

HOW DO NICKEL-CADMIUM CELLS COMPARE TO ZINC-CARBON DRY CELLS AND WHAT ARE THE IMPLICATIONS OF THEIR WIDESPREAD USE ?

INTRODUCTION

A battery is a device that produces electrical energy by conversion of chemical energy. Defined as a collection of cells, the term battery is now commonly used to refer to single celled batteries such as the common Duracel or EverReady battery. Batteries may be classified according to their basic design, it is this design that determines the amount of electricity provided. Produced in two general forms: primary and secondary cells, the efficiency of a battery can be compared. This investigative report aims to give a comparison of efficiency of a primary cell (Zinc-Carbon dry cell) and a secondary cell (Nickel-Cadmium cell). A comprehensive report will be given on two main areas of study. The first being (1) galvanic cells as a source of electrical energy; the transformation of energy in primary and secondary cells, the recharging process in a secondary cell; the general structural features and principals of operation of common galvanic cells. The second area of study will look mainly at (2) the electrochemical series and its use in predicting redox reactions in galvanic cells and finally the limitations of these predictions will be investigated. The approach to investigating these ideas is to use two chemical concepts, Energy and Chemical reactions. The implications of the use of Nickel-Cadmium cells will also be explored.

CHEMICAL PROCESSES:

CONVERSION OF CHEMICAL ENERGY INTO ELECTRICITY:

The basic structure of all cells involves the following essential features; Two electrodes, one negatively charged (ANODE), this is the site of oxidation, where electrons are produced and donated (by the reductant) The other electrode at the positively charged pole (CATHODE) is reduced, it accepts electrons and is where the oxidant is found.¹

A sheet of porous material or a salt bridge separates the electrodes. The partition prevents the electrode materials from coming into direct contact, reacting and discharging spontaneously. Reactions that occur when chemicals are directly mixed are described as naturally occurring or spontaneous reactions.² The other essential feature of a cell is the electrolyte. The electrolyte allows the free flow of ions between the two electrodes, ultimately completing the circuit and producing energy. The diagram below demonstrates these features.

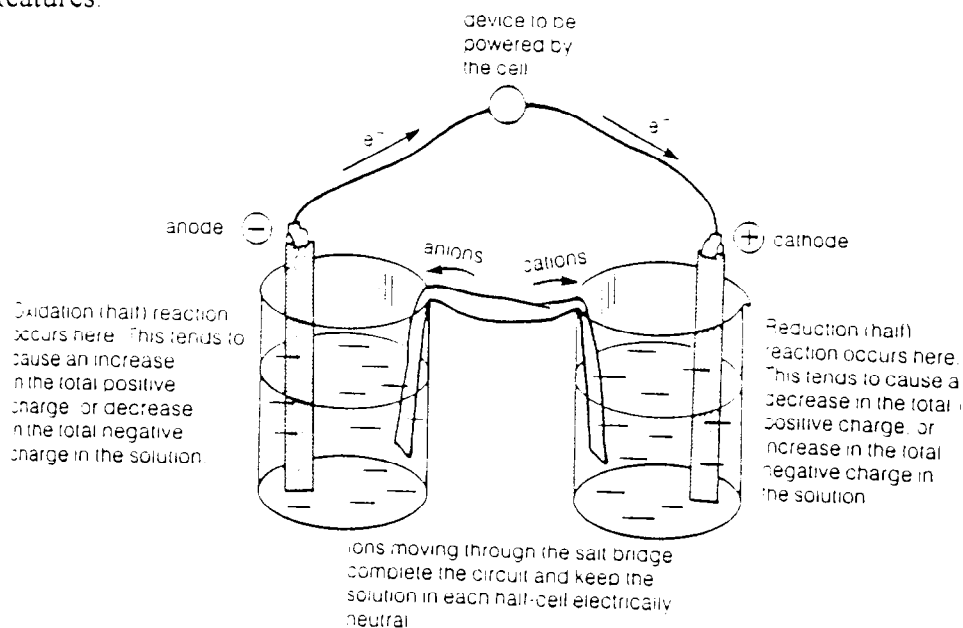


FIGURE 1- BASIC CELL³

¹ Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Hienemann, Port Melbourne

² Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Hienemann, Port Melbourne

The Galvanic cell is a good example of the basic cell, as the complete circuit (transfer of electrons) can be seen. There are three basic types of Galvanic Cells.(demonstrated in *Figure 2*)

