“Substitution of rechargeable NiCd batteries

A background document to evaluate the possibilities of finding
alternatives to NiCd batteries”

By Arne O. Nilsson

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1. General Remarks

Professor Dag Noreus, ("Noreus"), has made an attempt to prove in this report that nickel-metal hydride (NiMH) batteries can substitute for nickel-cadmium (NiCd) batteries in the market place. As background for this document, the report relies mainly upon information from NiMH battery manufacturers. It is remarkable that a report written by an academic scientist does not include any references to scientific or technical literature. There are only four appendices to the report, and they are all sales literature from NiMH battery manufacturers or users. It is obvious that most of the report's statements are based on pure speculation with little or no deeper involvement or knowledge of the battery industry.

It would be expected that any objective document should include a detailed discussion of the advantages and disadvantages of the products being compared. This objectivity is absent from this report, which presents personal speculations without any technically verified or verifiable corroboration. The result is that many of the report's statements and speculations are simply incorrect or at best misleading. Examples include statements regarding NiCd and NiMH battery development, battery characteristics, battery pricing as well as cadmium supply, demand and recycling.

Summarizing, it may be stated that the Noreus report is little more than a promotional document for the NiMH battery industry, and cannot be considered an objective analysis to evaluate the possibilities of finding alternatives to NiCd batteries. A more unbiased study comparing NIMH and NiCd batteries would reveal that NiMH batteries probably have an advantage over NiCd batteries in applications with low current drains at moderate temperatures, but in no other applications can they replace or substitute for NiCd batteries.

2. Development of Rechargeable Batteries

The Noreus Report ignores the fact that rechargeable batteries, both lead-acid and alkaline, were invented in Europe and North America during the 19th century. Lead acid batteries were developed by Gaston Planté in France in 1859, while batteries with an alkaline electrolyte, such as the nickel-iron and nickel-cadmium systems, were invented by Waldemar Jungner in Sweden in 1897 and Thomas A. Edison in USA in 1899. Both Jungner and Edison started to develop nickel iron batteries for industrial applications, which later led to the first patents for industrial NiCd batteries in 1901. These early batteries were vented (open) and had pocket or tubular electrodes. The first electrode utilizing sintered nickel was developed by Varta in Germany for military aircraft applications beginning in the 1920s.

The sealed NiCd battery with sintered electrodes was developed by SAFT in France in the 1950s. The fiber electrode NiCd batteries were developed by DAUG in Germany in the 1970s at about the same time as NiMH batteries were first developed and patented in Europe by Philips.

The consumer NiCd cells were not developed by General Electric in the USA as stated in the Noreus Report. General Electric received a license from SAFT, as did Gulton-Union in the USA. SAFT also granted a license on sealed NiCd batteries to Japan Storage Battery (GS), while Honda Denki in Japan was granted a license from NIFE

Jungner in Sweden on industrial NiCd batteries. The historical development of lead-acid batteries has taken place both in Europe and the USA, while the historical development of NiCd batteries has taken place almost exclusively in Europe, contrary to the assertions in this report.

The statement in the Noreus Report that:

> *"The traditional battery industries tend to be fairly conservative establishments with a long industry resting on an impressive amount of empirical knowledge"*

is quite simply false. As indicated above, the leading developers have been found in Europe and USA. In the battery industry, Japan has, as in many other industries, relied on licenses on technology in order to mass produce consumer products. This historical development has nothing to do with the Noreus Report assertion that:

> *"It was not until the last decade's general advancements in material science that the situation was significantly improved upon."*

3. The Battery Market

There is no one battery chemistry which can combine optimum performance under all operating conditions, i.e. high temperature, low temperature, mechanical abuse, light weight, low volume, high rate discharge, low rate discharge, long cycle life, low self discharge, reliability, low maintenance, etc.

Among rechargeable batteries, lead-acid batteries of various designs dominate the industrial market. The largest group is the automotive starting, lighting and ignition (SLI) battery. There are various types of SLI batteries depending on climate conditions and application types such as trucks, cars and boats. Both vented (open) and sealed types are available.

In cycling applications such as traction and vehicular propulsion for electric trucks and industrial vehicles for uses in mining, railroads or submarines, where long cycle life is required, lead-acid batteries of a different design than the SLI batteries are used. In stand-by applications such as telecommunication, computer backup, emergency lighting and power backup systems, various types of vented or valve-regulated (VRLA) lead-acid batteries are used depending on the specific application.

