

# ELECTROCHEMICAL POWER SOURCE SYSTEMS BASED ON HYDROGEN AS ENERGY CARRIER

V K VENKATESAN AND S PALANICHAMY

Central Electrochemical Research Institute, Karaikudi - 623 006, INDIA.

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The state of art of the three rechargeable power source systems viz. nickel-hydrogen, nickel-metalhydride and regenerative fuel cell is reviewed. The advantages, area of application and performance characteristics are briefly discussed.

**Key words:** Power sources, hydrogen as energy carrier, regenerative fuel cell

## INTRODUCTION

Hydrogen has many attractive advantages when used as electroactive material in power sources. They are (i) high ampere hour capacity (26.59 Ah/g) because hydrogen is the lightest element on earth (ii) source for H<sub>2</sub> viz. water is abundant (iii) it is a renewable energy carrier and (iv) devices based on H<sub>2</sub> are nonpolluting as the reaction product is only water (v) the power source systems employing H<sub>2</sub> as a reactant, exhibit high energy density and power density values (vi) the measurement of state of charge of the system is facilitated by the monitoring of the H<sub>2</sub> gas pressure (vii) the H<sub>2</sub> electrode exhibits high exchange current density values which allows high current drain and charging. There are also a few disadvantages attached with the use of H<sub>2</sub> because it requires (i) an efficient and low cost H<sub>2</sub> storage facility (ii) electrode material with good electrocatalytic activity for hydrogen oxidation (iii) high purity hydrogen.

The power source of the rechargeable type based on hydrogen, can be grouped under (a) rechargeable alkaline battery system and (b) regenerative hydrogen-oxygen fuel cells. The rechargeable alkaline battery system has two versions (i) hydrogen stored in the pressure vessel surrounding the electrodes e.g. metal hydrogen batteries housed in the same pressure vessel (ii) hydrogen stored as hydrides by some rare earth or titanium based alloys with nickel etc. Hydrogen in pure or impure form, is the only fuel employed in H<sub>2</sub>-O<sub>2</sub> fuel cells, which are successfully developed and some of them are nearing commercial application also. These fuel cells employ H<sub>2</sub> as fuel derived from different sources or as a by product in chlor-alkali and other industries. In a different kind of fuel cells, the reactants are regenerated either chemically or electrically (or electrochemically) and they function more like rechargeable batteries. Such regenerative fuel cells employing hydrogen as the electroactive material are only considered in this paper. The regenerative hydrogen-oxygen fuel cells are of two types and are operated at low temperatures. They are (a) alkaline and (b) proton exchange membrane H<sub>2</sub>-O<sub>2</sub> fuel cells.

## METAL-HYDROGEN BATTERY SYSTEM

Metal oxide-hydrogen batteries mainly consist of nickel-hydrogen and silver-hydrogen cell systems. The two systems combine the metal oxide electrode of Ni-Cd and Ag-Zn systems, with the hydrogen (gas diffusion) electrode of the H<sub>2</sub>-O<sub>2</sub> fuel cell type, thus giving the best resultant of both secondary battery and fuel cell. The OCV of Ni-H<sub>2</sub> and Ag-H<sub>2</sub> systems correspond to 1.25V and 1.4V, respectively. The theoretical energy density of Ni-H<sub>2</sub> systems

and Ag-H<sub>2</sub> battery systems are 378 Wh.kg<sup>-1</sup> and 500 Wh.kg<sup>-1</sup> respectively. The practically realised energy densities are however, 50-60 and 70-90 Wh.kg<sup>-1</sup> respectively[1].

The nickel-hydrogen system comprises of two nickel oxide electrodes positioned back to back, a separator which is either of fuel cell asbestos type, woven polyamide, zircar material or a combination of potassium titanate composite and an organic membrane layer, and a hydrogen electrode[2]. Thus the cell comprises of a stack of electrodes with alternating positive nickel (or silver) and negative hydrogen electrode insulated from each other by a separator and placed in a vessel. The Individual Pressure Vessel (IPV) is made of inconel 718 (or 625) which can withstand H<sub>2</sub> pressure of 30-40 kg.cm<sup>-2</sup>.

The electrochemical reactions during charge-discharge process are as follows.