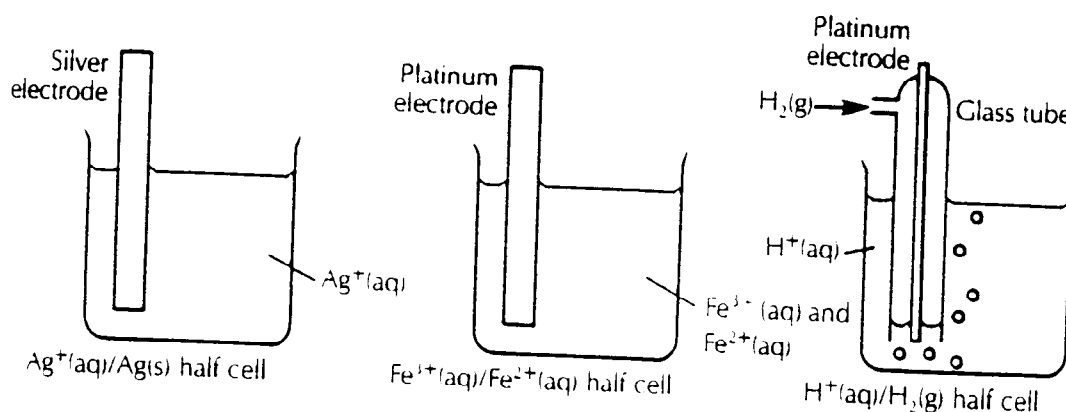


FIGURE 2- GALVANIC CELLS[‡]

PRIMARY & SECONDARY CELLS

Batteries can be classified into two separate groups, Primary or Secondary cells. The most prominent differences and uses of the two types of cells are:

Primary Cells	Secondary Cells
non-rechargeable	rechargeable
must be discarded	may be re-used
chemicals sources are exhausted	chemical reactions may be reversed
most contain dry or moist electrolyte	most contain liquid electrolyte
USES	
flash lights & radios	car batteries
tools & toys	remote area reserve energy supply

[‡] Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Hienemann, Port Melbourne

ZINC-CARBON DRY CELLS

The Zinc-Carbon dry cell is defined as a primary cell because the chemical reactions involved are irreversible.

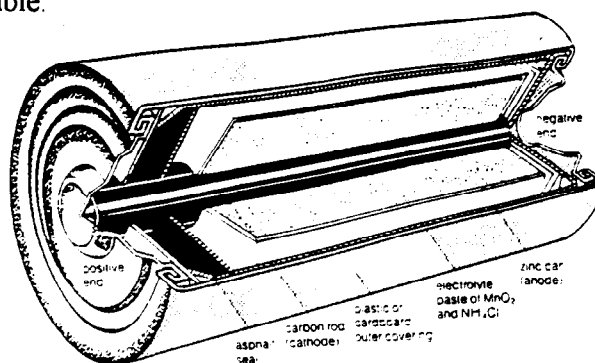
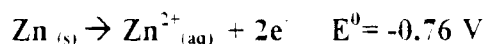


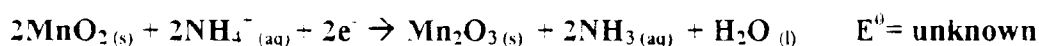
FIGURE 3- ZINC CARBON DRY CELL⁵

As shown in *Figure 3*, the zinc case of the battery acts as the anode, whilst the cathode is a carbon rod in the centre, hence the name, Zinc-Carbon cell. The electrolyte (consisting of a moist paste of zinc chloride and ammonium chloride) acts to complete the circuit between the two electrodes, allowing the transfer of ions. It can be seen that oxidation occurs at the Zinc electrode (anode), while the reduction occurs at the Carbon electrode (cathode). Alkaline solutions are used to help transfer of ions to specific areas (the electrolyte) of the cell. These chemical reactions are:

At the anode: oxidation of the zinc produces electrons:



At the cathode: manganese dioxide is reduced:



When a cell is connected to an external circuit, the excess electrons flow through the circuit to the carbon rod, this movement forms an electric current. The electrons then combine with molecules of manganese dioxide and ammonium. As these substances are reduced and react with one another, they form manganese oxide and negative hydroxide ions combine with positive ammonium ions that form when ammonium chloride is dissolved in water. These reactions continue to occur until the manganese dioxide wears

⁵ Smith, A. & Dwyer, C. (1988) Chemistry about you Thomas Nelson Publishers, Australia

away. The cathode is used up and the cell is dead as it can no longer produce energy, nor be effectively recharged.

