

The nickel/iron battery

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Abstract

The nickel/iron battery is a rechargeable electrochemical power source with certain special advantages. It has good scope for traction applications. The present state-of-art advantages, limitations, and uses of the nickel/iron battery, along with its electrochemical characteristics, are outlined in this review. Various methods available for fabricating both the negative iron and the positive nickel oxy-hydroxide ($\text{NiO} \cdot \text{OH}$) electrodes, as well as the electrochemical characteristics of these electrodes, are discussed.

Introduction

The nickel/iron (Ni/Fe) battery is a rechargeable electrochemical power source. The pioneers of its development were Thomas Alva Edison in the U S A and Waldemar Jungner in Sweden. The battery is fully developed commercially for various applications in the U S A, U S S R, Sweden, West Germany, and Japan. It is an ideal power source for India in view of the material resources and the prevailing climatic conditions, but the developmental activity has not reached the level of commercial production. Intensive work on the Ni/Fe system has started recently in the Central Electrochemical Research Institute, Karaikudi. The purpose of this review is to outline the electrochemical characteristics of the battery and its components, including fabrication techniques.

Operating principles

In simplistic terms, the Ni/Fe battery is a nickel/cadmium (Ni/Cd) battery with the cadmium negative replaced by an iron electrode. Potassium hydroxide (KOH) solution containing lithium hydroxide (LiOH) is the electrolyte. The negative and positive electrodes are separated by an alkali-resistant, polymeric sheet that is permeable to electrolyte. The Ni/Fe battery is represented as $(-)\text{Fe}/\text{KOH}/\text{NiO} \cdot \text{OH}(+)$.

The cell characteristics [1, 2] are as follows

Cell voltage (OCV)	1.37 V*
Working voltage	1.00–1.2 V
Theoretical energy density	267 W h kg ⁻¹
Attained energy density	82.5 W h kg ⁻¹ at C/5 rate (Japan)
	50 W h kg ⁻¹ at C/5 rate (Germany)
	50 W h kg ⁻¹ at C/2 rate (USA)
	26 W h kg ⁻¹ (USSR)
Charge/discharge efficiency	50%
Cycle life	> 1000
Calendar life	15–20 years

Advantages and limitations

The Ni/Fe battery can withstand mechanical shock or vibration, overcharge, and overdischarge. Storage under charged or discharged conditions will not affect the performance. Long service life is possible by virtue of high cycle life and long calendar life. Maintenance of the battery is quite simple; it needs only topping up of the electrolyte by water addition or replacement of the electrolyte after an appreciable period of operation.

The battery active materials are insoluble in alkali. Furthermore, the separator presents no special difficulties (by contrast, this is a very critical problem in both silver/zinc (Ag/Zn) and nickel/zinc (Ni/Zn) batteries). There is no toxic or corrosive effect either to the environment or to working personnel. The alkaline electrolyte permits the use of mild steel in the construction of the battery. The battery performs very well at an ambient temperature of about 308 K, this is an additional advantage for Indian conditions.

The energy efficiency of the battery is around 50%. The self discharge, however, is fairly high. The main causes for these two aspects are the low hydrogen overvoltage of the iron electrode and the close proximity of the potentials of the iron electrode (in alkaline medium) and the hydrogen evolution reaction [3]. As a result, hydrogen is evolved during charge/discharge and on stand. Further, the battery shows poor performance at sub-zero temperatures due to passivation of the iron electrode.

Applications

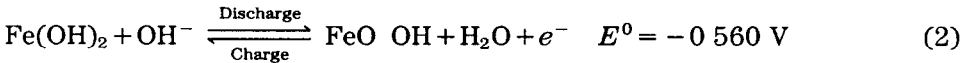
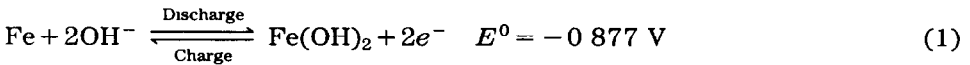
The combination of the proven ruggedness, reliability, and marginal cost of the Ni/Fe battery makes it useful in railways, roadways, and mining. Carriage lighting, fans, and air-conditioning in trains are powered by Ni/Fe batteries. Fork lifts, indoor transport, and electric road vehicles also use Ni/

*In this review, all potentials are reported with regard to the standard hydrogen electrode, SHE