Vented or sealed industrial NiCd batteries with pocket, sintered, fiber, or plastic-bonded electrodes are used in applications where the batteries are exposed to:

- temperature extremes
- mechanical abuse
- limited or no maintenance
- demand for long service life
- high reliability requirements

Industrial NiCd batteries are used in railroad and mass transit applications due to their high durability and excellent resistance to mechanical and electrical abuse. Other applications for industrial NiCd batteries are for stationary installations where power reliability is the highest priority as life and great economic investments could be jeopardized by a power failure. Examples of such installations are hospital operating theaters, offshore oil rigs, backup power for large computer systems in banks and insurance companies, standby power in process industries, and emergency power systems in airports. Another important use for industrial NiCd batteries is in aviation applications where they are used mainly for aircraft starting and emergency power. Specialized uses in space and military applications are also important because of their high performance, long life and dependability.

In recent years, there has been an interesting development. Lead-acid batteries have always dominated the telecommunication market, particularly in large central station batteries. With the development of fiber optic systems and more decentralized distribution systems, the traditional valve regulated lead acid (VRLA) battery could not meet the demand requiring 99,9% reliability and long service life. The VRLA batteries therefore have been replaced by low maintenance, long life NiCd batteries of 80 and 125 Ampere-hours (Ah). SAFT is now building a plant in the USA for manufacturing of 100 million Ampere-hours (MAh) per year for this new NiCd battery application.

It is interesting to note that, in this application, the industrial NiCd battery has been able to penetrate a traditional lead-acid market segment. The reason is that a NiCd battery was developed, which could meet the market demand of high reliability, low maintenance and long life in a wide temperature range, resulting in a cost per unit of performance that was superior to the lead-acid batteries being used.

The global market for consumer type rechargeable batteries has exploded during recent years as more and more electronic and portable devices are introduced in the market place. This rapid growth began in the 1980s with cordless devices such as shavers and phones and has now evolved into toys, household appliances, laptop and handheld computers, camcorders, cameras, memory back up, power tools, and, above all, cellular telephones.

The consumer portable battery market has been dominated by sealed cylindrical NiCd batteries for many years. However, in applications where a high specific energy and low weight in a moderate temperature range are required, the NiMH battery is now the preferred battery chemistry. More recently, the Li-ion and, most recently, Li-polymer batteries are now penetrating this market segment, and will probably command a significant share of the rechargeable consumer battery market in the future. Sealed lead-acid batteries have only a small market share of portable applications.

Sealed NiCd batteries still maintain their strong market position in applications which require:

- high power drains and drain rates
- temperature extremes
- long life

For all rechargeable battery systems, there are market demands that can be met only by a specific battery chemistry and where the key factor is the most competitive cost per unit of required performance to the satisfaction of the consumer. The Noreus Report appears to be unaware of the market demands of the battery industry, and largely disregards or ignores these market demands.

4. Battery Characteristics

As the intention of the Noreus Report was to show that the sealed NiMH battery could replace the sealed NiCd battery, this critique will be restricted to a comparison of the characteristics of these two battery types. The different types and characteristics of industrial lead-acid and NiCd batteries would be a subject of a study on their own merits, but is not discussed here so as not to confuse the issues brought up by the Noreus Report.

> *"Among the rechargeable batteries presently in use, it is easiest to start with the simplest type, namely that of the NiMH cells".*

This statement has some bearing on the overall and electrode reaction formulas for the NiMH cell compared with those for the NiCd cell, but is not the full truth. The principal difference between the two types of batteries is that the NiMH cell has hydrogen ions absorbed into a metal alloy as negative electrode active material while the NiCd cell has cadmium as negative electrode active material, as can be seen from the reaction formulas below.

In the NiMH cell, the overall reaction is actually a proton transfer from one electrode to another. In the alkaline electrolyte, the proton is combined with a hydroxyl ion and thus represents water transport from one electrode to the other. In the NiCd cell, the overall electrochemical reaction produces water. Therefore, the MH electrode is a three phase system (solid-liquid-gas) while the Cd electrode is a two phase system (solid-liquid). The reaction for the NiMH cell is not explained in the Noreus Report nor are the differences in electrode reactions between the two systems, but it does mention the two phase system for NiCd cells.

The stability of the MH electrode system depends on temperature because the reversible hydrogen pressure depends on temperature. As a consequence, the rate of hydrogen adsorption and desorption at the MH electrode in a NiMH cell is more sensitive to temperature than the rate of cadmium deposition or dissolution at the cadmium electrode in a NiCd battery. Another difference is that the charge reaction of the NiMH cell is exothermic (heat generating) whereas it is endothermic (heat absorbing) in the NiCd cell. The impact of these differences on cell performance will be subsequently discussed.