NICKEL-CADMIUM CELLS

The cells have a nickel hydroxide cathode and a cadmium anode, emersed in a potassium hydroxide electrolyte, this is all assembled in a steel container as demonstrated in *Figure 4*. The anode and cathode material are contained in porous plates, these plates hold the materials securely and serve another important purpose: they are conductive; increasing the efficiency of the system.⁶

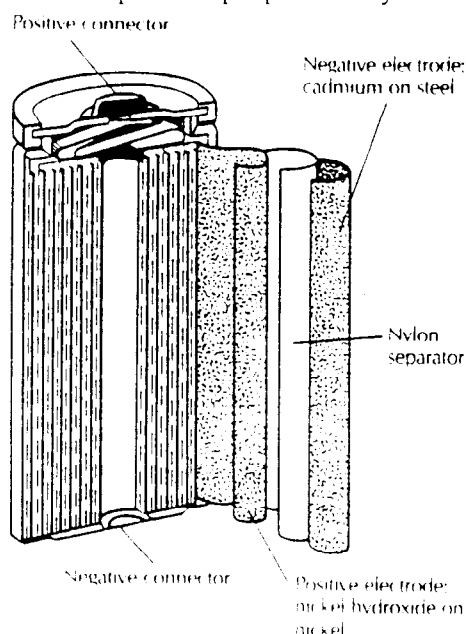


FIGURE 4- NICKEL-CADMIUM CELL⁷

It is this structure that allows the cell to be recharged, as "the anode structure is not seriously distorted as the cadmium is oxidised; nor is the cathode as the nickel is reduced."⁸ The reversible chemical reactions involved in this process are as follows

⁶ Lewis & Slade (1990) Second Edition A guide to HSC Chemistry Longmann Cheshire House, Melbourne

⁷ Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Heinemann, Port Melbourne

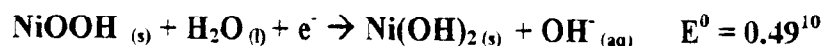
⁸ Lewis & Slade (1990) Second Edition A guide to HSC Chemistry Longmann Cheshire House, Melbourne

⁹ Vincent, C. Modern Batteries Publisher: Arnold, E

At the anode; oxidation of the cadmium produces electrons, this reacts with OH⁻ ions and precipitates:

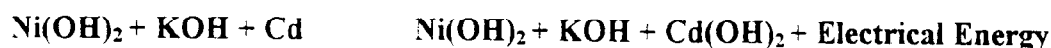


At the cathode; Nickel is reduced:



The overall reversible reaction is therefore¹¹:

Discharge



Charge

To reverse a chemical reaction, an external source of electrical energy is required. This electricity is then passed through the cell, reversing the terminals causing a backward direction of the chemical action, changing the products back into their original state, ready to be reused again. Each time the cell is recharge it does lose a minute amount of efficiency, eventually rendering it unusable, though most secondary cells last for many years.

COMPARING AND MEASURING EFFICIENCY

To gain an approximate prediction of cell voltage, the electrochemical series can be used. The electrochemical series lists E⁰ values, these give potential differences of cells at standard conditions.¹²

Standard conditions

Temperature: 25⁰C (298K)

Pressure: 1atm (101.325kPa)

Concentration of solutions: 1M

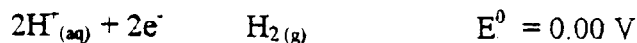
¹⁰Vincent, C. Modern Batteries Publisher: Arnold, E.

¹¹ (1993) Battery Technologies Produced by Energy Victoria, Australia

¹² Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Hienemann, Port Melbourne

The potential differences of half cell reactions given in the electrochemical series are measured by comparison to a standard half cell.

A standard hydrogen electrode (*s.h.e.*):



All other half cells are measured in comparison to this half cell. The voltage reading given on the voltmeter gives the E^0 value. Hence the value can be negative or positive, depending upon the electrochemical reaction given.