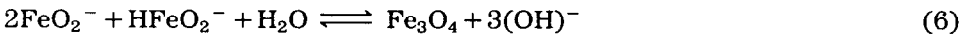
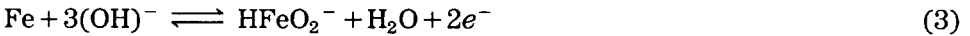
Fe units Further applications include power sources for mining locomotives, miners' cap-lamps, and communications equipment Finally, the nickel/iron battery is suitable for the storage of electrical energy derived from solar energy via photovoltaic cells

Iron negative electrode

The iron negative has high theoretical ampere-hour capacity (0.97 A h g^{-1}) It is low priced and is stable towards both mechanical and electrochemical mistreatment Iron is non-toxic and readily available The charge/discharge reactions take place at two distinct voltage levels (eqns (1) and (2)) The second step is of no importance for battery purposes and rarely takes place since Ni/Fe cells are designed with excess of iron-active material



Voltammetric studies on iron electrodes in alkaline medium [4, 5], and X-ray diffraction analysis of the different discharge stages [6] and products of commercial nickel/iron units [7, 8], reveal that the oxidation of iron proceeds in two main steps through the formation of soluble ferrite (HFeO_2^-) and ferrate (FeO_2^-) intermediates, i.e.,



The first oxidation step of Fe to Fe(II), as a result of reactions (3) and (4), is of more practical importance for battery operation than the second step of Fe(II) to Fe(III) due to reactions (5) and (6) The former step is highly reversible with an electrode potential of 0.87 V, while the latter has a lower potential (0.56 V) and does not accept charge readily Other studies on the kinetic behaviour of the iron electrode [9–13] provide evidence in favour of a dissolution–precipitation mechanism

The solubility of the oxidised iron is very low [14] and results in the precipitation of a layer of Fe(OH)_2 The latter blocks the active area and gives rise to a low utilization coefficient of the iron electrode. Further, the low solubility is temperature dependent and this is responsible for poor performance at sub-zero temperatures

The potential of the Fe/Fe(OH)₂ couple is only slightly more negative than that of the hydrogen evolution potential in alkaline medium The hydrogen overvoltage is very low. As a result, there is a simultaneous evolution of

hydrogen during charging and slow gassing on open circuit. This is the cause of the low charge/discharge efficiency and the high self-discharge rate of the Ni/Fe system.

In order to overcome the limitations of the iron electrode, a number of additives are incorporated in the iron negative during fabrication. Copper and mercury are generally used [15] to increase the hydrogen overvoltage. Ferrous sulphide, sulphur, and selenium are added [16] to reduce the ionization potential. Nickel hydroxide and cobalt hydroxide, which are isomorphous with ferrous hydroxide, serve [17] to effect significant improvement in the performance of the iron electrode by reducing its overpotential during both charge and discharge.

The active material for the iron electrode is a mixture of finely divided iron and ferrous hydroxide. These are generated from magnetite (Fe_3O_4) by charge/discharge cycling. Three different types of iron electrode are commonly manufactured: (i) pocket or tubular, (ii) pressed or roll compacted, (iii) sintered. Electrode production in different countries is listed in Table 1 [18].

Pocket or tubular electrodes

Iron is dissolved in dilute H_2SO_4 to produce ferrous sulphate. The latter is purified by recrystallization and roasted at 1070–1120 K. The roasted mass is washed thoroughly with water and then dried. The resulting material is treated with hydrogen at 1020–1070 K for reduction and again subjected to partial oxidation at 970–1070 K. This process yields a mixture of iron powder and magnetite. The mixture is blended with addition agents (Cu, FeS, HgO, etc.) and put into pockets or tubes made from perforated-steel sheet plated with nickel. The pockets or tubes are fixed over a suitable nickel-plated steel plate to form the negative electrode. The tubular version was first introduced by Edison [19] and is still manufactured in West Germany and France, whereas the pocket type is produced in the U.S.S.R.