The following reactions show the chemistry of the NiMH cell:

Ni electrode:	$Ni(OH)_2 + OH^- \Leftrightarrow Ni\ OOH + e^-$
MH electrode:	$M + H_2O + e^- \Leftrightarrow MH + OH^-$
Overall:	$Ni(OH)_2 + M \Leftrightarrow Ni\ OOH + MH$
Overcharge:	$2OH^- \rightarrow 1/2O_2 + H_2O + 2e^-$

$2M + 2H2O + 2e^- \rightarrow 2MH + 2OH^-$

Recombination: $4MH + O_2 \rightarrow 4M + 2H_2O$

Overdischarge: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
$MH + OH^- \rightarrow M + H_2O + 2e^-$

Recombination: $M + 1/2H_2 \rightarrow MH$

Overcharge Ni electrode:
$2OH^- \rightarrow 1/2O_2 + H_2O + 2e^-$

Overdischarge MH electrode:
$H_2 + 2OH^- - 2e^- \rightarrow 2H_2O$

The reaction formulas for overcharging and recombination are not included in the Noreus Report, but are important in understanding the advantages and disadvantages of the two battery types. The formulas for overcharging the Ni electrode and overdischarging the MH electrode are omitted in the Noreus Report. They are only indicated in two diagrams.

The following reactions show the chemistry of the NiCd cell:

Ni electrode: $Ni(OH)_2 + OH^- \Leftrightarrow NiOOH + H_2O + e^-$

Cd electrode:$Cd(OH)_2 + 2e^- \Leftrightarrow Cd + 2OH^-$

Overall: $2Ni(OH)_2 + Cd(OH)_2 \Leftrightarrow 2NiOOH + Cd + 2H_2O$

According to the Noreus Report:

> *"The electrolyte not only serves as an ionic conductor, but also participates in the electrode reaction. The amount of electrolyte in the cell becomes dependent on the state of charge of the electrodes and this has to be considered in the design of electrodes and electrode porosity especially in sealed cells with starved electrolyte".*

This statement is a personal theory of the author, and is not verified in battery industry research or experience. In his chapter on "Sealed Nickel Cadmium Batteries" in Handbook of Batteries, David Linden notes in this respect that: "Similarly, there is little if any change in the electrolyte concentration", which is also the experience in the NiCd battery industry.

With respect to NiCd batteries, the Noreus Report also states that:

> *"Sealed cells have to be designed so that gas can diffuse between the electrodes to ensure proper recombination reactions. This means that it is not possible to completely fill the cell with electrolyte. The amount of electrolyte has to be 'starved' to ensure passage of gases through the separator."*

This statement conflicts with a later statement to the effect that:

> *“Overcharge, overdischarge reactions .... in sealed NiMH cells are slightly different from sealed NiCd cells”.*

Here the Noreus Report states that, in overcharging reactions in NiMH cells:

> *“Sealed cells are designed with a certain amount of porosity in the separator that is not filled with electrolyte (starved electrolyte). This will allow for gas passage so that the oxygen produced at the positive electrode can diffuse through the separator and be recombined at the negative electrode”.*

It is remarkable that this behavior is considered a problem for NiCd cells but not for NiMH cells!

Another personal theory given credence in the Noreus Report concludes that:

> *“Furthermore, preferential crystal growth mechanism in the dissolution precipitation reactions may cause dendrites (so called “cadmium needles”) which cause internal shortcuts, when they penetrate the separator in the cell”.*

These dendrites were detected in early vented industrial NiCd cells, but they cannot grow in sealed cells as they will be broken by gas diffusion through the separator.

The Noreus Report further declares that preferential grain growth can lead to the so called “memory effect” in NiCd cells. The warnings given in this report about the so called “memory effect” and how to restore cells from this effect are completely unfounded. The “memory effect” is mainly a phenomenon in sealed cells with sintered electrodes and is not found in cells with other electrode structures. It has been observed in sintered NiMH cells as well as sintered NiCd cells. If a cell or battery has developed a memory effect, the recommended corrective action is simply to deep discharge the cell which will not destroy it.

After several attempts to discredit NiCd cells by speculation and personal theories and failing to do so, the Noreus Report tries another route to disqualify them:

> *“......many years of development and continuous improvements lie behind the modern NiCd battery. Much of this is empirical “company know-how” and is suspiciously kept secret”*.

Contrary to this assertion in the Noreus Report, there have been many books written about NiCd batteries by scientists and technicians in the industry as well as universities in Europe, the USA, and the former Soviet Union. There are at least 20 textbooks written about Electrochemical Power Sources and Primary and Secondary Batteries. In addition, there have been continual technical developments that have been presented at and published from at least a dozen major battery symposia and conferences each year all over the world. There is ample technical information on NiCd batteries available to anyone who looks for it.

Worst of all, the Noreus Report does not present any of the disadvantages of NiMH cells while seriously overstating the disadvantages of the NiCd battery. It touches upon overcharging and overdischarging, but attempts to minimize the problems with NiMH batteries in these areas. As stated earlier, the rate of hydrogen adsorption and desorption at the MH electrode is very temperature sensitive, and the charging reaction for the NiMH cell is exothermic. Both of these facts can be serious disadvantages to a NiMH battery, yet the Noreus Report barely discusses them.

