressed via the van 't Hoff equation (Eq. (2)) utilizing a heat input that is direct or through I^2R electrical means.

3.1.1. H_2 compression

Hydride-based hydrogen compressors have been an application of commerce more than 20 years. They are manufactured and sold mainly by Ergenics, Inc. in single- or multistage-designs [17]. In recent years, a number of new designs have been introduced, including a single stage, electrically-driven unit that is capable of output pressures greater than 400 bar (40 MPa), levels that are particularly useful for filling the high pressure gaseous H_2 tanks commonly being used in prototype fuel cell vehicles [18].

3.1.2. Closed thermodynamic systems

Although numerous prototype systems have been build over the years, most of the closed hydride systems are not yet commercial reality. There are notable exceptions to that, however. As far as we know, the hydride-based aircraft fire detector (a temperature sensor) [19] is still being manufactured and widely used after a quarter century.

Large-scale heat storage remains of limited interest because of the relatively high cost of hydriding alloys, but a design based on Ni-doped MgH_2 and AB_2 alloys offers hope for high-grade solar heat storage and steam generation [20]. There are also special small-scale heat storage possibilities that may tolerate moderately high hydride cost. One is the hydride cold start heater which is designed to store the $>350\,^{\circ}C$ waste heat of an automotive exhaust for later use to rapidly (5 s) heat the catalytic converter, thus quickly reducing the undesirable startup emissions [18,21].

Heat pumps (both temperature upgrading and refrigerator types) remain in positions of relatively strong research and prototype development, although it is not clear that they are approaching commercial viability. Good prototype demonstrations have been recently made in Germany [22,23], Korea [24,25], Finland (with two-stage compressor) [26], Russia [27] and the USA [18]. A conceptual design of an oscillating bed heat pump has been patented [28]. Ergenics, Inc. demonstrated a benchtop automobile air conditioner design capable of 9,000–18,000 BTU/h (9,500–19,000 kJ/h) cooling capability at 7 °C [18]. The unit weighed about 30 kg, including 14 kg of AB_5 hydride. In addition to these experimental demonstrations, there have been some theoretical heat pump models published recently [25,29,30].

Work on hydride heat engines and actuators, the direct conversion of heat to mechanical energy has been relatively inactive in recent years. A solar powered water pump was recently demonstrated in Russia [31]. Automatically resetting fire sprinklers have been developed and offer an interesting commercial possibility [18,32].

The concept of using a $La(Ni,Sn)_5$-based thermal H_2

compressor and Joule–Thomson expansion for aerospace cryocooling is being actively worked on by one of us [33,34]. Included in the cryocooler system are gas gap heat switches, spaces which can be reversibly switched from vacuum insulation to thermally conducting H_2 by using an electrically heated hydride-based H_2 dispenser (e.g. $ZrNiH_{1.5}$, a relatively stable hydride) [35]. The concept of hydride-based gas gap heat switches has also been developed for controlled heat insulation/conducting glass windows for buildings [36].

3.2. Gas separation

3.2.1. Isotope separation

As summarized in an earlier (1995) review [11], the major industrial use of hydrides for hydrogen isotope separation is in the Savannah River (USA) tritium plant where a Pd-based system is used. There have been rather limited isotope separation activities (using other hydrides) in more recent years, notably in Japan [37,38] and China [39]. A predictive, non-isothermal model for the separation of hydrogen isotopes using a Pd column was published [40].

3.2.2. H_2 gas concentration

With the exception of removing H_2 from ammonia purge gas in a small plant in China [41], separation does not seem to have developed into a commercial process. But interest remains. Modeling of the separation process has been performed in Russia [42,43] and the USA [44]. A new process for the separation of H_2 from mixed gas using a hydride sol–gel composite has been developed at Savannah River [45].

The purification of H_2 by metal hydrides is becoming more important in the growing new era of low-temperature PEM (proton exchange membrane) fuel cells. PEM fuel cells do not tolerate impurities like CO very well and hydrides supply exceptionally pure H_2 ideal for PEM fuel cell use [46,47]. For this purpose, Ergenics is designing a combined purifier–compressor capable of handling quite impure H_2 [48]. This is made possible by special bed designs that locally filter the impurities [49].