### Nickel-hydrogen Cell



### Silver-hydrogen Cell



There are two types of Ni-H<sub>2</sub> battery systems (1) Individual Pressure Vessel (IPV) and (2) Common Pressure Vessel (CPV)[1]. In IPV, the nickel/hydrogen electrodes are connected in parallel to give the desired optimum current and kept in a pressure vessel surrounded by H<sub>2</sub> gas. Such IPVs are connected in series to get the desired voltage output of the battery. In the CPV, the series connected batteries of vented prismatic cells are kept in a common pressure vessel where H<sub>2</sub> is stored. While the Ni-H<sub>2</sub> battery systems of the IPV type are well tested and commercialised, the CPV type batteries are under development trials. The Ni-H<sub>2</sub> batteries have been mainly developed in the early period for aerospace applications but now batteries for terrestrial applications as well are being developed. The nickel oxide electrode and separator are essentially of the same type as those used in Ni-Cd batteries employed in aerospace missions. The hydrogen anodes are made of platinised carbon (high surface area) with teflon as the binder and nickel mesh as the current collector. Similarly in Ag-H<sub>2</sub> system, the hydrogen anode is the same as that used in Ni-H<sub>2</sub> system. The silver electrode is similar to the one used in Ag-Zn system. However the separator employed in Ag-H<sub>2</sub> cells is non-oven polyamide/inorganic or zircar type separator used in Ni-H<sub>2</sub> cells. The charge-discharge characteristics including variation for charge, overcharge and the variation of H<sub>2</sub> gas pressure in a typical Ni-H<sub>2</sub> battery systems[4] are shown in Fig.1. It can be

seen from the figure that (a) during discharge the voltage remains practically constant (flat) and the end abruptly drops (cuts off) to a low cell voltage value and (b) the  $H_2$  pressure steadily increases during charging and decreases in the same way during discharge of the cell. The family of discharge curves shown in Fig. 2 for a 50Ah Ni- $H_2$  battery[2] as a function of temperature at 293K and 273K, indicate that the cell voltage level and capacity are relatively insensitive to the temperature for the rate used here. This has been ascribed to the low operating c.d. of  $14mA.cm^{-2}$  at the 2h rate which is relatively a low c.d. for which the nickel and hydrogen electrodes[5].

The discharge characteristics of silver-hydrogen cell at different rates are shown in Fig. 3 which clearly demonstrates the good high rate capability of the system[5]. Figure 4 shows the current-voltage characteristics of a 25Ah Ag- $H_2$  cell at 100% and 50% state of charge which shows that end of discharge (eod) cell voltage is fairly sensitive to state of charge[5].

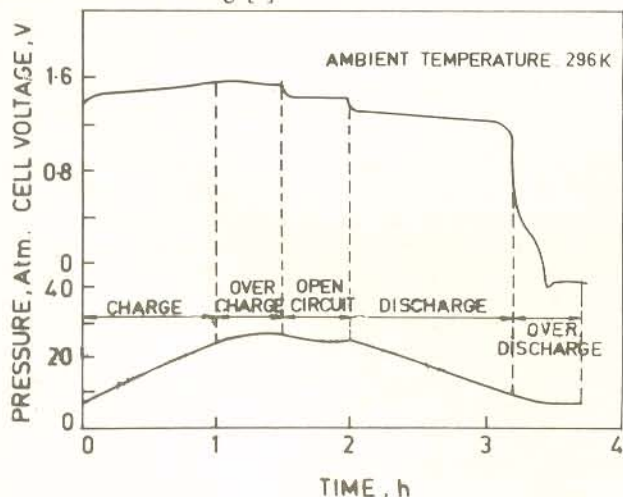


Fig. 1: Typical Ni- $H_2$  cell pressure and voltage characteristics

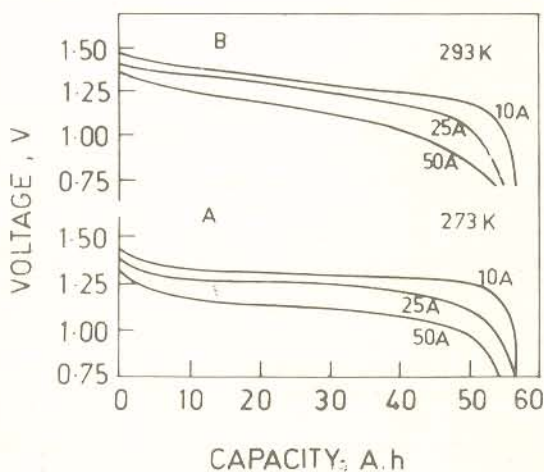


Fig. 2: Discharge characteristics for 50 Ah Ni- $H_2$  batteries

#### Advantages of Ni- $H_2$ and Ag- $H_2$ systems

The Ni- $H_2$  battery is very reliable and offers the advantages of extremely long stable cycle life and high energy density in the range  $50-60 \text{ wh.kg}^{-1}$ . The energy density is twice that of Ni-Cd. In excess of 1500 deep cycles, the Ni- $H_2$  cells have been demonstrated to show substantially no change in performance. The cells are insensitive to change at high rates of overcharge and reversal which is advantageous from a system stand point. The cells are totally