The Noreus Report also makes the statement that as long as the oxygen produced at the positive electrode in a NiMH battery can diffuse through the separator:

> *" .... the cell can be continuously overcharged without damage"*

It points out that heat from recombination will heat up a NiMH battery, which, if it becomes excessive, will cause it to fail. However, the report does not fully explain the depth of that failure. When the charging current during overcharge results in a high level of heat dissipation in a NiMH battery, the reversible hydrogen pressure becomes higher than the cell valve release pressure, both oxygen and hydrogen escape through the valve, and consequently create cell imbalance. After charging, the state of charge of the NiOOH electrode (positive nickel electrode) will be higher than that of the MH electrode (negative metal hydride electrode), and will limit cell capacity. With every cycle of over-charging when charging rate is kept high, the cell imbalance will increase as a result of escaping hydrogen.

In his textbook, Handbook of Batteries, David Linden points out very clearly these overcharging problems with NiMH batteries. As the cell temperature during charge is very dependent on charging current:

> *"The internal pressure increases similarly. This rise in temperature and pressure at the higher charge rates emphasizes the need for proper charge control and effective charge termination when "fast charging" to avoid venting and other deleterious effects".*

Overcharging of NiMH cells not only results in drying out of the separator as the Noreus Report states. In this context, it must also be mentioned that it is not only the starved electrolyte amount contained in the separator which is important but also in the negative electrode as well since the oxygen diffusion rate has to be comparable with the overcharging rate. The total pore size distribution for the whole system is a key issue. The positive electrode should have as small a pore size as possible. The separator and negative electrode should have a pore structure with two sized pores, small pores for electrolyte transfer and large pores for gas transfer.

The Noreus Report states that:

> *" ... the NiMH battery has, in principle, an advantage of being able to withstand a certain amount of overdischarging".*

This statement is highly doubtful as there is a question regarding hydrogen consumption on the discharging MH electrode. From a formal point of view the statement is correct, but it appears to have disregarded the reaction kinetics. From the equilibrium thermodynamic point of view, hydrogen can in theory be consumed on the almost completely discharged MH electrode, but from a kinetic point it is doubtful it will occur.

There is a risk in irreversible loss of capability for the MH electrode to be charged after being exposed to oxygen potential. Such a loss can happen if there is no hydrogen consumption and initial excess of the MH is depleted. The cell voltage is minus 0.4-0.6 V depending on discharge current. As the same amount of electric energy generates twice the hydrogen volume in comparison with oxygen volume, the amount of hydrogen not consumed can result in the cell voltage being reversed completely and the MH electrode starts producing oxygen.

The voltage of the cell will then equal minus 1.6 -1.8 V. The electrochemical oxidation of the MH electrode can adversely effect hydrogen adsorption capability in subsequent charging cycles. The Noreus Report ignores this issue by stating that:

> *"At high current discharging, the recombination kinetics is, however, too slow to be able to cope with the emitted gaseous hydrogen. The danger of damage by this pole reversal of some cells in the battery pack is reduced, if all cells can be fully charged to the same capacity before discharging"*

As explained above, Noreus' contention is not possible.

It is even more amazing how some facts are turned upside down in the Noreus Report:

> *"Ageing and thermal gradients across the battery pack will increase this spread in practical cell capacities and in this respect also the limited ability of the NiMH cell to withstand overdischargin will be beneficial for the life expectancy. This property will be especially valuable in EV/HEV, where several hundreds of cells are used in series."*

Here the Noreus Report concedes that the NiMH cell has a limited ability to withstand overdischarging, while earlier it stated that NiMH had the advantage of being able to withstand a certain amount of overdischarging! How then can the limited ability of the NiMH battery to withstand overdischarging, which will ruin a battery, be beneficial for its life expectancy and make it especially valuable in EV/HEV applications?

Besides the problems related to overcharging and overdischarging, NIMH cells have numerous other weak points not even mentioned in the Noreus Report. The NiMH cell has a narrow operating temperature range. The narrow operating temperature range is due to the fact that the rate of hydrogen adsorption and desorption at the MH electrode is very sensitive to temperature, much more so than the exchange current for the reaction on the cadmium electrode in a NiCd cell. The reaction in the liquid phase at the Cd electrode is less temperature sensitive than the one in solid state at the MH electrode.

The NiMH cell has relatively short cycle life compared to the NiCd cell. This shortcoming is again related to the pronounced dependence on temperature in the NiMH cell.