ELECTROCHEMICAL SERIES

		E^0/V
STRONGEST OXIDANT	$\text{F}_2(\text{g}) + 2\text{e}^- \rightleftharpoons 2\text{F}^-(\text{aq})$	2.87
	$\text{H}_2\text{O}_2(\text{aq}) + 2\text{H}^+(\text{aq}) + 2\text{e}^- \rightleftharpoons 2\text{H}_2\text{O}(\text{l})$	1.78
	$\text{MnO}_2(\text{aq}) + 8\text{H}^+(\text{aq}) + 5\text{e}^- \rightleftharpoons \text{Mn}^{2+}(\text{aq}) + 4\text{H}_2\text{O}(\text{l})$	1.50
	$\text{Cl}_2(\text{g}) + 2\text{e}^- \rightleftharpoons 2\text{Cl}^-(\text{aq})$	1.36
	$\text{Cr}_2\text{O}_7^{2-}(\text{aq}) + 14\text{H}^+(\text{aq}) + 6\text{e}^- \rightleftharpoons 2\text{Cr}^{3+}(\text{aq}) + 7\text{H}_2\text{O}(\text{l})$	1.33
	$\text{O}_2(\text{g}) + 4\text{H}^+(\text{aq}) + 4\text{e}^- \rightleftharpoons 2\text{H}_2\text{O}(\text{l})$	1.23
	$\text{Br}_2(\text{l}) + 2\text{e}^- \rightleftharpoons 2\text{Br}^-(\text{aq})$	1.09
	$\text{NO}_3^-(\text{aq}) + 4\text{H}^+(\text{aq}) + 3\text{e}^- \rightleftharpoons \text{NO}(\text{g}) + 2\text{H}_2\text{O}(\text{l})$	0.96
	$\text{NO}_3^-(\text{aq}) + 2\text{H}^+(\text{aq}) + \text{e}^- \rightleftharpoons \text{NO}_2(\text{g}) + \text{H}_2\text{O}(\text{l})$	0.81
	$\text{Ag}^+(\text{aq}) + \text{e}^- \rightleftharpoons \text{Ag}(\text{s})$	0.80
	$\text{Fe}^{3+}(\text{aq}) + \text{e}^- \rightleftharpoons \text{Fe}^{2+}(\text{aq})$	0.77
	$\text{O}_2(\text{g}) + 2\text{H}^+(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{H}_2\text{O}_2(\text{aq})$	0.68
	$\text{I}_2(\text{s}) + 2\text{e}^- \rightleftharpoons 2\text{I}^-(\text{aq})$	0.54
	$\text{Cu}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Cu}(\text{s})$	0.34
	$\text{Si}(\text{s}) + 2\text{H}^+(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{H}_2\text{Si}(\text{aq})$	0.14
	$2\text{H}^+(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{H}_2$	0.00
	$\text{Pb}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Pb}$	-0.13
	$\text{Ni}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Ni}(\text{s})$	-0.25
	$\text{Co}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Co}(\text{s})$	-0.28
	$\text{Cd}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Cd}(\text{s})$	-0.40
	$\text{Fe}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Fe}(\text{s})$	-0.41
	$\text{Cr}^{3+}(\text{aq}) + 3\text{e}^- \rightleftharpoons \text{Cr}(\text{s})$	-0.71
	$\text{Zn}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Zn}(\text{s})$	-0.76
	$2\text{H}_2\text{O}(\text{l}) + 2\text{e}^- \rightleftharpoons \text{H}_2(\text{g}) + 2\text{OH}^-(\text{aq})$	-0.83
	$\text{Mn}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Mn}(\text{s})$	-1.03
	$\text{Al}^{3+}(\text{aq}) + 3\text{e}^- \rightleftharpoons \text{Al}(\text{s})$	-1.71
	$\text{Mg}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Mg}(\text{s})$	-2.38
	$\text{Na}^+(\text{aq}) + \text{e}^- \rightleftharpoons \text{Na}(\text{s})$	-2.76
	$\text{Ca}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Ca}(\text{s})$	-2.76
WEAKEST OXIDANT	$\text{K}^+(\text{aq}) + \text{e}^- \rightleftharpoons \text{K}(\text{s})$	-2.93

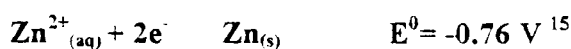
“The potential difference of a cell at standard conditions is the difference between the E^0 values of its two half cells.”¹³

Cell potential difference = higher half cell E^0 (V) - lower half cell E^0 (V) ¹⁴

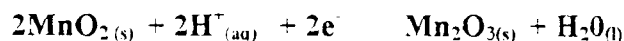
$$\text{e.m.f.} = E^0_{\text{oxidant}} - E^0_{\text{reductant}}$$

PREDICTING REDOX REACTIONS USING E^0 VALUES

The potential difference (voltage) can be predicted by using the electrochemical series. For example, using the Zinc-Carbon cell; because Zinc has a lower E^0 value (lower in the electrochemical series) it is more likely to be oxidised. (*See example:*)



