1 INTRODUCTION

In recent years there has been a trend for battery-powered portable equipment to become both smaller and at the same time more energy hungry. This trend has been facilitated by the introduction of lithium-ion (Li-ion) rechargeable batteries. Compared with more traditional rechargeable systems, such as Sealed Lead Acid (SLA), Nickel Cadmium (NiCd) and Nickel Metal Hydride (NiMH), lithium-ion batteries offer significantly improved performance combined with a compact and lightweight design.

Lithium-ion battery technology was pioneered by Sony EnergyTec Inc. of Japan, using under licence, AEA Technology's patented electrochemistry. Since the first successful market introduction in 1990, lithium-ion batteries have emerged as the leading power source for a wide range of applications. Driven by the demands of the portable electronic consumer market, the volume of manufacture of lithium-ion cells has grown at a phenomenal rate. AEA Technology has licensed 23 companies worldwide with its lithium-ion system.

AGM Batteries is a joint venture between AEA Technology plc, Japan Storage Batteries and Mitsubishi Materials, which was initiated in 1998 to manufacture specialist lithium-ion cells.

2 LITHIUM-ION CHEMISTRY

In the search for higher energy density rechargeable cells, employing lithium metal as the active material was always seen as the ultimate goal. Lithium is the lightest metallic element and generates a high voltage versus the standard hydrogen electrode (-3.045V). Early attempts used lithium metal in combination with a transition metal oxide or sulphide intercalation compound. This technology, although providing high energy density, suffered from two main problems; limited cycle life and a poor safety record.

During the discharge and charge cycle, the lithium metal was stripped from the anode and plated onto the cathode, and then reversed. Unfortunately this stripping and re-plating process was not 100% efficient. The process created high surface area particulate lithium, which gradually consumed the lithium metal foil anode, and increased internal resistance, limiting cycle life. More importantly, the particulate lithium created the possibility of internal short circuit and potential safety problems.

The solution was to replace the lithium metal anode with a second intercalation compound that can reversibly intercalate Li^+. Carbon material provides this active anode material in all commercially available lithium-ion cells.

Since the anode is carbon, the active material of the cathode must be a compound that already contains Li^+ and moreover the Li^+ must easily be removed without a change in its molecular structure. There are two types of compound in general use; layered transition metal oxides (e.g. $LiCoO_2$, lithium cobaltite, and $LiNiO_2$, lithium nickelite), and the spinel material $LiMn_2O_4$. All the major companies, which manufacture lithium-ion cells, have found that $LiCoO_2$ offers superior reversibility, discharge capacity and charge/discharge efficiency.

As lithium-ion cells are charged and discharged, Li^+ ions are transported between the carbon-based anode electrode and the $LiCoO_2$ based cathode electrode, with electrons exchanged as a result of lithium ion insertion (doping) and lithium ion extraction (undoping). During charging, the cathode is undoped (i.e. the lithium ions are removed, and the anode is doped (i.e. the lithium ions are inserted). The process is reversed on discharge. When lithium-ion cells are first charged (or 'formed'), the lithium ions are transferred from the layers of the lithium cobaltite to the carbon material which forms the anode:

$$\mathbf{LiCoO_2 + 6C \rightarrow Li_{1-x}CoO_2 + Li_xC_6}$$

Subsequent discharge and charge reactions are then based on the motion of lithium ions between anode and cathode:

Discharging→

$$\mathbf{2Li_{1-x}CoO_2 + Li_{2x}C_6 \longleftrightarrow 2Li_{1-dx}CoO_2 + Li_{2dx}C_6}$$

← Charging

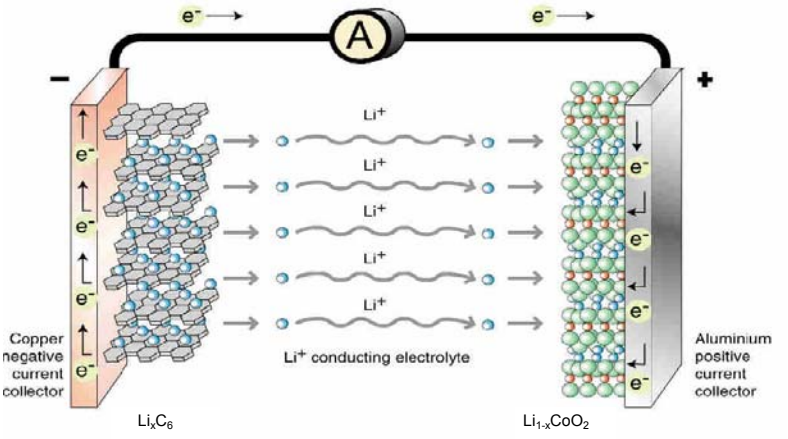

Figure 1: Lithium-ion discharge cycle

At present there are three types of carbon that are used as the active anode material in lithium-ion cells; coke, graphite and hard carbon. The earlier lithium-ion cells used coke. However, in order to achieve higher energy density, carbon materials with larger lithium ion doping capacities have been adopted.