The NiMH cell exhibits high heat dissipation during charging. This behavior is due to the difference in value of thermoneutral potentials for the NiMH and NiCd chemistries. The heat generated during the charging process is usually described by the formula:

$$W = I\,(V - \alpha E_T)$$

Where V = charging voltage
I = charging current
E_T = thermoneutral potential
α = charging efficiency

When $\alpha = 1$ there is no oxygen production and the heat dissipation is:

$$W = I\,(V - E_T)$$

When $\alpha = 0$ the positive electrode generates oxygen only and

$$W = I \times V$$

which is converted to heat.

E_T for the NiCd cell is 1.45 V and 1.35 V for the NiMH cell. The charging voltage of the NiMH cell is more than 1.35 V and a NiMH cell produces heat from the very beginning of the charging process. This heat generation increases significantly with higher current not only because of the higher current itself but also because of the simultaneously increasing voltage. The oxygen production (recombination) is a major increment in the heat generation. A cell voltage equal to 1,5 V and 90% efficiency (10% of oxygen production) doubles the generation of heat.

In a multicell battery, it is difficult if not impossible to avoid cell imbalances during cycling. As shown above, NiMH cells are more sensitive to temperature and dissipate more heat during charging. Therefore, a greater loss of hydrogen can be expected as discussed previously. Consequently, a high rate of cell imbalance for multicell NiMH batteries will be encountered in cycling applications. This excessive cell imbalance is very pronounced with larger cells such as those used for power tools, and is a significant problem with EV/HEV batteries of 250-300 cells. Noreus does not address this disadvantage of NiMH batteries in his report at all.

Another subject not discussed in the Noreus Report are the problems associated with larger NiMH cells. While electric vehicle (EV) and hybrid electric vehicle (HEV) batteries are mentioned, specific problems related to larger NiMH cells are simply avoided. All NiMH cells have the problems in common mentioned above. However, in larger cells there is yet another drawback as there is a maximum capacity or ceiling for NiMH cells associated with these thermal problems. Cell overcharging creates exothermal reactions of oxygen recombination and heat has to be removed from the cell. The heat generated (W_{gen}) is proportional to cell volume while the heat dissipated (W_{dis}) is proportional to cell surface area. Therefore the thermal problem may be presented as:

$$W_{gen}/W_{dis} = V/V^{2/3} = V^{1/3}$$

This relationship would indicate that the maximum capacity of a NiMH cell should be 70-80 Ah.

Another complication for NiMH cells is that in multicell batteries a simple charger such as that used for charging NiCd multicell batteries will ruin the NiMH battery. The NiMH battery requires a charger with more technologically sophisticated sensors to monitor cell temperature to prevent overcharge and overdischarge, current, and voltage. This requirement will call for complicated and therefore expensive electronic monitoring device for NiMH EV and HEV batteries, but it is also recommended for lower voltage cycling batteries. Again, the Noreus Report does not refer to this shortcoming of NiMH batteries in its analysis.

5. Pricing

The Noreus Report approach to cell pricing is somewhat strange:

> *"Anyhow, the dominant Japanese position and the fact that the Battery Association of Japan compiles very reliable statistics for the domestic Japanese production, can be used to better compare the price/cell and price/Wh for the different cells".*

It presents the author's personal conclusions from the wrong material:

> *"it is interesting to see that the Japanese battery industry with a very focused industrial policy and targeted R&D has managed to become totally dominant in this market ....."*

While it is true that Japan has focused on the small consumer battery market, their R&D efforts are not extraordinary compared to the USA and European efforts. The Japanese battery industry has relied upon technology from other countries as was previously discussed in Section 1. In recent years, they have concentrated their efforts on the consumer market and mass production where Asian industry always has been stronger than those have in Europe and USA.

To attempt to develop a realistic comparison on cost per unit performance for batteries on the price/cell or price/Wh in a competitive market place where everybody is fighting for market share is completely unrealistic. Noreus has made one realistic attempt at a cost comparison in his table from Toshiba on material costs, but this comparison is irrelevant as it compares a NiMH cell with a nickel foam electrode and a NiCd cell with a sintered nickel electrode. Cost comparisons would have to be made with both electrodes produced in the same manner.

If differences in cost between the nickels electrodes for NiCd and NiMH batteries are disregarded, as stated in the Noreus Report that they can be the same in both types of cells, then the costs in Noreus' table for the negative electrodes become 17.75 yen/Wh for MH material and 14.34 yen/Wh for Cd material. For some reason, there is 1.32 yen/Wh of conducting additive materials included for Cd electrodes in the Noreus Report table which is not normal for a punched steel substrate. Therefore a more realistic cost for Cd material is 13.02 yen/Wh. The NiMH material cost is thus 24% or 36% higher than the cost of Cd material.