TABLE 1

Types of commercial iron electrodes

Country	Manufacturer	Electrode type
France	SAFT	Sintered, tubular
F R G	VARTA	Pocket, tubular
Sweden	Swedish National Development Co (SU)	Sintered
U S S R	State owned companies	Pocket, pressed
U S A	Westinghouse, Eagle Picher Industries Inc (EPI)	Pressed, sintered
U K	Inco Europe Ltd	Pressed
Japan	Matsushita	Pressed, sintered

Pressed or roll-compacted electrodes

The active material with suitable addition agent(s) is blended with a polymeric binder such as poly(tetrafluoroethylene) (PTFE) or poly(ethylene). The resulting mixture is passed through a rolling mill with a nickel-plated steel screen reinforcement to produce a plate of the desired thickness. Sometimes, a pore-former such as sodium benzoate or finely divided sodium chloride is used during the rolling compaction. The pore-former is then leached out with boiling water to create sufficient porosity in the plate. This design of flat negative exhibits better performance than the pocket type, as shown in Table 2 [20].

Sintered electrodes

Finely divided iron powder is converted into a thin iron plate of 60–70% porosity by sintering over a nickel-plated steel grid at 970–1070 K in either a hydrogen atmosphere or a mixture of hydrogen and nitrogen. The sintered iron plate is further activated with suitable addition agents to function as an effective anode. In sintered iron electrodes, the matrix serves both as the active material and the current-conducting grid. Further, the sintered iron electrode contributes little to the internal resistance of the Ni/Fe battery, a feature that is very essential for high power traction batteries. The limitations of the sintered electrode design are rapid passivation and high cost. Copper powder (up to 50 wt %) is used [21] in the preparation of sintered iron negatives. The carbonyl iron powder is mixed with finely divided sodium chloride, which is a pore-former and a binder. The mix is then compacted on a current collector and sintering carried out [22]. After sintering, the pore-former is leached out with boiling water. In order to achieve sufficient iron electrode activity, 100 parts of the carbonyl iron powder are mixed [23] with 0.5–5 parts of a water solution of CdSO_4 , CuSO_4 , ZnSO_4 , $\text{Cr}_2(\text{SO}_4)_3$, or Li_2SO_4 , and dried. The sulphate-coated iron powder is pressed into a thin plate and sintered under hydrogen at 970–1070 K. This produces a self-supporting electrode structure.

The electrode active material (Fe and Fe_3O_4) is pressed over steel fibres and subjected to sintering [24] to form the porous iron negative. Loose sintering is also used to prepare the iron negative [25]. In this method, electrolytic iron powder or carbonyl iron powder is uniformly spread over

TABLE 2

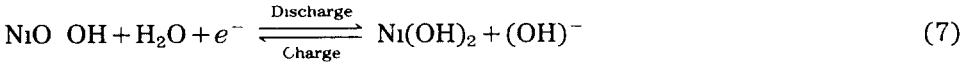
Comparison of roll-compacted and pocket types of negative plate

Characteristic	Roll-compacted electrode	Pocket electrode
Specific energy (A h kg^{-1})	110	68
Volumetric capacity (A h l^{-1})	460	240
Ampere hour efficiency (A h g^{-1})	0.2	0.18
Iron active material (g ml^{-1})	2.3	1.32

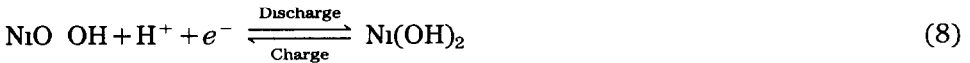
a nickel-plated steel grid that is placed in the rectangular cavity of a graphite plate. The dimensions of the cavity determine the size and thickness of the iron plate. Sintering is carried out under hydrogen at 1070–1120 K. The sintered iron plate possesses a porosity of 55–65%. The plate is further activated by using suitable addition agents.

Nickel positive electrode

Nickel is used as the positive electrode in Ni/Cd, Ni/Fe, Ni/Zn and Ni/H₂ batteries. The active material is nickel oxy-hydroxide (NiO·OH) which is generated from the starting material, nickel hydroxide (Ni(OH)₂), on charging.



There are several crystallographic forms of Ni(OH)₂ and NiO·OH. The reaction mechanism involves diffusion of hydrogen ions through the solid-state lattices of Ni(OH)₂ and NiO·OH to give a continuous change in the composition of the active material. The actual course of the reaction may be represented as:



It has been shown [26] that Ni(OH)₂ in nickel positive electrodes can exist as α-Ni(OH)₂ and β-Ni(OH)₂. The former has a sandwich-type structure with intercalated water [27] while the latter has a layered brucite structure [28] with small amounts of loosely bound water. α-Ni(OH)₂ is formed by electrochemical precipitation from a concentrated nickel nitrate solution [Ni(NO₃)₂·6H₂O]; on oxidation in an alkaline medium, it gives hydrated γ-NiO·OH [29]. β-Ni(OH)₂ is produced by chemical precipitation with concentrated alkali, on oxidation, it yields β-NiO·OH. Overcharging of nickel battery electrodes converts β-NiO·OH to γ-NiO·OH. On discharge, the α-Ni(OH)₂ produced from γ-NiO·OH can dehydrate to form β-Ni(OH)₂. Thus, the charge/discharge process can be represented as shown in Fig. 1.