AGM has selected graphite since the average discharge voltage (3.7V) is higher than for hard carbon (3.6V), and the delivered energy is therefore higher for the same cell capacity due to its 'flatter' discharge characteristics.

3 CELL CONSTRUCTION

Lithium-ion cells are available in two basic designs; cylindrical and prismatic. In principle, the prismatic design offers a number of benefits due to its improved packing efficiency when cells are packed together into multi-cell batteries. However, lithium-ion cells generate a certain amount of gas during initial and subsequent charges, and in order to avoid bulging the prismatic case needs to be made more sturdy making it heavier and larger. The cylindrical cell design is intrinsically stronger and hence the wall thickness is much less, providing a lower weight solution for a given capacity.

AGM has therefore based its cell design on the cylindrical type. The cell consists of a spiral wound 'coil-pack' of the two composite electrodes separated by micro-porous films, containing the electrolyte solution, in a sealed metallic case. Figure 2 shows a sectional view of the cell construction.

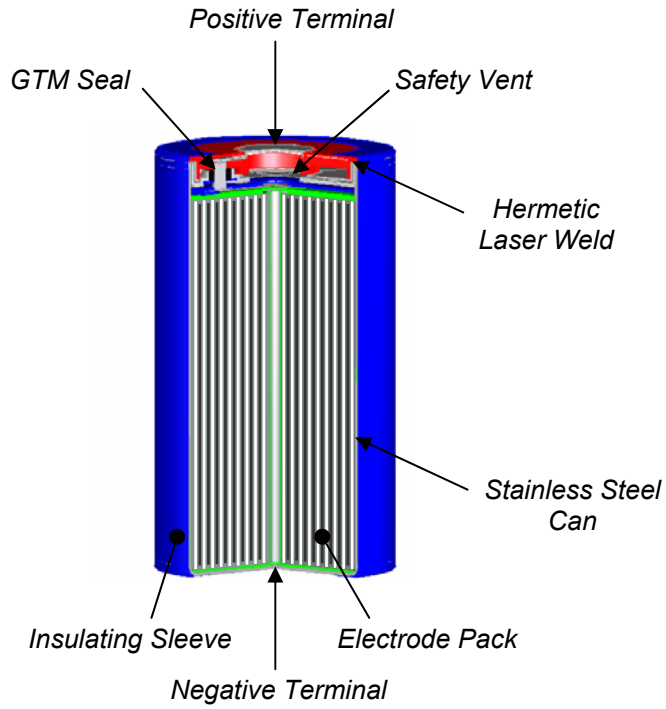

Figure 2: AGM cylindrical cell construction

The active material of the anode, graphite plus a binder, is coated on to a copper foil substrate. The cathode material ($LiCoO_2$ / carbon mix) plus binder is coated on an aluminium foil substrate. In both cases the coatings are applied uniformly to both sides of the metal foils.

The electrodes in an AGM ICR34600 ('D' size cell) are approximately 1.8m long, featuring multiple electrode tags to minimise cell resistance.

The selected separator is of the shutdown type, limiting cell activity at high temperatures. In addition it possesses excellent bi-directional mechanical strength for maximum electrode pack integrity against shock and vibration. The electrolyte solvent is a mixture of organic carbonates with a lithium hexafluorophosphate salt, providing good cell performance over a wide operational temperature range.

The cell case is a laser welded stainless steel cap / can assembly, incorporating a precision pressure bursting disc and glass-to-metal seal for the positive feed through pin. This construction has been selected to ensure maximum operational and storage life, hermetic sealing and abuse resistance.

4 FEATURES AND BENEFITS

Lithium-ion batteries have achieved very rapid market acceptance because of a number of significant features and benefits in comparison with more established battery technologies:

- Higher energy density
- Higher voltage per cell
- Better cycle life
- Excellent low temperature performance
- Lower self discharge
- Simpler battery management
- Simple charging methods
- Environmentally friendly

4.1 HIGH ENERGY DENSITY

Energy density determines the size and weight of any given battery. The objective is to minimise both size and weight. Energy density is usually expressed in terms of gravimetric energy density (Wh/kg) and volumetric energy density (Wh/litre). Figure 3 illustrates the comparison of lithium-ion cells with equivalent SLA, NiCd and NiMH.