The Noreus Report also remarks that there are current efforts to find a cheaper material in NiMH batteries to eliminate what he describes as:

> *"the fairly expensive Ni foam"*

and to persuade the NiMH battery producers to reduce their prices. This statement appears incorrect as both US and European manufacturers consider nickel foam less costly than nickel sinter. Furthermore, metal prices are not established by battery producers but by international pricing. It is also somewhat naive to believe that, with the HEV development, the car industry will be able to significantly reduce the cost of the battery. Why should the automotive industry be any more successful in cost reduction than the telecommunications industry that is the single largest consumer of cylindrical NiMH cells?

It is obvious from the discussion above that the cost of metal hydride negative electrode material is 25-30% more expensive than the cadmium negative electrode material. Therefore there is no realism in the Noreus Report statement that the price of NiMH cells is less than the price of NiCd cells.

The Noreus Report arrives at this conclusion by combining different data, but the discussion above clearly indicates that NiMH cannot compete with NiCd on material costs. The Japanese system of pricing products is familiar in the industry, but the currency exchange rates must also be taken into consideration. Therefore the cost of battery raw materials is the only realistic comparison.

In general, it may be stated that the real price drivers for both NiMH and NiCd batteries are the amounts of nickel and cobalt and the costs of negative electrode materials in the two battery chemistries. Because of the high cost of nickel and the very high cost of cobalt it is doubtful whether there will ever be a pure EV battery based on a nickel electrode chemistry for raw materials cost considerations alone. For a HEV battery where power is the performance parameter required and not the energy density, NiCd batteries should be the ideal battery in terms of cost per unit of performance considering its good high rate performance, tolerance to temperature extremes and mechanical abuse as well as its very long cycle service life.

Typically prices for electrolytic nickel in the past few years have been about $2 to $3 per pound (approximately 5 to 7.5 Euros per kilogram), and nickel powders and foams used as positive electrode materials are considerably more expensive than that. Cobalt metal is currently quite expensive, generally in the $20 to $30 per pound range (approximately 50 to 75 Euros per kilogram), and cobalt powder used in batteries is even more expensive as well. Cadmium metal is now about $0.26 per pound (approximately 0.65 Euros per kilogram), but the cadmium oxide with controlled impurities and controlled particle size which is used in NiCd batteries is more expensive, at least $1 to $2 per pound (approximately 2.5 to 5.0 Euros per kilogram), depending upon specific requirements. The materials which are encountered in NiMH batteries in sufficient to affect price are nickel and cobalt and probably the rare earth elements such as cerium. The price for mischmetal, a mixture of several rare earth metals has in recent years been selling for about \$5 per pound (approximately 12.5 Euros per kilogram). Price for pure cerium and in the form necessary for NiMH batteries would be substantially higher.

The expensive aspect of NiMH batteries has always been that the MH compounds used for the negative electrode must be of a very precise composition, based either on the AB_2 or AB_5 intermetallic compounds in the nickel phase diagrams. These alloys are therefore somewhat complex and are not nearly as forgiving as the cadmium electrode in the NiCd batteries.

The Noreus Report further alleges that:

> *"By the mid eighties MITI funded several R&D projects together with the Japanese industry to develop new types of batteries, not relying on cadmium. Cadmium shortage and not environmental concerns was the driving force…. The initial fear seemed, well founded, by the end of the eighties, the cadmium prices peaked due to shortage of cadmium."*

The cadmium price did indeed peak in 1986-88 due to the rapidly growing consumer NiCd battery market and some unprincipled speculation by a few traders. However, it was not due to a shortage of cadmium. Cadmium production increased steadily all during the 1980s and 1990s due to increased zinc production, since cadmium is a by-product of zinc production.

The author of this report is a scientist by profession, and appears not to be one who is well aquainted with the marketing and pricing of the battery industry or one who has followed closely the research and development of NiCd batteries through the publications and presentations in the electrochemical and battery industry and literature.

6. Cadmium Production, Consumption and Recycling

In presenting a short summary of cadmium consumption, the Noreus Report indicates that recycling of NiCd batteries is:

> *"almost solely made from the industrial NiCd batteries as effective recollection systems for the consumer size cells are still lacking."*

In reviewing cadmium consumption for 1995, Noreus indicates that:

> *".... about 11,000 tons (metric tons) of cadmium were reported to be used in the global NiCd production. About 3/4 or 8,500 tons were used in portable or consumer size cells (sealed NiCd). Only 2,500 tons of cadmium for batteries is used for making larger industrial size NiCd cells."*

It is of interest to examine cadmium production and consumption and establish how they have changed since 1995, the base year in the Noreus Report:

Production of refined cadmium

Year	1995	1996	1997	1998	1999
Tons production	19,478	18,489	19,917	19,851	18,767
% production by 7 largest producers	58	58	60	59	60

Consumption of refined cadmium 1999

Year	1995	1996	1997	1998	1999
Consumptions tons	18,847	17,726	18,506	18,104	18,936
% consumed by 5 largest consumers	89	88	87	84	82

As can be seen from the above data, world cadmium production has been very consistent during the last 5 years at approximately 19,000 tons per year, and roughly 60% of that amount has been produced by the world largest producers: Japan, Canada, China, Belgium, Germany, Kazakhstan and USA. Of these 7 countries, Japan and Canada together produce about 45%, or roughly 25% of the total world production.