The second, half equation is not listed in the electrochemical series, though we have been given the total voltage for the complete cell, the E^0 value can be calculated as follows:



If E^0 total = 1.5 V, the e.m.f. calculation used above can be adapted:

$$\text{e.m.f.} = E^0_{\text{oxidant}} - E^0_{\text{reductant}}$$

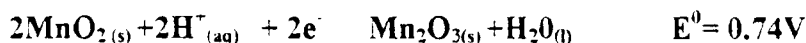
$$\text{e.m.f.} = \text{unknown } E^0 - E^0_{\text{reductant}}$$

$$1.5 = \text{unknown } E^0 - -0.76 \text{ V}$$

$$\text{unknown } E^0 = 1.5 - 0.76 \text{ V}$$

$$\text{unknown } E^0 = 0.74 \text{ V}$$

This therefore tells us that the redox reaction (shown below) is reduced



¹³ Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Hienemann, Port Melbourne

¹⁴ Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Hienemann, Port Melbourne

¹⁵ Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Hienemann, Port Melbourne

The same predictions can be made with the Nickel-Cadmium cell. The potential difference of the cell, where the oxidant has $E^{\circ} = 0.49^{16}$, and the reductant has $E^{\circ} = -0.81^{17}$, the e.m.f. is calculated as follows:

$$\text{e.m.f.} = E^{\circ}_{\text{oxidant}} - E^{\circ}_{\text{reductant}}$$

$$\text{e.m.f.} \approx 0.49 - -0.81$$

$$\text{e.m.f.} \approx 1.3 \text{ V}$$

Therefore it can be seen that the electrochemical series can be used to accurately predict the potential difference in redox reactions.

LIMITATIONS (of the electrochemical series and its' applications)

1. Electrochemical series is based upon standard conditions only.
2. The series assumes that the voltage is constant. If the two cells are compared under different conditions, used in different appliances the suggested voltage output would no longer be accurate.
3. The electrochemical series does not predict the rate of reaction¹⁸

COMPARISON OF THE ZINC-CARBON / NICKEL-CADMIUM CELLS

As seen in the graph below, the secondary cell holds its' voltage for a longer duration, while the primary cells' discharge diminishes. During use of the dry cell there is a build up of products at the electrodes, this slows the forward reactions, may even stop it. This effect occurs largely during prolonged operation and is known as polarisation.

¹⁶ Vincent, C. Modern Batteries Publisher: Arnold, E.

¹⁷ Vincent, C. Modern Batteries Publisher: Arnold, E.

¹⁸ Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Hienemann, Port Melbourne

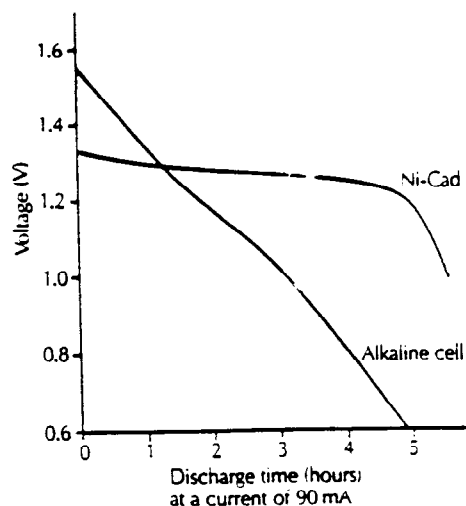


FIGURE 20.5 Changes in voltage as Ni-Cad and alkaline cells discharge.

Nickel-Cadmium	Zinc-Carbon
Rechargeable	Single use only
Shelf life: 25 years ¹⁹	Up to 3 years
Discharge/Recharge cycle up to 500 ²⁰	Discharge approx. 20 hours
USES ²¹	
Emergency power supply	torches
calculators	portable radios
toys	toys
small appliances	small appliances
$E^0 \approx 1.2V$	$E^0 \approx 1.5V$

The Nickel-Cadmium can be used as large energy source, varying in size and available voltage, as opposed to the dry cell which is impractical for use on a large scale.