H_2 gettering is a long-established commercial process that is used widely in vacuum technology and inert gas purification [50]. It is beyond the scope of this brief review.

3.3. Electrochemical and processing

3.3.1. Catalysts

There has been some renewed interest in using hydrides for catalytic purposes, for example, hydrogenation/dehydrogenation of organics [51,52], methanation [53] or the destruction of hazardous organic wastes [54].

3.3.2. Batteries

The ubiquitous NiMH battery (MH anode) represents the most widespread commercial application of reversible hydrides. They are used for high power applications and hybrid gasoline–electric vehicles, but they are being more and more displaced by lithium-ion batteries for low power applications such as cell phones or laptop computers.

A new kind of bipolar battery has been developed by Ergenics that does not use the hydride as an electrode but rather as a gas charged and discharged component [18,55]. In essence, it is a derivative of the nickel–hydrogen battery that is used for aerospace and military applications, but incorporating a 'segmented' MH to maintain low H_2 pressure in the charged state. The problem of protecting the MH from H_2O-saturated H_2 has been solved [49]. Because of its long cycle life and ability to be charged and discharged at extremely rapid rates, the bipolar 'segmented' battery has good potential for use in hybrid electric vehicles.

3.4. Miscellaneous other applications

Other interesting hydride applications have surfaced in the last few years. One is the switchable mirror whereby one makes use of the metal←→insulator transition $YH_2 \longleftrightarrow YH_3$ to change optical properties of a film from mirror to transparent, respectively [56]. This work, originated in The Netherlands, has spawned many interesting fundamental studies and potential practical optical applications. Similarly, the complex semiconducting hydride Mg_2NiH_4 exhibits profound changes in optical properties with temperature and mechanical pressure, suggesting a number of possible electronic applications [57]. We note from the recent patent literature the application of hydrides to certain electrical devices, e.g. a spark plug for internal combustion engines [58] or an end-of-life arc suppression feature for fluorescent light bulbs [59].

4. Hydrogen/hydride storage

We have left hydrogen storage to last because it bears more focus because a growing perceived potential for new commercial applications, stationary, portable and vehicular. There have been a number of companies that have offered commercial hydride storage containers for many years: Ergenics, Inc. [17], Hydrogen Components, Inc. (FuelCellStore) [60], Gesellschaft für Electrometallurgie [61], Japan Metals and Chemicals [62], among others [11]. In the last year, two new major joint companies have formed in North America, specifically to present a bold position to cover the future hydride storage market. On the USA side, ChevronTexaco joined with ECD Ovonic to form Texaco Ovonic Hydrogen Systems, L.L.C. [63], establishing an alloy production, container manufacture and R&D facility in Rochester Hills, MI, USA. The hydride technology for Texaco Ovonic comes from ECD Ovonic. On the Canadian–Dutch–German side, Hydro-Québec, Shell Hydrogen and Gesellschaft für Electrometallurgie formed HERA Hydrogen Storage Systems based in a new production and R&D facility in Longueuil, Canada [64]. This combines the low-temperature, intermetallic hydride expertise of GfE with the nanocrystalline expertise of Hydro-Québec. In addition, a joint development agreement was recently executed between the US company Air Products and Chemicals, Inc. and Japan Metals and Chemicals [65].

4.1. Stationary and portable storage containers

We would estimate that a few thousand small hydride storage units have been made over the last 25 years and used for a variety of stationary and portable purposes. Designs (at least the internal construction) are usually proprietary, but a wide variety of individual products are currently available [17,60–64]. What seems to be driving the near-future market is stationary and portable fuel cell power supplies for instantly available emergency backup power. For example, the Canadian company Hydrogenics now offers a 500 W fuel cell power generator that is supplied with H_2 from a chemical hydride [66]. In the USA, the Coleman Powermate Company reports that it is about to introduce a fuel cell power supply that is supplied by a rechargeable, low temperature hydride [67]. Most of the major fuel cell companies have interest in hydride supply of H_2 for portable and stationary power applications, e.g. United Technologies, Ballard, H-Power, Plug Power and others. There are numerous suitable low temperature hydrides available [13], so we feel no major new R&D is needed for this particular application.