Of the world consumption of cadmium, approximately 85% were consumed by the 5 largest consumers who are listed by the World Bureau of Metal Statistics as Japan, Belgium, France, USA and Germany. Japan, France, USA and Germany are the four largest producers of NiCd batteries. The consumption in Japan and Belgium, the two leading consumers, accounts for about 60% of the consumption among the 5 leading consumers and is approximately 55% of the world consumption in the years 1995, 1996 and 1997. In the years 1998 and 1999, it dropped to about 50% of world consumption. It must be further noted that the "consumption" of cadmium in Belgium is, in fact, almost exclusively the conversion of cadmium metal to cadmium oxide which is then shipped to Japan for the NiCd battery industry usage. Thus, Japan is, by far, the world's largest consumer of cadmium in addition to being one of its largest producers (*).

The producers in the world also keep a stock of refine cadmium as summarized below from the data of the World Bureau of Metal Statistics:

Primary Producer Cadmium Metal Stocks (tons)

Year	1995	1996	1997	1998	1999
Europe	1,413	1,717	1,341	1,268	1,204
Americas	1,029	1,856	1,000	1,380	1,356
Others	747	857	840	860	901
Total	3,189	4,429	3,780	3,501	3,460

The International Cadmium Association also makes annual estimates of cadmium consumption patterns by end use:

Percent of total consumption

Year Market segment	1995	1996	1997	1998	1999
Batteries	67	69	70	72	73
Pigments	14	13	13	13	13
Coatings Stabilizers Alloys	19	18	17	15	14

It is also estimated that 80% of the cadmium consumed in NiCd batteries is for consumer batteries and 20% for industrial batteries, thus enabling a calculation of the total amounts of cadmium consumed in industrial and consumer batteries.

Tons of refined cadmium consumed in NiCd batteries

Year	1995	1996	1997	1998	1999
Consumer, approx.	10,100	9,800	10,400	10,400	11,100
Industrial, approx.	2,500	2,400	2,600	2,600	2,800

As can be seen from the above data, there has not been a decrease but rather a slight increase in the amount of refined cadmium used in NiCd batteries in spite a growing NiMH battery market share and increased recovery of cadmium from recycling as detailed below.

Tons of industrial and consumer NiCd batteries recycled

	1995		1996		1997		1998	
	Ind	Cons	Ind	Cons	Ind	Cons	Ind	Cons
Japan	641	1,198	633	1,282	692	1,219	736	1,172
SNAM France	1,800	900	1,950	950	1,800	1,230	1,842	1,350
INMETCO USA	2,297	-	2,747	-	1,364	1,483	1,559	1,784
Total	4,738	2,098	5,330	2,232	3,856	3,932	4,137	4,306

(*) Note: It is astonishing to find that Japan, the country in the world with the largest production and consumption of cadmium in the last 15 years, is also the country which has had the world's worst disaster related to cadmium. In the 1950's, there was a spillage of cadmium wastes from a smelter on to rice fields which resulted in the so called *Itai-Itai* disease affecting hundreds of people in the general population. While this disease is not related to cadmium exposure alone, it is obvious that, after this disaster, Japan has been able to cope with any environmental issues and risks posed by cadmium.

In 1995 and 1996, INMETCO did not track industrial and consumer cells separately.

Another issue not often taken in consideration is that consumer cells recycled in any given year were generally produced many years earlier, and industrial cells may have been produced as much as 10 to 15 years earlier.

The recycling numbers available for 1999 are presented in the next Table below.

Tons of industrial and consumer batteries recycled in 1999

	1999	
	Industl	Consr
Europe	2,982	1,650
From Sweden	592	207
USA	1,430	1,956
Total	5,004	3,813

The Noreus Report states that:

> *"Recovery of cadmium from spent NiCd cells is almost solely made from the industrial size NiCds as effective recollection systems for the consumer size cells are still lacking"*

As shown in the data above, this statement is simply not true. The increasing amounts of recycled cadmium have been well publicized in many publications and presentations in recent years, especially the growth in the NiCd consumer battery collection programs. The Noreus Report refers to none of this extensive information. Furthermore, the Noreus Report refers instead to a 1986(!!) study by the Metra Consulting Group under contract to the EEC which concluded that available NiCd battery recycling capacity for Western Europe was only at most 350 tons of cadmium metal. While this statement may have been true in 1986, it certainly is not true in 2000, the date of the Noreus Report. Today, worldwide NiCd battery recycling capacity is 50 times higher.