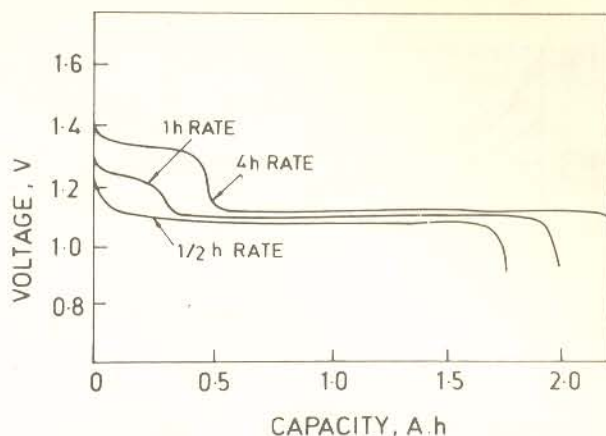


Fig. 3: Discharge characteristics of Ag- $H_2$  cell at different discharge rates

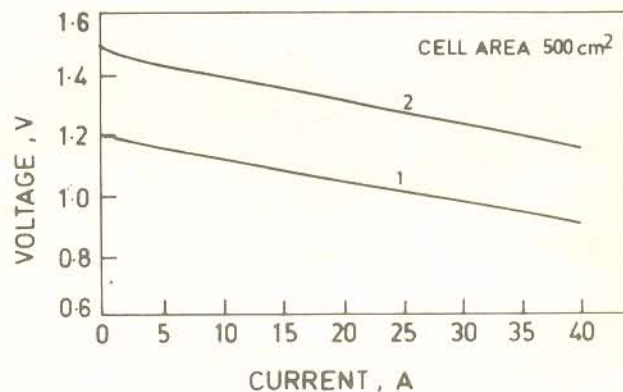


Fig. 4: Current-voltage characteristics of Ag- $H_2$  cell at different state of charge (1) 50% (2) 100%

sealed, maintenance free and are capable of a rapid rate of charge and discharge due to the high rate nature of the electrode.

When the discharge characteristics of Ni- $H_2$  and Ni-Cd at 313K 298K and 283K are compared (Fig. 5a & 5b) it can be seen[3] that while the available capacity is nearly the same for both the systems at 298K the Ni- $H_2$  exhibits a lower capacity than Ni-Cd. However, when the charge (eoc) and end of discharge (eod) voltages are compared for the two systems, (Fig. 6) the Ni- $H_2$  system always shows a higher voltage even after 1200 cycles thereby indicating the advantage[3] of the Ni- $H_2$  system in Fig. 6. The main disadvantage of the Ni- $H_2$  battery is the charge retention capacity at higher operating temperatures as compared to Ni-Cd. In the case of Ni- $H_2$  system, the available capacity drops at a faster rate with storage time. Further the electrocatalyst employed in the negative electrode influences the charge retentivity compared to platinum black. Further it has been found that the nickel oxide cathode loses its capacity with increasing  $H_2$  gas pressure due to the reduction of the oxide of hydrogen [3].

The silver-hydrogen battery has an exceptionally high energy volume density for room temperature batteries and also high energy and power densities. The Ag- $H_2$  has clear advantages over Ag-Zn. One of these is the large current carrying capability of the  $H_2$  which allows the use of thicker silver oxide electrodes and thus reduces the weights of separator and negative electrodes and the cell volume for a given cell capacity. Another is the extreme stability of the  $H_2$  electrode which makes the silver oxide electrode the life limiting factor. The Ag- $H_2$  with hydride/hydrogen storage provides high energy density on the basis of both weight and volume combined with long cycle life and high reliability. Further, the