Table 3
Volume and weight comparisons for state-of-the-art on-board vehicular storage of 3 kg H_2 [76]

Technology	System volume (l)	System weight (kg)	Weight % H_2
5,000 p.s.i. (34.5 MPa) compressed H_2	145	45	6.7
10,000 p.s.i. (69 MPa) compressed H_2	100	50	6.0
Low-temperature metal hydride	55	215	1.4
Liquid H_2	90	40	7.5

4.2. Vehicular storage

In the last few years, immense commercial interest has developed in fuel cell vehicles as an answer to poor internal combustion efficiency, pollution and fuel dependence. The need for lightweight, compact onboard H_2 fuel supply is acute. Storage is a major barrier in the minds of the automobile manufacturers. This has led to suggesting the concepts of onboard reforming of hydrocarbon fuels and chemical hydrides, both of which have debatable viability and economics. As shown in Table 2, some recent demonstration vehicles have used reversible metal hydrides [68–75]. But most have used high-pressure compressed gas. The reason for this can be seen from Table 3, which compares the properties of compressed, liquid and hydride storage of H_2 [76]. Compressed hydrogen (C-H_2) offers

Table 2
Recent vehicles using hydride tanks [68–75]

Maker	Designation	Power[a]	Size (kW)	Hydride	Year
GM Opel	Precept FCEV	FC	75	?	2000
Honda	FCX-V1	FC	60	JMC[e]	1999
Mazda	Cappela	ICE	?	JMC	1994
Mazda	Demio	FC	50	?	1997
Toyota	RAV4 FCEV	FC	20	?	1996
Toyota	FCHV-3	FC	90	JMC	2001
John Deere[b]	Gator 1	FC hybrid	8.5	Mm(Ni,Al)$_5$	1998
John Deere[b]	Gator 2	FC hybrid	8.5	Ti(Fe,Mn)	1998
SRTC Bus[b]	Augusta	ICE hybrid	75[i]	Lm(Ni,Al)$_5$[f]	1996
FCPI/SNL[c]	Mine Locomotive	FC	12	(Ti,Zr)(Mn,V,Cr,Fe)$_2$[d]	2001
ECD[g]	Motor Scooter	ICE	?	ECD	2002
Germany	U212 Submarine	FC hybrid	300	GfE[h]	2004

[a] FC = Fuel cell; ICE = internal combustion engine.
[b] Savannah River Technology Center.
[c] Fuel Cell Propulsion Institute/Sandia National Laboratories.
[d] GfE C15, 1.8 wt.% H_2.
[e] Japan Metals and Chemicals.
[f] $Lm_{1.06}Ni_{4.96}Al_{0.04}$, where Lm = La-rich mischmetal.
[g] Energy Conversion Devices.
[h] GfE Gesellschaft für Electrometallurgie.
[i] ICE only (approximate).

excellent gravimetric H-capacity, more than 11 wt.% in advanced designs, far better than we in the hydride community can provide. Composite high pressure gas cylinders are simple and require no heat exchange for release of the contained H_2 for the vehicle use or recharging. But C-H_2 offers poor volumetric H_2 capacity compared to hydrides, not to mention the compression energy and safety disadvantages of C-H_2 at 350–700 bar (35–70 MPa) pressure. From the gas storage proponents' points of view, however, the concept of C-H_2 is safe and composite tanks have been officially certified for high pressure H_2 use [76].