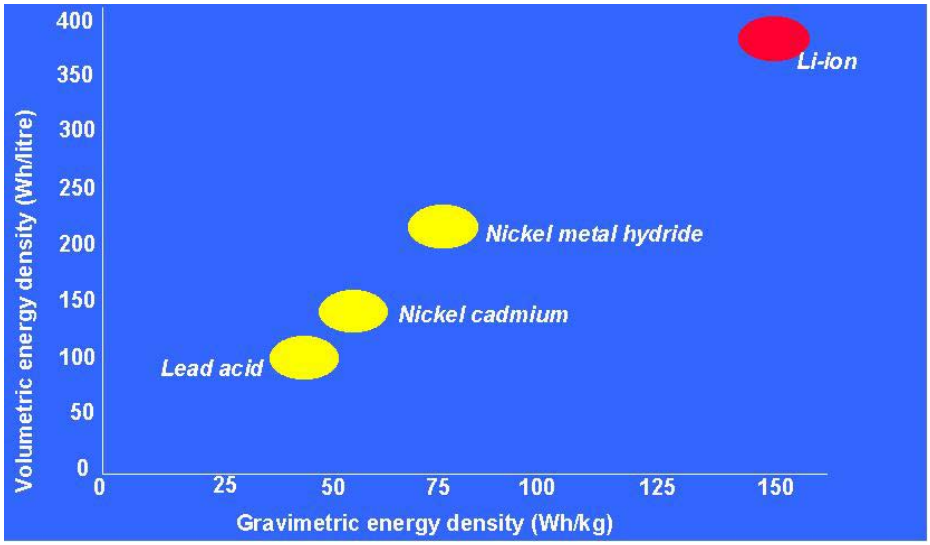

Figure 3: Energy density comparison

The AGM ICR34600 'D' size cell has a specific energy density of 150Wh/kg, and volumetric energy density of 375Wh/l, significantly better than NiMH or NiCd. The benefit to the designer is the ability to design much more compact and lighter portable equipment for todays ever more demanding markets.

4.2 HIGH VOLTAGE PER CELL

Lithium-ion cells have a typical operating voltage of 3.6V to 3.7V. The system has three times the operating voltage of both NiCd and NiMH cells. This provides the basis for the significantly higher energy density, but also means that fewer cells are required to build up an equivalent pack. For example, a 24V battery would require 20 NiCd or NiMH cells but only 7 lithium-ion cells. The benefit is reduced battery assembly costs and increased reliability.

4.3 EXTENDED CYCLE LIFE

The cell design and electrode formulation used by AGM, results in cells with an excellent cycle life. Typically cells will continue to cycle for a long time, gradually reducing in capacity, rather than suffering a catastrophic failure. Users must decide for themselves when they consider the cell / battery to have reached the end of its useful life (for example at 80% or 60% of its rated capacity).

Users also need to be aware that the number of useful cycles will be related to a number of factors, including; the rate at which the cells are discharged, the depth of discharge per cycle, the rate at which the cells are recharged, the operating temperature and the voltage to which the cells are charged.

In general at optimum rates of charge and discharge, and based on 100% depth of discharge, AGM lithium-ion cells will provide 1000 cycles before the capacity falls below 70% of rated capacity. In practice users rarely discharge to 100% depth of discharge on a regular basis, therefore cycle life would be expected to be well in excess of this. This compares very favourably with NiCd and NiMH cells, which have to be 'well managed' to achieve any significant cycle life.

4.4 EXCELLENT LOW TEMPERATURE PERFORMANCE

Lithium-ion cells exhibit significant advantages over NiCd and NiMH cells when discharged at low temperature. For example, when discharged at the C/2.5 rate, at -40ºC the AGM ICR34600 cell delivers 90% of its rated capacity (Ah). A typical NiCd cell would deliver significantly less than 50% of rated capacity at -30ºC at this discharge rate and negligible capacity at -40ºC.

The superior low temperature performance of AGM lithium-ion cells makes them the obvious choice for future military equipment, and other portable devices subject to low temperature exposure. In fact lithium-ion rechargeable batteries can compete with lithium primary batteries in many applications, with the significant benefit rechargeability.

4.5 LOW SELF-DISCHARGE

Self-discharge is caused by electrochemical processes within the cell. AGM lithium-ion cells typically lose 4% of their capacity during the first month's storage and 1% per month thereafter, when stored at +20ºC.

A typical NiCd cell will lose 25% in the first month and then 10% per month. This presents the user with a logistical problem, since charging before use is almost always needed for NiCd and NiMH cells. However, lithium-ion cells can be used even after a number of months in storage.

4.6 SIMPLER BATTERY MANAGEMENT

NiCd and NiMH cells suffer from a problem known as the 'memory effect'. The symptom is that after repeated partial discharges, the cells 'remember' the capacity last delivered and only deliver this capacity when next discharged. This effect is only removed by undertaking a slow full discharge and battery management therefore becomes necessary. Lithium-ion cells have no such characteristic. They do not have to be 'managed' in the same way, and can be repeatedly partially discharged with no subsequent loss of capacity.

4.7 SIMPLE CHARGING METHODS

Lithium-ion cells are easy to charge. A combination of constant current and constant voltage is used (the so-called CCCV method). The typical charge time is five hours, with a C/3 constant current stage followed by 2 hours at a constant 4.2V. Unlike NiCd cells, lithium-ion cells do not need any complex charge termination procedure, such as -ΔV, and can be terminated after 2 hours at constant voltage or when the current falls below a pre-determined level.

4.8 ENVIRONMENTALLY FRIENDLY

Cadmium content is the reason why restrictions on the use and disposal of NiCd cells are increasing throughout the world. Unlike NiCd cells, lithium-ion cells contain no cadmium.