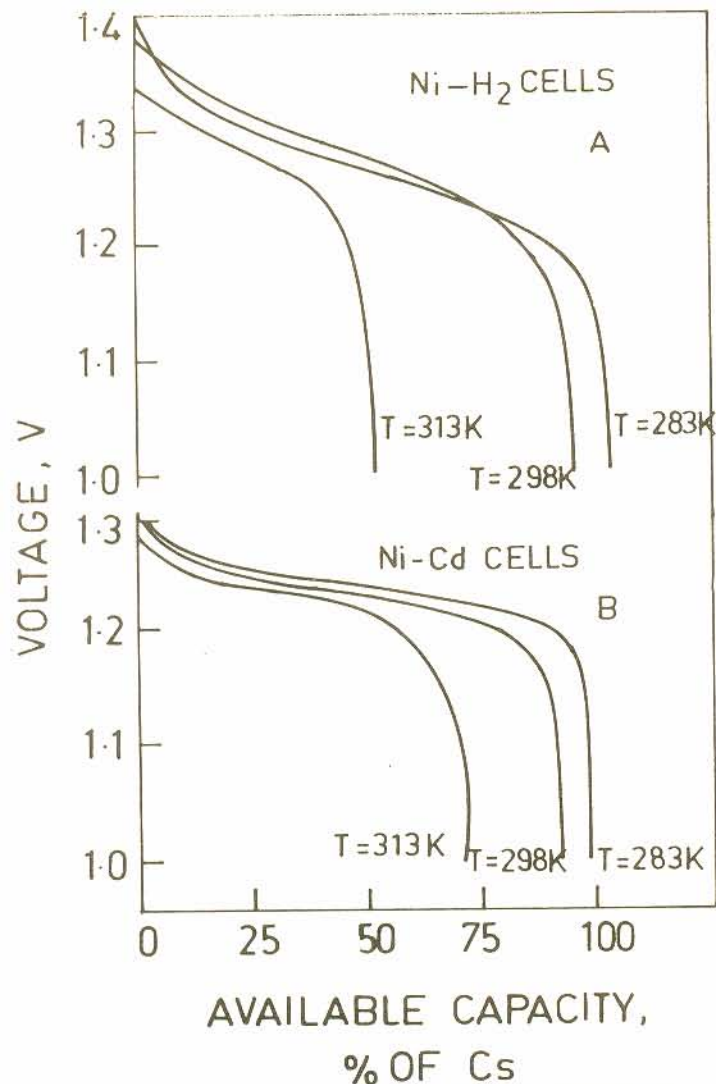


Fig. 5(a): Discharge characteristics of Ni-H<sub>2</sub> cell at different temperatures  
 (b): Discharge characteristics of Ni-Cd cell at different temperatures

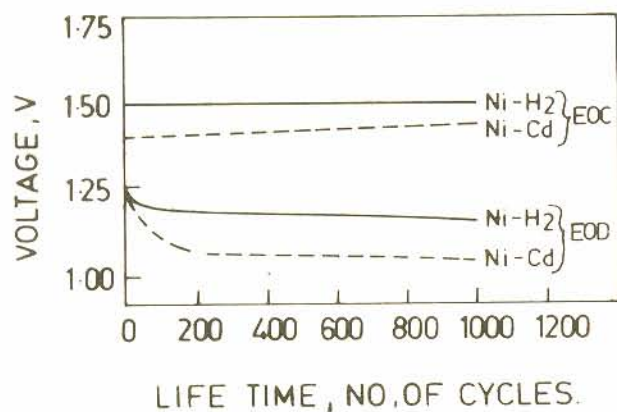


Fig. 6: End of charge (EOC) and end of discharge (EOD) voltage variation in a life test of Ni-Cd and Ni-H<sub>2</sub> cells  
 $T = 295 \pm 2K$ , DOD 72% of the rated capacity (c), charge 0.17 c rate for 7h, Discharge 0.72 c rate for 1 hr

## APPLICATION

In view of the very good characteristics, Ni-H<sub>2</sub> battery with IPV configuration has been used in the Geosynchronous (GEO) space crafts. IPV 3.5 in dia and 50Ah capacity GEO type Ni-H<sub>2</sub> batteries are in production in a few countries. Other sizes and capacities are available using scaled up existing components. Also IPV Ni-H<sub>2</sub> batteries have been selected for "space platforms" on the basis of weight, reliabilities, development rise, and schedule. The Ni-H<sub>2</sub> battery is half the weight and lower in cost than Ni-Cd batteries and more reliable than the regenerative fuel cell system (RFC). The space station advanced development program is beginning to test 'LEO' type cells into a global of minimum life time of five years. Ni-H<sub>2</sub> batteries for terrestrial applications are also being developed by COMSAT and Johnson Controls Inc. USA. The program envisages use of cost effective electrodes (anode) and prismatic type common pressure vessel. This system appears to be a prime candidate for replacement of Ni-Cd, Ni-Zn, Ag-Zn and Pb-PbO<sub>2</sub> in many applications. One such use is for harnessing of non-conventional energy source (solar, wind, energy etc). The cost of energy from various batteries[7] is compared in Table 1.