In January 2002, the US Department of Energy announced the FreedomCAR initiative setting cost and performance targets for future fuel cell vehicles [77]. We are asked to provide a complete onboard storage system that provides 6 wt.% H_2. When we consider the hydride container and heat exchange components, we probably need a hydride medium with 7.5+ wt.% H_2 capability. Ideally speaking, we need to have relatively low temperature thermodynamics such that we can use the $<100\,°C$ waste heat of the vehicle fuel cell to provide the endothermic heat of H_2 desorption without burning some of the desorbed H_2 for that purpose. This is far beyond the present state-of-the-art for all known reversible metal hydrides and provides a very strong challenge for us.

5. Conclusion

Hydride applications R&D is alive and well. The most important future application will be elemental H_2 storage for fuel cell vehicles. But we need to develop a new generation of hydrides with far greater gravimetric H-capacity than the present families of metallic (intermetallic compound and solid solution) hydrides, yet with near-ambient thermodynamic and kinetic properties. Recent work on the catalyzed Na-alanates may offer hope, especially if the concept can be extrapolated to the transition metal complexes and the borohydrides [78]. We need new 'breakthrough' concepts. Our task is very difficult, but the technical, environmental and economic rewards will be immense if we succeed.

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References

[1] M. Ron, J. Less-Common Metals 104 (1984) 259.
[2] M. Ron, Y. Joshepy, Z. Phys. Chem. NF 164 (1989) 1475.
[3] M. Ron, Y. Joshepy, in: Proceedings of the 24th Intersociety Energy Conversion Engineering Conference, IEEE, New York, 1989, p. 2097.
[4] M. Ron, D.M. Gruen, M.H. Mendelsohn, J. Sheft, US Pat. 4 292 265, 29 September 1981.
[5] M. Ron, in: Proceedings of the 11th Intersociety Energy Conversion Engineering Conference, AIChE, New York, 1976, p. 954.
[6] M. Ron, D.M. Gruen, M.H. Mendelsohn, J. Sheft, J. Less-Common Metals 74 (1980) 445.
[7] E. Bershadsky, Y. Joshepy, M. Ron, J. Less-Common Metals 172 (1991) 1036.
[8] E. Bershadsky, A. Klyuch, M. Ron, Int. J. Hydrogen Energy 20 (1995) 29.
[9] M. Ron, J. Alloys Comp. 283 (1999) 178.
[10] G. Sandrock, S. Suda, L. Schlapbach, in: L. Schlapbach (Ed.), Hydrogen in Intermetallic Compounds II, Topics in Applied Physics, Vol. 67, Springer, Berlin, 1992, p. 197.
[11] G. Sandrock, in: Y. Yurum (Ed.), Hydrogen Energy System—Production and Utilization of Hydrogen and Future Aspects, NATO ASI Series E, Vol. 295, Kluwer, 1995, p. 253.
[12] P. Dantzer, in: H. Wipf (Ed.), Hydrogen in Metals III, Topics in Applied Physics, Vol. 73, 1997, p. 279.
[13] G. Sandrock, G. Thomas, Hydride Information Center, http://hydpark.ca.sandia.gov.
[14] G. Sandrock, J. Alloys Comp. 293–295 (1999) 877.
[15] Millennium Cell Corp. (http://www.millenniumcell.com).
[16] H-GeneTech Alliance (http://alliance.hydrogen.co.jp).
[17] Ergenics, Inc. (http://www.ergenics.com).
[18] D.H. DaCosta, M. Golben, D.C. Tragna, Metal hydride systems for the hydrogen planet, in: R.D. Ventor, T.F. Bose, N. Veziroglu (Eds.), Proceedings of the 14th World Hydrogen Energy Conference, IAHE, 2002.
[19] D.E. Warren, K.A. Faughnan, R.A. Fellows, J.W. Godden, B.M. Seck, J. Less-Common Metals 104 (1984) 375.
[20] B. Bogdanović, A. Ritter, B. Spliethoff, K. Strassburger, Int. J. Hydrogen Energy 20 (1995) 811.
[21] P.M. Golben, D. DaCosta, G. Sandrock, J. Alloys Comp. 253–254 (1997) 686.
[22] E. Willers, M. Wanner, M. Groll, J. Alloys Comp. 293–295 (1999) 915.
[23] E. Willers, M. Groll, Int. J. Hydrogen Energy 24 (1999) 269.
[24] J.-G. Park, K.-J. Jang, P.S. Lee, J.-Y. Lee, Int. J. Hydrogen Energy 26 (2001) 701.
[25] G.A. Fateev, K.-J. Jang, J.-G. Park, S.-C. Han, P. Lee, J.-Y. Lee, J. Alloys Comp. 313 (2000) 174.
[26] J.P. Vanhanen, M.T. Hagstrom, P.D. Lund, Int. J. Hydrogen Energy 24 (1999) 441.