Cobalt as an additive [30–32] reduces both the oxidising and the reducing potentials of nickel hydroxide and increases the overpotential of oxygen.

Electrochemical Reactions

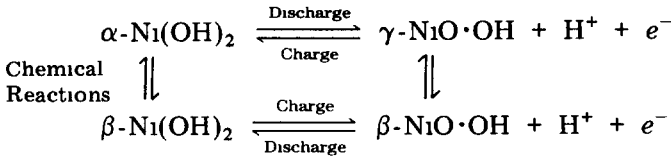


Fig. 1 Charge/discharge processes at the nickel electrode

evolution. Thus, the utilization coefficient of the active material is improved. Further, cobalt stabilizes the performance of nickel electrodes. Barium (as $\text{Ba}(\text{OH})_2$) has similar beneficial effects in the presence of lithium ions which come from lithium hydroxide added to the KOH electrolyte. The following different types of nickel positive electrode are in use: (i) sintered, (ii) pressed, (iii) tubular or pocket, (iv) nickel composite.

Sintered electrodes

Sintered electrodes are intended for high to extremely high loads. Carbonyl nickel powder is embedded bilaterally on a suitable substrate and sintered under a reducing atmosphere at about 1120 K to produce a porous matrix. The substrate may be one of the following materials: (i) nickel netting or nickel-plated mild steel (m.s.) netting, (ii) perforated nickel foil or nickel-plated, perforated m.s. foil, (iii) nickel-fibre mat or nickel-plated steel-fibre mat.

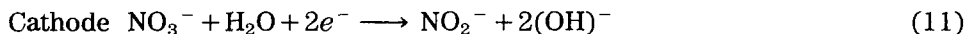
Bilateral embedding of the carbonyl nickel powder is carried out prior to sintering under dry conditions using a graphite mould. This process is termed a 'dry powder sintering' or 'loose sintering'. 'Wet slurry sintering' is another approach wherein a nickel powder slurry of suitable consistency is used. Stable plates of definite thickness and 80–90% porosity are produced by these methods [33–35]. Nickel hydroxide and cobalt hydroxide are incorporated into the pores of the nickel plaques by vacuum impregnation or by electrochemical method.

Vacuum impregnation is a multi-step process wherein the plaques are treated with 4 M $\text{Ni}(\text{NO}_3)_2$ containing about 5 wt % $\text{Co}(\text{NO}_3)_2$. The plaques are then transferred to hot alkali and cathodized [36–38]. The process is repeated until a sufficient loading of $\text{Ni}(\text{OH})_2$ is achieved. The resulting plates are thoroughly washed and dried. This process is tedious but readily provides good quality control and can be automated.

In the electrochemical method, the porous nickel plate is cathodized in $\text{Ni}(\text{NO}_3)_2$ solution. The cathodic current liberates hydrogen and reduces nitrate. This leads to an increase in pH which, in turn, causes $\text{Ni}(\text{OH})_2$ to precipitate in the pores, i.e.,



Different approaches are followed in the electrochemical precipitation method: (i) low current density (5 mA cm^{-2}) with 0.3 M $\text{Ni}(\text{NO}_3)_2$ solution and a soluble nickel anode, (ii) high current density (175 mA cm^{-2}) with 4 M $\text{Ni}(\text{NO}_3)_2$ [39, 40], (iii) nickel nitrate and cobalt nitrate dissolved in a 1:1 water-ethanol mixture is used for the precipitation [41] (this process yields a high $\text{Ni}(\text{OH})_2$ loading (viz. 0.43 A h cm^{-3})), (iv) a solution containing $\text{Ni}(\text{NO}_3)_2$, $\text{Co}(\text{NO}_3)_2$, and NaNO_2 maintained at pH = 3 with platinum-plated platinum as the anode [42]. The reactions at the respective electrodes are





As the precipitation proceeds, the pH decreases in the bulk of the electrolyte leading to the formation of NO gas



The electrochemical precipitation is a fast method. It is found to give greater capacity per unit volume or unit weight than the vacuum impregnated (chemical) method. Nevertheless, quality control is difficult as the bath parameters are changing with time. The superiority of the electrochemically-filled nickel electrode is clearly outlined in ref. 43. Inco Europe Ltd [44] has developed a Controlled Micro Geometry (CMG) electrode, made by coating perforated nickel foil (4–5 μm thick) with $\text{Ni}(\text{OH})_2$ up to a thickness of 60–70 μm , and then pressing a number of these coated foils to yield a plate of the required thickness. Such electrodes are found to perform well in Ni/Zn batteries.