The Ag-H<sub>2</sub> batteries have accumulated more than 500 cycles in accelerated tests under GEO condition, and utilisation of the Ag-H<sub>2</sub> system looks promising for lone mission in geosynchronous orbit. Also under low earth orbit conditions (LEO), results obtained at depth of discharge of 20 to 30% show promise as a light weight alternative to the nickel systems. The Ag-H<sub>2</sub> cells with hydride hydrogen storage provide high energy density on the basis of both weight and volume combined with long cycle life and high reliability. Further, the Ag-H<sub>2</sub> system is insensitive to overcharge, continued float and reversal. A Ag-H<sub>2</sub> common pressure vessel battery with hydrides has been built by 'SAFT' for aircraft applications. The battery with a capacity of 90Ah and an average voltage of 20 volts has a total weight of 30kg. resulting in 50Wh.kg<sup>-1</sup> of energy density[11].

## NICKEL-METAL HYDRIDE BATTERIES

A number of metal alloy hydrides have been studied for possible applications in rechargeable alkaline batteries. Nickel-titanium alloys were first reported by Beccu et al [9,10] for use as battery electrodes. Justi et al [11] while studying the electrocatalysis of hydrogen oxidation reaction, by TiNi-H<sub>2</sub> electrodes found that though it could not surpass Raney nickel electrodes in H<sub>2</sub> oxidation, it showed considerable H<sub>2</sub> storing capacity. They had further suggested that this property of Ti-Ni alloy could profitably be used for providing peak power for a short time especially when used in electric vehicles. Beccu et al showed that titanium when alloyed with nickel can adsorb and desorb hydrogen electrochemically. The hydrogen is located interstitially in the lattice. It is known that nickel, cobalt etc. stabilise  $\beta$ -Ti which has a cubic structure and stable only at temperature above 723K and can absorb large amounts of hydrogen and gets transferred to Ti at lower temperatures. While Ti<sub>2</sub>Ni was shown to have a theoretical capacity of 430Ah.kg<sup>-1</sup> for a hydride corresponding to Ti<sub>2</sub>NiH<sub>2</sub>, TiNi is having a theoretical capacity of 250 Ah.kg<sup>-1</sup> for a hydride of TiNiH. Beccu et al have found that only for TiNiH, the measured capacities (210-250Ah.kg<sup>-1</sup>) are in good agreement with the theoretical values. However with Ti<sub>2</sub>NiH<sub>2</sub> the practically attainable capacity is only 170Ah.kg<sup>-1</sup> indicating that about 50-60% of the hydrogen atoms are not dischargeable under the test conditions[9]. Justi et al found that the discharge capacity of Ti<sub>2</sub>Ni electrodes degraded to 50% after 60 cycles due to oxidation while TiNi electrode reached this deterioration after 300 cycles only. Beccu et al showed that sintered mixtures of Ti<sub>2</sub>Ni and TiN phases possess reversible capacities in excess of

system is insensitive to overcharge, continued float and reversal[6].

300 Ah.kg<sup>-1</sup> which correspond to hydrogen exchange efficiencies of nearly 100%. Therefore it was suggested that an interaction between the Ti<sub>2</sub>Ni and TiNi must exist with respect to the hydrogen transfer.

TABLE-I: Photovoltaic battery systems of 15kwh capacity (and life 30 year) available between 1986 and 1991

	Ni-H <sub>2</sub>	Lead acid		Zn-Br <sub>2</sub>	Sod/Sulphur
		Flooded	Sealed		
Initial cost	375 to	80 to	99 to	40 to	400 to 1200
\$ per kWh	930	120	160	120	
Cycle life	15,000 to	1600 to	1200 to	1800 to	2000 to 90
(80% DOD)	5,200	800	600	400	
Units required	1 to 2	7 to 13	9 to 17	6 to 25	5 to 11
(for 10,000 cycles)					
Present value	3.8 to	3.4 to	5.3 to	4.7 to	13.2 to 84.6
(cents/kWh-cycle)	14.5	9.3	16.2	17.80	
Estimated maintenance	0.1 to	6 to	0.5 to	7 to 54	0.5 to 20
cost (cents/kWh cycle)	2	46	17		
Present value	0.1 to	3.5 to	0.3 to	4.0 to	0.3 to 11.5
(cents/kWh-cycle)	2	26.4	9.8	31.1	
Total life cycle cost	3.9 to	6.9 to	5.6 to	8.7 to	13.5 to 96.1
(cents/kWh-cycle)	15.7	35.7	26.0	48.0	

The charge discharge mechanism given by them is as follows: During discharge, H<sub>2</sub> in lattice position in the alloy diffuses to the metal/electrolyte interface where the electrochemical charge transfer reaction occurs. When charged, H<sub>2</sub> present in the highly active atomic state at the cathode surface diffuses into the lattice position of the metal phases forming the metal hydride.