The actual NiCd battery recycling capacities today are:

Available recycling capacity

Company	Country	Capacity, tons of NiCd batteries
INMETCO	USA	3,500
SNAM	France	5,400
SAFT	Sweden	1,500
Accurec	Germany	1,000
Hanil Metal Recycle	Korea	3,000
Toho Zinc	Japan	1,700
Mitsui Mining	Japan	1,800
Total		17,900

As can be seen from this analysis, it is not the recycling capacity that is the problem, it is the collection of spent batteries. The industry has now made large investments in recycling capacity, and recollection has been organized in North America, Europe and Japan. The industry's NiCd collection programs, along with their appropriate recyclers, are summarized in the Table below.

Battery collection and recycling industry

Region	Collection Organization	Recyclers
North America	RBRC	INMETCO
Europe	CollectNiCad	SNAM SAFT AB Accurec
Japan/Korea	BAJ Japan Recycle Center	Mitsui Mining & Smelting Co Toho Zinc Co Kansai Catalyst Ltd Hanil Metal Recycle

7. Conclusions

- NiMH cells have gained market share over NiCd cells in applications with demand for high volumetric energy density and low discharge currents in operations with close to normal temperatures. Typical applications are batteries for lap top and handheld computers and, above all, cellular telephones. The NiMH batteries dominate in these market areas. However, it can be expected that lithium ion (Li-ion) and lithium polymer (Li-polymer) will be seriously competing with NiMH batteries in these applications, once high cost and safety issues have been resolved.

- NiCd consumer cells have maintained their strong position in applications for high power requirements and where batteries are exposed to temperature extremes, severe deep cycling and mechanical abuse. It is also in these areas and where high reliability and a long dependable life as well are required that the industrial NiCd cells have their strongest market position. Here the vented industrial lead acid and Valve Regulated Lead Acid (VRLA) batteries cannot compete in price per unit of performance and customer satisfaction. Recently, low maintenance industrial NiCd cells have grown strongly in the decentralized systems telecommunications market which used to be exclusively dominated by lead acid batteries.

- As large NiMH cells are very sensitive to temperature, it is expected that the maximum realistic capacity for NiMH batteries will be 70-80 Ah, which will limit their presence in the industrial market. NiCd and lead acid batteries in industrial applications have achieved capacities 10 to 15 times higher than this limit.

- The major disadvantages with NiMH cells are their narrow operating temperature range, relatively short cycle life, high heat dissipation during charging, and very limited tolerance to overdischarge. All of these cell deficiencies can result in significant risk of individual cell imbalance in multicell batteries.

- Most of the cadmium produced and consumed today is used in NiCd batteries, and the amount consumed in batteries compared to total cadmium consumption has increased steadily in the past 15 years. It is indeed remarkable that the amount of cadmium consumed in batteries in Europe has not dropped significantly when considering secondary cadmium recovered from the recycling of spent NiCd batteries and the increasing NiMH market share in the consumer cell market. It must be concluded, therefore, that there remains a high demand for NiCd batteries in applications where its unique characteristics make it the preferred battery chemistry.

- As Japan is the largest producer and consumer of cadmium for NiCd batteries, and considering its concern with environmental issues and quality of life, it also must be concluded that it is possible to manage the risks of cadmium in the production, use and disposal of NiCd batteries. Adequate risk management has also been demonstrated in Sweden where NiCd batteries have been produced since the early 1900s. Sweden has been a pioneer in research on the effects of cadmium on human health, and, beginning in the early 1950s, the NIFE Jungner plant in Sweden cooperated closely with the medical community there to protect the health of cadmium-exposed workers. At about the same time, the first industrial process for recycling spent industrial NiCd batteries was developed at NIFE Jungner in Sweden.

- The recycling of spent industrial NiCd batteries has been established in the industry for many years. The recycling of consumer NiCd batteries is neither an economic or technical problem as the recycling technology was developed in Sweden in the 1960s. Home storage (hoarding) of portable rechargeable consumer batteries, however, is an important phenomenon, which must be recognized when considering collection and recycling programs. It has been proven that the quantity of NiCd batteries in Municipal Solid Waste represents only a small fraction (a few percent) of the batteries available for collection. Most of the quantities sold during the last ten years remain stored at home because of the perceived inherent value of battery-powered appliances and rechargeable batteries.

- The costs of the raw materials in NiMH cells are higher than the costs of the raw materials in the long-established lead acid and NiCd cells. This cost difference will limit the use of NiMH batteries, as cost factors will always play a role in battery price per unit of performance. It is the price per unit of performance that is the price driver when it comes to purchasing decisions at original equipment manufacturers (OEMs) and end users. The high material costs will also eventually have an impact on the NiMH consumer battery producers when the fight for market share is no longer the key element.

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