Pressed electrodes

A mix containing $\text{Ni}(\text{OH})_2$, $\text{Co}(\text{OH})_2$ and graphite powder in appropriate proportions is incorporated with PTFE or poly(ethylene) (5–10 wt %). The plastic-containing material is hot pressed over a suitable conducting grid, or fed into a rolling machine along with the grid. The applied pressure and the gap between the rollers generally control the thickness of the plate [45–47]. Sometimes, a pore-former such as finely divided sodium chloride is used to create sufficient porosity. These electrodes are found to have good discharge characteristics and durability under normal drains.

Tubular or pocket electrodes

A nickel salt is converted to its hydroxide. Cobalt is added during the precipitation stage (Ni/Co = 20/1). The hydroxide is washed thoroughly, filtered, dried, and powdered. The resulting $\text{Ni}(\text{OH})_2$ and $\text{Co}(\text{OH})_2$ mix is blended with about 20 wt % graphite powder or nickel flakes to enhance the conductivity, and is then put into perforated tubes or pockets made from thin nickel sheet or nickel-plated, m.s. sheet [48]. These electrodes are suitable for low-current drain applications.

Nickel composite electrodes

Composite electrode fabrication is a new technology with comparatively low weight and high active material content. The electrodes possess good electrical conductivity and provide high energy density. Nickel-coated, chopped graphite fibre or nickel fibre is subjected to compact sintering [49–51] to produce a highly porous fibre mat. The latter is loaded with $\text{Ni}(\text{OH})_2$, together with a small percentage of $\text{Co}(\text{OH})_2$, by electrochemical precipitation. The nickel composite electrodes display good performance characteristics with energy densities between 120 and 180 A h kg^{-1} .

Electrolyte

The electrolyte used in Ni/Fe batteries is 25–30 wt % KOH solution containing 50 g l^{-1} LiOH. The LiOH improves the life and capacity of the positive electrode. Other addition agents that have been examined include Na_2S , K_2S , NaK tartrate, sodium salt of EDTA, polyoxyethylene dodecyl ether, cyclohexylamine, and hydrazine sulphate [52, 53]. At concentrations in the range 1–5 wt %, these agents have been found to improve the utilization coefficient of the iron electrode and to reduce its self discharge.

Separator

The active materials of Ni/Fe batteries, viz, $\text{Fe}(\text{OH})_2$ and $\text{Ni}(\text{OH})_2$, are insoluble in the electrolyte. As a result, simple physical separation of the positive and negative electrodes is sufficient. There is no need for special separators of the type used in Ag/Zn, Ni/Zn, and Zn/ O_2 batteries. Nylon cloth and felt, porous PVC, or non-woven poly(propylene) cloth normally serve as the separator material for Ni/Fe batteries.

Impurities

Impurities associated with the negative electrode are Mn, Al, V, Ti, Mg, Ba, Ca, and their ions. Some of these tend to form a passive film on the iron electrode, while some enhance the self-discharge rate. The most serious impurities in the positive electrode are oxides and hydroxides of Mg, Si, and Fe. These tend to reduce the oxygen overpotential on the positive electrode. The addition of lithium hydroxide to the electrolyte helps to minimize this effect.

Battery assembly

The negative iron electrodes and positive nickel electrodes are arranged alternately, with separators in between. A common terminal is provided for each of the negative and positive plate groups. Usually, there is one extra negative plate. The whole electrode assembly is immersed in the electrolyte and housed in a container made from plastics, glass, or nickel-plated steel. Cell terminals and links are of nickel-plated steel. A special type of venting is provided in the lid in order to allow gases to escape and to avoid electrolyte spillage and carbonation.