The exchange current density of the hydrogen electrode reaction on Ti<sub>2</sub>Ni/TiNi depends on the charge state of the electrode and pH of the electrolyte. The maximum value (for Ti<sub>2</sub>Ni, TiNi)=0.1mA.cm<sup>-2</sup> BET surface area) is obtained for a strongly alkaline electrolyte and the electrode is fully charged. It had also been suggested by Beccu et al that the mass transport in the solid state is quite rapid and should not be rate determining upto a 3C discharge current. The charge efficiency, at high rate charging (2C) was found to be between 60-70% and at slow rate of charging (5 to 10h) it was 80-90%Ah - efficiency.

Using a sintered mixture of Ti<sub>2</sub>Ni and TiNi, Beccue et al had obtained a higher capacity of 320Ah.kg<sup>-1</sup> as against the theoretically expected value of 380Ah.kg<sup>-1</sup>. However, the average value is 200 and 250Ah.kg<sup>-1</sup> with satisfactory cycling behaviour. At 80% discharged depth, 450 cycles were obtained while at 10% capacity, the cycle life exceeds 20,000. In view of the high mobility of the hydrogen in the alloy phase, the behaviour of the hydride hydrogen electrode was found to be good even at 303K. This Ni-H<sub>2</sub> battery is being developed in Germany, Japan and USA.

Ovonic Battery Co., USA had developed an alloy of titanium, vanadium, chromium, zirconium and nickel [12]. The firm claims that this alloy has shown ease of large scale fabrication, excellent cycle life, high rate discharge capability, fast charge capability in a

sealed cell, and costs allowing widespread commercial application. The Ovonic cells based on the new hydride material developed by the Ovonic Battery Co., have a cycle life comparable to Ni-Cd, an excellent discharge rate capability and the ability to be rapidly charged. These cells do not suffer from memory effect and are environmentally safer. The cost of the hydride cells is competitively priced to Ni-Cd. The specific capacity values for the alloy is approx. 0.32Ah/g.

TABLE-II: Specific electrode capacity and energy density for an Ovonic C cell compared to standard Ni-Cd

	Ovonic	Nickel-cadmium
Capacity (Ah) nominal	2.0 - 2.4	1.2 - 1.5
Voltage (V)	1.2	1.2
Watt-hours (Wh)	2.4-2.88	1.44 - 1.80
Watt-hours/kilogram (Wh.kg <sup>-1</sup> )	48-58	32.5 - 40.7
<i>Negative electrode</i>		
Milliamp-hours/gram (mAh.g <sup>-1</sup> )	320	196
Milliamp-hours/cc (mAh.cm <sup>-3</sup> )	1650	545
<i>Positive electrode</i>		
Milliamp-hours/gram (mAh.g <sup>-1</sup> )	175	124
Milliamp-hours/cc (mAh.cm <sup>-3</sup> )	510	425

The characteristics of the Ovonic cell and Ni-Cd are given in Table II. The most mechanical degradation occurs at very high and very low states of charge. The extent of expansion or contraction of the metal hydride during cycling depends on the level to which it is charged or discharged. The degree of embrittlement will be less when the hydride is not fully utilised. Further, it was found that maintaining the electrode at full charge or full discharge is not as aggressive mechanically as cycling to high depths of discharge. The firm also has the production facility for the scaled up C size cells with significantly higher capacity (3.5 Ah) than Ni-Cd. Attempts are being made to build sealed cells with discharge rate capabilities comparable with Ni-Cd cells thus making the system feasible for widespread applications.

#### La/Mm-Ni<sub>5</sub>H<sub>6</sub> (HYDRIDE) - NICKEL SYSTEM

Justi et al had studied the oxidation of hydrogen on LaNi<sub>5</sub> alloy electrodes[13]. They had found that LaNi<sub>5</sub>H<sub>6</sub> has a capacity of 0.10Ah.g<sup>-1</sup> and that this remained the same even after 100 cycles. Further, it was found to have good electrocatalytic activity for hydrogen oxidation when lanthanum content in LaNiAl alloy is 16.1 atomic percent. The polarisation was considerably lower than that for Raney nickel catalyst in the range 1.0 to 3.0 A.g<sup>-1</sup>. The corrosion of the alloy LaNi<sub>5</sub> occurs when the hydrogen in the hydride is reduced considerably.