¹⁹ World Book Multimedia Encyclopedia (1996) Battery Microsoft, USA

²⁰ Commons et al (1995) Second Edition Chemistry Two, Chemistry and the Marketplace: Energy and Matter Rigby Heinemann, Port Melbourne

²¹ Microsoft Encarta Encyclopedia (1996) Electrochemistry Microsoft, USA

IMPLICATIONS OF WIDESPREAD USE OF NICKEL-CADMIUM CELLS AND ZINC-CARBON DRY CELLS

ENVIRONMENTAL IMPLICATIONS

“The contamination of our environment by heavy metals is a constant and disturbing problem.”²² Heavy metals are among the most dangerous and least understood of contaminants. In this context, the term heavy metals indicates the metals mercury, cadmium and zinc. Disposal of the Nickel-Cadmium cells and of a large quantity of Zinc-Carbon cells can eventually have a detrimental effect on the environment. Soils, rivers oceans, and animals are at risk of contamination by these metals. Large concentrations of Cadmium that have a long residence in the body can lead to bone porosity and total inhibition of bone repair²³. Mercury and zinc in excess amounts are also known to cause major problems. Heavy metals are in widespread industrial use. When they are released carelessly into the environment, air or rivers, they distort naturally occurring distribution of metals.²⁴

ECONOMICAL IMPLICATIONS

The Nickel-Cadmium cells have been limited to a relatively small share of the market due to their short charge shelf life and inability to store large amounts of energy initially. This causes them to require frequent charging, several times during the normal time that an Alkaline battery may last. The units are expensive in their initial costs, due to the expense of Nickel.²⁵ A comparison of the costs between the two cells Nickel-Cadmium and Zinc-Carbon can be made. Allowing that the Nickel-Cadmium has a discharge/charge cycle of up to 500 times, the following figures demonstrate the difference in overall expense.

²² Selinger, B. (1981) Third Edition Chemistry in the Marketplace Harcourt Brace Jovanovich, Publishers, Australia.

²³ Selinger, B. (1981) Third Edition Chemistry in the Marketplace Harcourt Brace Jovanovich, Publishers, Australia.

²⁴ Selinger, B. (1981) Third Edition Chemistry in the Marketplace Harcourt Brace Jovanovich, Publishers, Australia.

²⁵ New scientist, 15 April 1995

• Nickel-Cadmium Battery			
Recharger:	\$24.95 ²⁶		
Battery:	\$3.48 ²⁷		
Electricity:	≈\$3.50	Total costs:	≈\$31.93
• Zinc-Carbon Battery			
Battery:	\$1.94 ²⁸	Total costs:	≈\$970

The above calculations prove that the cost of buying 500 Zinc-Carbon batteries is approximately 30 times higher than the cost of purchasing and maintaining a Nickel-Cadmium battery.

CONCLUSION

All cells consist of the basic essential parts of two electrodes (an anode and a cathode), an electrolyte (allowing flow of electrons), separators(or salt bridges). Chemical reactions involve the general transfer of electrons (oxidation and reduction) A complete circuit is required, allowing the transformation of chemical energy from chemical reactions into electrical energy. Primary and secondary cells are the two main basic groups of cells, though only a secondary cell may have the chemical reactions reversed, allowing it to be recharged.

When comparing the Nickel-Cadmium (secondary) cell and the Zinc-Carbon (primary) cell, there are many important issues involved in the two cells, that in some cases make them similar, in other the two cells, appear to be completely different. Whilst generally the two cells share the same uses, powering small appliances, tools, toys, the Nickel-Cadmium cell is more effective in an economical sense. The Nickel-Cadmium battery, (as a

²⁶ Costs courtesy of K-MART, East Burwood (1996)

²⁷ Costs courtesy of K-MART, East Burwood (1996)

²⁸ Costs courtesy of K-MART, East Burwood (1996)

[REDACTED]

secondary cell) may be recharged and therefore its initial high cost is accounted for in its ability to be recharged up to 500 times. The Nickel-Cadmium battery however does not have an extremely high voltage, though it is able to retain its' power at a more constant level of 1.2 Volts, whilst the dry cell has a short duration of maximum power (1.5V) before it diminishes. Both cells have similar efficiency with their E^0 values lying within the same range, as can be seen on the electrochemical series table. It can be said that when all features concerned are considered, the Nickel-Cadmium is a more efficient cell in its' features of reliability and recharging ability.

The Zinc-Carbon cell appears to have a larger market appeal due to its numerous uses in portable torches, radios etc. Whilst the Nickel-Cadmium still has only a comparatively smaller share of the market, dealing mainly with calculators. The Nickel-Cadmium cell lasts for an extensive period of time. The Nickel-Cadmium however, has the potential to be further developed and used in more larger scale applications across the world.

*"Battery development is evolutionary in nature. It takes both money and time."*²⁹

WORD COUNT: 1987

²⁹ New Scientist 15 April 1995. James Glanz

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