Performance characteristics

Iron at the negative electrode reacts galvanically with the nickel hydroxide at the positive electrode during discharge and charge according to the following reactions

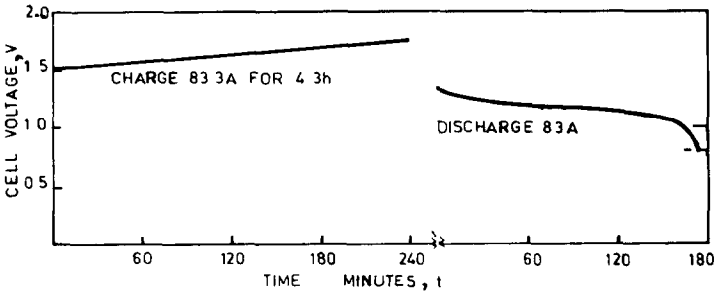
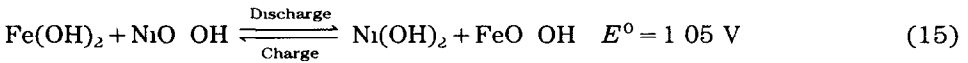
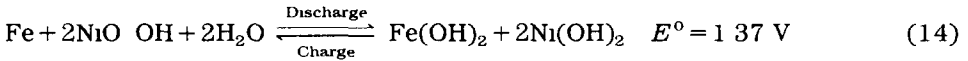


Fig 2 Charge/discharge characteristics of 250 A h Ni/Fe cell [54]



The second step normally takes place under deep-discharge conditions and is of little practical importance. Excessive use of active material at the negative electrode, and the mode of discharge of the battery to a cut-off voltage of 1 V, do not normally lead to the second step. The OCV, discharge voltage, and charging voltage of Ni/Fe cells are 1.37 V, 1.3–1.00 V, and 1.7–1.8 V, respectively. The discharge voltage–time curve is fairly flat, as demonstrated by the typical charge/discharge curve [54] for a 250 A h nickel/iron cell (Fig 2).

The discharge capacity depends on both the discharge rate and the ambient temperature. When a nickel/iron system is discharged at the $C/1$ rate, the capacity realised is only 50% of the nominal value. The batteries, particularly those with tubular positive electrodes, are intended for low- or moderate-rates of discharge, i.e., $C/8$ to $C/1$. Sintered-electrode designs normally yield high power because of the very low internal resistance. As the temperature goes down, the capacity output decreases considerably. The derived capacity at 255 K is about 50% of the nominal value when discharge is carried out at the $C/8$ rate [55], performance is reasonably good at ~ 308 K. The behaviour at sub-zero temperatures is due to passivation of the iron electrode. Self-discharge is 0.1–2.5% of the nominal capacity per day below 293 K, 1–2% at ~ 298 K, and 8–10% at ~ 313 K. Batteries can be stored for long periods in either the charged or discharged condition without any deterioration. Service life is 7–25 years. High-power batteries use sintered negative and positive electrodes.

Battery development in different countries

Efforts are constantly being made, worldwide, to develop Ni/Fe batteries for traction and other purposes. In 1908, Edison developed the tubular

version to power electric vehicles State-owned firms in the U S S R have produced [20] different designs of battery with energy densities around 26 W h kg⁻¹ for various applications, see Table 3

In the U S A , Westinghouse has been involved in the development of Ni/Fe batteries for electric vehicles for over a decade The units utilize sintered, steel-wool matrices for the negative and positive electrodes Different multi-cell modules have been developed The characteristics [56] of one such module (E-180) are as follows

Specific energy	44 W h kg ⁻¹
Specific power	100 W kg ⁻¹
Energy efficiency	55%
Cycle life	1500

The Westinghouse system has been tested in an electric vehicle in the form of a 25 kW h battery pack with an energy density of 50 W h kg⁻¹ [49] The pack consisted of 14 modules each comprising a 6-cell unit with a rated capacity of 250 A h and weighing 29 kg

The Swedish National Development Company (SU), and Eagle Picher (EPI) in the U S A , have combined efforts to produce a Ni/Fe battery with an energy density of 55 W h kg⁻¹ at the C/5 rate Sintered electrode technology has been preferred The 12 V, 260 A h battery weighed 794 kg The discharge characteristics [55] are given in Fig 3 When this battery was tested in an electric vehicle, a distance of 190 km at an average speed of 60 km h⁻¹ was obtained over a single discharge