It has been found that LaNi<sub>5</sub>, exhibits three phases when it absorbs hydrogen. They are solid solution  $\alpha$  phase,  $\beta$  hydride and  $\gamma$  - hydride phase. It was first shown by Philips Laboratories in 1970 that LaNi<sub>5</sub> can absorb and desorb H<sub>2</sub> and that lanthanum nickel hydride is formed. Both LaNi<sub>5</sub> and mischmetal nickel alloy have been evaluated by Japanese workers for use in nickel-

metal hydride batteries. A number of battery manufacturers in Japan have been developing this battery system and have also patented their process [14-16]. The first one to enter this field is Matsushita. Others include Toshiba, Sanyo and Sharp, Asahi Glass Co., Ltd, Toppan Printing Co. and Daido Special Steel Co. Of these manufacturers, Matsushita, Toshiba, Sanyo and Sharp are currently actively involved in R&D of batteries. The patents applied for the alloy materials are mainly concentrated on titanium, magnesium, calcium and rare earths metal systems. It has been found that for making cost effective batteries, mischmetal-nickel alloy can be used in the place of  $\text{LaNi}_5$  alloys. Further, they have found that to increase the flatness of the equilibrium pressure from 1.13 to 0.196, heat treatment at 1323K in vacuum is desirable as it will help in improving the homogeneity of the alloy. The optimum hydrogen dissociation pressure of the alloy for sealed battery use is  $0.25\text{kg}\cdot\text{cm}^{-2}$ . The alloy  $\text{MmNi}_{4.3-x}\text{Mn}_{0.4}\text{Al}_{0.3}\text{Co}_x$  can have enhanced charging and discharging cycle life when  $x$  exceeds 0.5[17].

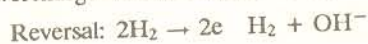
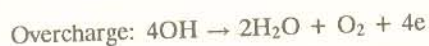
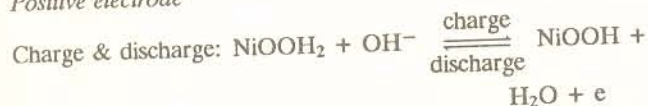
In general, the cycle life of the hydride electrode is enhanced when a copper coating is given to the alloy powder. The copper coating of the alloy powder prevents oxidation of the alloy surface and also enhances the ability of hydrogen to absorb and desorb in alkaline solution[18]. The alloy powder coated with copper is formed into a sheet or nickel matrix (formed) as current collector and using PTFE binder. In the case of mischmetal where lanthanum content varies from 21% to 48%, the one with 21wt.% (such as  $\text{MmNi}_3\text{Co}_{1.5}\text{Al}_{0.5}$ ) showed a good cycle performance. While Matsushita, Toshiba and Sanyo are developing mischmetal nickel alloy based metal-hydrogen battery system, Sharp is developing a TiNi alloy based metal-hydrogen battery system. Ni-H(MH) batteries of 1050-1100 mAh and R6 size have also been successfully tested to have 500 cycles. The self discharge characteristics can be improved by improving the separator[19].

It is reported that, in Japan, the demand for development of Ni-H(MH) batteries is increasing steadily as the Ni-H(MH) battery can have a capacity of approximately 1.4 times that of Ni-Cd and can in many applications replace Ni-Cd. Japan Metal & Chemicals Co., has planned to increase the production of hydrogen storing alloy required for nickel-hydrogen battery from 300 tons to a 1000 tons a year at their organic factory[20].

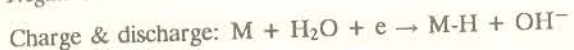
In view of the high energy density compared to Ni-Cd of same size, the nickel-metal hydride rechargeable battery system is being tested by leading OEMS in USA, for portable computer, laptop computers, portable communication systems etc. Gates Energy Products Inc. USA started marketing recently Ni-metal hydride cells of 2.3Ah capacity wherever Ni-Cd cells are used at present[21].

The electrochemical reactions taking place in a nickel-metal hydride cell are as follows.

#### Positive electrode



#### Negative electrode



(M = Hydrogen absorbing alloy)



### REGENERATIVE HYDROGEN-OXYGEN FUEL CELLS (RFC)

In the regenerative  $\text{H}_2\text{O}_2$  fuel cells, unlike the two rechargeable

systems discussed above, the power and energy are separated resulting in a distinct advantage. It needs only to increase the reactant storage without increasing the factor stack (s) to increase the stored energy. This makes the advanced batteries lose their mass advantage to regenerative fuel cells when the discharge time is increased beyond a few hours. However the main advantages are (1) lower efficiency and (2) complexity of the system as compared to batteries. The energy-out to energy-in ratio range for the regenerative  $\text{H}_2\text{O}_2$  fuel cell is 55-65% while the advanced batteries are operating at 75% energy efficiency. The main reason for the low energy storage efficiency for the RFC is related to electrode performance. A breakthrough in low temperature electrode performance is awaited. In view of this lower efficiency for RFC, an increase in the size of the solar array, is necessitated when it is used with photovoltaic power source.