[27] A.S. Chernikov, L.A. Izhvanov, A.I. Solovey, V.P. Frolov, Yu.I. Shanin, J. Alloys Comp. 330–332 (2002) 907.
[28] B.A. Astakhov, US Pat. 6 000 463, 14 December 1999.
[29] B.H. Kang, A. Kuznetsov, Int. J. Hydrogen Energy 20 (1995) 665.
[30] E.M. Federov, Y.I. Shanin, L.A. Izhvanov, Int. J. Hydrogen Energy 24 (1999) 1027.
[31] A.I. Solovey, V.P. Frolov, Int. J. Hydrogen Energy 26 (2001) 707.
[32] D.J. Hanley, E.L. Huston, P.M. Golben, US Pat. 5 485 884, 23 January 1996.
[33] R.C. Bowman, Jr., M. Prina, D.S. Barber, P. Bhandari, D. Crumb, A.S. Loc, G. Morgante, J.W. Reiter, M.E. Schmelzel, Evolution of hydride compressor elements for the planck sorption cryocooler, Proceedings of the 12th International Cryocooler Conference, 2002, in press.
[34] R.C. Bowman, Jr., J. Alloys Comp. 2003 (in press).
[35] M. Prina, J.G. Kulleck, R.C. Bowman Jr., J. Alloys Comp. 330–332 (2002) 886.
[36] D.K. Benson, T.F. Potter, C.E. Tracy, Design of a Variable-Conductance Vacuum Insulation: SAE Tech. Paper 940 315, SAE, Warrendale, PA, 1994.
[37] S. Fukada, K. Fuchinoue, M. Nishikawa, J. Alloys Comp. 201 (1993) 49.
[38] S. Fukada, K. Fuchinoue, M. Nishikawa, J. Nucl. Mater. 226 (1995) 311.
[39] Q. Jiuxin, D. Xiaoping, Z. Chaogui, Y. Yupu, Int. J. Hydrogen Energy 11 (1986) 129.
[40] S. Charton, J.P. Corriou, D. Schweich, Chem. Eng. Sci. 54 (1999) 103.
[41] M. Au, C. Chen, Z. Ye, T. Fang, J. Wu, Q. Wang, Int. J. Hydrogen Energy 21 (1996) 33.
[42] V.Z. Mordkovich, Yu.K. Baichtock, N.V. Dudakova, N.N. Korostyshevsky, M.H. Sosna, Int. J. Hydrogen Energy 18 (1993) 839.
[43] A.V. Kruglov, A.N. Perevezentsev, B.M. Andreev, Int. J. Hydrogen Energy 19 (1994) 363.
[44] W.H. Fleming, J.A. Kahn, C.A. Rhodes, Int. J. Hydrogen Energy 26 (2001) 711.
[45] L.K. Hueng, G.G. Wicks, M.W. Lee, US Pat. 5 965 482, 12 October 1999.
[46] G. Sandrock, State-of-the-art Review of Hydrogen Storage in Reversible Metal Hydrides for Military Fuel Cell Applications, Final Report for Contract N00014-97-M-0001, US Office of Naval Research, 1997, NTIS Order No. AD-A328 073/2INZ.
[47] G. Sandrock, Hydride storage, in: W. Vielstich, H. Gasteiger, A. Lamm (Eds.). Handbook of Fuel Cells—Fundamentals, Technology and Applications, Vol. 3, Chapter 9, Wiley, 2003.
[48] M. Golben, D.H. DaCosta, Disproportionation resistant alloy development for hydride hydrogen compression, Proceedings of the 2002 US DOE Hydrogen Program Review, NREL/CP-610-32405, 2002, http://www.eren.doe.gov/hydrogen/docs/32405toc.html-#Storage.
[49] M. Golben, D.H. DaCosta, Advanced thermal hydrogen compression, in: 34th Intersociety Energy Conversion Engineering Conference, SAE Technical Paper 1999-01-2524, SAE International, Warrendale, PA, 1999.