In Japan, Matsushita Electric Industrial Co , Ltd has developed [57] a 16.8 V, 165 A h Ni/Fe battery weighing 41.25 kg and yielding more than 55 and 60 W h kg⁻¹ at the C/1 and C/2 rates, respectively The cycle life is over 1000 cycles at a C/5 constant charge and discharge rate This advanced Ni/Fe battery uses sintered electrode technology

In France, SAFT is engaged in the development of Ni/Fe traction batteries A five-cell module (6 V – 30 A h) has been fabricated with sintered positive

TABLE 3
Ni/Fe battery development in U S S R

Battery type	Nominal capacity, C (A h)	Charge & discharge rate	Weight (kg)	Application
TZh N-250	250	C/5	18	traction
TZh N-950	950	C/5	52	traction
ZhN N-22	22	C/4	1.69	general use
ZhN-100	100	C/4	6.6	general use
10 ZhN-22T	22 (12.5V)	C/4	20.6	communications equipment
10 ZhN-100T	100 (12.5V)	C/4	76.4	communications equipment
2 FZh-8-1	8	C/4	1.45	miners' cap-lamp
2 ShZhN-15-11	15	C/4	2.04	miners' cap-lamp

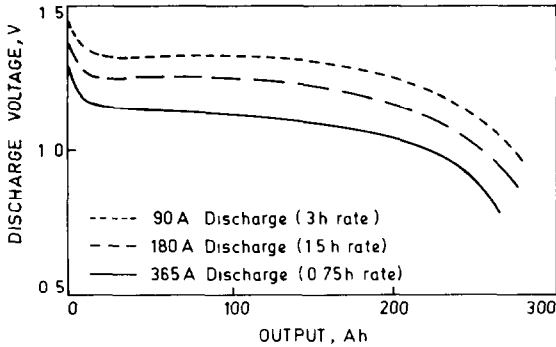


Fig 3 Discharge characteristics of SU/EPI Ni/Fe battery [55]

TABLE 4

Ni/Fe battery development in Germany

Battery type	Nominal capacity (C/5) (A h)	Energy density	
		W h kg ⁻¹	W h l ⁻¹
E ₄	300	22.5	51.7
E ₅	375	23.7	54.2
E ₆	450	24.6	56.3
E ₇	525	25.2	56.8
E ₈	600	25.7	58.7
E ₁₀	750	26.5	57.5
E ₁₂	900	26.4	57.5

and plastic-bonded negative electrodes The module has the following electrical and physical characteristics

Specific energy	60 W h kg ⁻¹ (C/5 rate) 50 W h kg ⁻¹ (C/1 rate)
Peak power	172 W kg ⁻¹ (fully charged) 153 W kg ⁻¹ (50% discharged)
Energy efficiency	60–65%
Weight	25 kg
Outer dimensions	244(L) × 190(W) × 280(H) mm

VARTA in Germany and Inco Europe Ltd in the U K are involved in the advancement of Ni/Fe batteries for different applications including motive-power service The different versions developed in Germany [20] are summarized in Table 4

Work is in progress at CECRI, India, to develop Ni/Fe batteries for traction, train lighting, and air-conditioning, and other stationary purposes Sintered technology has been adopted for fabrication of the negative and positive electrodes Different substrates that have been investigated for

electrode manufacture include (i) punched, thin m s sheet plated with nickel, (ii) steel mesh plated with nickel, (iii) expanded m s plated with nickel, (iv) nickel-plated steel wool fibre-mat.

In order to fix the metal powders bilaterally onto the substrate, dry powder loose sintering and wet slurry sintering are employed. A few prototypes of Ni/Fe batteries assembled with sintered electrodes are undergoing laboratory trials. The electrical characteristics of a Ni/Fe battery prototype are

Capacity	20 A h
Working voltage	1.3–1 V
Specific energy	23 W h kg ⁻¹ (C/1 rate)
Energy efficiency	75–80%
Cycle life	1000 (C/1 rate)

Conclusions

Among various types of rechargeable battery systems, the Ni/Fe alkaline battery exhibits the longest service under field conditions. The battery performs very well at normal ambient temperatures. The technology of manufacture of the positive and negative electrodes is simple. Low cost, good performance, ruggedness, environmental safety, reliability, and ease of manufacture are the factors contributing to its usefulness. Efforts are being made in various parts of the world to minimize self discharge and to maximize specific energy and specific power. Improved, or advanced Ni/Fe batteries could serve as the main source of power for future electric vehicles, as well as for stationary applications.

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