The disadvantage viz. difference in the mass between RFC and advanced batteries becomes less significant when the charge time increases. However, the complexity of state of the art RFC is much greater than more advanced batteries and they are

(a) water removal from the reactant chamber by dynamic reactant recirculation

(b) separation of product water from the reactant

(c) circulation of fluid at controlled temperature

(d) pumping of water in the electrolyser gas generation pressure

(e) separate fuel cell and electrolysers.

As the RFCs have to operate at low temperature, the option is restricted to alkaline fuel cell (AFC) and proton exchange membrane fuel cells (PEMFC) and their corresponding water electrolysers.

In the case of alkaline RFC, a three electrode cell was developed by Ewe et al [22] who used two oxygen electrodes with a common hydrogen electrode and an asbestos diaphragm and based on the Eioflux principle. One of the oxygen electrodes employing silver catalyst; served as the cathode while the other one using nickel catalyst was employed as the oxygen evolving anode with asbestos. It has been claimed that the RFC has an overall energy efficiency of 60%. But no studies with larger size cells have been reported. Similarly an RFC with alkali immobilised on asbestos, and two electrode system, in a bipolar arrangement was also reported [23]. The efficiency of the RFC was found to be 53%.

In recent years, RFCs based on PEM fuel cell electrolyser have been reported[24] for extra terrestrial applications. In this RFC, separate dedicated SPE fuel cells and SPE electrolysers have been preferred earlier for obtaining higher overall energy storage efficiency.

The reason for considering separate dedicated systems, is that the same electrocatalyst cannot be used in SPE fuel cell and SPE electrolyser. However, later, compromise catalyst system has been developed and this leads to overall energy storage efficiency within 5% of the dedicated configuration. Figure 7 depicts the performance of the RFCs of different configurations. In this RFC, the current output of the FC is  $100\text{mA}\cdot\text{cm}^{-2}$  (i.e. 100A per sq. foot). The RFC is being considered for extraterrestrial applications along with photovoltaic power source. Trials are being conducted with this RFC to assess the performance of various systems regarding simplification aspects. If selected, the system will fly on a future shuttle mission, in a simulated low earth orbit energy storage configuration.

A number of studies have been reported [26] on the development of suitable electrocatalysts and supports for use in alkaline  $\text{H}_2\text{-O}_2$  RFC. Yeager et al have studied in detail the compound lead ruthenate pyrochlore  $\text{PbRu}_2\text{O}_{6.5}$  as electrocatalyst for both oxygen reduction and evolution in alkaline solutions. Substitution of part of Ru by Ir improved the performance as oxygen reducer. They had also used two different anionically conducting polymer overlayers which slow down the diffusion of ruthenate and plumbate out of the electrodes. Swette and Kacklay[26] had

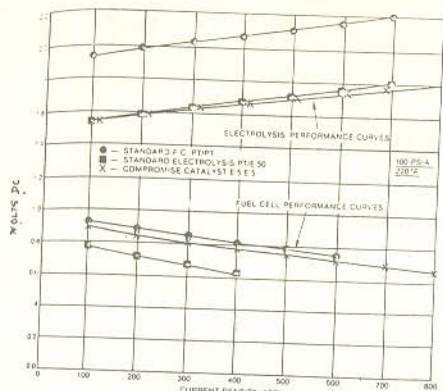


Fig. 7: Performance of regenerative fuel cells of different configuration (From Ref. 24)

evaluated a number of cathode borides and nitrides of Ti, Zr, etc. and oxides of La, Sr, Cr, Mo, Mn, Ni etc. as support materials (for carrying electrocatalysis). Similarly they had evaluated the electrocatalytic property of oxides of the type  $ABO_3$  where  $A = Pb, Mn, La, Sr$  etc. and  $B = Pr, Pd, Ru, Ir, Ni, Co$  for  $O_2$  evolution or  $O_2$  reduction. They had identified the following materials

(a) supports:  $TiN, ZrC, ZrN$

(b) catalytic supports:  $LaNiO_3, LaSr_{0.5}CoO_3, LiNiO_x$  and

(c) electrocatalysts:  $PbPdO_2, RuMn_2O_x,$

$Pb_2(Ir_{1.33}Pb_{0.67})O_{7-y}, Pb_2(Ru_{1.35}-Pb_{0.65})O_{7-y}, Na_{0.8}Pt_3O_4$  They had programmed for further development of these materials.

It is clear from the above that for an RFC both alkaline and PEM, and of the reversible type an efficient and stable electrocatalyst support for  $O_2$  reduction and evolution, is yet to be perfected.

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