[50] Saes Getters (http://www.saesgetters.com).
[51] H. Imamura, T. Tanaka, Y. Sakata, S. Tsuchiya, J. Alloys Comp. 293–295 (1999) 919.
[52] H. Imamura, Y. Noda, Y. Sakata, S. Tsuchiya, J. Alloys Comp. 323–324 (2001) 601.
[53] K. Iwata, Y.-M. Sun, S. Suda, Int. J. Hydrogen Energy 24 (1999) 251.
[54] D.D. Back, C. Ramos, J.A. Meyer, US Pat. 5 922 926, 13 July 1999.
[55] P.M. Golben, US Pat. 5 688 611, 18 November 1997.
[56] J.N. Huiberts, R. Griessen, J.H. Rector, R.J. Wijngaarden, J.P. Decker, D.G. de Groot, N.J. Koeman, Nature 380 (1996) 231.
[57] H. Blomqvst, D. Noréus, J. Appl. Phys. 91 (2002) 5141.
[58] V.I. Gorokhovsky, US Pat. 6 019 077, 1 February 2000.
[59] J.W. Shaffer, US Pat. 5 705 887, 6 January 1998.
[60] FuelCellStore (http://www.fuelcellstore.com/products/index/hydrogen_storage.html).
[61] GfE Gesellschaft für Electrometallurgie (http://www.gfe-online.de).
[62] Japan Metals and Chemicals (http://www.jmc.co.jp/e221kino.htm#L2).
[63] Texaco Ovonic Hydrogen Systems, 2983 Waterview Drive, Rochester Hills, MI 48309, USA (http://www.ovonic.com).
[64] HERA Hydrogen Storage Systems, 577 Le Breton, Longueuil, Quebec J4G 1R9, Canada (http://www.herahydrogen.com).
[65] Anon, Japan Metals and Chemicals & Air Products and Chemicals, Inc., Sign Joint Development Agreement, Press Release, 30 January 2002 (http://www.jmcusa.com).
[66] Hydrogenics Corporation (http://www.hydrogenics.com).
[67] Coleman Powermate Company (http://www.colemanpowermate.com/fuelcell.shtml).
[68] Fuel Cells 2000 (http://www.fuelcells.org).
[69] US Fuel Cell Council (http://www.usfcc.com).
[70] T. Motyka, W.A. Summers, L.K. Heung, Industrial fuel cell vehicles with metal hydride storage, presented at the 11th Canadian Hydrogen Conference, Victoria, 19 June 2001.
[71] T. Motyka, Savannah River Technology Center, private communication.
[72] M. Fuchs, F. Barbir, M. Nadal, Performance of third generation fuel cell powered utility vehicle #2 with metal hydride fuel storage, in: European PE Fuel Cell Forum, Luzern, 2–6 July 2001.
[73] W. Replogle, Sandia National Laboratories, private communication.
[74] Krishna Sapru, Energy Conversion Devices, Inc., private communication.
[75] Anon, U212/U214 attack submarine, Germany, Naval technology website (http://www.naval-technology.com/projects/type_212/index.html#specs).
[76] A. Niedzwiecki, Storage, in: Proceedings of the Hydrogen Vision Meeting, Washington, DC, 15–16 November 2001, (http://www.eren.doe.gov/hydrogen/features.html).
[77] P. Hoffmann, The hydrogen & fuel cell letter, February 2002 (http://www.hfcletter.com).
[78] B. Bogdanović, G. Sandrock, MRS Bull. 27 (No. 7) (Sept. 2002) 712.